Nordic Nuclear Power Generator Stator Vibrations

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Fortum Turbine and Generator Services

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Foreword and acknowledgment

- This paper is generally focused on vibrations in turbo generator stators in the Nordic nuclear power plants in Ringhals, Forsmark, Oskarshamn and Olkiluoto. The purpose of the project is to provide a background and basic knowledge of the generator stator structure, design requirements and various vibration conditions.

- Authors are Kent Engvall senior consultant and Gabor Csaba, Generator Product Line Owner at Fortum Turbine and Generator Services.

- The study has been carried out within the Energiforsk Vibrations in nuclear applications research program. The stakeholders of the program are Vattenfall, Uniper, Fortum, TVO, Skellefteå Kraft and Karlstads Energi.

Outline

- Main Components and Functional Requirements
- Excitation and Dynamics
- Problems/Failures Caused by Vibrations in Stators
- Study of 4-pole Generator Stators
- Study of 2-pole Generator Stators
- Methods to avoid/mitigate “unhealthy” vibrations
- Experiences from other plants

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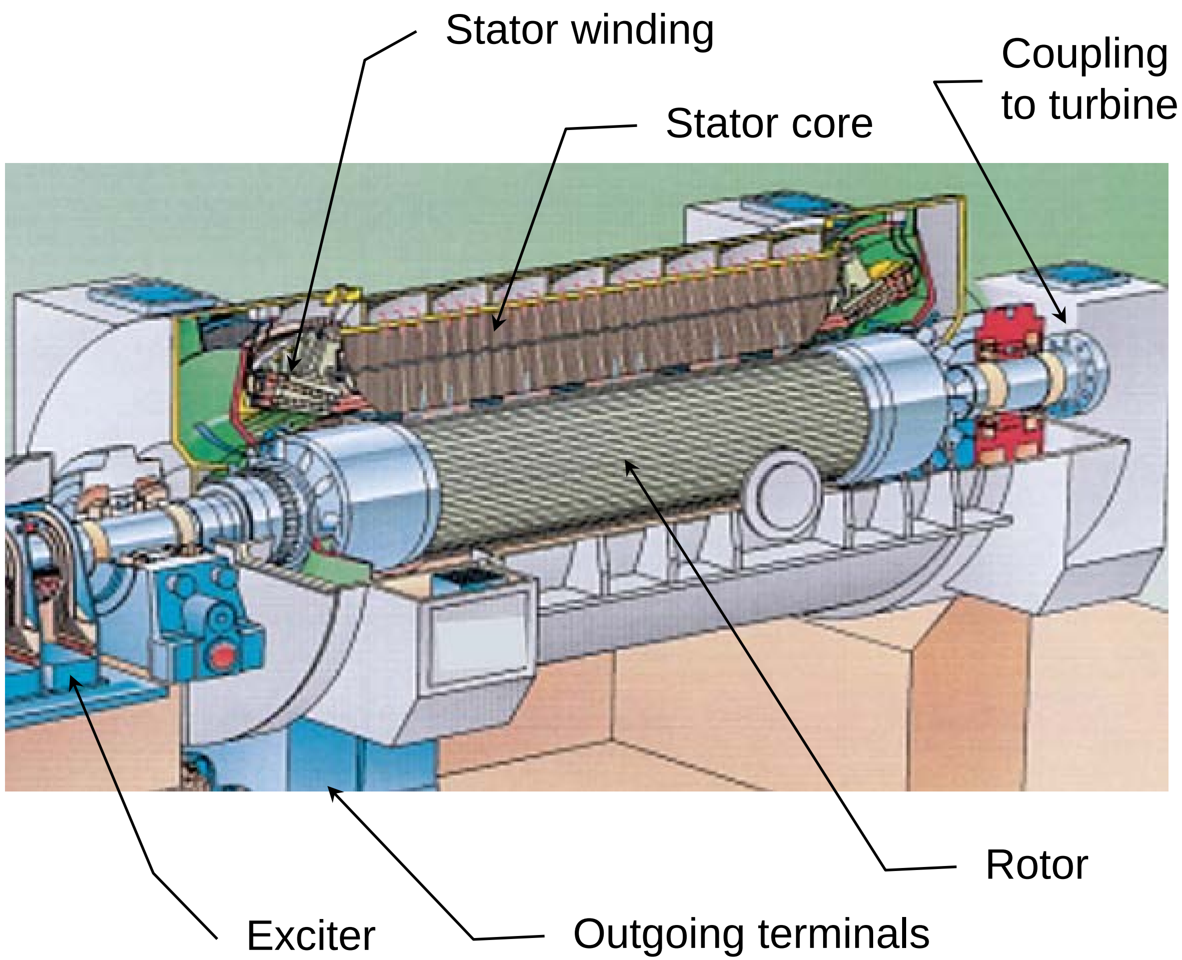
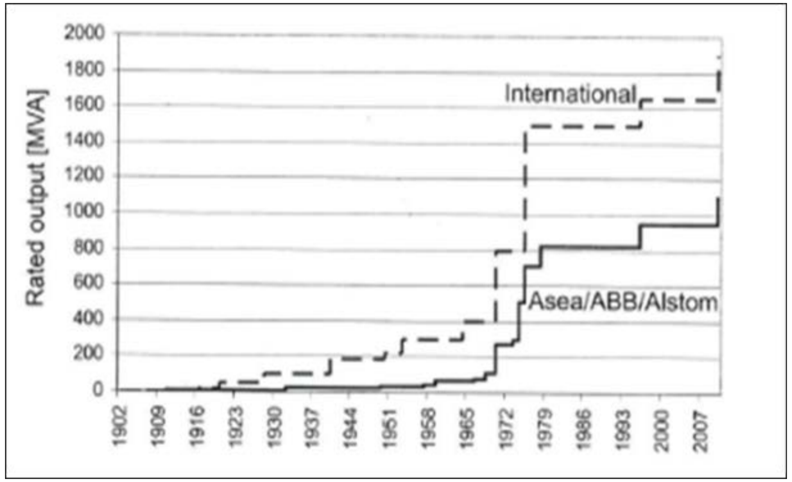
The Turbo Generator´s Main Components and Functional Requirements

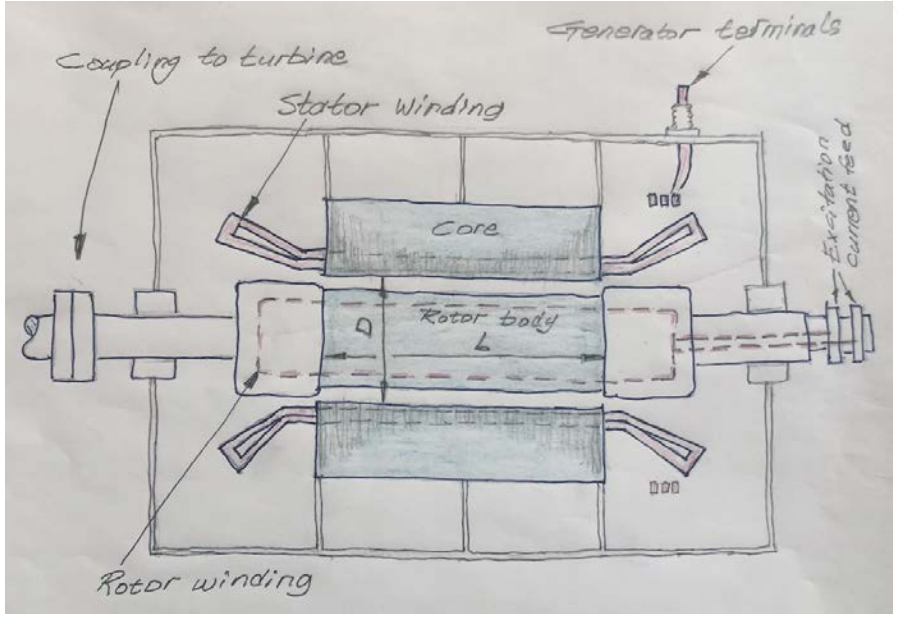
- Generator main purpose: to transfer mechanical energy from turbine to electrical energy.
- When the **rotor winding** feed with direct current, the **rotor** transfers the mechanical power of the turbine to a rotating magnetic field.
- The **stator core** closes the magnetic field from the rotor.
- **Stator winding** transfer 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.

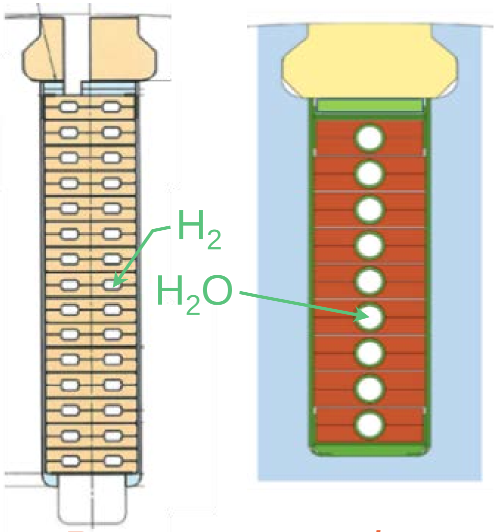


The Turbo Generator´s Main Components and Functional Requirements



- Turbo Generator rating made a large jump in mid-1970s due to development of Nuclear Power Plants.
- Rapid growth of rating gave many new experiences, some related to failures.
- Internationally 2-pole and 4-pole generators with H_2-cooled rotor and core, H_20-cooling stator winding were developed.
- Development in Sweden was 2-pole generators with H_2O-cooled rotor and stator windings and Air-cooled core.
- Rotor designed to withstand centrifugal loads.
- Stator designed for electro-magnetic forces in operation and fault conditions



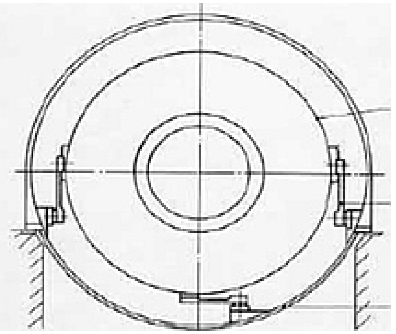


Rotor cross section

The Turbo Generator´s Stator

Stator frame:

- Support core plates
- Guides cooling media
- Support for winding
- Withstand short circuit forces
- If H_2-cooled, contain media at pressure



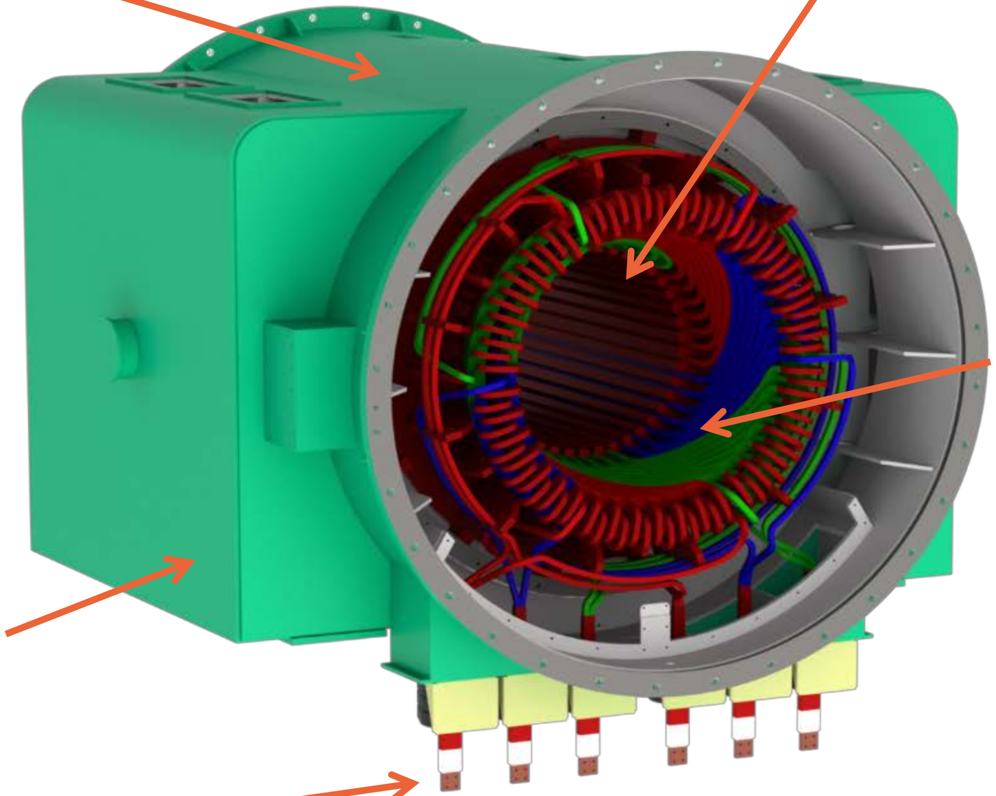
Flexible core connection

Cooler compartment:

- Space for coolers
- Air guiding

Terminals:

- Connection to bus bars and further to transformers



Stator core:

- Lead magnetic flux
- Place for stator bars
- Guide cooling air

Stacking of core

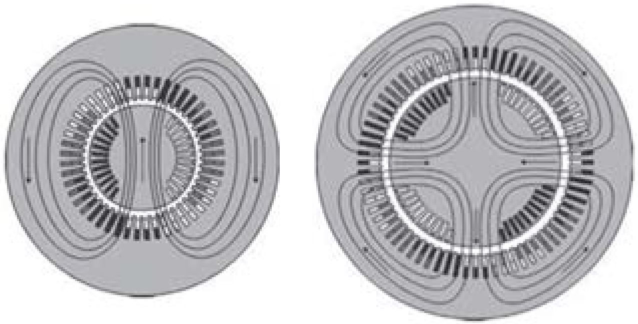
Stator winding:

- Induce electrical energy from rotating magnetic
- Fixed in slots in core
- Withstand short circuit forces

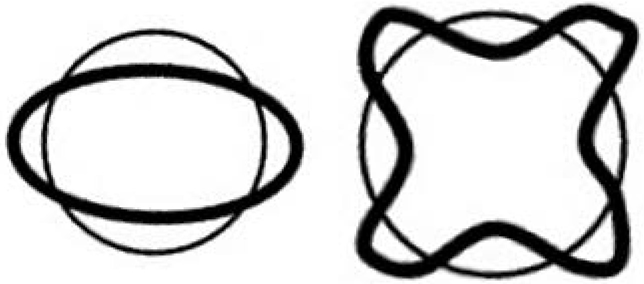
H_2O-cooled stator bars

Excitation and Dynamics

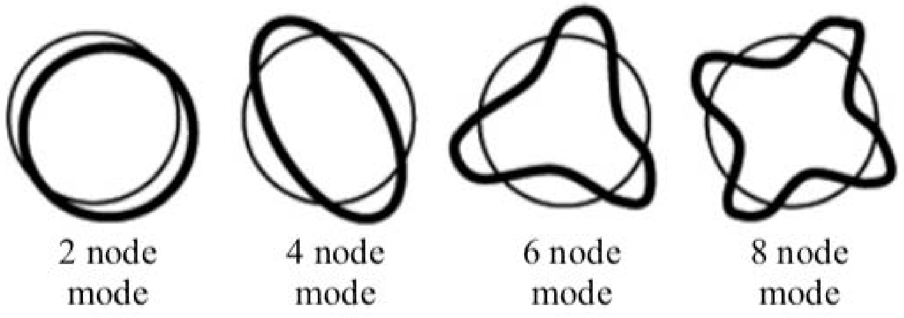
- A Turbo Generator will always vibrate.
- Magnitude of stator core vibration depends mainly on how close its eigenfrequencies are to main excitation frequency.
- End winding vibration is more complex due to several excitation forces and dynamic characteristics of end winding structure.
- For the 4-pole, 8 node mode is far away from main excitation freq.
- For the 2-pole, 4 node mode can be close to main excitation freq.
- Mode forms shown are for a “perfect” ring structure.
- If vibration cause looseness, raised vibration occurs.
- Vibration monitoring is therefore important.



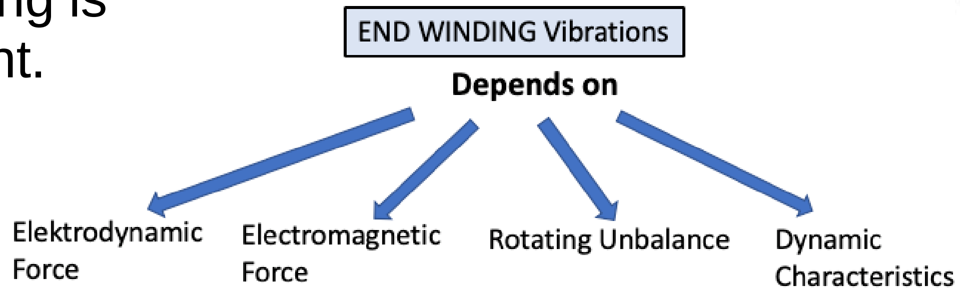
Flux pattern in rotor body and stator core, 2-pole and 4-pole



Stator core deformation due to magnetic forces, 2-pole and 4-pole



Mode forms of end winding



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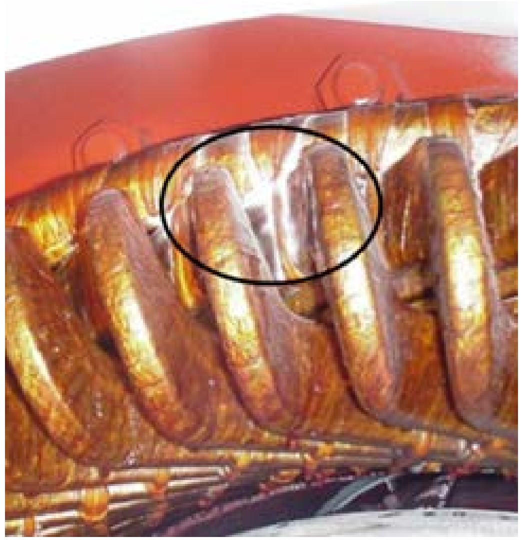
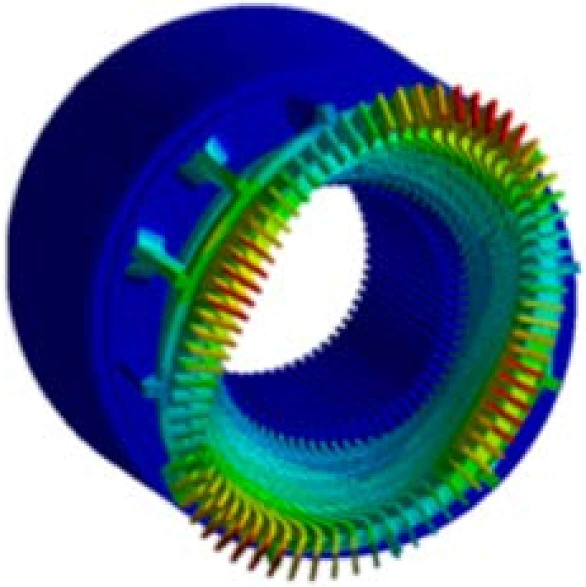
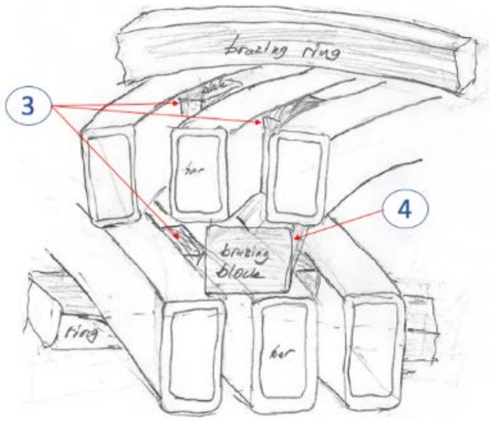
Problems/failures caused by vibrations in stators

- End winding support designed to create ring structure.
- In 2-pole generators f_{eigen} is close to f_{excit}, it is an issue of concern.
- When end winding support structure degenerate, vibrations become an issue. Normally starts by signs of vibration dust.
- E.g. broken copper strands or cracked main insulation can cause forced outage.
- A loss in axial core pressure together with vibrations can cause several issues, such as meltdown of core





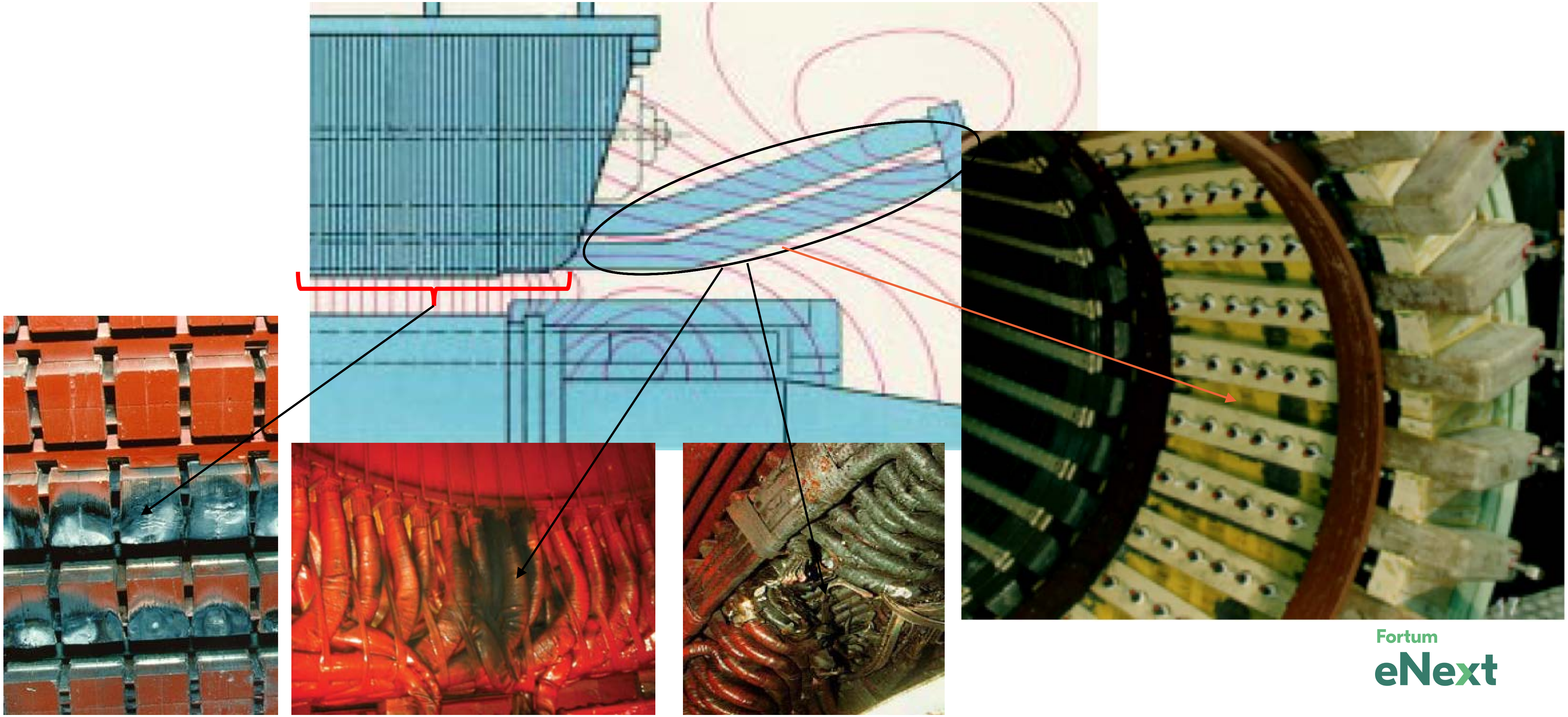
Mode shape of end winding with perfect ring structure



Bracing blocks in end-winding

Other problems, due to foreign objects

- NEVER leave any types of metallic pieces, tools or particles in the generator.
- This will soon result in severe failures causing long lasting forced outages of the production.



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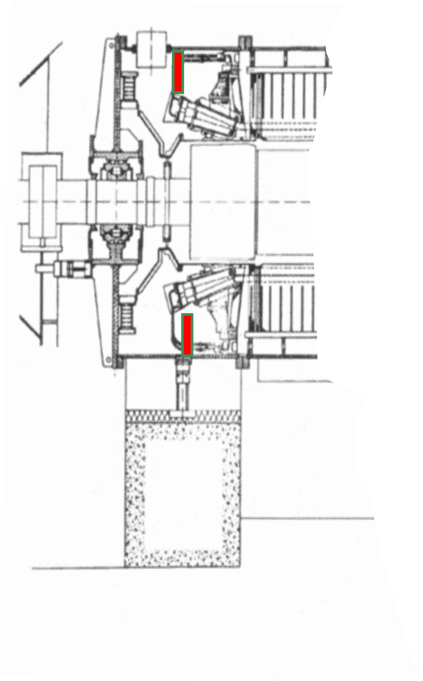
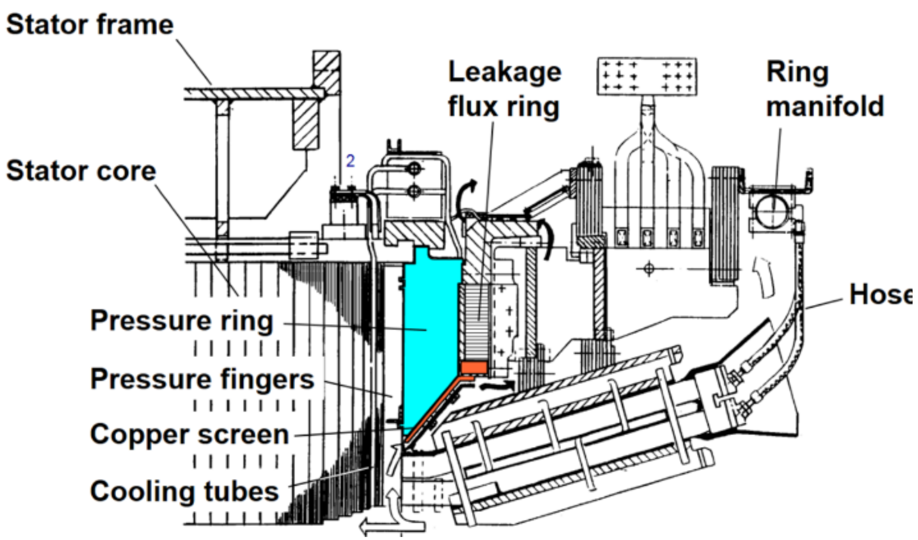
Study of 4-pole Generator Stators

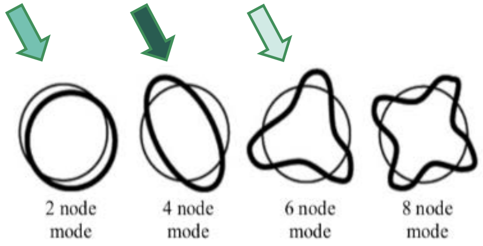
- Gigatop at Oskarshamn 3 and Forsmark 3
- Siemens SGen 4000W at Olkiluoto 3
- Rotor and core H_2-cooled, stator winding H_2O-cooled
- End winding 8-node mode well above excitation freq.
- In F3/O3 22 vib. sensors, in OL3 12 sensors
- Typical stator vibrations at F3:
  - End winding 1 – 2 mm/s
  - Connection bar braids ~4 mm/s
  - Stator core ~2 mm/s
- One can expect stable vibration conditions over time.
- If trend shows deviations, investigation is recommended even if absolute values are low.

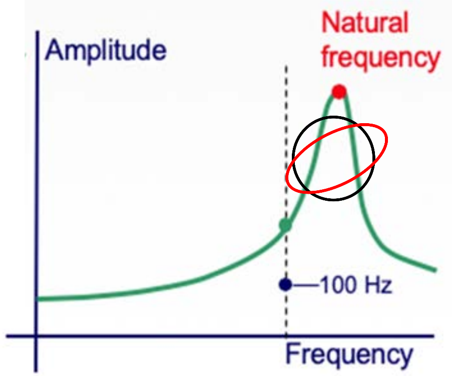
GE Gigatop 4-pole turbo generator

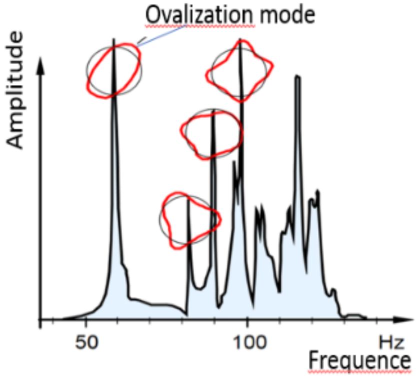
Study of 2-pole Generator Stators

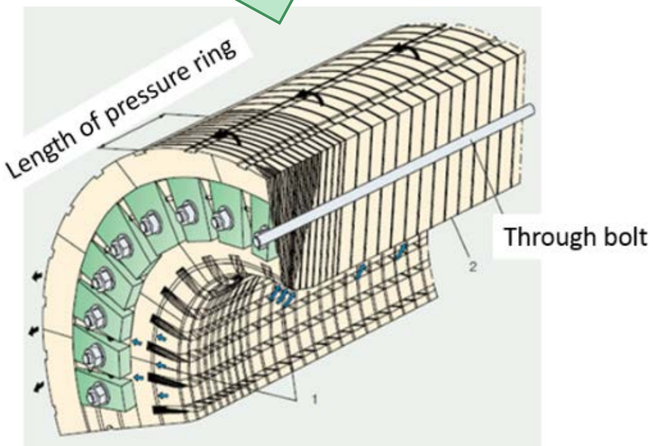




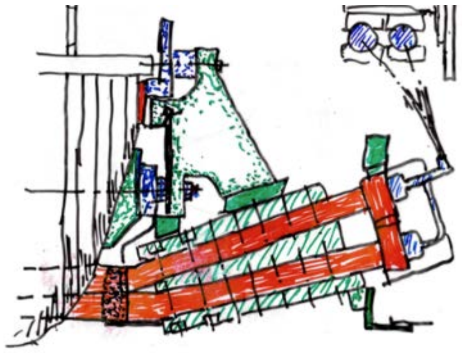




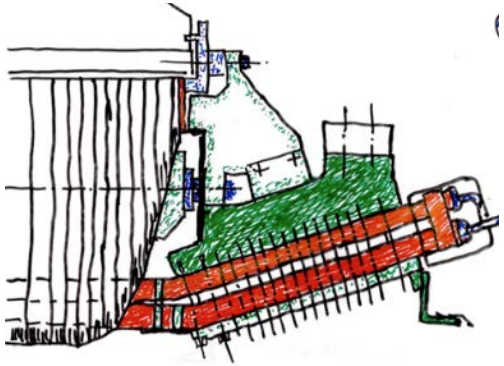




Core with laminated pressure rings

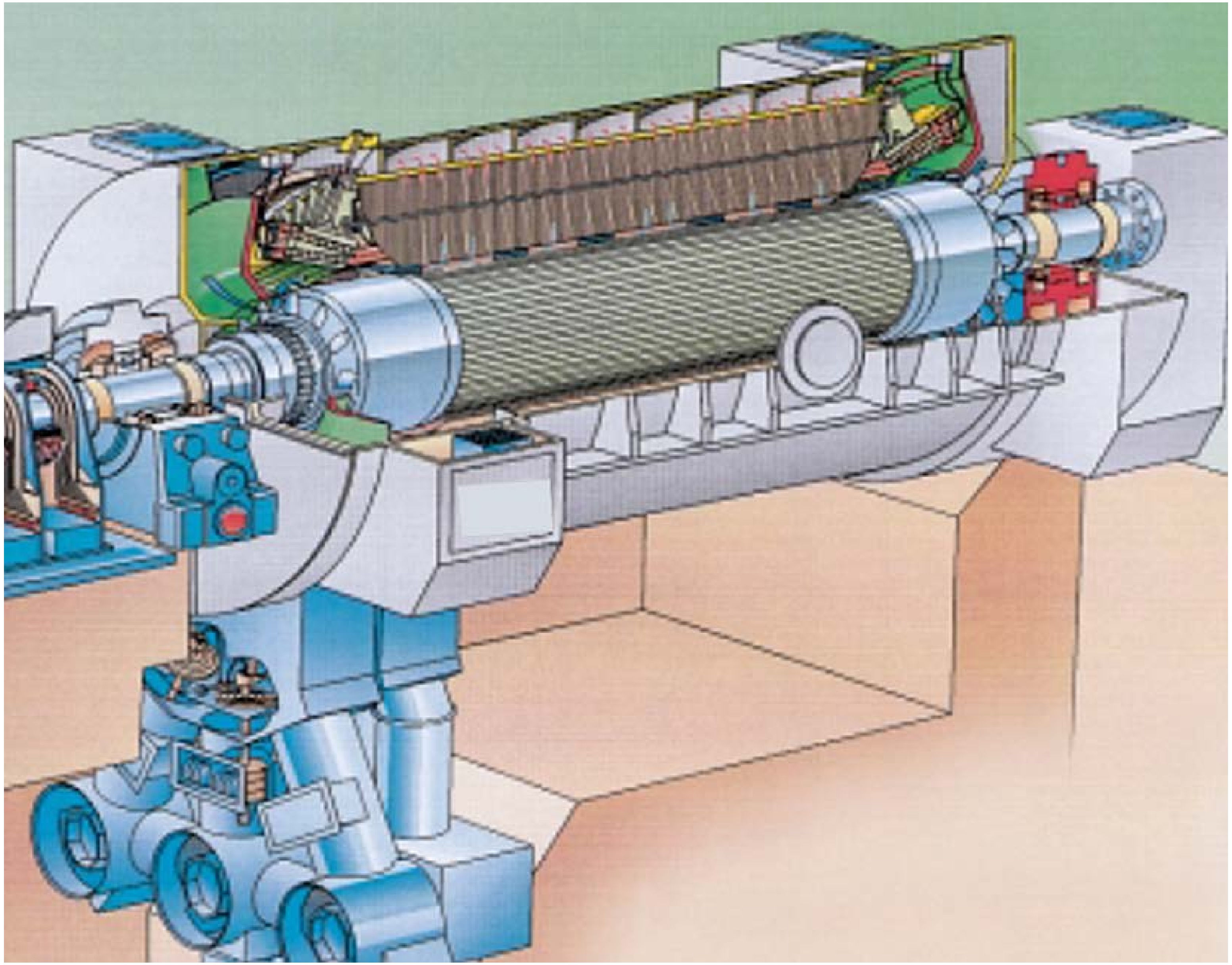


Ring type

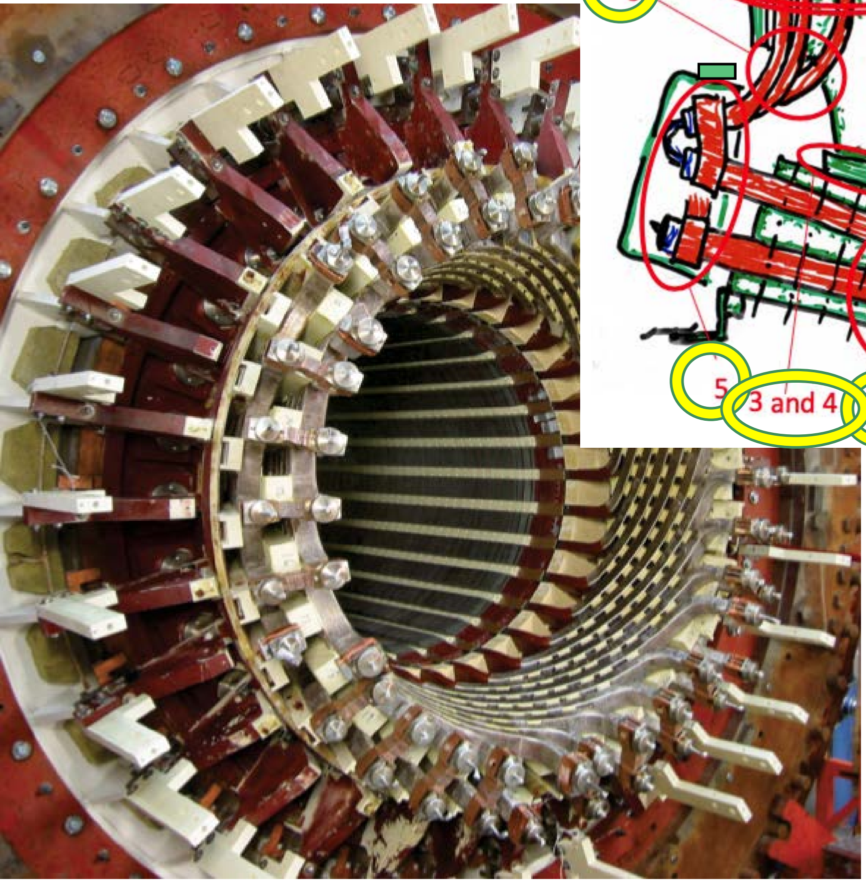


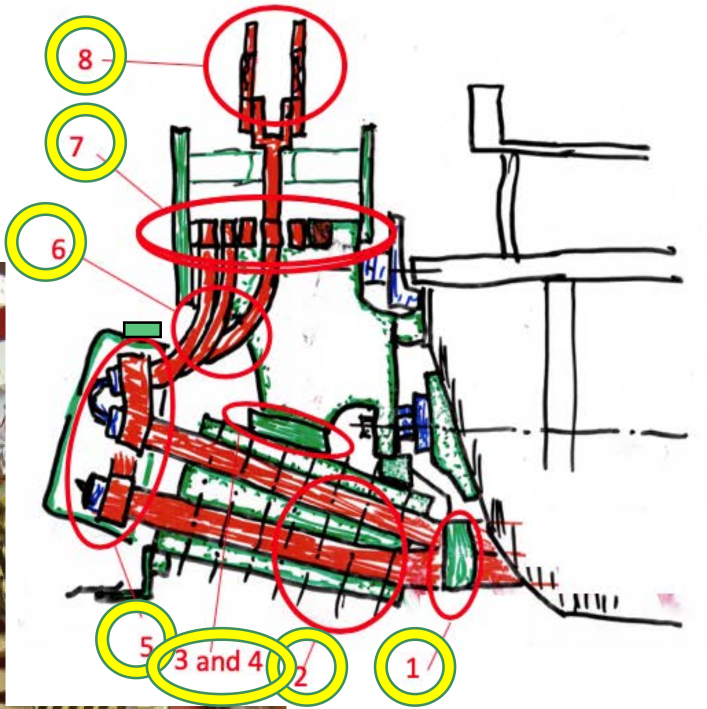
Cone type

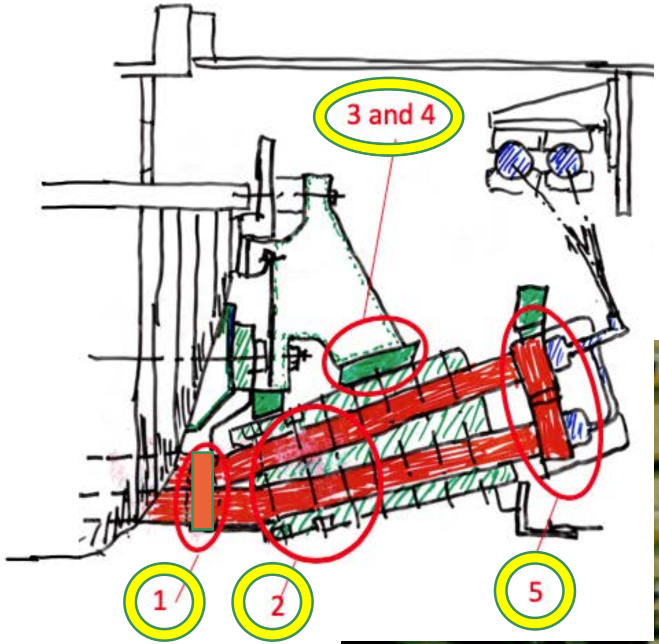
2-pole generators in Forsmark and Ringhals

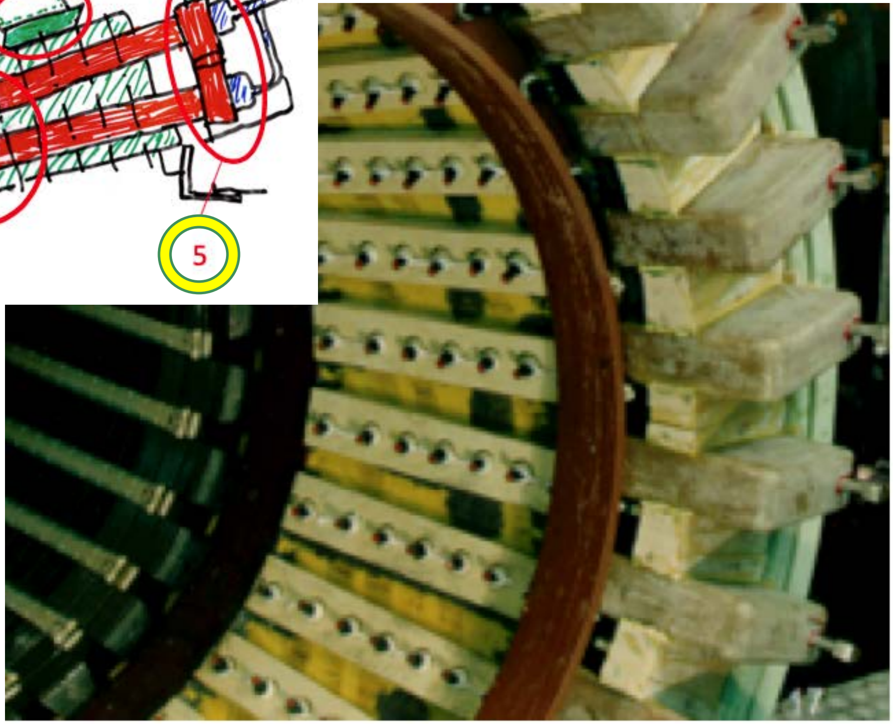


Identifying potential parts/areas for malfunctions with impact on operation





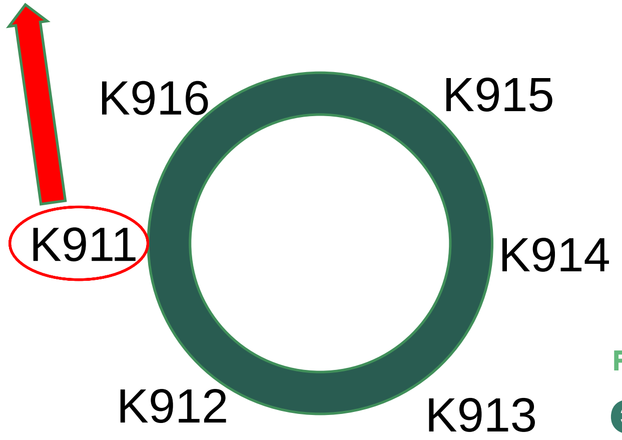




Case from Forsmark with changed end-winding vibrations.

irvkorgsgivare TS och MS 2xN (mm/s rms /grad)

K911 S57	K912 S58	K913 S59	K914 S60	K915 S61	K916 S62
503 MW	DS18/19				
9/168	10/84	7/345	6/162	5/40	6/348
510 MW	DS18/19				
18/158	9/119	5/337	12/169	7/27	2/330
514 MW	DS18/19 Decision to stop and inspect				
28/186	3/167	8/305	17/196	11/13	6/269
515 MW	DS18/19 After reconditioning				
8/202	14/82	8/335	5/167	4/66	8/345
518 MW	DS18/19				
7/205	15/96	7/338	6/162	5/60	7/343



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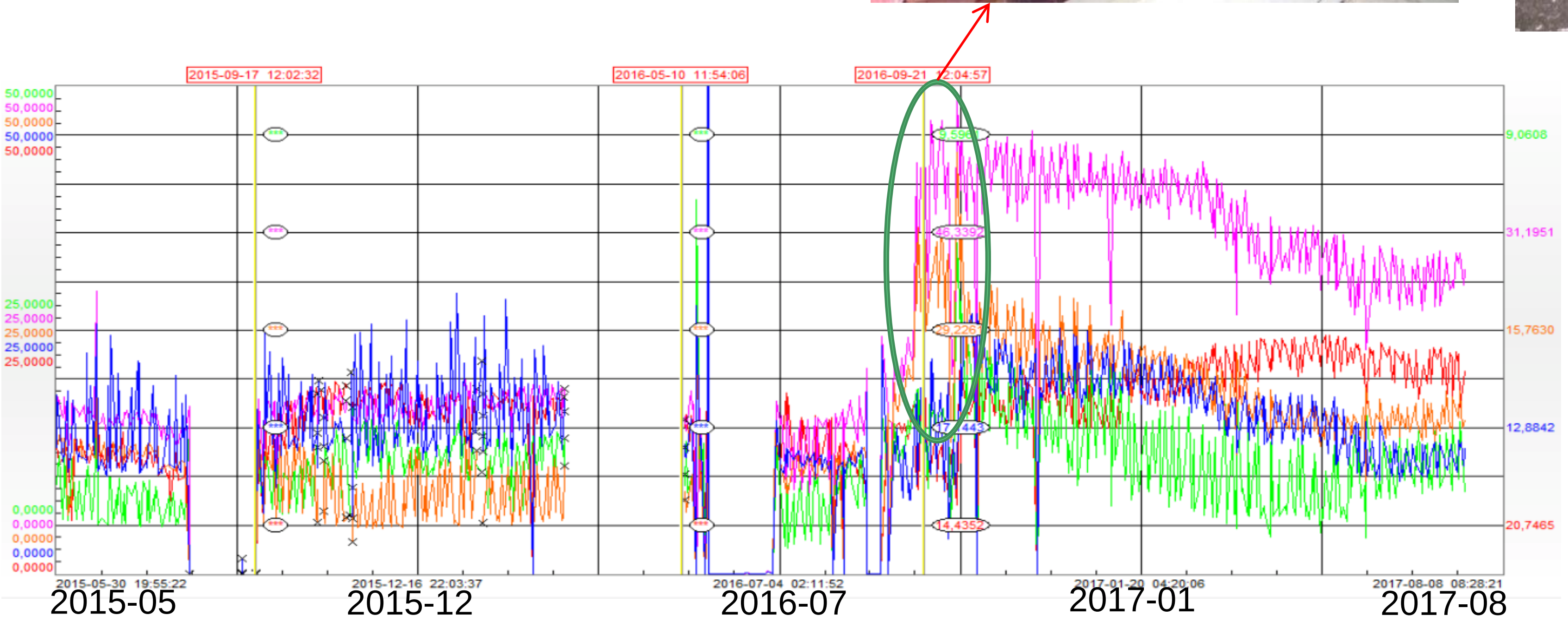
Ringhals unit G32 and G41 with changed end-winding vibrations.

Wear marks on manifold



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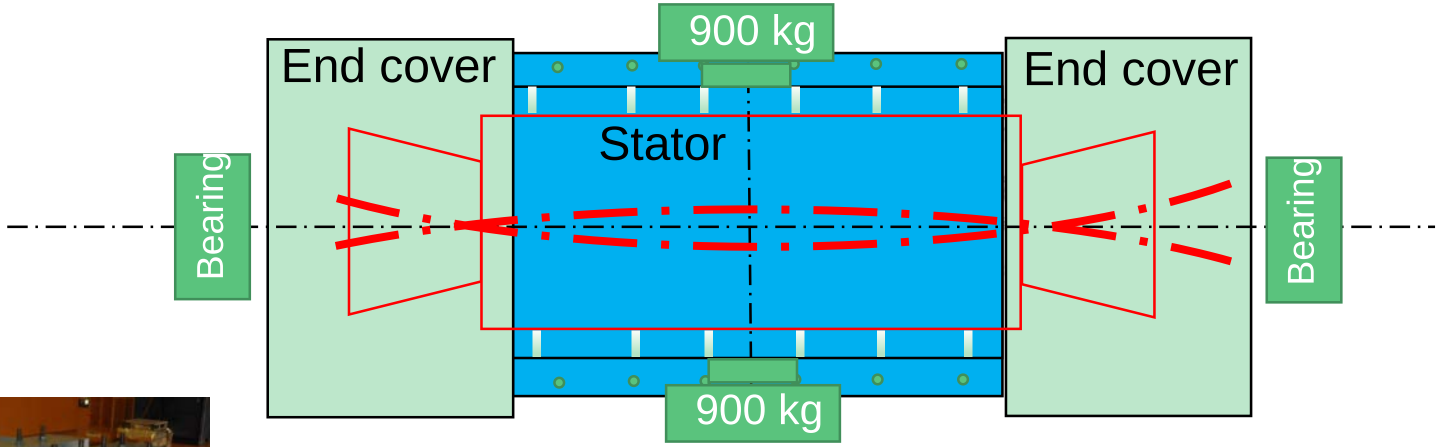
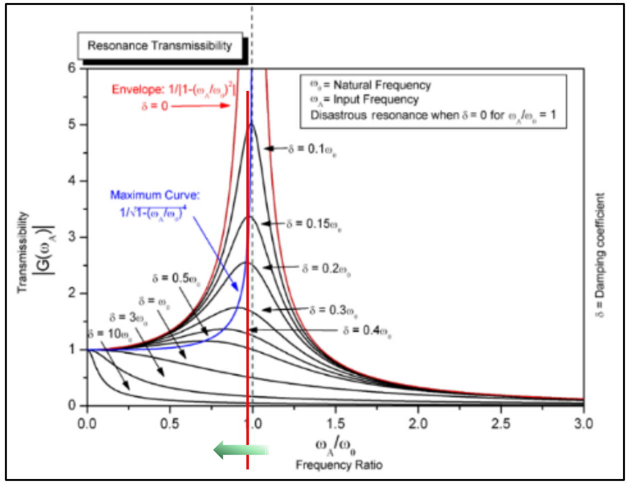
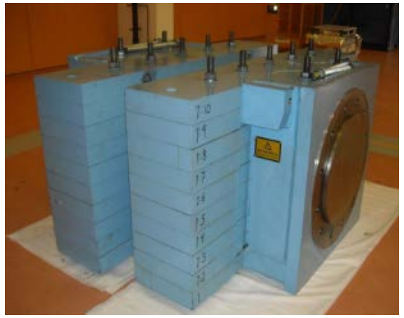
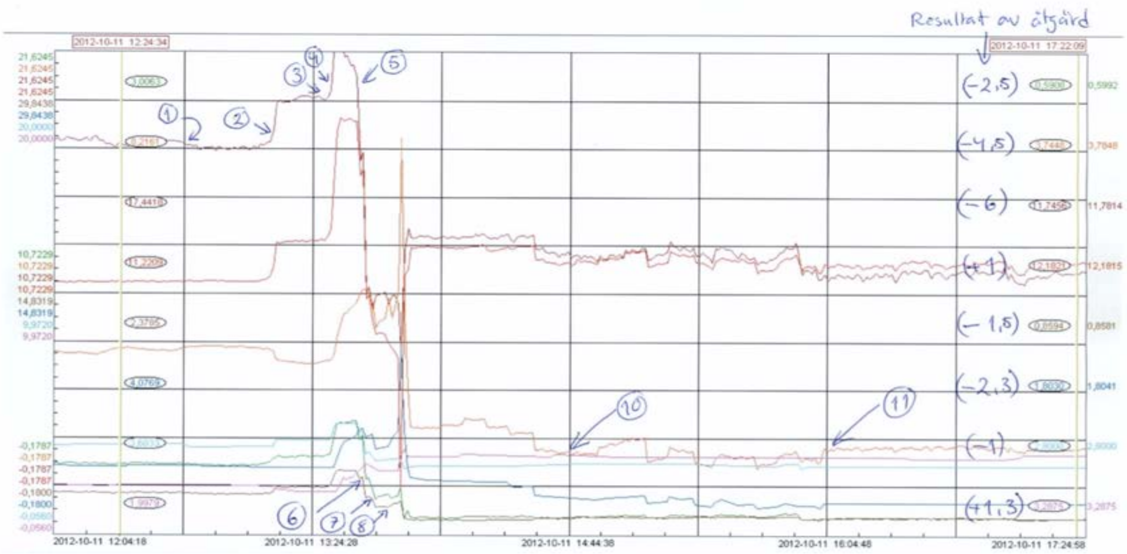
Ringhals unit G42 Bending mode in stator frame/core.







$$\omega\ (Natural\ frequency) = \frac{1}{2 * \pi} * \sqrt{\frac{k\ (stiffness)}{m\ (mass)}}$$



2-pole Generators in Olkiluoto

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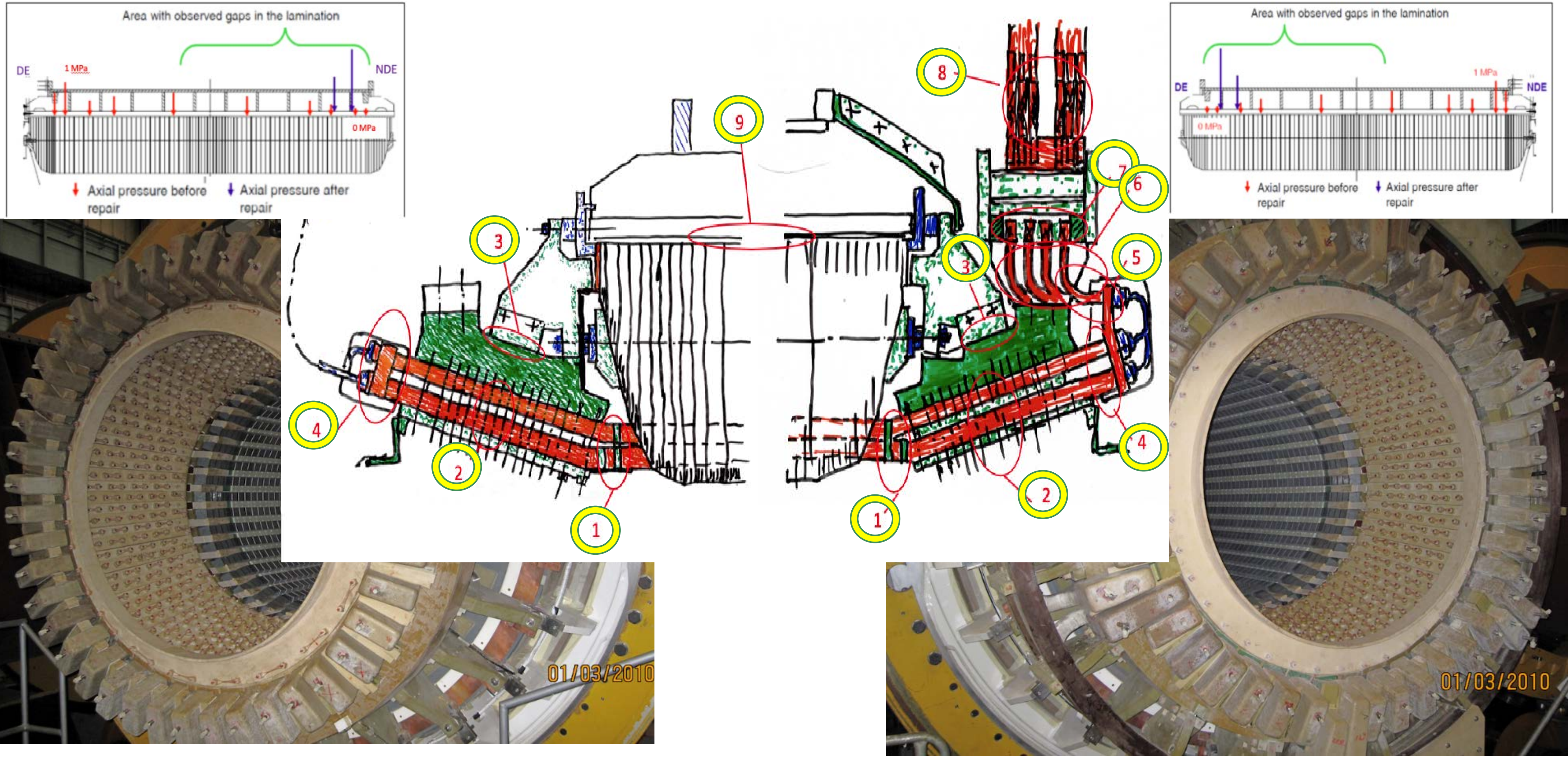
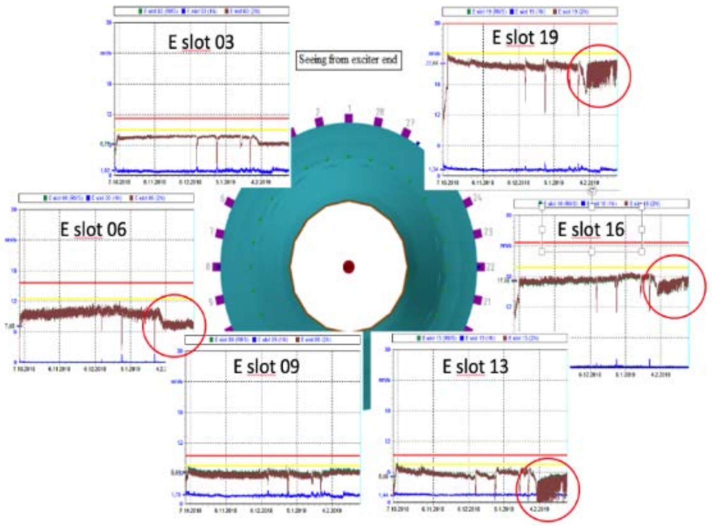
Potential parts/areas for malfunctions with impact on operation

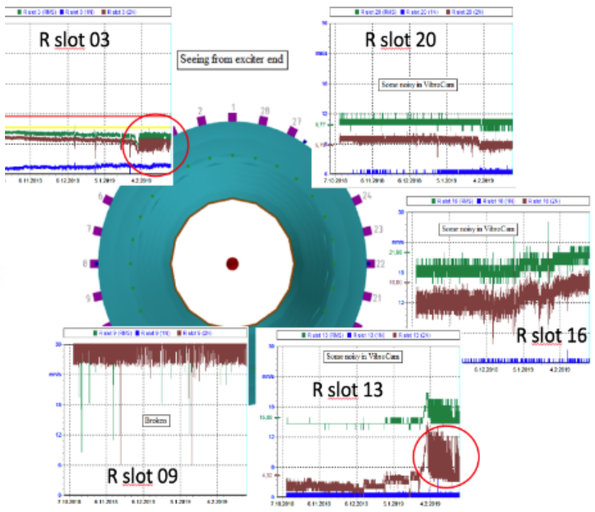


Changed vibrations in Stator S4 2018-2019

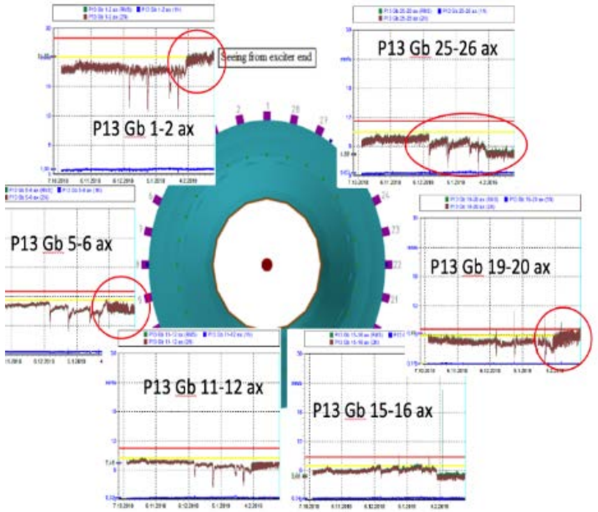
Trends of vibration okt 2018 – feb 2019. => Change since january 25 after load change



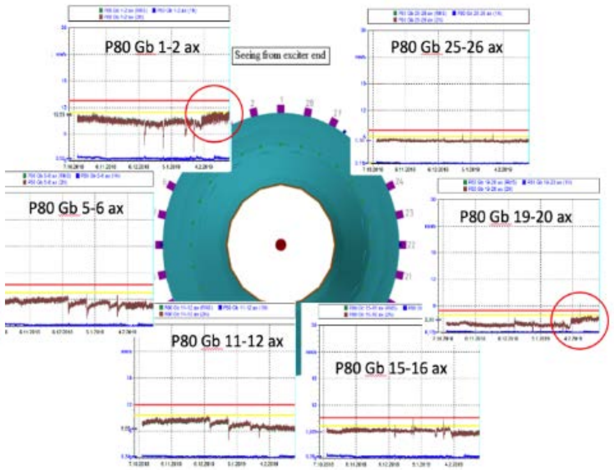
Radial
in end winding NDE



Axial
in round Connections

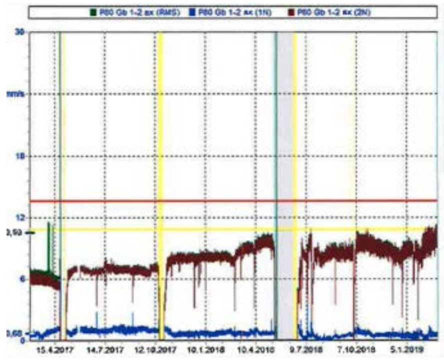


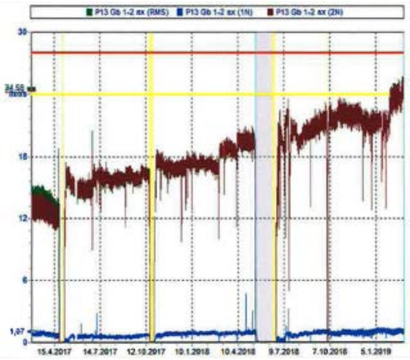
Axial
in Core NDE



Axial
in Core DE

Axial
in core packet 80 & 13
2017-2019





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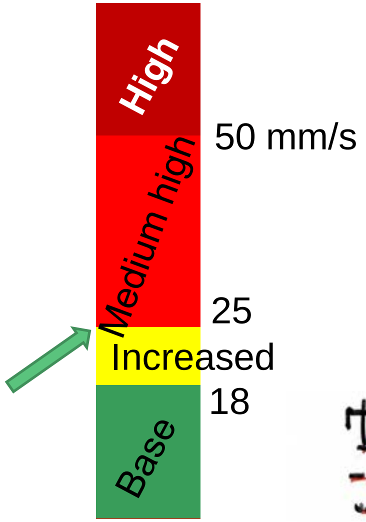
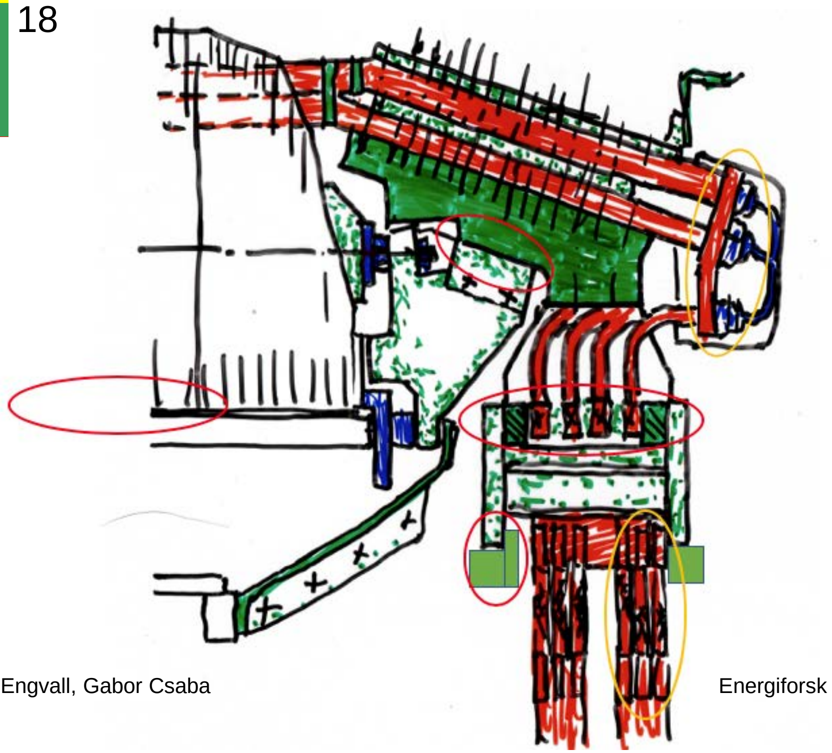
Changed vibrations in Stator S4 2018-2019

Estimated Risk levels
For axial core vibration





Conclusions

- **Changes are real and due to changes in the stator structure**
- **<u>Potential root causes</u>**
  1. Loss of core back pressure
  2. Loosening of support in the round connections
  3. Contact to short circuit supports

- **<u>Recommendations</u>**
  1. Inspection of core back in both ends
  2. Inspection of round connections in area of S1
  3. Prepare to be able to reconditioning/replace
     1. Cracks in end winding and Round connections
     2. Replace braids in S1

Historical vibration case in the old stator S3

- S3 was a replacement stator for S1
  - Stator frame equal with spring suspende
    connections
  - Improved cooling of core ends
  - Some improvement on end covers

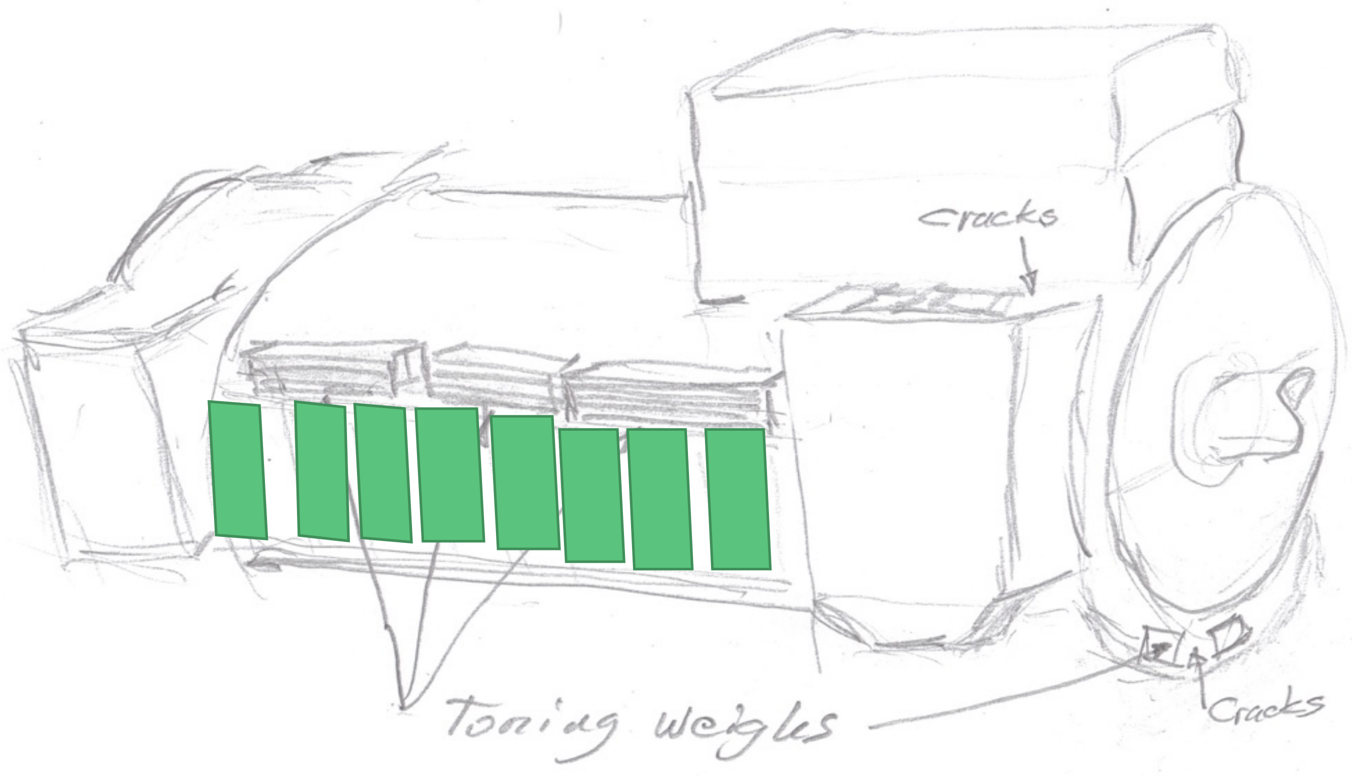
1. High vibrations from comisssioning
   - Cracks in end cover E-end

Conclusion from the case:

- **Even small changes can give large impact**
- **Useble bump test can be done**
- **OMA should have been a good tool**

spark processing

4. Release end cover from the stator frame
   - Resulted in cracks in the suspension springs
5. **Solution after 2 years of trial and error**
   - **Conclusion => Resonance in stator**
   - **Bump test with use of 5 m rails**
   - **Several tons of Tuning weights was applied**



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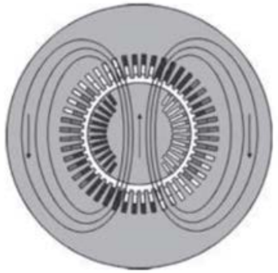
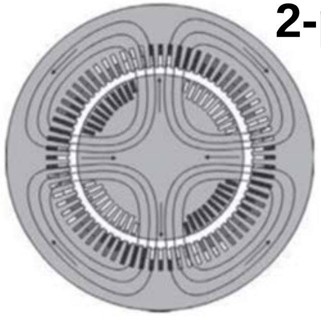
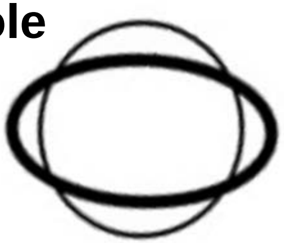
Methods how to avoid or mitigate development of “unhealthy” vibrations

Monitoring of stator conditions

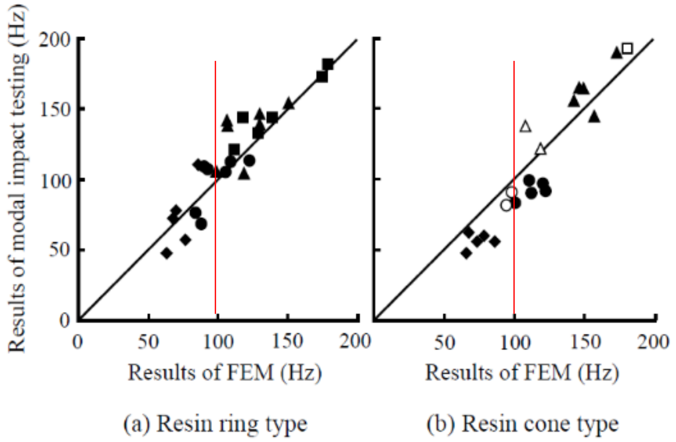
1. Vibration in end-winding, round connections and the core
2. Actual load and temperatures

2-pole vs 4-pole


Modal shape	2-pole
2 node	◆
4 node	●
6 node	▲
8 node	■

Modal shape	2-pole	4-pole
2 node	◆	-
4 node	●	○
6 node	▲	△
8 node	-	□



Changes can even occur in rigid and stable structures related to thermal and load cycling in combination with poor workmanship or defects in material. Such changes will most probably be possible to observe but difficult to identify.

It is essential to combine vibration monitoring with visual inspections at planned outages

2-pole have larger potential to create scenarios to analyze

The Analysis work may include steps/actions

1. Confirm that the vibration data is true
2. Form hypotheses and identify how to confirm or reject these.
3. Evaluate the most probable hypothesis
4. Analyse the probable impact and ranking of the risk to impact on the production availability. Ranking the risk in three levels will give a good background for decision making.
    a. **RED level**. A high-risk scenario will most probably exist. The hypothesis is clearly identified and it will most probably cause severe destruction and a forced outage. Recommended action involves a planned outage within a near future to implement mitigation actions or changes
    b. **YELLOW level**. A mid-risk scenario, with more than one possible hypothesis and which most probably can be identified to have slow development to destructive level. This type of scenario needs to receive extra attention during further operation to be able to see changes. Additional problem-focused inspections have to be planned at the next planned outage.
    c. **GREEN level**. A low-risk scenario, where no destructive hypothesis can be identified and the vibration level most probably is harmless to create dangerous destruction. Focused inspections in correlation with the changed vibrations shall be performed at the next planned overhaul.

Experiences from other plants

- End-winding failures are the largest cost for insurance companies, due to the repair time and loss of production.
- Several failures occur also in the winding slots, either related to vibrations or improper condition or wrong requirements on the corona protection system.
- How to manage end-winding vibrations in the form of monitoring, bump test and visual inspections, together with a serious explanation of the background to normal and abnormal conditions.
- Altogether those papers provide comparable information with this paper for Energiforsk, with one exclusion, which is the focus on Partial Discharge.

Recommended long term maximum vibration levels

Institut/OEM	year	Recommendation	F Hz	Trans to velocity rms mm/s	Note
IEEE	2014	Unfiltered radial displacements p-to-p µm 50 – 125 OK 200-250 alert level	60	 33 66	See [6]
EPRI	2011	Radial displacements p-to-p µm < 127 normal 203 alarm level 254 absolute maximum	60	 34 54 68	See [6]
CIGRE	2014	radial dicplacements p-to-p µm < 250	50	 55	
ASEA	1980	radial disp. p-to-p µm 270 270	 50 100	 30 60	

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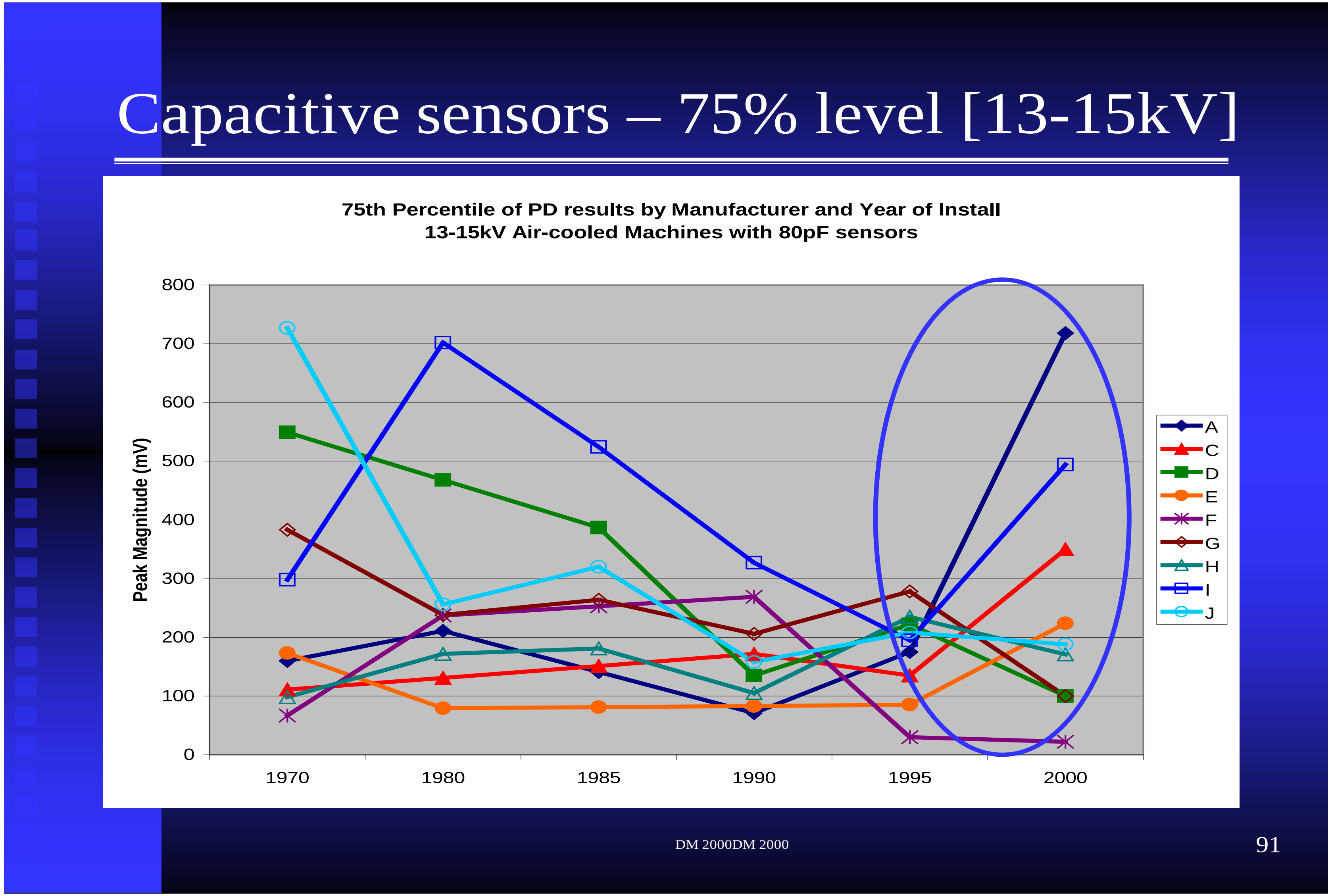
Importance of to keep the competence and knowledge



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