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Diagnostics of generators- From failure modes to risk of forced outage

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Electronically reviewed and approved original is in BASE.

Summary:

Today's generators are inherently reliable. A breakdown can, therefore, come as an unexpected and unwelcome surprise for the operator. What's more, if spare parts are not readily available, the resulting downtime can be significantly prolonged. In the worst case, failure of high-speed rotating parts can have catastrophic consequences for both equipment and personnel.

Fortum Turbine and Generator Services (TGS) has developed a concept for generator diagnostics that supports condition-based maintenance of generators. Based on about 100 failure modes of a generator, individually tailored diagnostics is performed.

Inspections and diagnostic tests are analyzed by experts and a four-level risk assessment is made for each component, from **level 1, base risk** to **level 4, high risk**. The risk level of the generator is equal to highest component risk. Recommendations are given that reduces the risk of forced outage and its consequences.

The diagnostics report gives plant owners a powerful basis for updating their maintenance plans and guides future investments in maintaining risk at an acceptable level or reducing it to such a level.

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1 Background.

Today's generators are inherently reliable. A breakdown can, therefore, come as an unexpected and unwelcome surprise for the operator. What's more, if spare parts are not readily available, the resulting downtime can be significantly prolonged. In the worst case, failure of high-speed rotating parts can have catastrophic consequences for both equipment and personnel.

In the past, plants had dedicated personnel for different equipment, for instance the generator. He knew the generator and has been taking care of it, most likely since the plant was built and commissioned. Service providers, usually OEM, performed overhaul and presented test results to the plant operation staff. The customer made conclusions and own analysis of the state of their equipment and their own recommendations for future service and upgrade of the equipment.

Today, the situation is often that plants have less and less own in-house expertise on the equipment. At many older plants, still in operation there has also been generation shifts so that older experienced staff has been replaced with younger, less experienced. The customers need therefore to rely more on the analysis and recommendations that the service providers give.

Service providers still presents results in terms of what and how they did at the outage, but not why. Customers need results from outages that help them and give advice for the future that is tangible. For this reason, we started developing a new concept for generator maintenance, based on failure modes approach.

2 Generator Maintenance

A generator is a technically-complex item of machinery designed for long life. However, even when its design and materials continue to meet specified requirements, several conditions or events will nevertheless affect its function, reduce availability and shorten lifetime. The main factors that shorten lifetime are operating and handling issues, exceptional events and material aging. Allianz insurance company has made an investigation into the causes for failures on turbogenerators, see below.

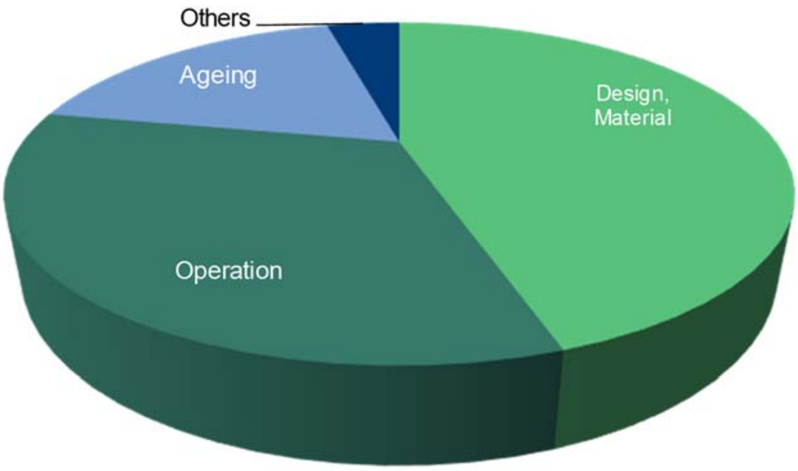

Figure 1 Cause for failure, source Allianz insurance company

Which part that normally caused the failure depends of course on the type of generator and its design. NERC has made a reliability analysis in North America for turbogenerators, see figure below. It can clearly be seen that the rotor has the most failures. For 4-pole generators operating at 1500 or 1800 rpm, the relations changes and there the most failures are found on the stator. This is not surprising as doubling the speed results in four times higher centrifugal loads on the rotor for the turbogenerator.

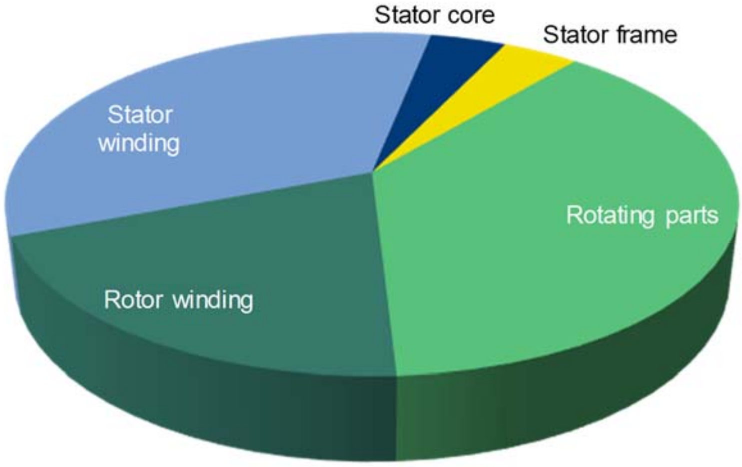

Figure 2 Component that failed, source NERC – North America Electric Reliability Analysis

Generators are fitted with protective relays to prevent abnormal operation and avoid adverse events. However, to ensure the intended service life and maintain expected availability, it is necessary to check the true conditions of critical generator parts and perform maintenance to mitigate the impact of degradation and restore them to their original condition. This is done thru maintenance.

Maintenance can be divided into corrective maintenance and preventive maintenance. The latter is designed to keep the generator's initial reliability and availability, and to minimize the need for corrective maintenance. Preventive maintenance can in turn be divided into operational maintenance and maintenance planning, see figure 3. In this work we have concentrated on the maintenance plan activities.

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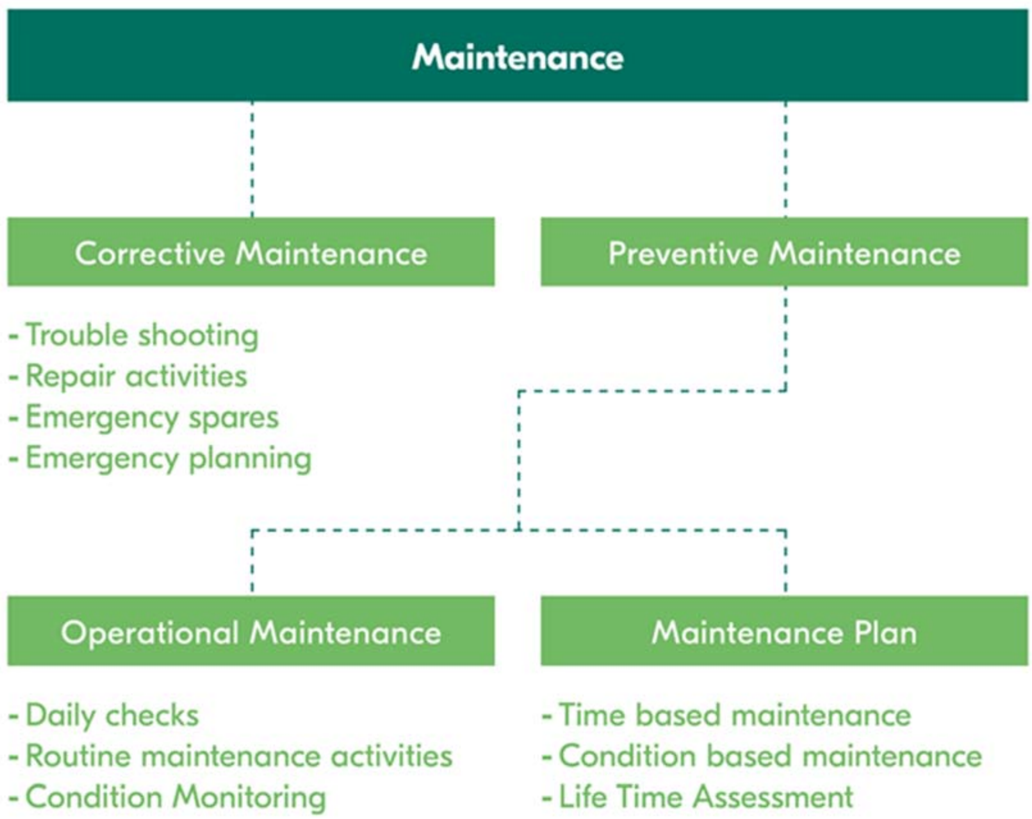

Figure 3 Generator maintenance divided into corrective and preventive maintenance.

2.1 Time Based Maintenance

The maintenance plan for a new generator is normally time-based according to the manufacturer's experience of the current generator type. The content of the plan and its execution are generally determined by how possible errors can develop and be detected. For practical reasons, it is very important to coordinate the generator maintenance plan with the turbine plan. Good coordination, resource planning and materials and spare parts acquisition will all result in effective maintenance.

A maintenance plan is generally designed in three different levels.

- Major Overhaul (MO)
- Limited Inspection (LI), can also be called Minor Overhaul
- Safety Check(SC), can also called Yearly Overhaul or Routine Inspection

2.1.1 Major Overhaul (MO)

This is the most important part of the maintenance plan since it permits comprehensive inspection and diagnosis of all critical generator components, as well as cleaning and reconditioning. The rotor needs to be removed from the stator for this inspection.

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Visual inspection with a ‘trained eye’ is an important information-gathering tool and performed both before and after cleaning. Diagnostic testing / measuring both of electrical and mechanical properties is then added. Finally, the combined information is analysed to identify any fault development.

The complete scope of a Major Overhaul consists of:

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

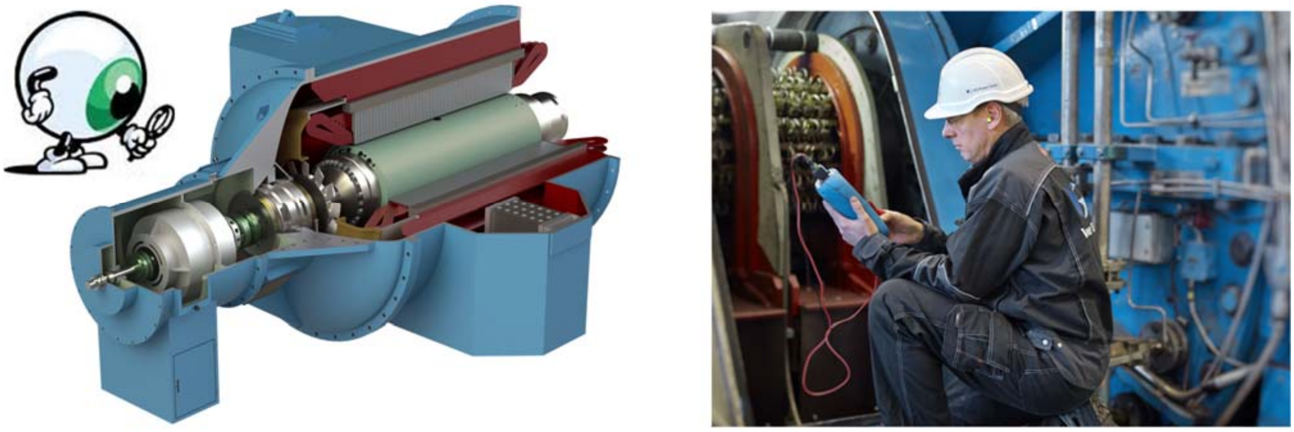

Figure 4 Visual inspection with the trained eye and electrical testing is important parts of the Major Overhaul

2.1.2 Limited Inspection (LI)

One to two years prior to the next planned major overhaul, a Limited Inspection should be performed to prepare and plan the activities needed.

A Limited Inspection consists of:

- Removing the bearings upper half, end gables and winding covers
- Visual inspection of accessible parts
- Less extensive diagnostic testing of electrical circuit integrity and insulation

2.1.3 Safety Check (SC)

Safety Checks are performed in the interval between Major Overhauls. They capture dramatic changes in generator condition or detect unexpected events. Safety Checks, which only require a
minor effort is usually performed at planned yearly outages.

A Safety Check consists of:

- Removing inspection hatches
- Visual inspection of accessible parts

Less extensive diagnostic testing of electrical circuit integrity and insulation

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2.2 Condition Based Maintenance

After several years in operation, it becomes more and more relevant to base maintenance activities on the actual condition of critical components, i.e. to start switching from time-based maintenance to planned, condition-based maintenance. However, some potential causes for unplanned outage are difficult be identify by on-line monitoring, so switching completely to condition-based maintenance is not feasible.

For today's generators, it makes sense to mix time-based and condition-based maintenance. The foundation of this strategy is a maintenance plan with activities planned according to time, but where the inspection's findings (and measurements from the monitoring equipment) are used to update the intervals and the scope of the maintenance plan.

In addition to normal monitoring such as temperatures and vibrations, it is for example recommended to monitor partial discharges (PD) and changes in rotor flux (RFM). These are shown in the figure below.

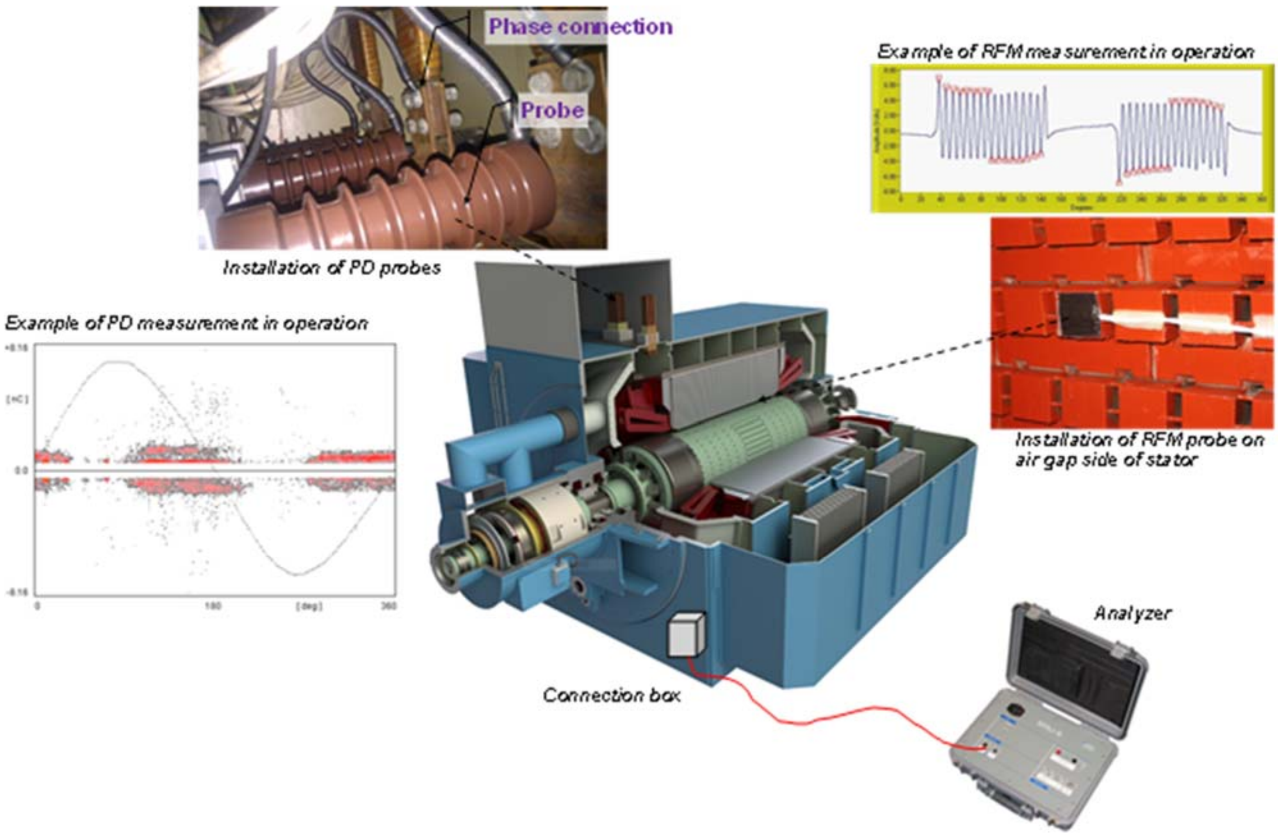

Figure 5 Example of RFM and PD sensors installation on an air-cooled turbogenerator.

Doing this analysis and introducing a more condition-based maintenance requires that you are aware of the anomalies can occur with your generator, as well as how they are diagnosed and how often measurements are needed. This is described in the Fortum TGS concept for generator diagnostics.

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2.3 Timing of Maintenance Levels

The intervals of the maintenance plan are determined by the generator type and the type of fault that can develop. These intervals should then be coordinated with the turbine maintenance plan. The Major Overhaul is most critical since it requires removing the rotor. A typical interval for Major Overhauls is 60,000 adjusted operating hours see figure 6. Adjusted means that the actual operating time is adjusted by adding 20 hours for each start / stop.

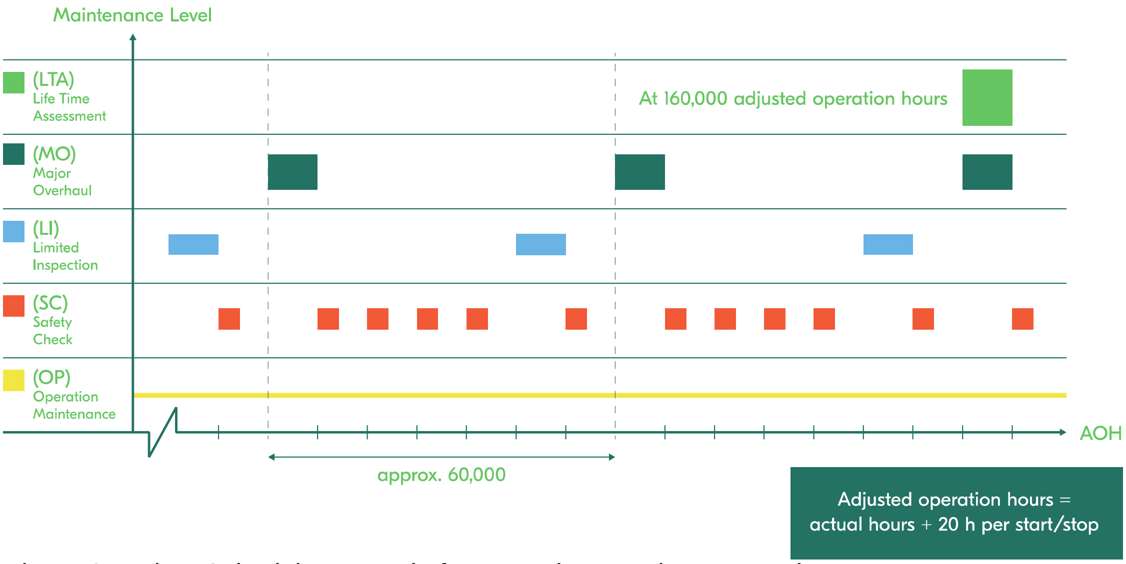

Figure 6 Time Schedule, example for executing a maintenance plan.

2.4 Life Time Assessment

When a generator has reached 160,000 adjusted operating hours, a Life Time Assessment (LTA) is strongly recommended. An LTA, usually done as an extension of or in combination with a Major Overhaul, provides information about how well the generator fulfils its requirements for future operation.

3 Concept for generator diagnostics

One key feature with the generator is that performance does not deteriorate with time. This contrasts with the turbine where there is always an amount of wear and tear that eventually results in a decrease in power output that can be measured by the operator. There are very few cases were this happens to the generator. In the eyes of the operator it can be "standing there" for a long time, working well and suddenly it doesn´t.

Therefore, we say that generator gverhaul is 10% reconditioning and 90% diagnostics.

Examples of reconditioning are for instance: cleaning, changing gaskets, slot wedge re-tightening and grinding sliprings.

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3.1 Failure Modes of a Generator

As stated before, the main causes of disrupted operations for generators are operating and handling issues, adverse events and material aging. The actual effects these factors have on the generator, as well as the risk of downtime, largely depend on how well it is designed, manufactured and maintained.

The overall goal of developing a new approach for maintenance is to give the customer the opportunity to maintain the generator's original properties in terms of performance, functional and operational safety. To realize this, a well-balanced ability is required to determine the current condition and what are the risks of disturbances associated with an identified fault mode. One shall also be able to propose short- and long-term measures that reduce the risk of operational disruptions. Fortum TGS have concluded that for an air-cooled turbogenerator, as an example, there are about 100 failure modes that can cause a forced outage, see figure 7.

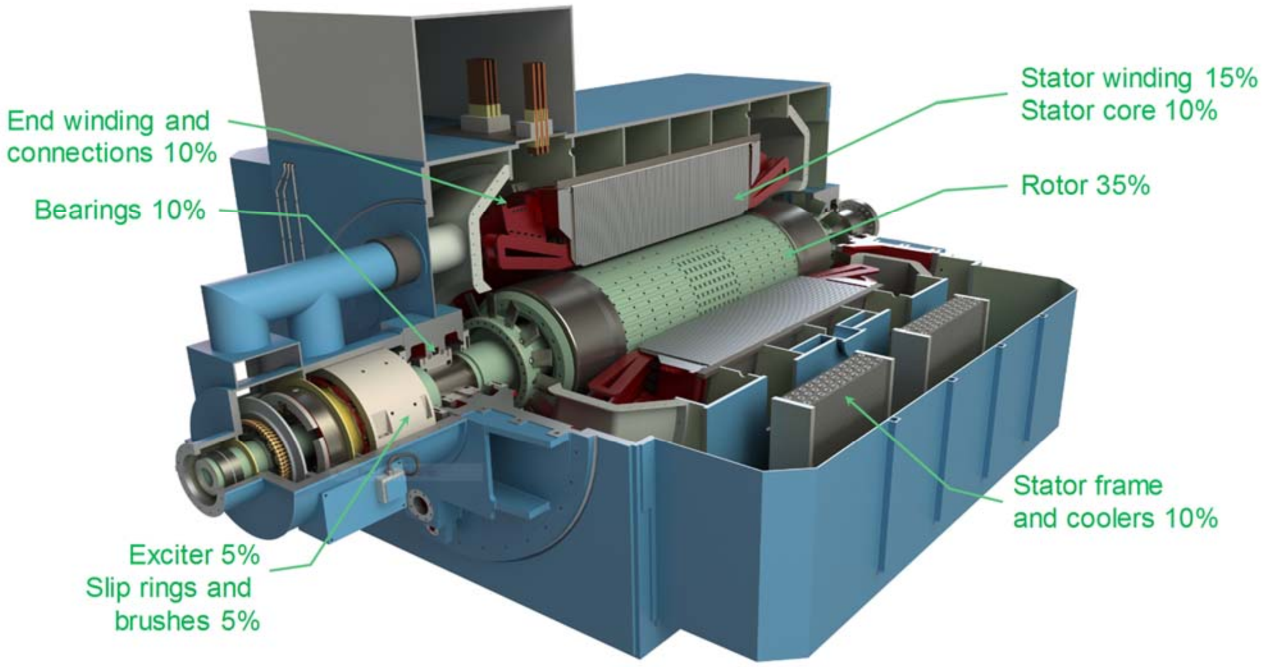

Figure 7 The operation of a generator can be disrupted by approximately 100 known failure modes. The distribution of these per component is shown in the figure for an air-cooled turbogenerator.

Component by component we have gone thru the design of a typical air-cooled generator and listed the potential failure modes that can occur. The ones of interest are those that has the potential to cause an unplanned outage. The following picture illustrates the 20 failure modes that have been identified for the stator winding and end winding.

In figure 9 it can be seen what the potential consequence of those failure modes is. The maximum interval of 5 years has been chosen since a longer period is difficult to observe and anticipate, but some modes may have a longer time to develop into a malfunction in the form of a forced outage or other type of disturbance.

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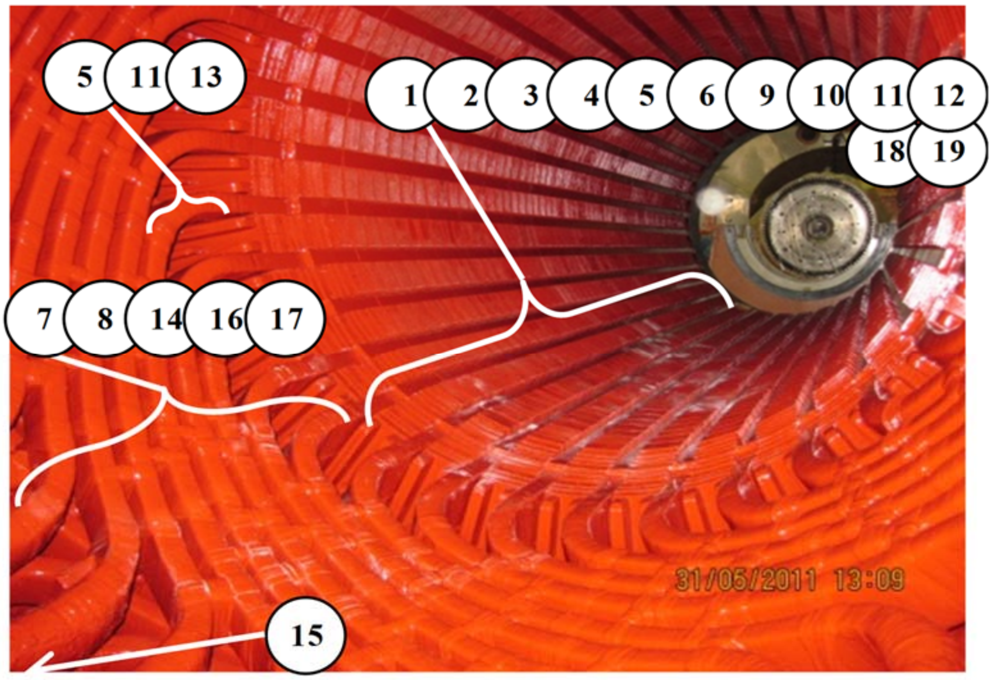

Figure 8 Principal localization of identified failure modes for stator winding and end winding

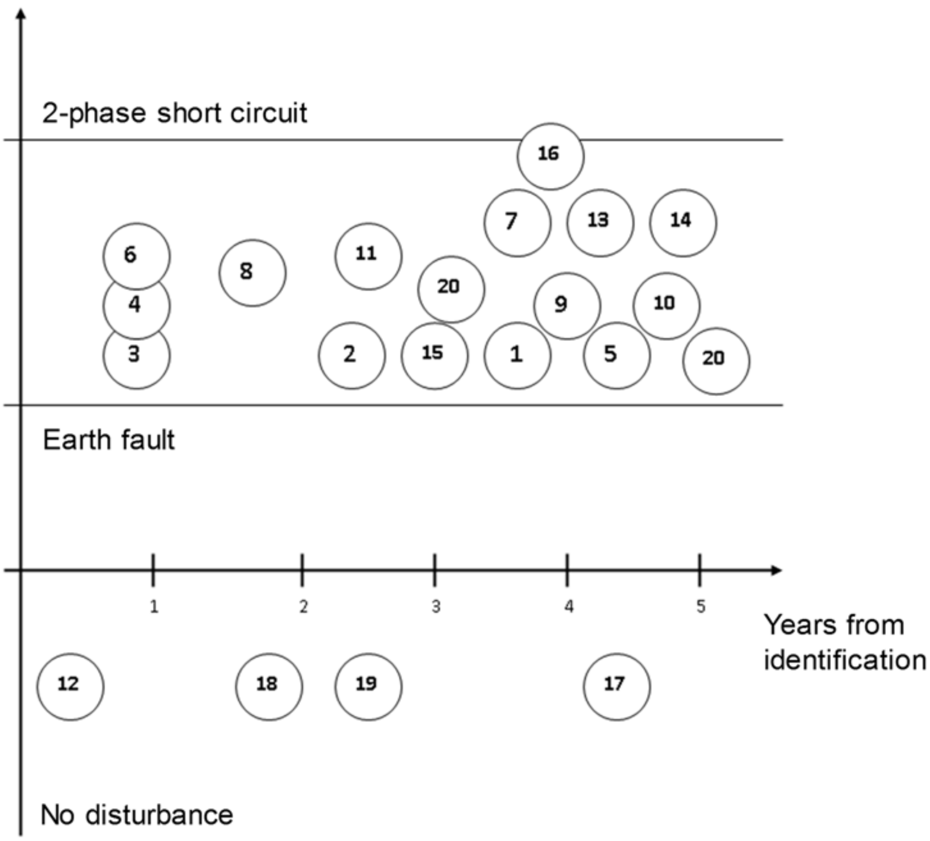

Figure 9 Consequence of stator winding failure modes as function of years since identification

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3.2 Diagnostic tools

We have also mapped different diagnostic methods and the probability with which they can detect different failure modes.

Diagnostics of stator and stator winding consists for example of the following tests:

- Stator frame and core
  - Visual — Overheating, signs of vibration, ...
  - ElCID — Short circuits between core sheets
  - Core test — Short circuits between core sheets
- Stator winding
  - Visual — Signs of vibration, damages, ...
  - Wedge tap test — Looseness of winding in the slot.
  - Resistance — Breakage, bad soldering, ...
  - Insulations resistance — Condition of main insulation
  - Partial discharge — Signs of bad contact bar-to-slot, damage inside insulation and other failure modes
- Testing is finalized with a high voltage test of the winding at 1.5xUn to show that there are no other faults not detected with the other diagnostic tests.

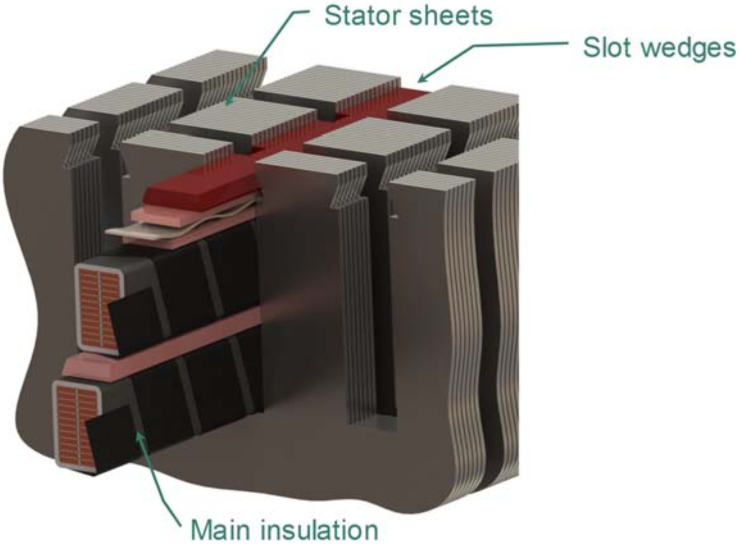

Figure 10 Typical cross section of stator slot with its winding and fixation system.

Diagnostics of rotor and rotor winding consists for example of the following tests:

- Rotor body etc.
  - Visual — Overheating, damages, ...
  - Ultra-sonic — Cracks in retaining rings, bearings, rotor wedges
- Rotor winding
  - Visual — Coil end elongation, bracing, ...
  - Resistance — Breakage, bad soldering, ...
  - Insulations resistance — Condition of slot insulation
  - RSO — Damage to turn insulation, turn-to-turn short circuit
  - RFM (at rotation) — Turn-to-turn short circuits, how many, and location of these faults.

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- Exciter resistance and insulation resistance tests.
- Diodes tested in forward and back direction

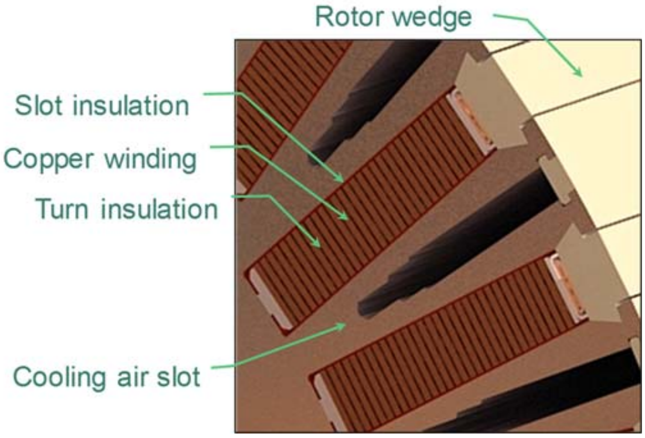

Figure 11 Typical cross section of rotor slot with its winding, insulation and fixation system

3.3 Mapping of failure modes versus diagnostics tools

Based on all our impressions and experiences, the respective failure mode has been analyzed / evaluated against which diagnostics tools can find them. In this evaluation we have defined two terms:

- Detecting a failure mode is when the diagnostics testing has shown that there are one or more failure modes active, but we do not have enough information to decide which one.
- Identifying a failure mode is when we have a high confidence level on which one (or which ones) are active. It is only then that a precise risk assessment and remedy actions can be taken.

The table in figure 12 shows examples of the failure modes versus diagnostic test methods. The tests are group in three corresponding to the possible tests that can be performed at Major Overhaul, Limited Inspection and Safety Check. A filled green box means that this test can identify that specific failure mode. An orange box means that this test can detect that specific failure mode.

It can be concluded that identification of failure modes becomes much more powerful when several methods are combined.

Main Component	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					

Figure 12 Table showing examples of the 100 failure modes versus diagnostics test.

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3.4 Maintenance Levels Ability to Identify Failure Modes

As described before, the usual maintenance levels for a turbogenerator are classified as: Major Overhauls (MO), Limited Inspections (LI) and Safety Checks (SC). The ability of each one to find active failure modes failure differs.

Combining this information with knowledge of which diagnostic tests can be performed at the different inspection types, we have determined how many of the approximately 100 failure modes each inspection is able to detect, see figure 13.

Major Overhauls (MO) can identify 80% of the failure modes and detect an additional 15%. The remaining 5% can only be identified during operation.

A Limited Inspection (LI) can identify 25% and detect an additional 5% of the failure modes. The remaining 70% are not detectable by a Limited Inspection.

A Safety Check (SC) only identifies 15% and detects an additional 10% of the failure modes. 75% are not detectable by a Safety Check.

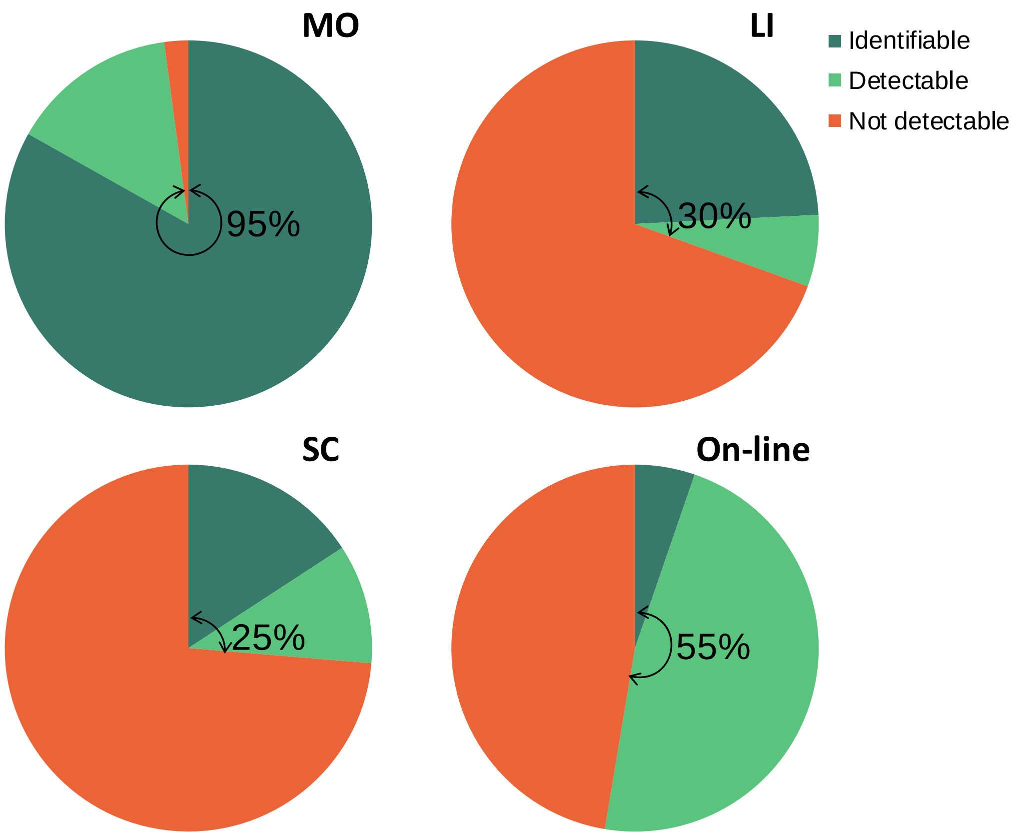

Figure 13 Maintenance levels´ ability to detect and identify failure modes

For all the three maintenance levels, MO, LI and SC the generator needs to be off-line and disconnected from the grid. However, some failure modes can also be diagnosed when the generator is in operation.

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As an example, can an air-cooled generator be equipped with on-line monitoring of the following:

- Rotor Flux Monitoring
- Monitoring stator winding and cooling air temperatures
- Monitoring bearing vibration
- Monitoring shaft voltage
- Monitoring end-winding vibration
- Algorithms for evaluating temperatures against load parameters
- Operating parameter trends
- Generator protection relays
- PD monitoring in each phase of the stator winding

Monitoring with On-line Diagnostics (OD) can identify 5% and detect an additional 35% of the failure modes. Generator protection detects an additional 15% of the failure modes.

Installing monitoring equipment increases the ability to discover the actual condition of a generator. By helping to detect abnormal trends early, it helps prepare maintenance measures. In addition to normal monitoring, e.g. temperature and vibration, we recommend monitoring partial discharges (PD) and changes in rotor flux (RFM) for air-cooled generators.

Comparing the different maintenance levels ability to detect and identify failure modes, it can be concluded that Major Overhaul is the most powerful tool and the most important way of detecting failure modes that can cause unplanned outages. On-line diagnostics is the next most powerful detection tool.

3.5 Examples of two failure modes and their detection

One failure mode that can affect the stator is ‘Loosening of slot wedges’, see figure 14. Its effect will be vibrations of the stator bar and wear of the corona protection. In time, this will lead to an earth fault between the stator bar and stator core. In the worst case, the fault can damage the stator core and lead to a very extensive repair.

This failure mode can be detected on-line by partial discharges (PD) measurement and it can be identified by a knocking test at a Major Overhaul.

This failure mode cannot be found during a Limited Overhaul or a Safety Check using regular inspection tools. However, if a robotic tool is used which is inserted into the air gap between rotor and stator, this failure can also be found at those inspections.

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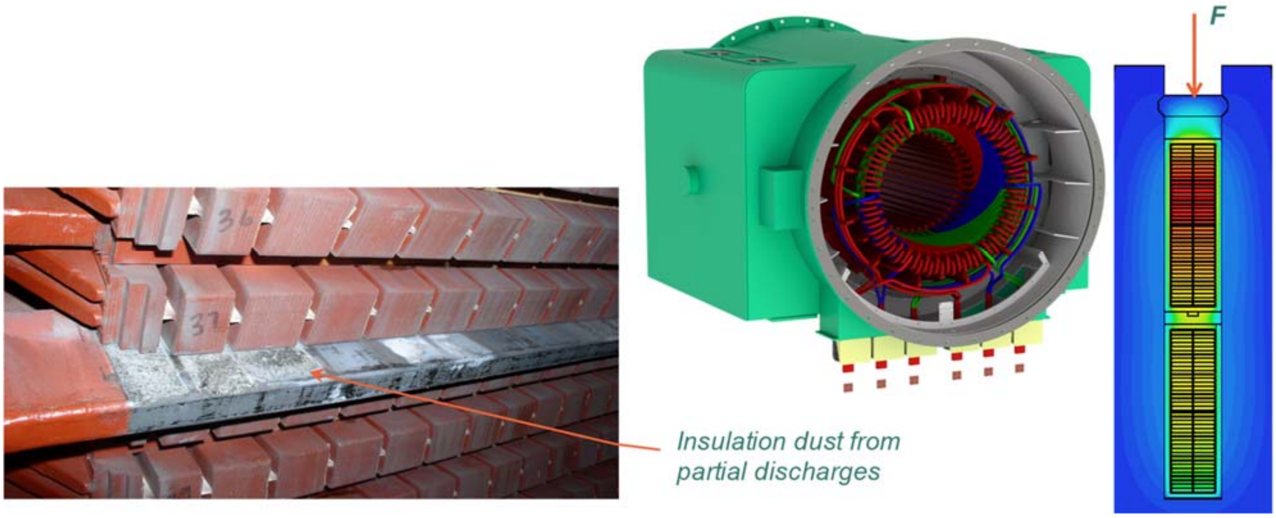

Figure 14 Loosening of slot wedges is a failure mode that in the worst case can lead to an earth fault with consequential damages to the core and a long-lasting repair.

A failure mode that can affect the rotor is 'turn-to-turn short circuit'. Over time, start/stop cycling leads to elongation of the rotor coil end winding, see figure 15. This elongation can result in failure modes such as turn-to-turn short circuit, as well as contact to retaining ring support and dislocated support blocks. Eventually, this will lead to a forced outage due to high vibrations or, in the worst case, a rotor earth fault.

Turn-to-turn short circuit can be detected at MO, LI or SC by doing an RSO test of the rotor at stand still. Note, however, that some short circuits only appear at full rotation speed, which can give a false picture during standstill tests. Installing Rotor Flux Monitoring (RFM) on-line allows turn-to-turn short circuits to be identified during operation. It also allows for monitoring the trend of how many they are as function of time.

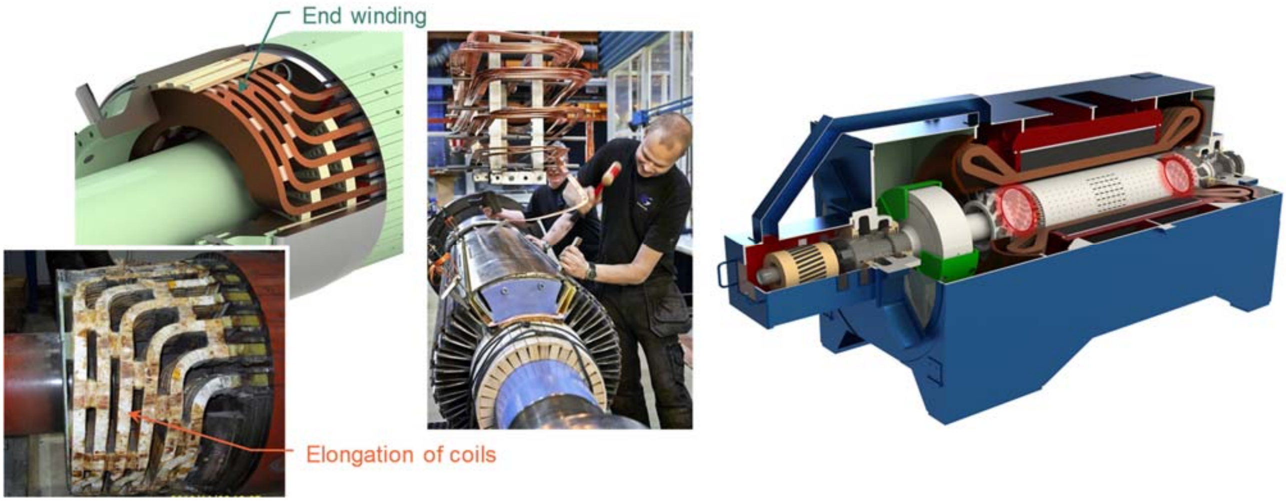

Figure 15 Turn-to-turn short circuits due to elongation of coil end winding is a common failure mode for turbogenerator rotors. But the elongation can also lead to the failure mode earth fault, which is more severe.

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4 Risk Assessment and Recommendations

The result of each diagnostic activity must be individually evaluated to then be merged with the total information from all tests, which then result in an assessment of the condition of that component. Predicting a future operating outcome in the form of operational disturbances would be desirable, but in practice it is impossible to perform. On the other hand, it is easier to describe the condition in the form of changed risk of operational disturbances during a defined period. The assessment must relate to a "normal state" and a defined future scenario.

Normal conditions can be what one can expect from a fully functional component without known defects and which are subjected to the operating conditions for which it is designed, and this condition is then referred to as a base risk level. Deviations from this normal state / condition give an increased level of risk regarding operational disturbances. The deviations are preferably divided into three steps, which gives a total of 4 levels of risk, that is.

1. **Base Risk**
2. **Increased risk**
3. **Medium high risk**
4. **High risk**

The risk level is related to a continued normal operating condition and that the next Major Overhaul (including a complete diagnostics of the generator) is performed according to the recommended maintenance program and that intermediate safety inspections (SC and LI) are also performed according to the recommendation for the current generator type.

Risk assessment is given at the per-component level. The risk to the generator is equal to that of the highest-risk component. In this way, the current risk situation can be related to that of the inspected generator, see figure 16.

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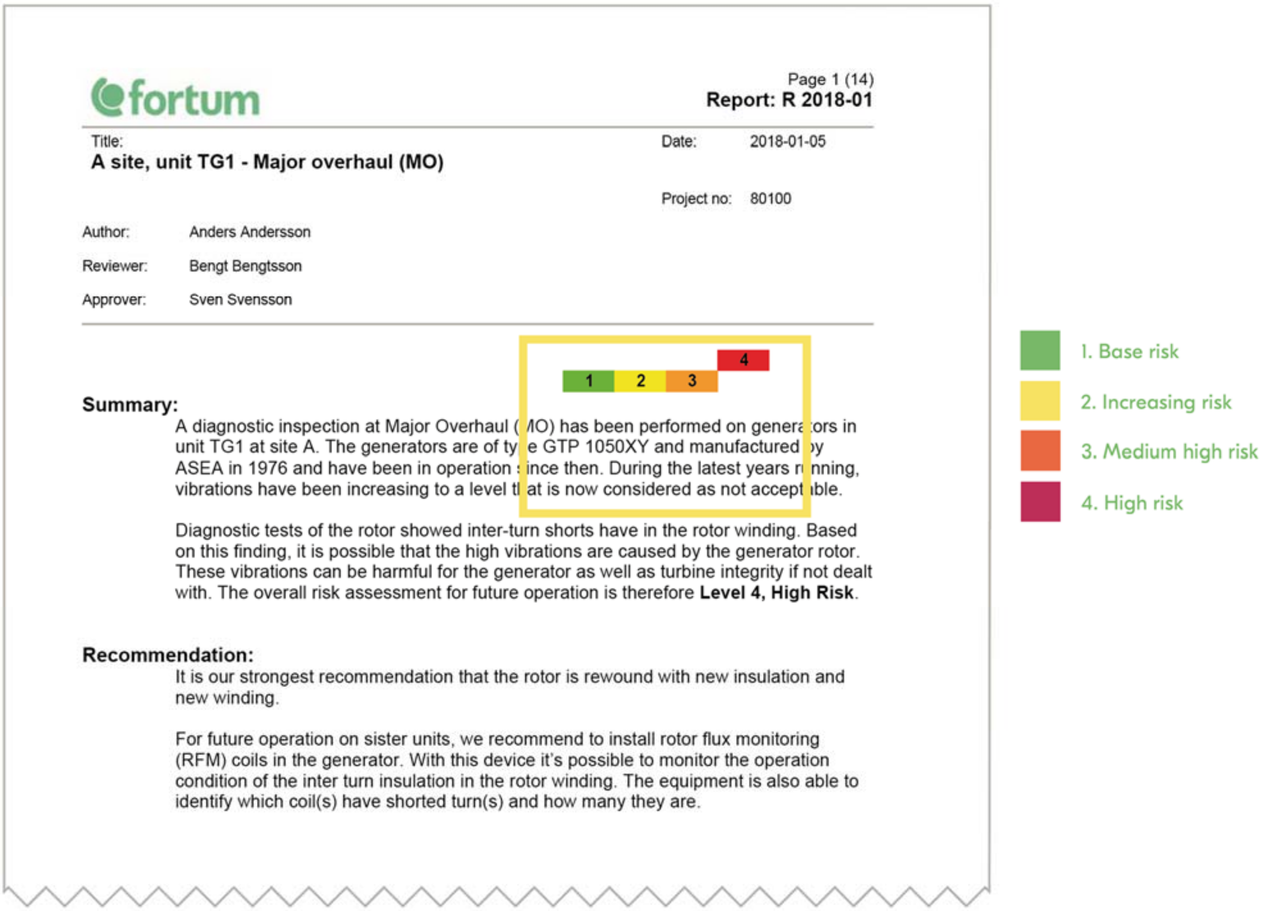
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Report: R 2018-01

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

Date: 2018-01-05

Project no: 80100

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

Summary:

A diagnostic inspection at Major Overhaul (/IO) has been performed on genera ors in unit TG1 at site A. The generators are of ty e GTP 1050XY and manufactured y ASEA in 1976 and have been in operation ince then. During the latest years r nning, vibrations have been increasing to a level t at is now considered as not accept ble.

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.

Figure 16 Results of the diagnostics are reported as four levels of increasing risk. The report includes many valuable recommendations for reducing these risks.

Our inspection reports always include recommendations for measures that can reduce the risk of operational disturbance and/or mitigation measures that reduce the consequences of such an outage. This can, for example, include strategic spares or installing monitoring equipment such as PD couplers or RFM. The result gives the plant owner a powerful basis for updating the maintenance plan. It also guides future investments needed to maintain risk at an acceptable level, or to reduce the risk to such levels.

5 Adapted maintenance plan

Our working philosophy is to identify the generator condition from a risk perspective in terms of downtime. As noted earlier, a complete diagnosis can only be made at a Major Overhaul, which is thus the only time a complete picture of the risk to the generator can be gained.

For a new generator, the maintenance plan is drawn up as an accrual activity at fixed intervals. For an older generator with a higher overall risk level, the maintenance interval must be adjusted to the diagnostic tools capable of detecting failure modes, and to the growth rate of these failure modes.

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The earliest a fault can be detected is when the growth phase begins, see figure 17. The phase of rapid growth before a failure occurs may be very short. This means that it is in the growth phase we are able and should find the active failure mode.

Therefore, must the maintenance plan be designed with intervals short enough to detect active failure modes. If this gap is too long, a fault may go from undetectable to failure in the interval between two diagnostic inspections.

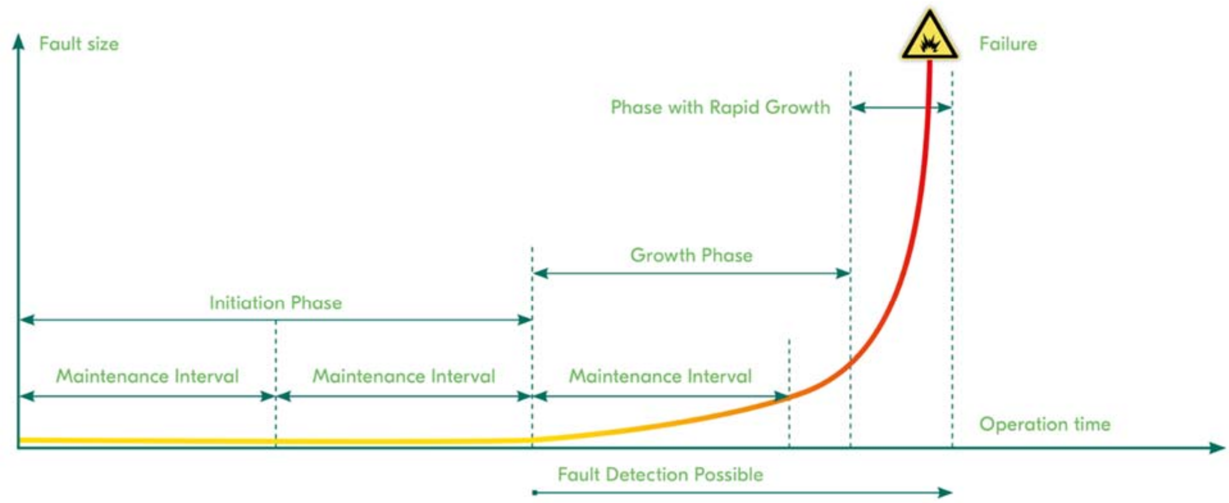

FIG. 8.
FAULTS CAN ONLY BE DETECTED WHEN THE GROWTH PHASE BEGINS.

Figure 17 Faults can only be detected when the growth phase begins. If we do not detect it before the rapid growth starts, it might be too late as at the last stage the growth can be very quick.

5.1 Example of an adapted maintenance plan

A plant's original maintenance plan initially had a 7-year interval between Major Overhauls. At one of these overhauls, inspection with an ultrasonic test revealed a few cracked rotor slot wedges, a known weakness for this rotor type and caused by stress corrosion. The rotor was taken to our workshop to replace the faulty wedges. Subsequent investigation showed that stress corrosion was indeed the cause of the cracks, see figure 18.

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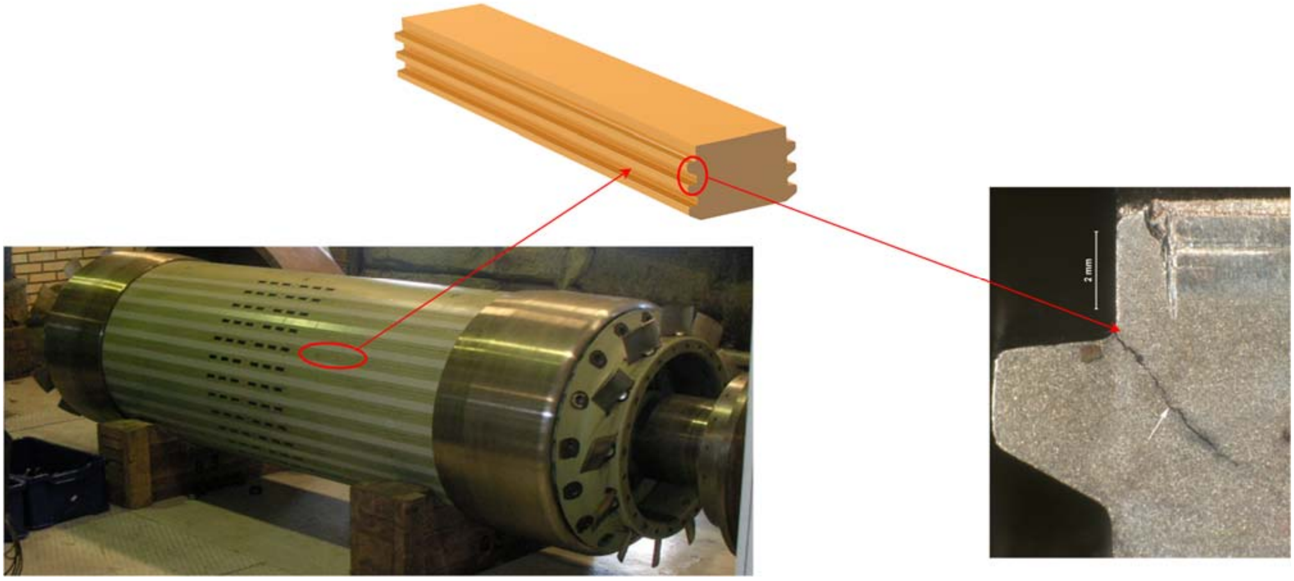

Figure 18 A Major Overhaul revealed a few cracked rotor slot wedges, a known weakness in this rotor type and for which a re-design is not possible. A series of other corrective measures were introduced.

One corrective measure introduced was to install equipment to monitor the moisture content inside the generator. Another was to reduce the interval between Major Overhauls from 7 years to 5 years. This keeps the risk of cracks in the rotor wedges at an acceptable level.

A re-design of the wedge i.e. changing material from brass (Cu-Zn alloy) was also investigated, but it was concluded that it is not possible. For instance, a change to alloy of Cu-Ni-Si, which is a commonly used alloy would result in too high creep stresses.

6 Summary and Conclusions

Fortum Turbine and Generator Services (TGS) has developed a concept for generator diagnostics that supports condition-based maintenance of generators. Based on about 100 failure modes of a generator, individually tailored diagnostics is performed.

The ability to detect failure modes at different inspection levels have been mapped and it shows that the Major Overhaul is most powerful, as expected. If all available tests are performed, about 95% of the failure modes can be identified or detected. The next most powerful is on-line diagnostics where 55% % of the failure modes can be identified or detected

When a diagnostics assignment is performed, the inspections and diagnostic tests are analyzed by experts and a four-level risk assessment is made for each component, from **level 1, base risk** to **level 4, high risk**. The risk level of the generator is equal to highest component risk. Recommendations are given that reduces the risk of forced outage and its consequences. The first page of the diagnostics report shows summary with total risk as well as recommendations for reducing risk levels.

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Diagnostics of generators- From failure modes to risk of forced outage.

This methodology can also be applied to other parts of the plant, such as turbine, gear box or transformer.

The diagnostics report gives plant owners a powerful basis for updating their maintenance plans and guides future investments in maintaining risk at an acceptable level or reducing it to such a level.

Fortum TGS approach for generator diagnostics based on about 100 failure modes can also be summarized in the following flow chart.

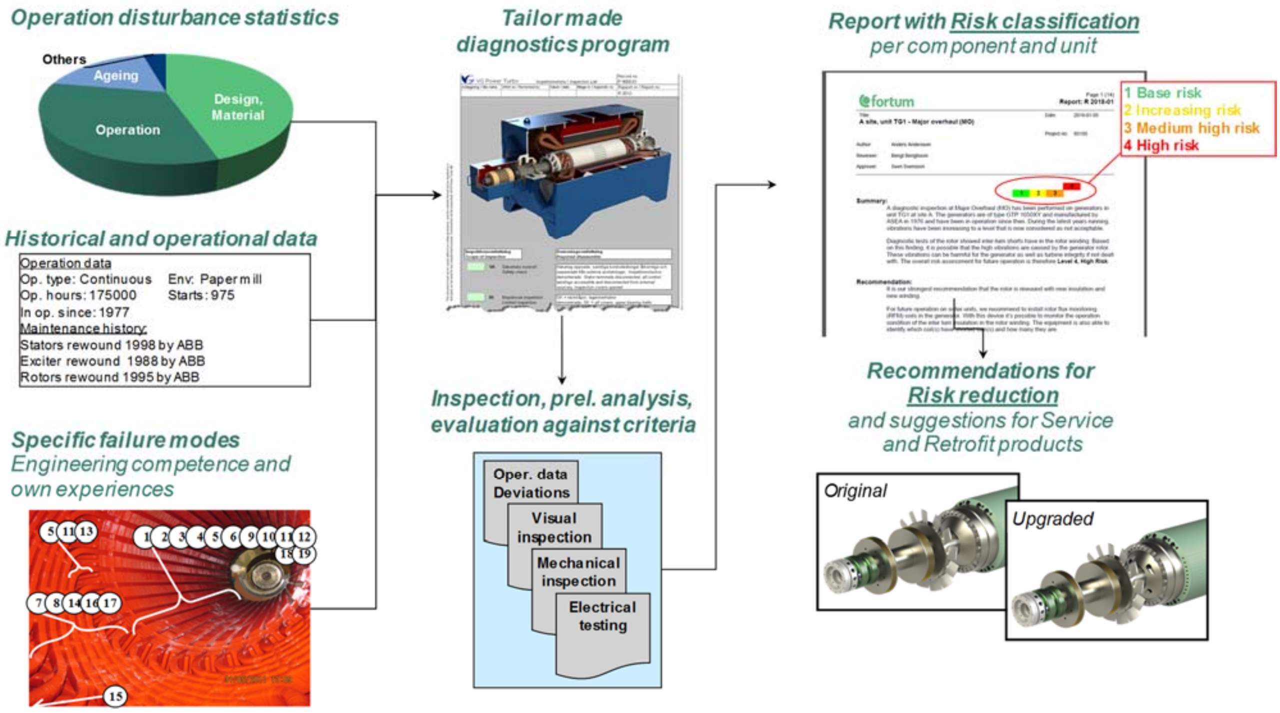

Figure 19 Flow chart for Fortum TGS generator diagnostics approach.