Stator lamination stacks: Condition monitoring and repair of lamination short-circuits

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1 Summary

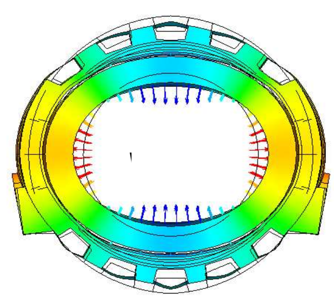
A major concern with respect to the safe, efficient operation of a large generator is the condition of the stator lamination stack. One of the primary aspects associated with this issue, one with great consequential costs, is damage to the stator lamination stacks of large generators. It is therefore essential that manufacturers and operators have conclusive methods of monitoring and evaluating the condition of the stack insulation system.

In the power generation industry today, the two most prevalent lamination stack tests utilize either low induction or high induction test methodology. Over time, the low induction methods became the preferred method, largely because they required less complex technology and could frequently be performed with the rotor in place at a comparably low cost. Over the past few years, however, an increasing number of utilities and equipment manufactures have begun performing high induction tests to asses the condition of their unit(s). Measurements on generator stators in diverse performance categories have shown that the high induction methods provide the most reliable results.

2 Design of the lamination stack and failure mechanisms

Typically, the most effective test method to monitor the condition of a particular component can best be selected on the basis of the potential failure mechanism(s) of that component. In the case of a generator stator core it is first important to understand the basic design of the stack iron in order to fully understand the failure mechanism,.

The core lamination stacks are made up of tens of thousands of single, thin sheets of iron that are electrically isolated from one another. In early generator designs, paper insulation was used, but in the last twenty years insulating varnishes have generally been applied to provide the insulating function. By using pressure plates and clamping bolts, the lamination stack is compressed and mounted within the generator frame. Depending on the manufacturer, the stack is generally mounted in one of two ways – either insulated from the frame with only a single ground point, or installed without the frame insulation such that it is grounded at all the core support beams (mainly at the fusion welds).


Elliptical deformation of core due to electromagnetic forces

In operation, the lamination stack is subject to several loads – a relatively slow thermally-dependant load and a rapid, alternating mechanical load caused by electromagnetic forces. The electromagnetic cycle deformation of the lamination stack occurs periodically, at double line frequency, and is significantly higher than the other operating loads. The radial deflection at the stator bore due to this load can reach values of 10 µm and higher. In addition to this elliptical movement, all of the stator laminations vibrate in the axial direction. No matter how firmly the stack is compressed, the laminations begin to pulsate axially as soon as the machine is energized.

Due to the presence of these operating loads, the lamination sheets of the stack are continuously exposed to small relative movements. This continuous movement can have detrimental effects on the stack, in most cases on the insulating materials, which are intended to electrically isolate the sheets from one another (and, as stated above, from the frame on certain units). The operation-induced wear process begins slowly at random points in the lamination stack. Over time, the approximately 20 µm thick insulating layer between the sheets begins to disintegrate, leading to a loss of the necessary insulating function and resulting in localized lamination shorts, or "hot spots". Hot spots can also be caused by non-operational factors such as fabrication defects or maintenance-related core surface damage. They can occur in generators with bonded core backs as well as those with insulated lamination core support.

Based on this failure mechanism, condition monitoring of lamination stacks is best accomplished by detecting the lamination short circuits and evaluating the risk of propagation during operation. Uncontrolled growth of a hot spot can lead to various unwanted conditions, from failure of the main insulation of the stator bars due to localized heating to a catastrophic failure such as a core iron fire. Since the thermal output of the hot spot is the driving force for its growth, the degree of damage should ideally be evaluated in terms of its excess temperature in relation to rated unit operating conditions.

3 3. Test methods

The lamination stack, basically a large hollow cylinder, is not directly accessible. Therefore, only indirect test procedures can be utilized to determine the condition of the stack.

Insulation defects lead to an increase in eddy current magnitude in the stack, producing higher I^2R losses at the point of contact, and generating excessive heat in the process. At the same time the increased eddy currents alter the stray magnetic field of the stack. It is upon these two principles that the two established test methodologies are based.

3.1 Low induction method

When testing the lamination stack with the low induction method, the stator is energized with approx. 5% of the rated induction. The stray field data for each slot is collected at the bore surface over the entire length of the core. Based upon this data, curve progressions can be derived, from which the size and location of the defects in the lamination stack can be determined.

This test is easy to set up and perform, and the costs are relatively low. Since testing is done with only 5% rated induction, significantly less than 0.1 Tesla, a simple 110 V (230 V in European standards) power supply is required. Thin, commercially available cabling is sufficient for the induction loop(s). Also, because the detector is small, this test can be performed without removing the rotor for certain makes of turbo-generators.

3.2 High induction method

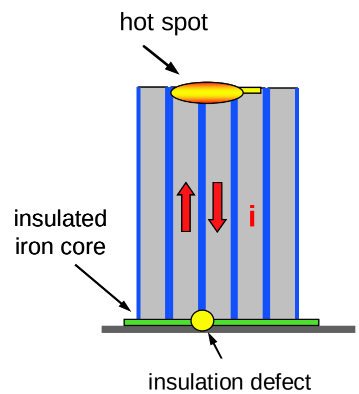
High induction methods, on the other hand, utilize approx. 75% of the rated induction, 15 times that of the low induction procedure. As such, the test equipment, and the test procedure itself, is slightly more complex. In order to create high induction test conditions similar to normal operating conditions, a medium voltage power supply capable of producing up to 500 kW of power is required, although the actual test conditions are dependent on the design characteristics of the particular generator. Throughout the testing period, from initial energizing to final temperature stabilization, the thermal behavior of the core iron is recorded via thermal imaging camera(s) focused on the bore in order to identify areas outside the expected normal temperature profile.

4 Theoretical analysis

4.1 Assessment criteria

To date, there are no national or international standards for the methodical analysis of lamination stack testing. Hence, the test conditions and evaluation criteria for the results must first be discussed.

Faults in the lamination stack typically only occur as a consequence of mechanical and thermal stresses, both being of an operational nature. Once present, the faults will in many cases only come to evidence under operating conditions. The behavior of the same defective spots in a lamination stack not subjected to the normal mechanical and thermal stresses present during unit operation, e.g. during low induction testing, is not known; therefore, the low induction testing may not detect the area(s) of concern.



Regardless of the test method used, detection of the core lamination faults relies on the presence of an increased eddy current at a particular axial location. During the testing procedure, this eddy current is generated due to damage of the insulation between adjacent lamination sheets, providing the first point of contact in a necessary closed loop current path. The second point of contact will typically either be a second defect or faulty insulation at the lamination core support. As explained previously certain units are not insulated at the core support and, therefore, inherently provide a second point of contact.

It is important to note that the contact is not pure metallic (low Ohm resistance) but depends on the progress of the degradation as well as manufacturing and assembly tolerances. Also, the particular contact resistances can vary significantly between the operating and shutdown conditions – warm and energized lamination stack vs. cold and de-energized.

Faults can only damage the lamination stack while under operation, i.e. when the generator is energized. The higher the energization, the better the contact in the faults will be, and consequently the higher the heat generated, increasing the risk of damage. These operational and design relationships demonstrate that realistic results of lamination stack testing can only be expected when the **test conditions** are not significantly different from the actual operating conditions.

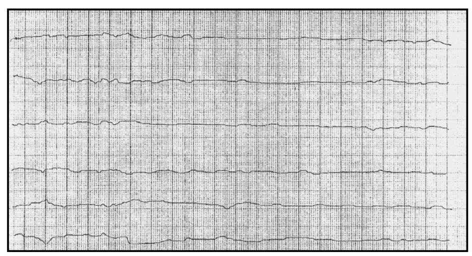
There is only one requirement to minimize the risk of a forced outage of the generator: the measurement and evaluation system must identify all the defects accurately and reliably.

4.2 Analysis with low induction

When utilizing the **low induction method,** the energy input to the lamination stack is very low. Therefore, there is no noticeable temperature increase and no electromagnetic vibrational stress imparted during the test. The optimum test conditions are thus not reached.

The low induction method works according to the principle of data collection of the stray fields directly above each slot over the length of the lamination stack and a corresponding anomaly analysis. The measurement curves have no direct relation to the faults and must be interpreted.

The theoretical analysis must under these circumstances conclude that the combination of low induction and magnetic detection is not suitable to provide adequately accurate and reproducible results for reliable assessment of lamination stacks.

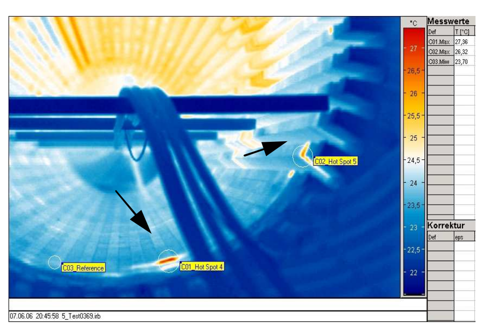


Progression curve showing variation of stray field along each slot

4.3 Analysis with high induction

In the **high induction method,** the energy input to the lamination stack is much higher – approximately 75% of the normal operating unit induction. As such, the lamination stack is subjected to heating and vibration as a result of the electromagnetic excitation, which corresponds to realistic operating conditions. Therefore, the requirement regarding test conditions is fulfilled.

Detection of hot spots is performed with a thermal imaging camera. More concentrated monitoring can be achieved by moving the camera or using several cameras. The faults in the lamination stack can be identified as a function of the



Thermal image of core showing hot spots as red dots; blue = lowest and red = highest temperature test time, with a direct local reference point at the location(s) where temperature increases are identified. Hot spots which lie radially deeper in the lamination stack can also be detected on the basis of heat conduction due to a time-delayed temperature increase at the surface. Once the faults are identified, additional details can be determined by utilizing other available tools such as localized temperature instruments and engineering evaluation software and calculations (e.g. Finite Element Analysis); these supply information on the radial position, size and heat generated by the “hot spot”. It is also important to note, however, that not only hot spots, but also their thermal reflections on the stator bore surface are detected with a thermal camera. Therefore, certain experience is required when interpreting the machine thermal picture.

The following theoretical analysis demonstrates that high induction in combination with the thermal camera can be considered a suitable method for condition monitoring of the lamination stack.

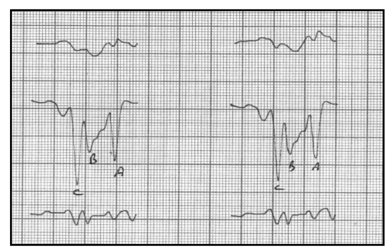
5 A practical example: low induction vs. high induction

The report examines lamination stack inspections on three generators using low induction methods from diverse suppliers, as well as the high induction method. The HI testing was done at the request of the operator. The tests were conducted in 2006 on several 2-pole generators, one in the 600 MVA class and one in the 800 MVA class, and on a 16-pole machine of the 250 MVA class.

5.1 600 MVA class generator

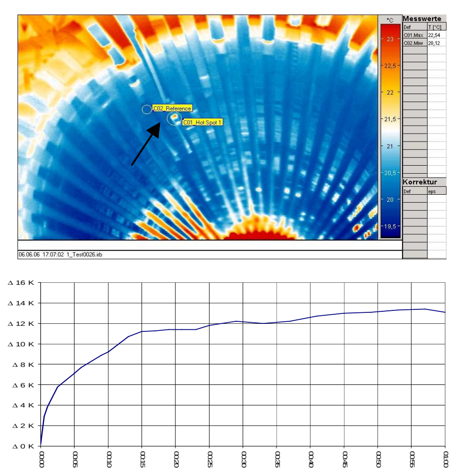
High induction condition monitoring was performed on this machine at the request of the operator after the manufacturer had discovered a fault with several low induction test runs. The fault was located in the radial direction under the slot base.

The relevant part of the low induction test curve shows a significant deflection above the 100 mA limit value and two additional, closely adjacent deflections just under this threshold. No other apparent problems were found with the low induction tests.



Low induction test indicating one large and two adjacent smaller faults

The following high induction test was performed in several steps. The preliminary test with approx. 30% rated induction (corresponds to 0.65 Tesla) focused on the low induction test findings. The fault was clearly identifiable; after a 60-minute test there was a localized temperature increase of 12 degrees K as compared to the reference temperature.



High induction test showing thermal image of hot spot (top) as well as development of hot spot temperature vs. time (bottom)

In coordination with the generator manufacturer, two further HI test runs were performed at 60% (1 hr.) and 80% (2 hrs.) rated induction (corresponding to approx. 1.2 Tesla and 1.6 Tesla); these were carried out to determine the exact location of the fault on the slot base. The differential temperature during these tests went up to 29 degrees K.

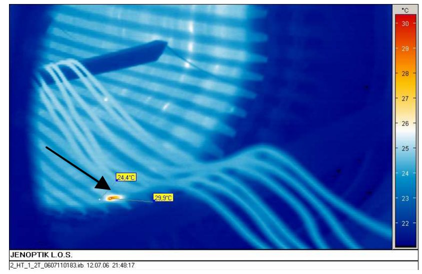
Several repair attempts were performed by the manufacturer; however, the maximum temperature at this location could only be reduced by 3 degrees K, resulting in a value of 26 degrees K above rated, which was still unacceptably high. Control tests with the low induction method, however, showed an unrealistic drop of the maximum deflection by nearly 50 mA in the area of concern, inconsistent with the local temperature noted following the repair attempts.

In addition to the previous in-depth information, the high induction testing method also resulted in finding 4 more defects, which had not been detected in the previous low induction tests.

5.2 800-MVA class generator

Immediately following performance of a low induction test without any abnormalities noted, a high induction test was carried out on this turbo-generator at the request of the operator.

This test was first performed as a preliminary test with approx. 60% of the rated induction (corresponding to 0.94 Tesla). No abnormalities were noted during this preliminary test. The subsequent main test, however, was performed with approx. 80% rated induction (corresponding to 1.19 Tesla) over the entire 75 minutes and resulted in locating a clearly visible fault.

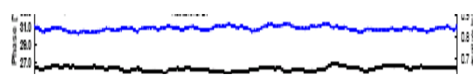


Thermal image of high induction test showing hot spot near core end

This test demonstrates how extremely important it is to achieve conditions similar to actual operation during condition monitoring of generator lamination stacks. As previously noted, no heating was detected during the preliminary test with 60% rated induction. Only when the mechanical and thermal stresses approached values similar to operating conditions did this fault become visible – such faults are termed “latent”. Consequently, low induction methods that utilize 5% of the operating load cannot detect latent defects reliably.

5.3 250-MVA class generator

The lamination stack of this machine was tested on site using the HI method as part of a new unit acceptance test in accordance with the operator requested acceptance test specifications. A total of five high induction tests (each at approx. 0.9 Tesla) were performed, in conjunction with the low induction test methodology used by the manufacturer.

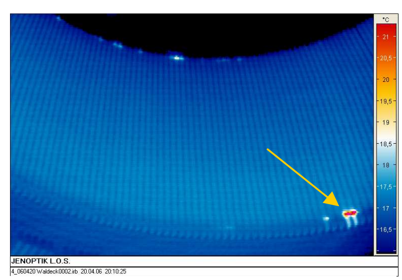


Progression curves of low induction test

Both test methods revealed four defects, each at the identical location. However, the potential risk was determined to be different.

In the low induction method, the lost heat – the risk potential – is calculated analytically following calibration and analysis of the magnetic slot stray field using physical relations and conversion from 5% test induction to the rated induction. The accuracy of the results is directly dependent on the measurement and evaluation accuracy and the accuracy of the mathematical model for this precise measurement point.

In the high induction method, at approx. 75% rated induction, the defects can be seen in the color variations produced by the thermal imaging camera. The temperature (in degrees Kelvin) of the area in question is referred to as the immediate online reference temperature and is a direct measurement. The temperature increases alone are sufficient for determining the risk potential. However, to provide a more extensive evaluation, the recorded temperature fields can then be analyzed with the help of proven FE models and calculations, and the heat loss and various characteristics can be determined reliably.



Thermal image of hot spot near core end

In addition to the 4 original locations which matched the low induction testing results, 4 more faults were detected with the high induction method only; these spots were below the acceptance threshold.

The repair activities on this lamination stack also deserve a closer look. The manufacturer performed two initial repairs conventionally with Mica sheets and the application of resin. These repair attempts were unsuccessful. Following completion of these repairs, follow-up testing revealed that four more faults had to be repaired. The final repair was then performed using the patented SENSOCORE Inject® repair procedure, which consists of separating the stack layers and inserting Mica sheets in the damaged area and then injecting a special insulation varnish under pressure into the deep layers. Once hardened, the faults are durably repaired.

As seen in the table, the previously untreated defects C and D were flawlessly repaired with the SENSOCORE-Inject® technique. For the other two defects, A and B, the required restoration was more extensive and very difficult to carry out because the initial failed repair attempts resulted in the presence of hardened resin in the location, making parts of the SENSOCORE-Inject procedure impossible to perform. This accounts for the minimal temperature increases (below the acceptance threshold) noted on these two repairs.

Fault	ΔT before repair	ΔT after repair with SENSOCORE-Inject®
A	3.8 K	3.7 K
B	5.1 K	1.7 K
C	7.0 K	0.0 K
D	8.0 K	0.0 K

The advantages of the high induction test method are also clearly demonstrated in this case of condition monitoring on the lamination stack of the 16-pole machine in the 250-MVA class. This example reveals once again that defects which fall under the “latent” category cannot be detected with the low induction method. Furthermore, a problem of accurately determining the risk potential is present when applying this method. On the other hand, testing the stack using the high induction method can be accomplished speedily with thermographic pictures, often eliminating the need for complex analytical calculations.

For repair procedures, the SENSOCORE Inject® method has proven more effective than conventional methods with cast resins.

6 Conclusions

The comparison of condition monitoring of lamination stacks in several generators of various sizes and types using the high induction and low induction methods respectively resulted in the following findings:

- There are defects in the lamination stack which are only identifiable under near-service conditions (the so-called “latent“ hot spots). These present the same risk potential for the generator as the “non-latent“, apparent defects.

- High induction test methods with a test induction of approx. 75% reveal latent defects with a significantly higher reliability than low induction tests with only approximately 5% of the rated value. Conversely, it can safely be assumed that all the defects located with the low induction test will also be detected with the high induction test method.

- Low induction test methods do not supply sufficiently reliable data regarding the heat output of defects in operation and the associated risk potential to the generator.

- High induction test methods also reliably detect hot spots which lie radially deeper in the lamination stack.

On the basis of these findings, a cost-benefit analysis of the different test methods clearly favors the high induction method for the reliable and conclusive condition monitoring of generator lamination stacks.