Generator diagnostics - From 100 failure modes to risk of forced outage

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About the author

“Generating peace of mind”

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Gabor holds a Ph. D. in rotor dynamics and he is the main author of 5 academic papers related to modelling of microslip friction damping. His thesis was applied to solve a generic vibration issue in the jet engine for Swedish Airforce fighter Viggen.

Today Gabor has more than 20 years of experience in generators with deep knowledge of generator diagnostics.

Gabor has been responsible for generator engineering at Fortum TGS since 2017, when VG Power Turbo AB in Västerås, Sweden was acquired by Fortum. He was one of the 8 founders of VG Power Turbo AB. Prior to that Gabor has been working for Alstom Power and Volvo Aero Corporation.

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Background – From presenting test results to giving a “Doctor’s diagnose”

IN THE PAST

- Dedicated personnel at the plant to take care of the generator
- Service provider, usually OEM performing overhauls and presenting test results
- Analysis and conclusions of the state of their equipment left to the customer

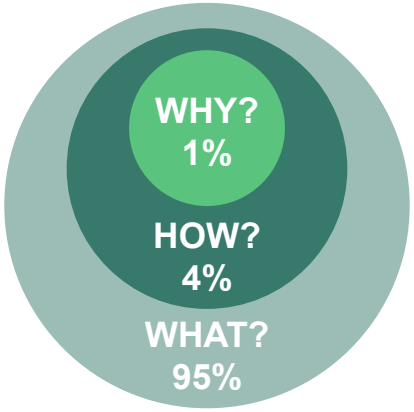
TRENDS TODAY

- Customers with less personnel and in-house expertise on the equipment
- Moving from buying single inspections to service contracts
- Reports still present what has been done at the outage, **BUT NOT WHY**
- Prediction of “remaining lifetime” in many cases incorrect

RISING CUSTOMER NEED

- Tailored inspection and test program, based on history of each unit
- Findings analyzed → cause & consequences → risks
- Recommendations on how to manage identified risks

COMMUNICATION



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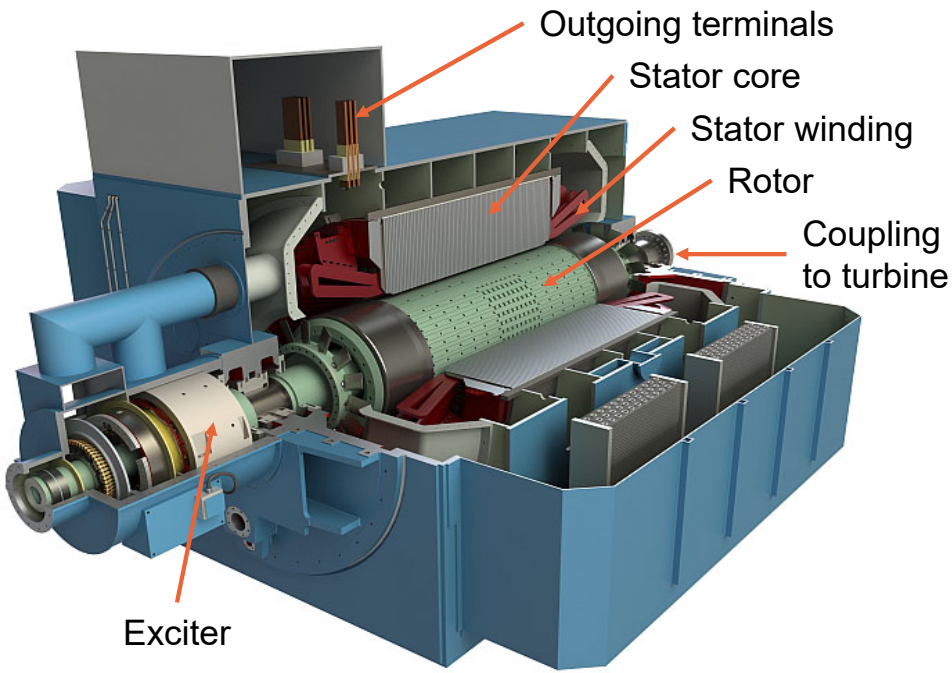
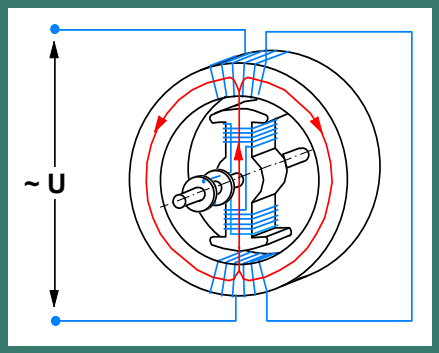
Main components of a generator

- Generator's main purpose: to transfer mechanical energy from the turbine to electrical energy
- As the **rotor winding** is fed with direct current, the **rotor** transfers the mechanical power of the turbine to a rotating magnetic field
- The **stator core** closes the magnetic field from the rotor
- **Stator winding** transfers magnetic flux to electrical energy, that is lead to the electrical grid via terminals, bus bars, breaker and the transformer
- **Excitation system** controls thru the **exciter** the generator behavior on the grid





Schematic sketch

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Agenda for
Generator diagnostics based on 100 failure modes

- Risk statistics and failure modes
- Diagnostic tools
- Generator maintenance levels
- Ability to detect failure modes by maintenance level
- Risk assessment and recommendations
- Examples
- Summary

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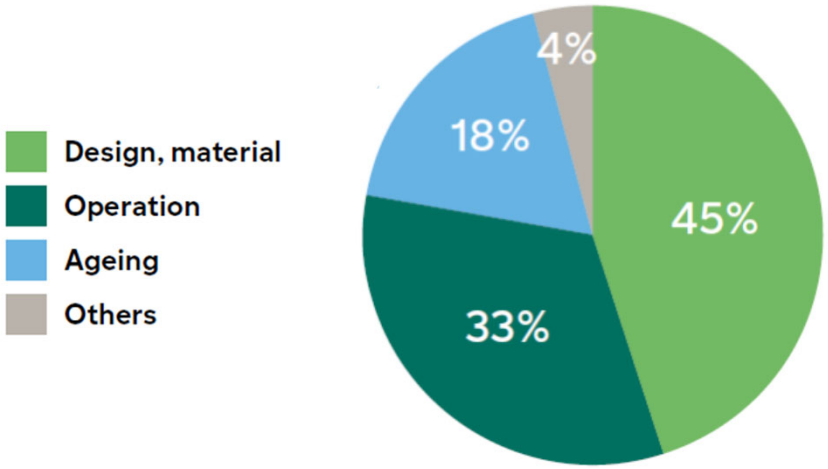
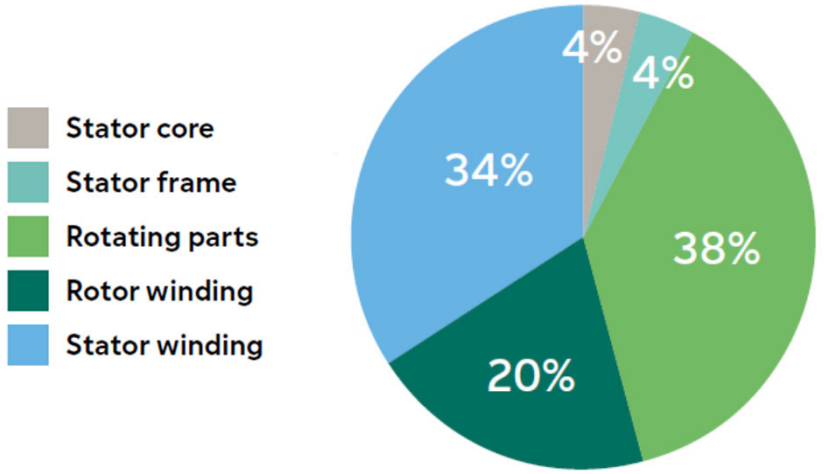
Turbogenerator failures causing forced outage

Causes for failures of turbogenerators



Source: Allianz insurance company

Components of turbogenerators that have failed



Source: NERC – North America Electric Reliability Analysis

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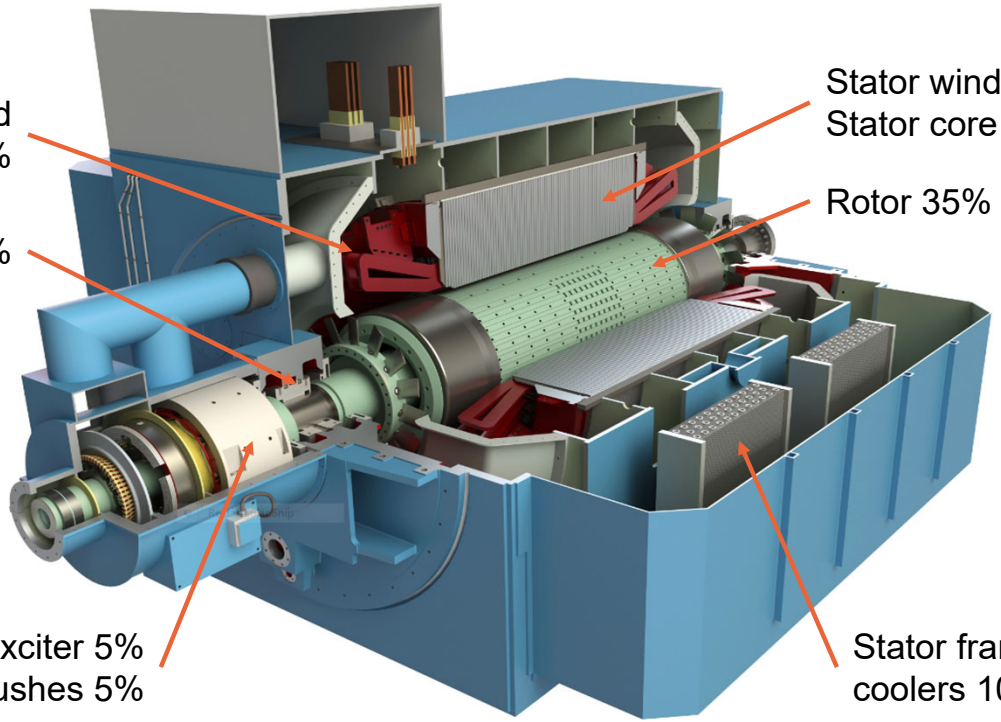
What is generator maintenance?

- Turbogenerators are inherently reliable, yet technically complex items of machinery designed for a long life
- Performance of a generator does not deteriorate with time

Generator overhaul =
10% Reconditioning + 90% Diagnostics

- Examples of reconditioning:
  - Cleaning
  - Changing of gaskets
  - Slot wedge tightening
  - Grinding of slip rings

What shall be diagnosed?



Failure modes are the ways a fault can occur in the generator's function

Interesting failure modes are those that cause operational interruptions

About 100 failure modes can occur on an air-cooled generator

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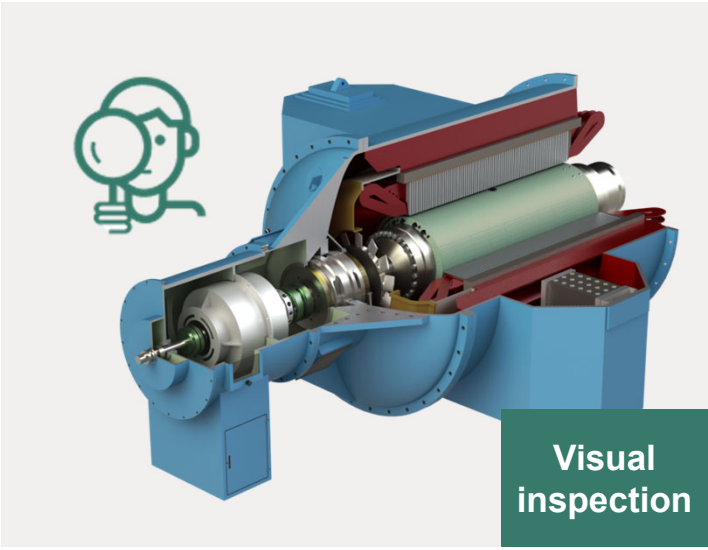
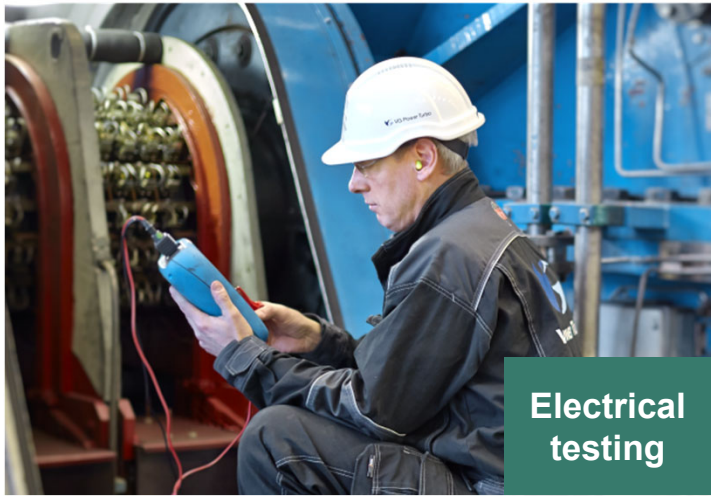
Diagnostic tests

- Electrical tests are performed to identify
  - Short circuits in stator core
  - Breakage in rotor and stator windings
  - Condition of the main insulation in rotor and stator winding
  - Defects in contact between stator bars and stator slots
  - Short circuits in the rotor winding
- Visual inspection with the “trained eye” is and important tool to gather information about
  - Overheating, signs of vibration
  - Contamination, signs of PD, and others
- All information is analyzed together with our fleet experience to form a diagnose





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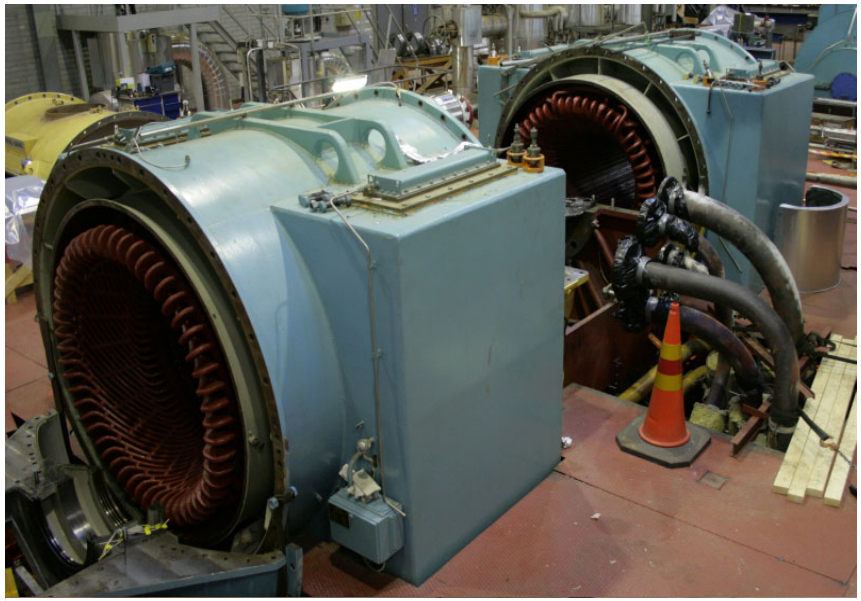
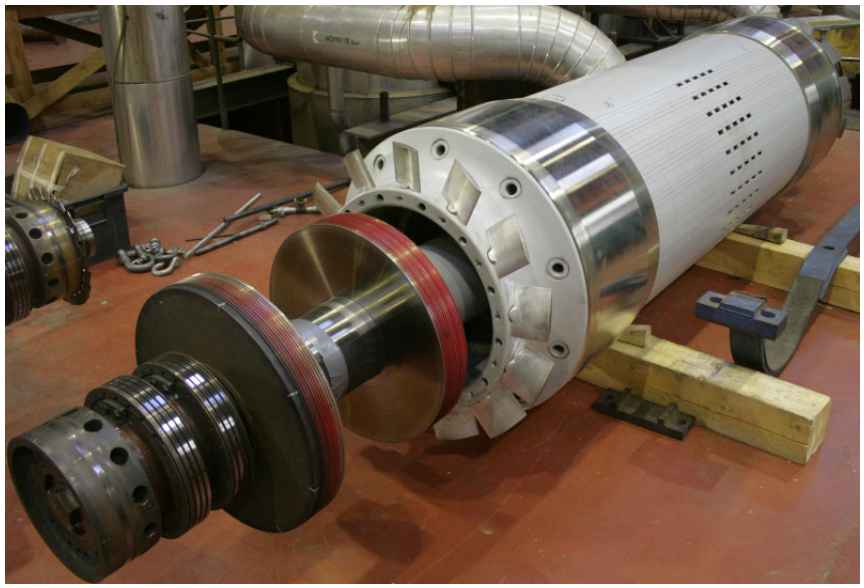
Maintenance levels for a turbogenerator

- A maintenance plan is generally split into three different levels:

1. **Major Overhaul**
   Bearings, coolers and the rotor are disassembled
2. **Limited Inspection**
   Parts of bearings and some winding covers are removed
3. **Safety Check**
   Only inspection hatches are removed / opened

- Maintenance time plan governs which level should be done when
- With time, the plan needs adaption based on operation and possible active failure modes





Which diagnostic test can detect which failure mode?

- We have identified and described approximately 100 failure modes, which can cause a forced outage for a generator
- Possibility to detect and identify failure modes depends on the maintenance level being performed
- Consequences depend on the fault type and generator design

MAINTENANCE LEVEL AND DIAGNOSTIC TEST

FAILURE MODE

Main comp.	Failure mode	Major overhaul							Limited insp.			Safety check		
		Visual inspection	EL-test basic	High voltage testing	High pot	Core testing	RSO or Impedance	NDT	Visual	EL-test basic	RSO or Impedance	Visual	EL-test basic	RSO or Impedance
Stator	Ageing of main insulation	d	d	i	i					d			d	
Stator	Hole in the main insulation, at the straight part of the bar	i			i									
Stator	Contaminated end windings	i		d					i					
Stator	Short circuit between core laminations	d				i								
Rotor	Cracks from negative sequence heating	d						i						
Rotor	Thermal instability of vibration													
Rotor	Inter turn fault	d?					i				i			i
Rotor	Crack growing in fan blade	d						i	d					

Detected = Something is wrong, but not enough information to determine which failure mode

Identified = We know which failure mode has occurred, a more precise risk assessment can be made

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Detection and identification of failure modes – Examples

- **Contamination of stator end winding**, detected by PD measurements and identified by visual inspection. Can only be correct during major overhaul.
- **Inter turn rotor faults**, identified by RSO or Impedance at stand still or RFM during operation.
- **Thermal instability** of rotor not detectable at stand still, but possible to identify thru vibrations in operation.

Main comp.	Failure mode	Major overhaul							Limited insp.			Safety check		
		Visual inspection	EI-test basic	High voltage testing	High pot	Core testing	RSO or Impedance	NDT	Visual	EI-test basic	RSO or Impedance	Visual	EI-test basic	RSO or Impedance
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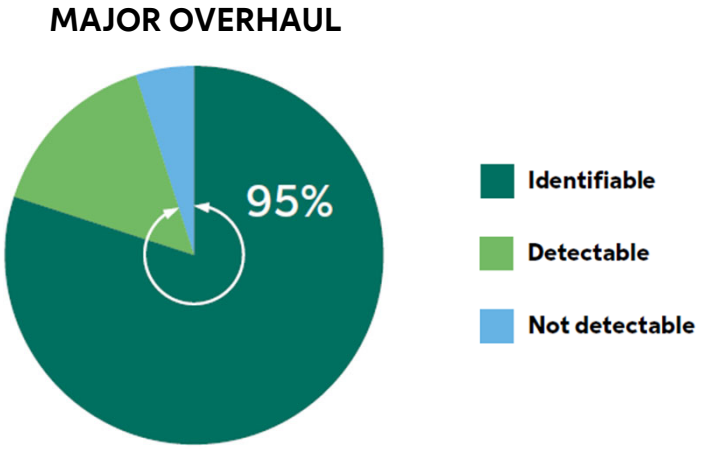
Detectability at Major Overhaul

- Major overhaul is the most important part of the maintenance plan
- Complete inspection and diagnostics of all critical components possible
- Gives possibilities for reconditioning



A complete major overhaul contains:

- Removing bearings, winding covers, rotor and coolers
- Visual inspection of all components
- Diagnostic tests of all critical components

A major overhaul can:

- Identify 85% of failure modes
- Detect another 10%.
- Remaining 5% of failure modes can be identified during operation.

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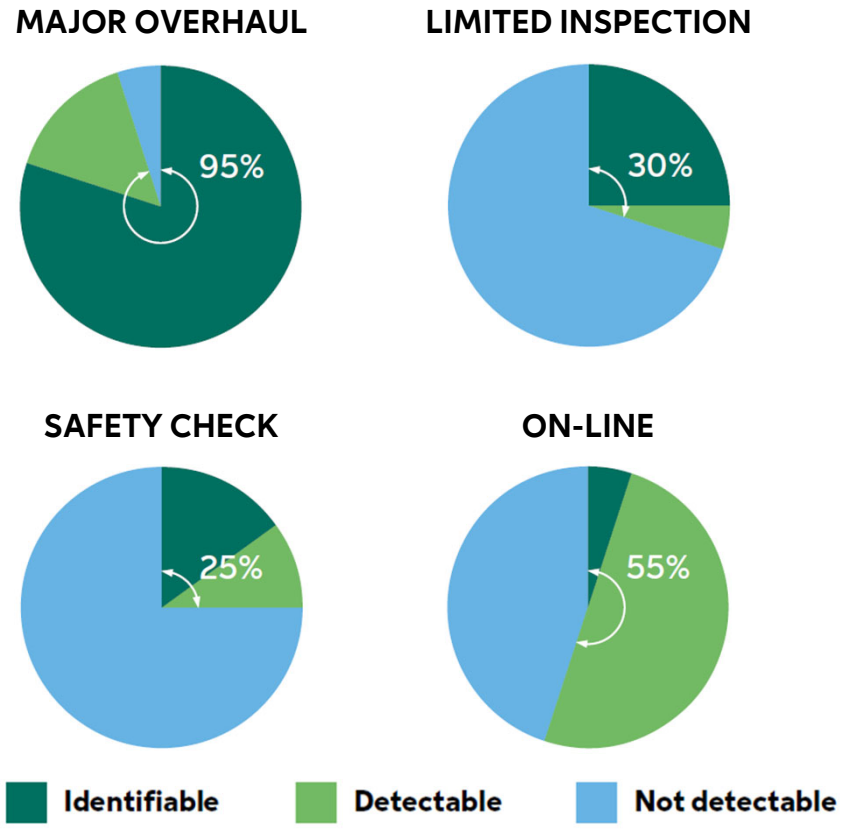
Detectability at different maintenance levels
Conclusions

- Major overhaul is a much more powerful tool to identify failure modes than limited inspection or safety check
- On-line diagnostics is the next most powerful tool and it can be performed at any time during operation
  - Generator fitted with on-line sensors for monitoring rotor and stator windings
  - Operational data collected and analyzed
  - Identify 5% failure modes, detect an additional 50%



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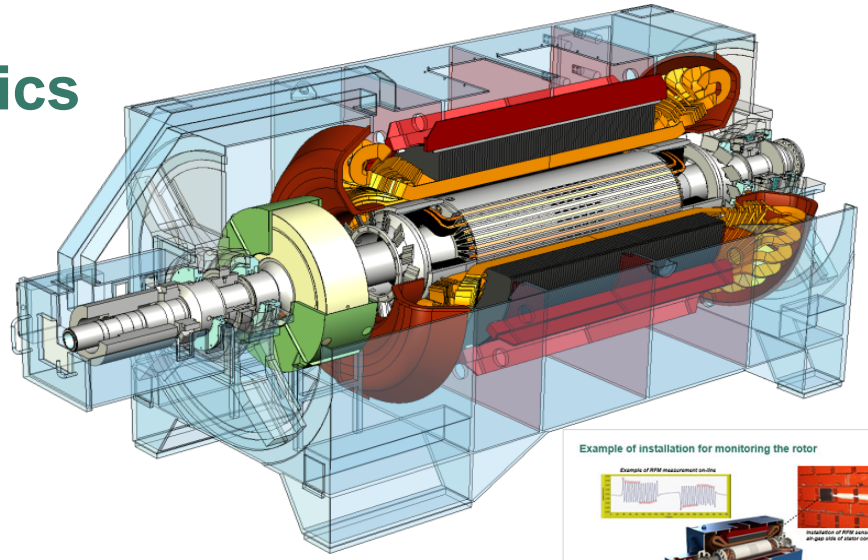
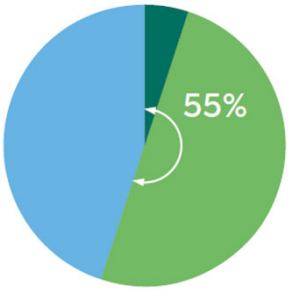
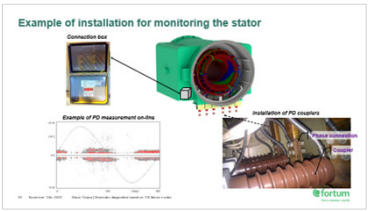
Detectability using on-line diagnostics

- Failure modes can also be detected during operation by on-line diagnostics.
- Air-cooled turbogenerator can be fitted with:
  - PD monitoring in each phase of the stator winding
  - Rotor Flux Monitoring
  - Monitoring stator winding and cooling air temperatures
  - Monitoring bearing vibration
  - Operating parameter trends
  - Generator protection relays
- On-line diagnostics can:
  - Identify 5% failure modes.
  - Detect an additional 35%.
  - Protection system detects an additional 15% of the failure modes, but the reason for the trip must be investigated before the restart.



RFM





PD

Identifiable **Detectable** **Not detectable**

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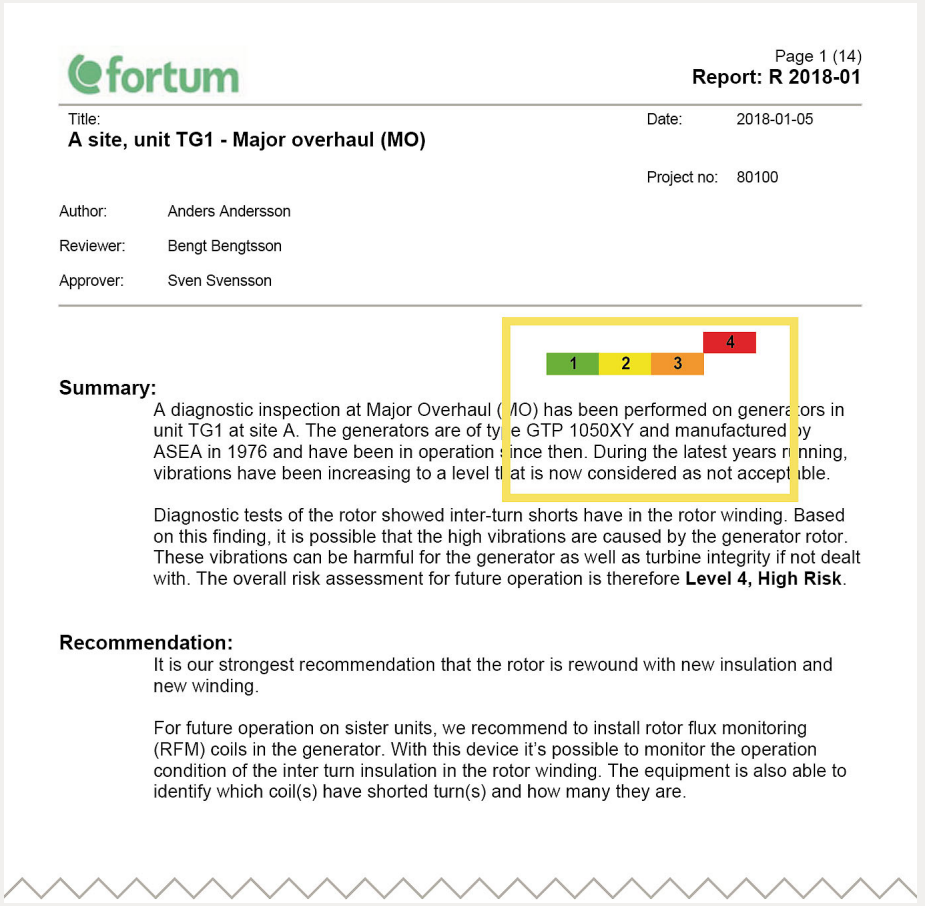
Results of the diagnostics

- **We provide you the present risk situation**
- Analysis of the data results in a risk assessment at component level
- The risk to the generator is equal to that of the highest-risk component, taking into account planed operation until next major overhaul
- Results are reported as four risk levels from base risk to high risk



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Page 1 (14)
Report: R 2018-01

Title:
A site, unit TG1 - Major overhaul (MO)

Date: 2018-01-05

Project no: 80100

Author: Anders Andersson
Reviewer: Bengt Bengtsson
Approver: Sven Svensson

1 2 3 4

Summary:

A diagnostic inspection at Major Overhaul (MO) has been performed on generators in unit TG1 at site A. The generators are of type GTP 1050XY and manufactured by ASEA in 1976 and have been in operation since then. During the latest years running, vibrations have been increasing to a level that is now considered as not acceptable.

Diagnostic tests of the rotor showed inter-turn shorts have in the rotor winding. Based on this finding, it is possible that the high vibrations are caused by the generator rotor. These vibrations can be harmful for the generator as well as turbine integrity if not dealt with. The overall risk assessment for future operation is therefore **Level 4, High Risk**.

Recommendation:

It is our strongest recommendation that the rotor is rewound with new insulation and new winding.

For future operation on sister units, we recommend to install rotor flux monitoring (RFM) coils in the generator. With this device it's possible to monitor the operation condition of the inter turn insulation in the rotor winding. The equipment is also able to identify which coil(s) have shorted turn(s) and how many they are.

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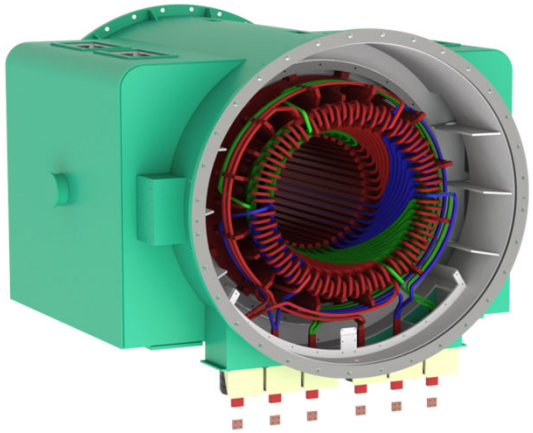
Recommendations for risk reduction

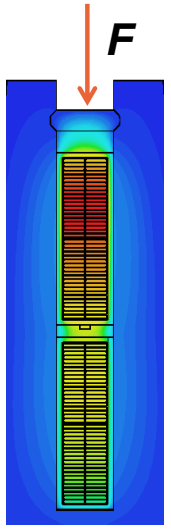
- Fortum TGS's report always includes recommendations for:
  - Actions that can reduce the risk for operational disturbance, e.g. monitoring equipment or changing time between major overhauls
  - Actions that can reduce the consequence of such an outage, e.g. spare parts or spare components
- Purpose is to maintain the risk at an acceptable level until next planned major overhaul OR to reduce the risk level

The result gives the plant owner a solid basis for updating the maintenance plan. It also gives guidance to future investments needed, in order to maintain risk at an acceptable level.

Example: Loosening of stator slot wedges

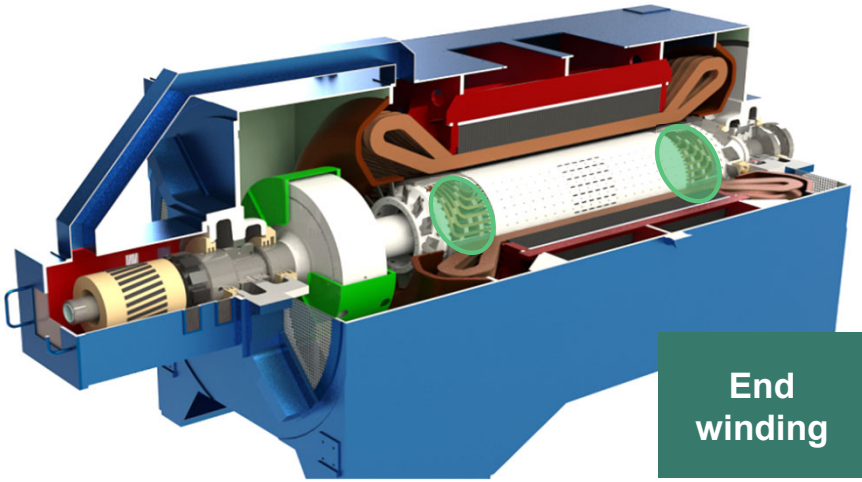
- Slot pretension force ***F*** may reduce with time
- Vibration starts
  - → wear of corona protection
  - → partial discharges
  - → accelerated wearing
- Eventually an earth fault occurs
  - → damages on stator bars, in worst case also core
- Diagnostics performed at major overhaul or on-line can identify the failure mode – it can not be detected at limited inspection or safety check

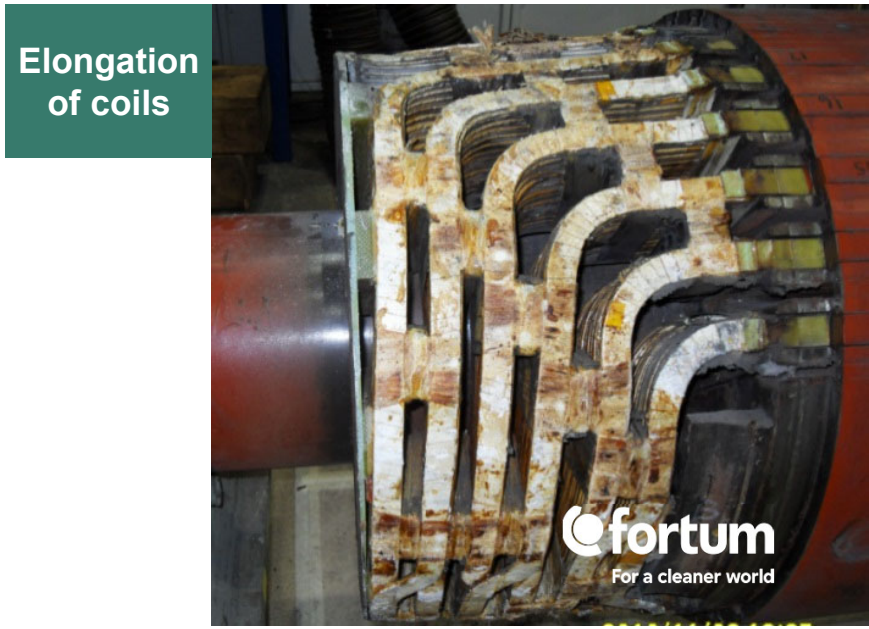


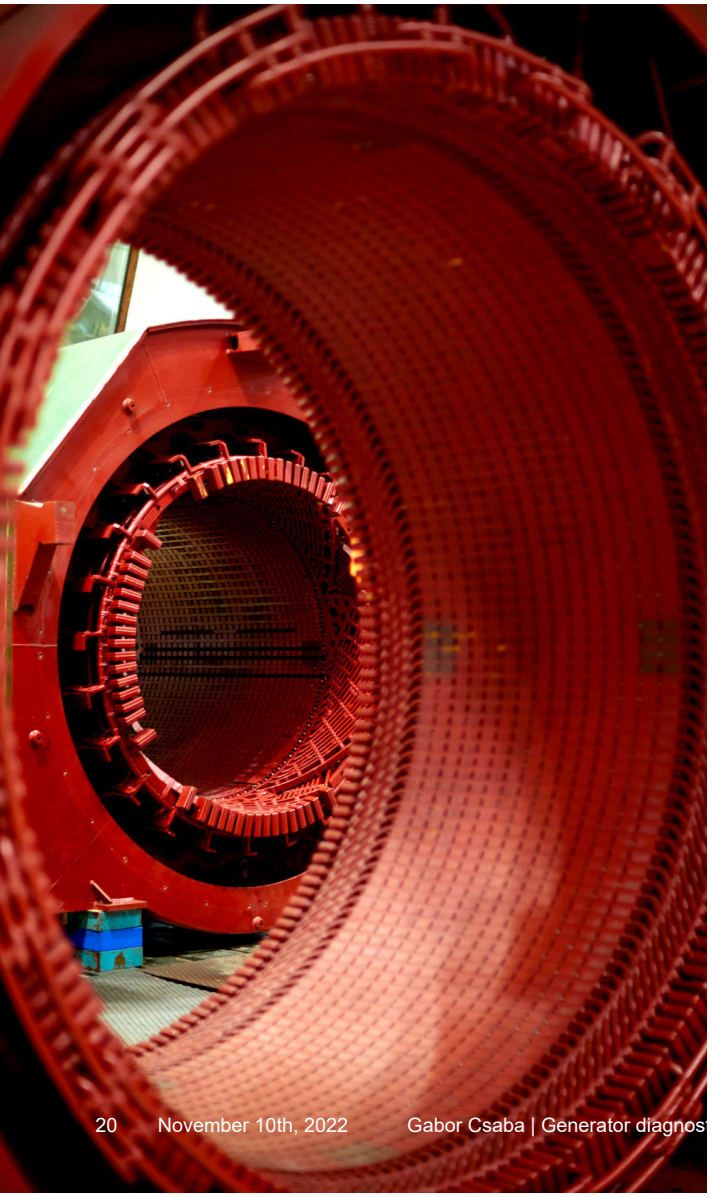


Example: Turn-to-turn short circuits of rotor coils

- Start/stop cycling leads with time to elongation of rotor coil ends
- Elongation can for instance lead to:
  - Turn-to-turn shorts → vibrations
  - Broken winding → earth faults
- Both problems eventually lead to outage and repair of rotor
- Failure mode can be identified using RSO at standstill (safety check, limited inspection or major overhaul)
- At major overhaul it is recommended to install RFM for detecting turn-to-turn shorts during operation







Summary

- Approximately 100 fault modes have been identified for an air-cooled turbogenerator
- Ability to detect failure modes at different maintenance levels have been mapped and risk level in 4 steps defined
- Diagnostic results from electrical tests and visual inspections are weighted together with operation history, design weaknesses and planned operation
- Analysis is presented in a report where each component is classified by risk – the highest gives the generator risk
- The report gives the owner powerful tools to keep risks at acceptable level
- We call it **GENERATING PEACE OF MIND**
- Methodology can also be applied to turbines and other equipment

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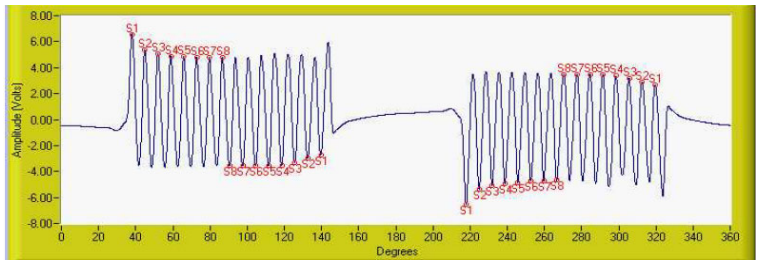
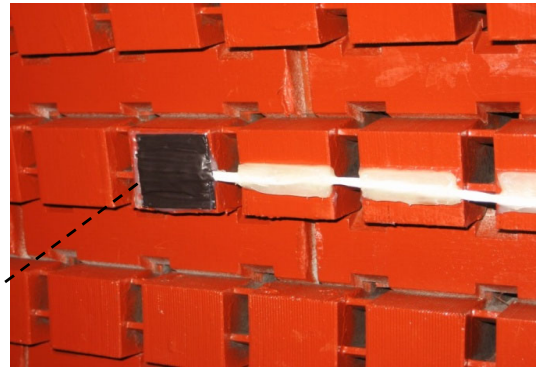
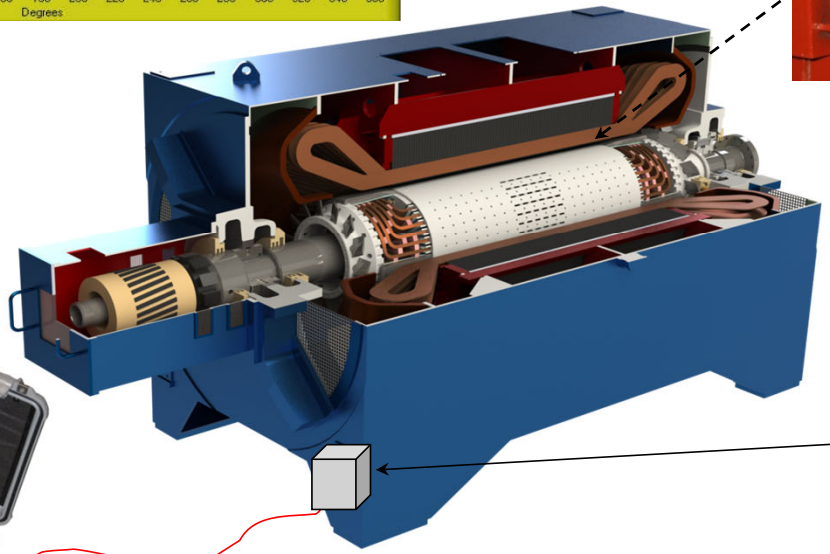
Example of installation for monitoring the rotor

Example of RFM measurement on-line





Installation of RFM sensor on air-gap side of stator core



Analyzer

Connection box

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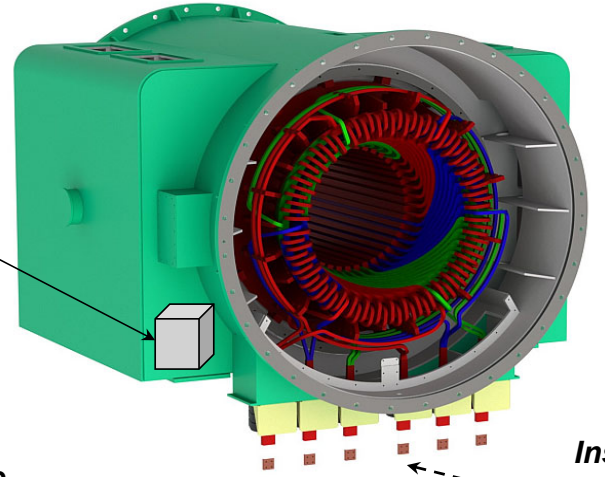
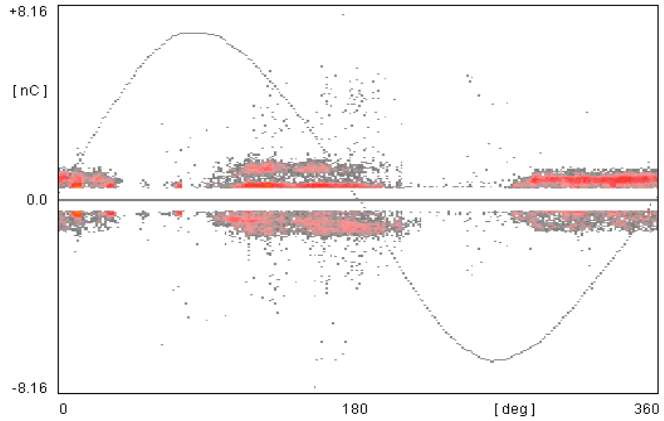
Example of installation for monitoring the stator

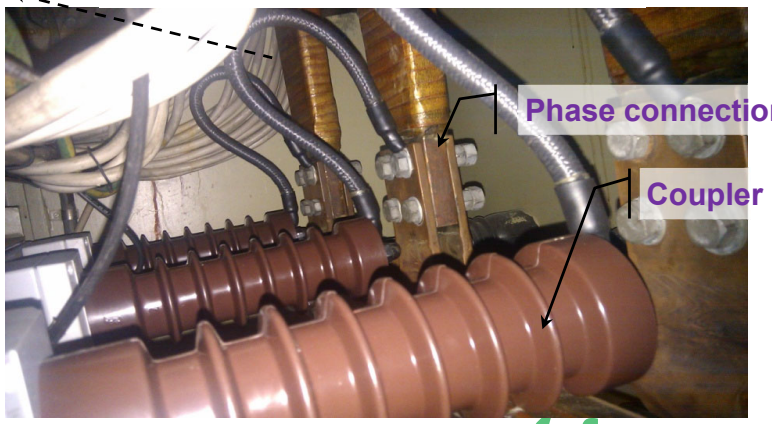
Connection box



Example of PD measurement on-line



Installation of PD couplers



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Definition of risk levels

1 A fully functional component without known/identified defects that is exposed to operational conditions that it is dimensioned for is assessed to have **Base risk**. This means that age does not automatically increase risk for damage. It is, however, demanded that an extensive diagnosis of the component condition is performed, and that this diagnosis does not give any indication of defects.

2 **Increasing risk** is the classification of a fully functional component with observations that indicate possible degradation. However, these observations don't point to a specific failure mode.

3 **Medium high risk** is the classification of a fully functional component with clear observations that a components state has changed. However, these observations don't point to a specific failure mode. This category may also include components with temporary repairs depending on the results and the expected durability of the repair.

4 Components with **High risk** have one or more failure modes identified and it can be described what this/these failure mode(s) will lead to. This category may also include components with temporary repairs depending on the results and the expected durability of the repair.


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