Testing stator cores of turbo generators using the ring flux method

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1 Abstract

Generators are subjected to high electrical, thermal and mechanical stresses over the course of their service life. Continuous extreme thermo-mechanical stresses and thermal cycles can have a particularly severe impact on the stator core. Over time, this can lead to deficiencies in the core insulation. A damaged insulation can cause the formation of larger eddy currents and local hot spots, which spread out during time.

Therefore, it is recommended to regularly check the insulation condition, to avoid possible consequential damage such as core burning or damage of the bar insulation. A deficient bar insulation can result in a stator ground fault which can cause an unscheduled outage.

The flux test is used to measure the condition of the stator core insulation and thus to detect possible local insulation damage. Insulation failure can result in local hot spots between several sheets of the core during magnetization. These hot spots can be detected and localized with thermal imaging.

For evaluating the condition of generator stator cores, three test methods exist:
- Electromagnetic core imperfection detection (EL-CID)
- 50-60 Hz ring flux testing
- 500 Hz ring flux testing

The existing testing methods and their benefits will be explained and compared in theory and by examples.

2 Introduction

Power plant generator operation must be safe and reliable. For a power plant to be operated efficiently, high availability of its key component, the generator, must be achieved. To ensure this, the condition of the generator must be checked regularly and inspections planned predictively. The stator core of the generator is constantly under a load during operation and ages as the result of mechanical, thermal, and electrical stresses. In particular, the insulation between the many thousands of individual laminations may be damaged both during operation
and when work is performed on the generator. Damaged insulation can result in higher eddy currents and local hot spots, which gradually spread. Therefore, it is particularly essential to ensure that the inter-laminar insulation remains intact, to prevent consequential damage such as core burning or damage to the bar insulation. Damage to the bar insulation can result in interturn faults around the stator core and complete failure of the machine.

Fig. 1: Possible forms of damage to the stator core

Fig. 2: Traces of burning on back of the stator core due to excessive magnetic flux

Three measurement methods are in use globally for assessing the condition of the stator core, each of which will be studied and compared in this paper. Two of these methods deliberately generate hysteresis and eddy current losses in the stator core in order to create hot spots at defective points and detect them by means of thermal imaging.
3 Design basics of stator cores

Essentially, the laminations punched from electrical steel are covered or coated with suitable insulating material to keep eddy current losses as low as possible in the fully stacked stator core. Suitable insulating material is paper or insulating varnish.

Along its back, the stator core is held in place by rails, which are bolted to so-called guide bars. These guide bars can be mounted with insulation. When stacking is complete, the stator core is heated and pressed with a defined force.

Using insulated clamping or through bolts, the required pressure is applied to the stator core in the axial direction by means of end plates and clamping fingers.

Fig. 3: Stacked laminations

The stator core design typically used throughout the world is based on non-insulated stacking beams, which connect the stator core to the frame and provide the grounding. The figure below contrasts this design with the SIEMENS designs in a cross-section through several laminations.

In the SIEMENS design, the stacking beams are insulated so that a short circuit between two adjacent laminations will directly result in an additional closed current circuit. Only one stacking beam is connected via a conductive metal strip to the stator core to ensure grounding.

Because the design of other manufacturers does not provide this insulation on the back of the stator core means that an additional fault current produced by the magnetic field can occur as the result of just one insulation damage and thus cause hot spots in the damaged region.
Insulation of the individual laminations in modern high-performance turbogenerators is ensured by applying a layer of varnish to both sides of each lamination. The varnish is automatically applied as a diluted phenolic resin solution with an anorganic filler after the laminations have been punched and machined.

Older designs, on the other hand, were insulated with paper, which decomposed over time, necessitating more frequent inspections of older generators.

4 Magnetic flux distribution in the stator core

The distribution of magnetic flux during operation and during flux testing is contrasted below. Whereas, during operation, radial field components occur in the region of the teeth, on the back of the lamination the magnetic flux comprises only a tangential component and almost no magnetic field occurs in the teeth.

This differing field distribution plays a secondary role in stator core inspection because, if there is insulation damage on the inner bore with a short circuit on the outer diameter, a large part of the magnetic flux is involved in generating the additional eddy current.

During operation of the generator, a primarily tangential field component will occur in the stator yoke, whereas a radial field component will dominate in the stator teeth.
All inspection methods inject a primarily tangential flux into the stator core by means of an additional winding that surrounds the yoke. The teeth remain largely without a magnetic field, with flux densities of no more than a few milliteslas. Consequently, irrespective of the method used, not all defects that may theoretically occur and could occur during operation will be discovered.

If, for example, the stator core is fitted with insulated stacking beams and there are only two points of insulation damage in the region of the teeth of a stator core, this fault will not result in any significant additional temperature rise and thus remain invisible. If several incidents of insulation damage occur on the same tooth flank, no additional temperature rise is to be expected during operation either, because no current circuit can build up perpendicularly to the field and across multiple laminations. However, if the insulation faults are located on opposite sides of a tooth, an additional current circuit can arise, depending on the maximum distance between the laminations affected and cause additional losses in accordance with the flux linkage.
If the current circuit can be closed by a short circuit at the outer diameter of the stator core, the damage described above will become apparent because, in this case, the maximum flux is involved in generating the current.

### 5 Description of existing test methods

The aim of flux tests is early detection of insulation damage on the stator core, which might lead to additional eddy currents and thus to local overheating, and, in the worst case, to core burning. It is therefore important to test and appraise the quality of the existing insulation. A flux test should therefore simulate the magnetic load during operation on the object being tested as realistically as possible and thus approximately induce the rated voltage.

Three internationally recognized test methods currently exist:

- **Electromagnetic Core Imperfection Detection (EL-CID):**
  
  Excitation at a low energy level with 4% of rated induction, corresponding to an induced longitudinal voltage of approximately 5 V/m.

- **50-hertz ring flux testing:**
  
  High-flux ring test at high energy level of up to 85% of rated induction. This corresponds to a magnetic induction of ~1.3 T or approximately 100 V/m of induced longitudinal voltage.

- **500-hertz ring flux testing:**
  
  Developed since 2002 and patented internationally in 2005. A further test method that works by exciting the object under test at a higher frequency (500Hz) and induces voltage levels comparable with those of a high-flux ring test - roughly 100 V/m.

The basic setup of a flux test is illustrated below. Besides an excitation winding, a reference winding for measuring the induced voltage is used. The excitation winding should be placed as close to the center of the bore as possible, projecting by at least one meter at both ends, and closing again outside to avoid near-field effects and field distortions. While with EL-CID measurement no significant temperature rise in the stator core occurs, higher stator core temperatures do occur with the other two methods, which cause an increase in mechanical stress. This allows damage to be discovered that would go unnoticed in the cold state.
Fig. 7: Basic setup of a flux test

The magnetic flux density $B$ that flows through cross-sectional area $A$ in the stator core can be determined by measuring the induced voltage according to the following equation:

$$V_{\text{ind}} = 2nf \cdot B \cdot A \quad (1)$$

5.1 Electromagnetic Core Imperfection Detection (EL-CID)

In the EL-CID measurement, only very low magnetic flux densities are applied. This makes the test setup very simple and it is easier to comply with safety requirements. The fault currents can be detected by a Chattock coil, which is routed along each slot of the stator core. The output signal is proportional to the magnetic potential difference between the two contact points on the stator core surface, and is applied via the corresponding axial position of the bore and evaluated.
Examination of each slot together with its adjacent teeth results in overlapping that provides additional information about the defective points.

The measurement signal is split by a signal processor into one component in phase with the excitation field and one component caused by the fault current. To split the signal, a phase reference is required, which can, for example, be determined from the current of the excitation winding. Because of the presence of interferences, a threshold value for the detection of faults must be used. As the stator core does not heat up during measurement and the induced voltages are considerably lower than the voltage in rated operation, the full extent of defective points is not visible, which renders EL-CID testing with its difficult-to-interpret test recordings unsuitable for insulated stator cores of large machines.

5.2 50 Hz versus 500 Hz ring flux testing

Both test methods involving a stator core temperature rise are compared below:

In the flux test at a frequency $f$ of 500 Hz, considerably lower magnetic flux densities must be applied to generate voltages that are comparable with those induced with 50-Hz testing. To avoid overheating, induced longitudinal voltages of 80% to 90% are aimed at during testing. When recording thermal images, it is important to remember that the full intensity of hot spots is not recorded because of the wide imaging angle for a full image of the inner surface. So if hot spots are close to tolerance limits it is advisable to inspect them more thoroughly using a hand-held camera as soon as flux testing has been completed.

The alternating magnetic field excites vibration in the stator core. In the 50-Hz test, excitation is stronger due to the higher magnetic flux density, so the stator core has a 0-lobe vibration of
100 Hz in the radial direction. The considerably lower vibration excitation associated with the 500-Hz test has no negative effects because contact between two axially adjacent laminations is not made more likely by radial vibration.

The two methods therefore produce comparable results, although the 500-Hz test has considerable economic advantages.

When assessing any detected hot spots in the stator core, it is important to consider the intensity with which the stator core was magnetized.

In flux tests at a higher frequency, the yoke induction decreases relative to the frequency and is therefore an unsuitable criterion. Instead, the longitudinal voltage induced in the reference turn should be used as the criterion for intensity.

\[
\Delta \theta_{\text{WStB}} = \frac{1}{F_{\text{Rel}}} \left[ \frac{U_{\text{PNenn}}}{U_{\text{PMess500Hz}}} \right]^2 \cdot \Delta \theta_{\text{Mess500Hz}}
\]

(2)

where

- \( \Delta \theta_{\text{Mess500Hz}} \) Temperature rise of hot spot during test
- \( \Delta \theta_{\text{WStB}} \) Temperature rise of hot spot for assessment
- \( U_{\text{PMess500Hz}} \) Voltage in reference turn during test
- \( U_{\text{PNenn}} \) Voltage in the reference turn (rated value acc. to Gl. 1)
- \( F_{\text{Rel}} \) Factor 0.67 for temperature rise \( \frac{\text{d}J}{\text{d}t} \) after switching on (\( t=0 \))
- Factor 0.99 for temperature after a prolonged period (\( t \rightarrow \))

In the tables below, the characteristics of the various measurement methods are compared:

<table>
<thead>
<tr>
<th></th>
<th>EL-CID</th>
<th>50 Hz</th>
<th>500 Hz</th>
</tr>
</thead>
<tbody>
<tr>
<td>Magnetic flux density B</td>
<td></td>
<td>Corresponds to 4% of the flux density during rate operation (approx. 60 mT)</td>
<td>Corresponds to approx. 85% of the flux density during operation, smaller flux densities of up to 1 T are also common</td>
</tr>
</tbody>
</table>
| Induced longitudinal voltage |       | approx. 5 V/m                 | Corresponds to the induced voltage during | Corresponds to the induced voltage in the 50
**Table 1: Comparison of existing test methods**

<table>
<thead>
<tr>
<th>Magnetization losses</th>
<th>approx. 1 kW to 1.5 kW</th>
<th>In the stator yoke comparable to magnetizing losses under operation</th>
<th>Higher frequency causes rather high losses at lower flux densities</th>
</tr>
</thead>
<tbody>
<tr>
<td>Detection of defective points in the stator core</td>
<td>By evaluation of the test</td>
<td>Defects in stator core can be detected by hot spots</td>
<td>The hot spots have comparable intensity to the 50 Hz test</td>
</tr>
<tr>
<td>Test effort</td>
<td>Measurement easy to set up</td>
<td>High power of up to approx. 3 MVA and high-voltage connection required</td>
<td>Lower power of up to approx. 250 kVA using a 400V connection sufficient</td>
</tr>
</tbody>
</table>

**Detection of Defective Points in the Stator Core**

Defects in the stator core can be detected by hot spots. The hot spots have comparable intensity to the 50 Hz test.

**Test Effort**

Measurement easy to set up. High power of up to approx. 3 MVA and high-voltage connection required. Lower power of up to approx. 250 kVA using a 400V connection sufficient.

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**Table 2: Comparison of limit values for fault detection**

<table>
<thead>
<tr>
<th>Supplier recommended limit values for fault detection</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tooth top horizontal position</td>
</tr>
<tr>
<td>EL-CID Test</td>
</tr>
<tr>
<td>Ring flux test at rated frequency B=1.3 T (105 V/m)</td>
</tr>
<tr>
<td>500Hz Ring flux test at higher frequency ** (75 V/m)</td>
</tr>
</tbody>
</table>
Any defects detected can be repaired with mica board by carefully pressing the relevant laminations apart and pushing the mica board between them.

6 Application examples

6.1 50 Hz flux test of an old paper-insulated stator core
The four-pole turbogenerator inspected has a rated output of approx. 1500 MVA and a rated voltage of 27 kV and had been in operation for 150,000 hours. The laminations are insulated against each other with a layer of Sinullin-31 paper.
The 50-Hz high flux test was performed with a magnetic flux density of 1.3 T. This corresponds to an induced voltage of 100 V/m in the axial direction of the stator core.
The illustration below shows the surface temperature after 20 minutes of magnetization. The power loss occurring during measurement as a result of hysteresis and eddy current losses was 600 kW. The thermal image shows four hot spots with temperatures of 6 K and 20 K above the normal temperature. This is additionally indicated by the temperature curve along the relevant teeth.

![Fig. 9: 50 Hz flux test of a 1530 MVA generator (thermal imaging)](image)

Because of the large temperature differences and the resulting insulation damage to the stator core, the stator core was replaced together with the winding.
As a rule of thumb, a temperature difference of 10 K can be used as a limit value in continuous monitoring for a 50-Hz magnetization at 1.3 T. A temperature increase of 20 K is a sign of serious damage of the lamination insulation and requires repair.
6.2 500 Hz flux test of an old paper-insulated stator core – 300 MVA
The direct water-cooled generator inspected has paper insulation and had been in operation for 33 years. Its rated output is 300 MVA and its rated voltage is 16 kV. After 60 minutes of magnetization a thermal image of the inner bore was taken at an induced voltage of 110 V/m. On it, four hot spots with temperature rises of more than 10 K and two hot spots above 5 K can be seen. As the result of these findings, deployment of a new generator was included in a planned power upgrade.

Fig. 10: 500 Hz flux test of a 300 MVA generator (thermal imaging)

6.3 500 Hz flux test of an old paper-insulated stator core – 700MVA
The inspected generator with direct water cooling has a rated output of 700 MVA and a rated voltage of 21 kV. At the time of the inspection, the stator core was 31 years old and had been in operation for 114,000 hours with 1,400 start-stop cycles. There is only one layer of paper between two laminations.

Fig. 11: 500 Hz flux test of a 700 MVA generator (thermal imaging)
The illustration shows the temperature distribution inside the stator core after 45 minutes of magnetization at 500 Hz at an induced voltage of 113 V/m. Three hot spots with a relative temperature rise greater than 10 K can be seen (\(\Delta \theta = 11 \text{ K to } 13 \text{ K}\)), which indicate serious damage of the insulation and make repair necessary. Two other hot spots at \(\Delta \theta = 6 \text{ K to } 9 \text{ K}\) are more than 5 K above the average tooth surface temperature and should therefore be monitored regularly.

7 Conclusion

Both 50 Hz flux test and also testing at higher frequencies of 500 Hz are suitable methods for detecting defects in stator cores.

The stator core test using the EL-CID method is, however, less suitable because here the stator core cannot be tested under realistic operating conditions and the measurement result has to be interpreted. Defects may then be overlooked and incorrect assessments made.

The 500-Hz test produces results comparable with the established test at 50 Hz, but is considerably easier to implement due to the lower power losses and considerably lower apparent powers. Its advantages include, in particular, the considerably smaller test setup, the concomitant simpler transport and the possibility of connecting it to the 400-V grid.

With regard to testing of paper-insulated stator cores it is possible to add the following summarizing statements:

- Paper insulation ages as the result of operating stress by the decomposition of its cellulose structure
- Decomposition of the insulation increases the electrical conductivity between two laminations
- Remaining burr can result in contact between two adjacent laminations through the damaged insulation
- The increase in eddy currents can cause local hot spots in the stator core
- The condition of old paper insulation must be inspected regularly to prevent core burning
8 References

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9 Disclaimer

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