NORDIC NUCLEAR POWER GENERATOR STATOR VIBRATIONS

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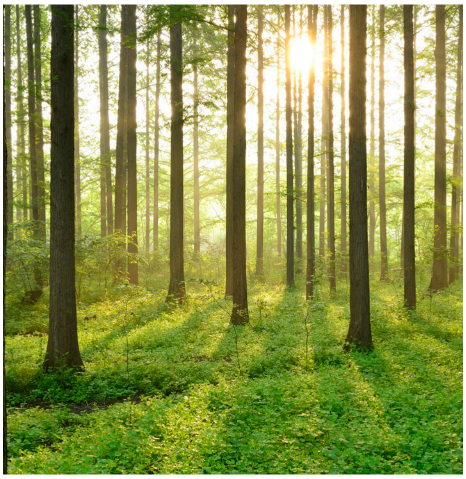

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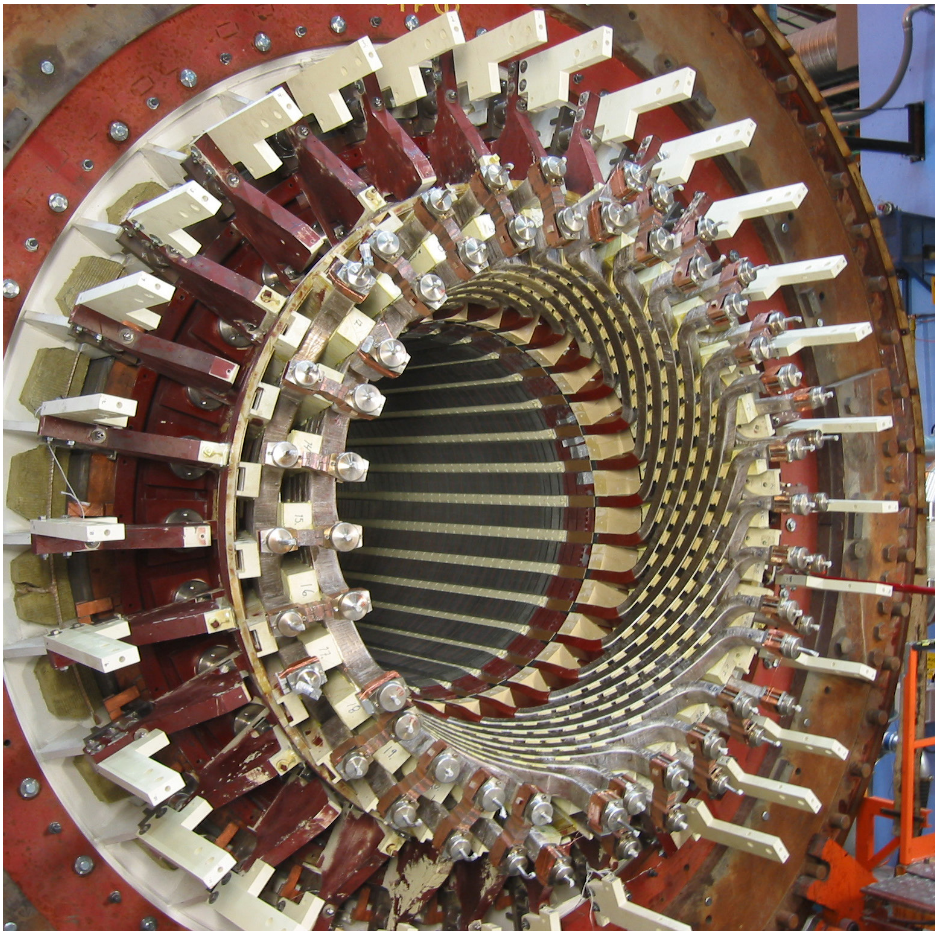

Energiforsk

Nordic Nuclear Power Generator Stator Vibrations

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Foreword

To minimize the risk for deterioration and premature failures caused by high vibrations in the generator, it is vital to have an understanding of what type of problems may occur and how it might affect the main components of the generator. Apart from understanding the problematics, it is of course important to know how to avoid problems or mitigate them, assuring a safe and reliable long-term operation of the nuclear power plant.

In this project stator vibration problems have been investigated. Excitation mechanisms are explained and the impact on the dynamic behavior of significant systems, structures and components is described. Furthermore, experience from stator vibration problems in the Nordic nuclear power plants are summarized. This report constitutes an encyclopedia on stator vibrations, where the reader can get background on the phenomenon, understand the impact of the problem on the plant and learn from experience gained at other plants.

Authors are Kent Engvall and Gabor Csaba, senior consultants 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.

These are the results and conclusions of a project, which is part of a research program run by Energiforsk. The author/authors are responsible for the content.

Sammanfattning

Projektet har allmänt fokuserat på vibrationer i turbogeneratorstatorer i de nordiska kärnkraftverken i Ringhals, Forsmark, Oskarshamn och Olkiluoto. Syftet med projektet är att ge en bakgrund och grundläggande kunskap om statorns uppbyggnad, designkrav samt olika vibrationstillstånd.

Särskilt fokus har getts till härvändsvibrationer, där även grundläggande designkrav beskrivs samt vilka skillnader som finns mellan 4-poliga och 2-poliga generatorer/statorer.

Generella felmoder/orsaker beskrivs vilket sedan kompletterats med maskinspecifika felorsaker som har potential att uppstå i respektive härvändar. Även statorkärnans vibrationer och hur de kan påverka övriga komponenter beskrivs.

En generell kort beskrivning av förväntade vibrationsnivåer vid olika lasttillstånd återges samt systematik för utvärdering och riskanalys av vibrationstillstånd. Till detta är några verkliga fall för de i projektet ingående maskinerna beskrivna, med syfte att ge tillgång till erfarenheterna från dessa fall.

Det finns även ett avsnitt om vilka verktyg som finns för att mäta och analysera härvändsvibrationer. Dessutom ges generella råd för hur defekter i härvkorgar kan åtgärdas samt erfarenheter från specifika fall.

Det ingår även en studie av omvärldens erfarenheter och slutsatser vad gäller vibrationer i stator med fokus på härvändar. Här återges även de nivåer som institut som EPRI, IEEE och Cigre rekommenderar.

Fler verkliga fall beskrivs utförligt i de bilagor som bifogats, och i flera av dessa upprepas det som återges i detta projekt. Det anmärkningsvärda är de frekventa förekomsterna av defekter i statorlindningen som orsakats av partiella urladdningar, PD främst i statorspåret.

Slutligen beskrivs ett förslag till generatorunderhåll.

Summary

This paper are 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.

Particular focus has been given to vibrations in the end windings, which also describe basic design requirements and the differences that exist between 4-pole and 2-pole generators / stators.

General fault modes / causes are described, which are then supplemented with machine-specific fault causes that have the potential to occur in their respective end windings. Also stator core vibrations and how they can affect other components are described.

A general brief description of expected vibration levels at different load cases is presented, as well as systematics for evaluation and risk analysis of vibration conditions. To this, some real cases for the machines included in the project are described, with the aim of giving access to the experience of these cases.

There is also a section of useful tools available for measuring and analyzing end winding vibrations. In addition, general advice is given on how defects in end winding baskets can be corrected as well as experiences from specific cases.

A study of the world 's experience and conclusions regarding vibrations in stator with focus on stator end windings is also included. The levels recommended by institutes such as EPRI, IEEE and Cigre are presented.

Several real-life cases are described in detail in the reference cases, and in several of them, what is reproduced in this project is repeated. Noteworthy are the frequent occurrences of stator winding defects caused by partial discharge PD, mainly in the stator slots.

Finally, a proposal for generator maintenance is described.

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1 Introduction

This paper is intended to provide knowledge and help on how to manage vibration conditions in Turbo Generator Stators in the nuclear power plants in Ringhals, Forsmark, Oskarshamn and Olkiluoto. However, it is necessary to understand that a requirement of the reader is to have a basic knowledge of Turbo Generators.

2 A brief look back on the early development of large Turbo Generators

Steam turbines were used to drive dynamo machines in the late 19th century. The first direct driven Turbo generator with a cylindrical rotor was introduced right in the beginning of the new century. Since that time, the rating of turbine units has started to grow.

Once, a power plant was fueled by coal and oil, which was the common way to electrify the world. However, in Sweden and Norway, water power was the dominant source for this.

Both 2- and 4-pole generators were developed and manufactured, but the 2 pole generators were dominant, based on the dimensions of the generator and even the turbines, which in the end were cheaper than the 4-pole solution.

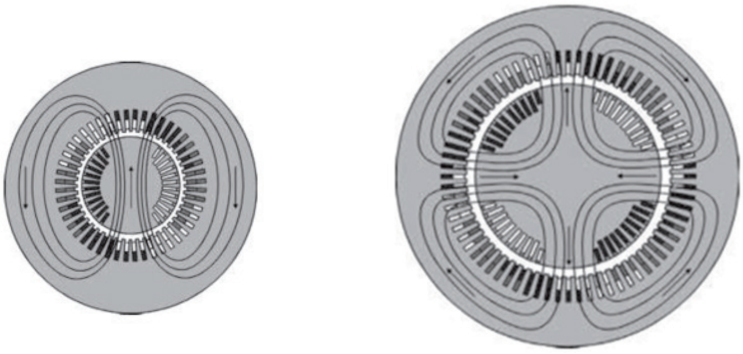

Figure 1.Schematic view of electromagnetic circuits of a 2-pole and 4-pole generator

Efficient cooling is essential to increasing the rating of a generator and will be more and more important with the growth of the rated power. Critical parts to be cooled include the stator core, stator, and the rotor windings, where the rotor is the most critical and limiting part. The rotor diameter will be limited by the large centrifugal forces and the strength of available material for the rotor forging, retaining rings and the slot wedges. The rotor length is limited by rotor dynamic properties. The cooling system mainly used for the large Turbo Generators was, and still is, pressurized hydrogen together with water in the stator bars.

When the nuclear era started, there were about 20 suppliers of large Turbo Generators in the world. Also ASEA decided to be a supplier of large Turbo Generators to the Nordic Nuclear Program.

A completely new 2-pole generator type was developed with water-cooled rotor winding, but the ambition was to use water cooling for all the main parts of the generator as core and windings in the stator. One argument, perhaps the strongest, was the ability to use this concept in Turbo Generators as well as in Hydropower Generators. Other strong arguments were the compact dimensions in combination with the estimated lower total cost for manufacturing and loss evaluation. Even the ability to meet the market demands of the rapidly increasing rating of power should be easily achieved with this concept.

The new generator type ASEA GTD was sold and installed in the Nuclear Power Plants Ringhals 2, 3 and 4 and Forsmark 1 and 2. Each of these units were designed with two parallel turbine generator sets. Even Barsebäck 1 and 2 and Olkiluoto 1 and 2 received this type of generator, but those units have a single turbine generator set. Oskarshamn 3 and Forsmark 3 also has single sets, but with 4-pole generators delivered by BBC. The choice of a 2- or 4-pole generator will be a question for the power rating for the plant, and ratings above 1200MVA will most probably be 4-pole generators.

The rating of the nuclear units demanded even larger turbine units and even the Turbo Generator rating made a large jump and peaked in the mid-1970s. The largest 4-pole turbo generator at that time was about 1500, and the largest 2-pole about 1300 MVA. One international study states that the technology limitation for the power rating should be 2000 MVA for a 2-pole generator, and 3000 for the 4-pole.

This large jump in rated power created several new negative events to occur which resulted in deeper knowledge, and development of as well design concepts as new materials. These new experiences were established and is today applied in new generators.

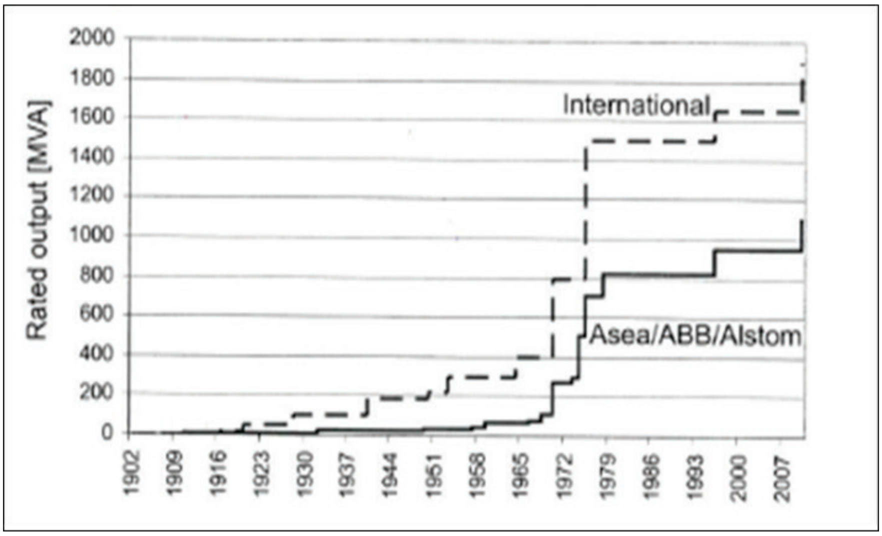

Figure 2. Development of rating for Turbo Generators

Nowadays, the maximal rating is about 1300 MVA for a 2-pole and 1900 for a 4-pole generator.

2.1 SOME EARLY EVENTS WHICH IMPACTED DESIGN AND DIMENSIONING

The rapid growth of ratings for Steam Turbine Generator sets was related to many new experiences creating some negative events. Large diameters and a growing rotor length, in combination with limited material requirements was one area, while the other included an increased density of magnetic and voltage fields; all this in combination with limited dimensioning tools.

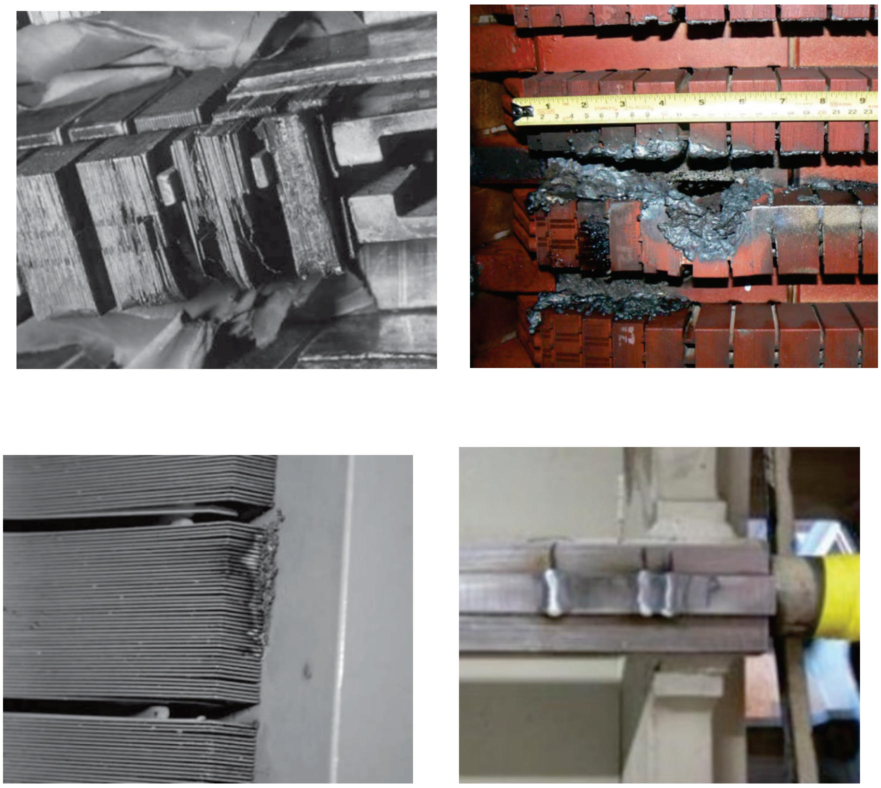

Figure 3. Examples of core failures

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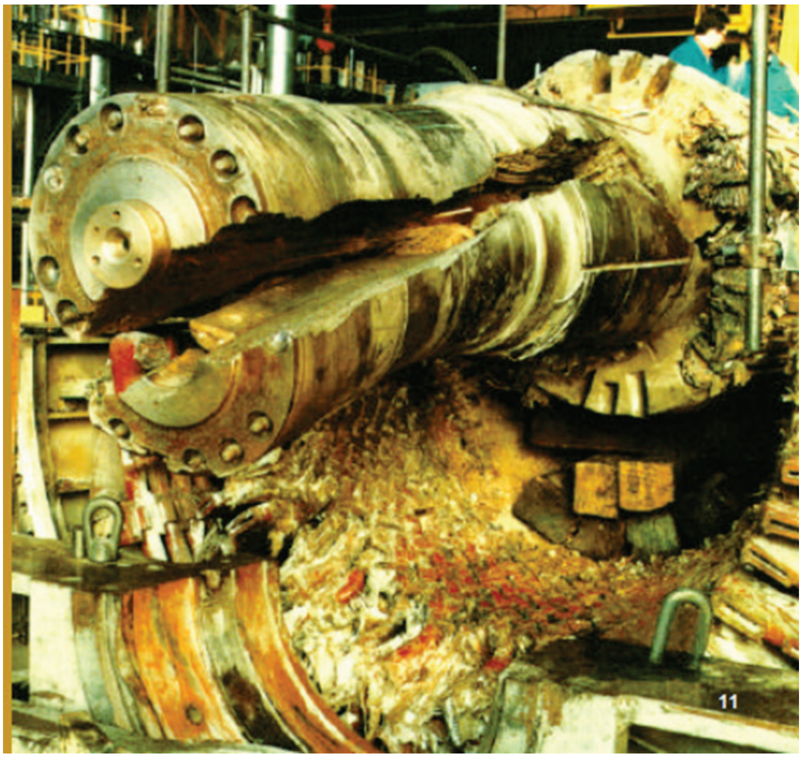
Figure 5.Explosion of retaining ring caused by stress corrosion cracking (Barsebäck)



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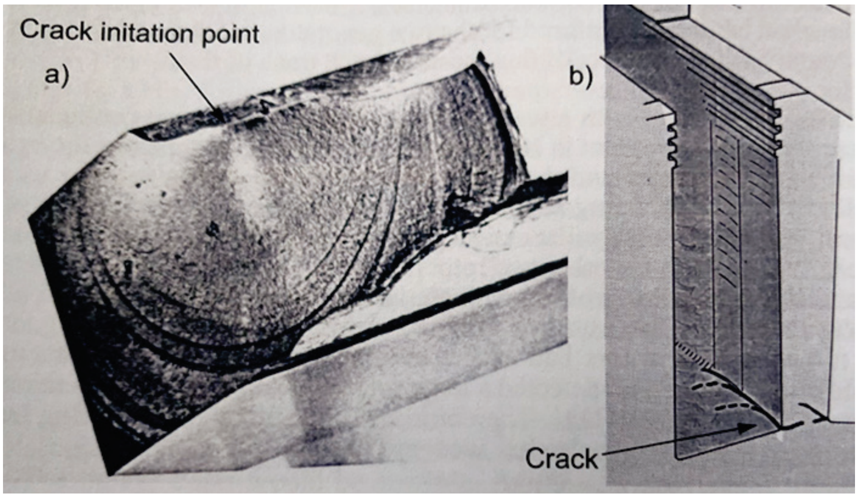

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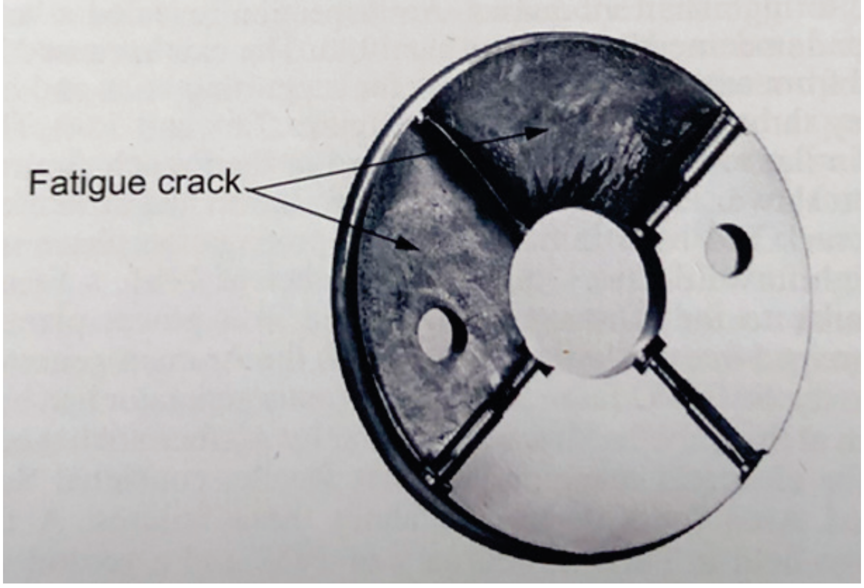


Figure 8.Crack in rotor shaft initiated by Fretting Fatigue which then changed to turning frequent growth (Olkiluoto)

3 The Turbo Generator's Main Components and functional requirements

In developed countries, the availability of electric power is an obvious part of society, and it is easy to forget the line of different technologies and to each part knowledge is connected to realize this. Figure 9 shows a greatly simplified view of how to create and handle electric power. The mission for the generator is not only to convert the mechanical energy to electrical, but it must even be able to manage influences from the line and different types of load; and added to this it has to handle and sustain impacts from failure events from the line. This section will try to give an overview of a generator's main components and the connected requirements and influence the design of generator parts.

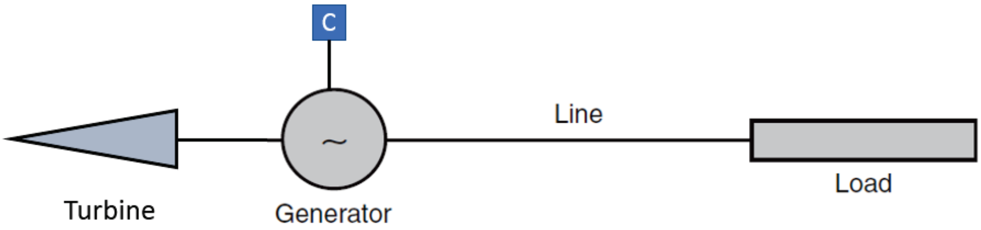


Figure 9. Simplified view of a generator

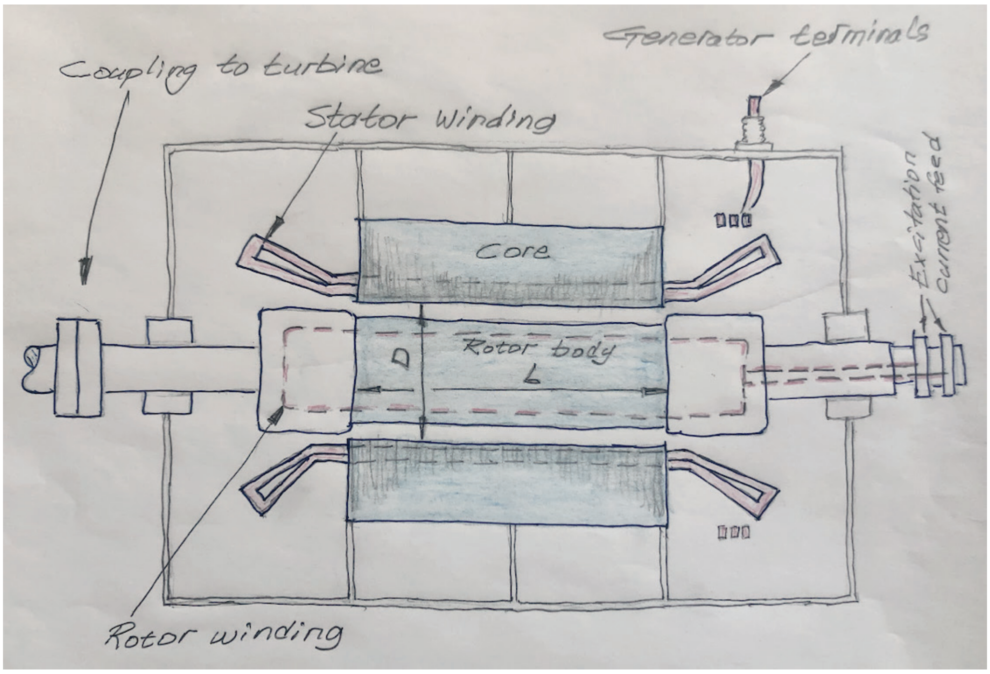


Figure 10. Principle view of generator active and main parts

Along with the “generated” active power from the turbine, magneto electric power also exists, generated from loads and the line’s so-called reactive power. The generator must be designed to manage the total amount of this power. Together that will be the necessary Apparent Power for the generator. The governing equation for the generator design in Figure 11 will give an overview of how this will impact on the generator design.

$$S \cong D^2 * L * B * A * \omega$$

S = Apparent power in Mega Volt Ampere, MVA
D = Bore diameter of Core in meters, m
L = Length of Active Rotor Body in m
B = Air Gap Flux Density in Tesla
A = Stator Ampere-Turn Loading in Ampere per meter
ω = Angular speed in radians per second, rad/s

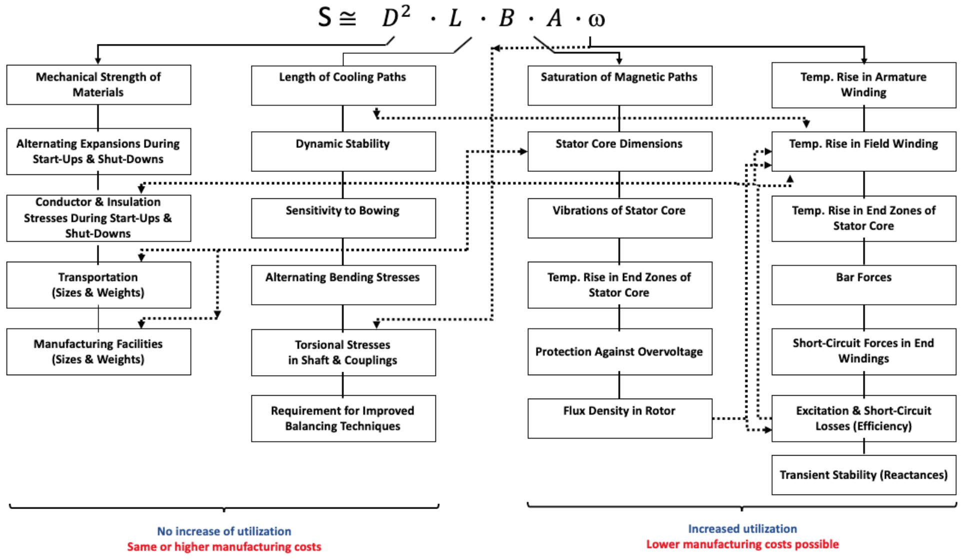


Figure 11. Generator "dimensioning" matrix

3.1 GENERATOR ROTOR

The rotor is the input for the mechanical power from the turbine in to the generator to be converted to electrical power. For large units, the most common method is to use a 2-pole generator rotor which produces a rotating speed equal with the line frequency i.e. 50 or 60 Hz. However, for the largest unit, with ratings above 1300MVA, this will be a 4-pole solution which will rotate with half the speed of the line frequency.

Nevertheless, the rotor will be manufactured from a single piece of forging, and for the 2-pole design there will be a maximum rotor diameter of about 1250 mm, due to the large stresses generated from the rotation. The limiting parts are the rotor body, retaining rings for the rotor end-windings, and also the slot wedges for fixation of the winding in the active part of the rotor. Even the length for the 2-pole rotor will be limited by rotor dynamic properties and maybe even an increased risk for fretting fatigue. The 4-pole rotor does not have these limitations, but the large diameter will impact on the all-over cross section dimensions of the stator frame which complicates transportation to the plant.

The other essential part of the rotor is the winding, where the ampere turns (number of turns times the excitation current) are required to be as high as possible within the allowed temperatures. The winding temperatures are strictly regulated in international standards. To achieve large currents, the winding must be cooled by force, which for large generators will always be by direct cooling with the use of hydrogen or water.

One can easily understand the need for as much copper as possible and the opposite for insulation to the forging and between the winding turns. The most mechanically stressed part of the rotor is the retaining rings which support the end-windings and the heavily created forces by the rotation.

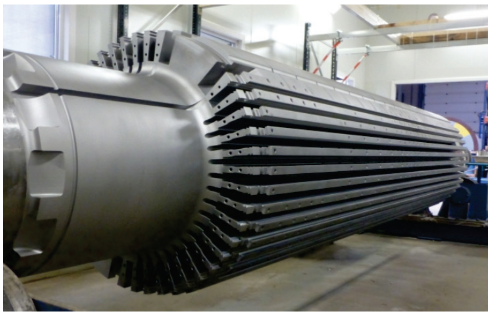


Figure 12. A 2-pole rotor forging in the milling machine

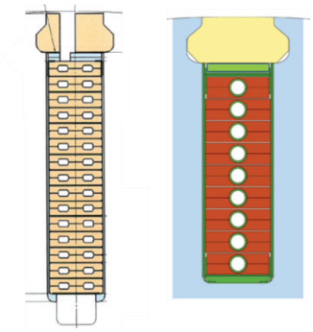


Figure 13.Example of Winding slots

3.2 GENERATOR STATOR

With use of the magnetic field from the rotor the power conversion will then be executed in the stator parts.

The strong magnetic field from the rotor passes through the airgap and will then be closed to the next rotor pole via the stator core (see Figure 14, showing the pattern for 2- and 4-pole generators). This rotating magnetic field will induce voltage in the stator bars and the generator can be connected to the line to deliver electric power from the plant.

As previously mentioned, the load on the generator consists of the active power capable to be used for “work” and the reactive power useful to compensate the induction or capacitive effects from the line and the loads. All this will have an influence on all the main parts of the generator. For the stator this results in losses and forces acting in the winding and core. At normal operations these forces and losses are large and about 1% of the rating. But the forces will be even more than 10 times larger in a short circuit scenario compared to normal operation. The stator, as well as the rotor must be dimensioned to sustain such abnormal events.

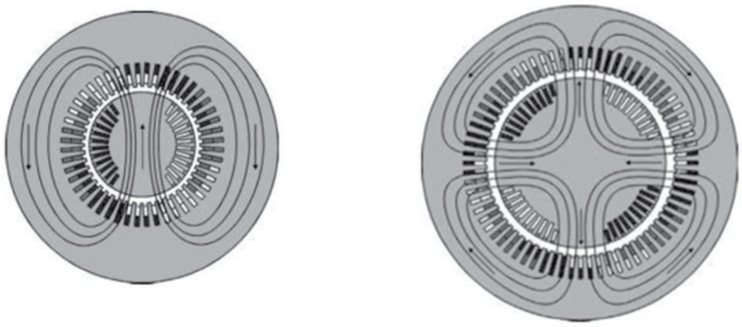


Figure 14. Flux pattern in rotor body and stator core for 2-pole and 4-pole generators

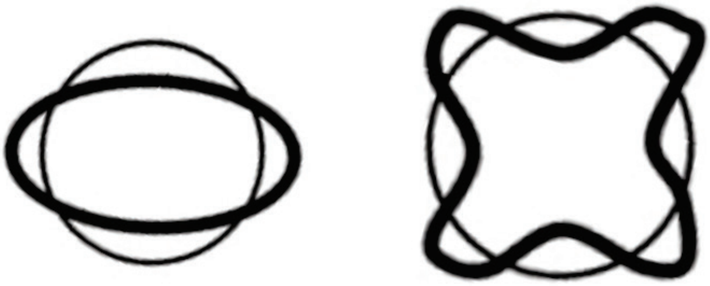


Figure 15. Deformation of the core for 2-pole and 4-pole generators

3.2.1 Stator Core

One can easily understand that the turning torque from the rotor field acting on the stator core must be equal to the torque in the turbine coupling. A cautious conclusion could be that the magnetic field must be very powerful and most likely even produces radial forces on the core, which is true, and the solid core will be radially deformed by the rotating field as shown in figure 14. For a 2-pole generator this radial deformation is in the range of 15 to 30 micro meters, and in the 4-pole one significant lower. The torque acting on the stator core must finally be anchored in the turbine foundation which also must sustain larger forces of about ten times from a short circuit event.

Regarding the design of the core, it has already been concluded that this must sustain large torque and radial forces. It must also handle the variable strong magnetic field with small or reasonable magnetic and eddy current losses. The use of silicon alloyed steel in the core makes this possible; but added to the material choice is the necessity to build the core from thin-insulated plates of 0.5 mm or less, to avoid severe eddy currents and meltdown of the core. The whole core is therefore built up of thin segments in half overlap (see Figure 16). The segments are a maximum 0.5 mm thick and coated with about 10 micrometer insulation varnish on each side.

Note that if about 5 of the laminations are short circuit over the insulation layers, the magnetic energy will cause the beginning of a meltdown event of the core.

Figure 16. Stacking of core with the use of thin segments

When the core is built up of these segments, the next step will be to bring it to a solid ring element. This will be managed with the use of stiff press rings at the ends of the core, which are able to realize a surface pressure of about 1MPa between the laminations. This will result in a solid core where the radial stiffness is close to a ring of solid steel, which for a 2-pole generator creates the natural frequency for the four-node mode ovalization of about 200 Hz, and the eight-node mode for the 4-pole of about 250 Hz. In axial direction, the stiffness is only 1/150 of the solid steel, in other words it is very weak, which results in a lot of different axial and bending eigenmodes in the core.

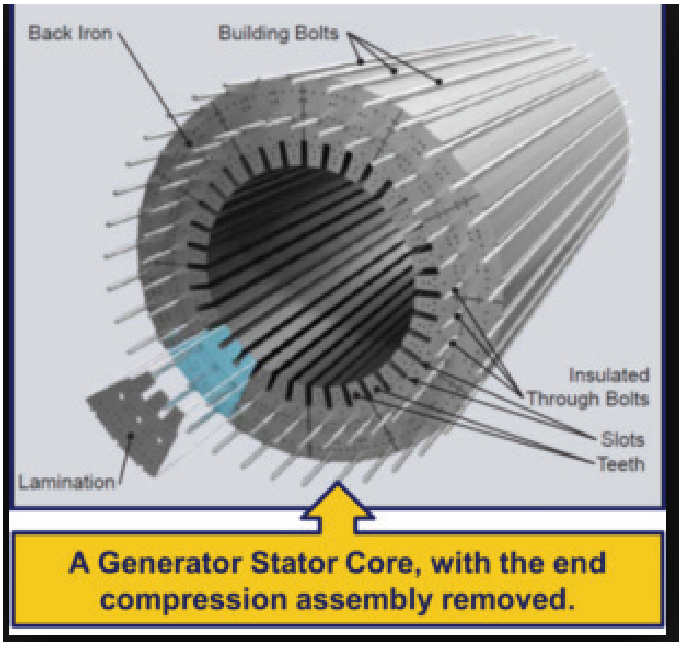


Figure 17. Stator core, principle view

Dimensioning of the magnetic circuit is essential to meet the requirements of the generator rating. The main parts of this circuit are the solid rotor body, the air gap and the core (see Figure 14). This part of the generator is popularly called "the active part". The airgap has the largest influence on the design of the magnetic circuit, even with impact of the steady state stability and the Short Circuit Ratio. Dimensioning of the outside diameter of the core is to keep the flux density at a controlled level for the required operations. However, the inner and outside diameters will also impact on the mechanical ring stiffness and the vibrations caused from the rotor flux, which can sometimes result in a larger outside diameter to meet the vibration criteria.

In large generators there will be a phenomenon called "back-of-core leakage flux" which is a leakage flux from the core back. This flux will induce voltage which results in a current flow in a circuit contents of the building bar and tangential in lamination. This phenomenon is located at the end parts of the core and is related to the added flux from the stator and rotor end-windings. To mitigate this, it is common to build some type of squirrel cage where building bars are short circuited by a copper ring. Even the building bar can have copper leads. Another solution is to weld the building bars to the core back. Without these solutions the contact areas between the core back and building bars will be destroyed by arcing and meltdown, and the event of failure tends to develop.

One third and opposite solution is to make an electrical insulation between the building bars and the core. But even for this solution it is necessary to take care of the fringing flux out from the core back. The core must even be earth connected which will be done in one of the building bars. Figure 18 gives a view of a core electrically insulated from the frame.

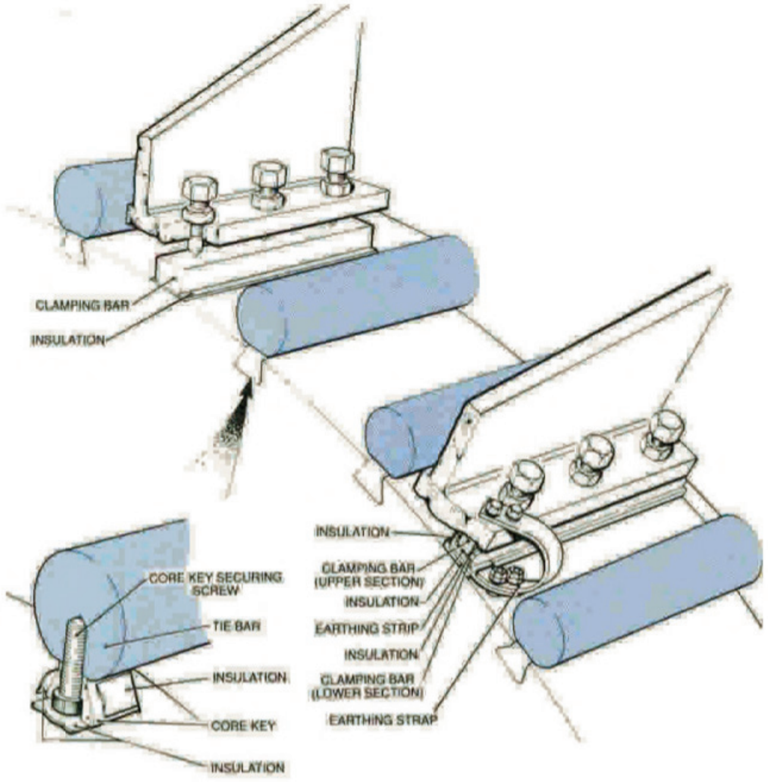
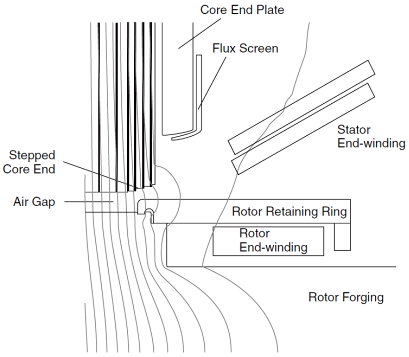


Figure 18. Core elecrtically insulated to the frame

The design and dimensioning of the press rings in the core ends must be managed with the aim of taking care of the complicated and variable magnetic flux environment in this area. This can be managed with use of magnetic shields (see figure 19), or with use of pressure rings built from stator laminations (see figure 20). The magnetic flux field in the end region is strongly coupled to the actual reactive power level and type. Deeper information's within this area can be found in [17].

Regarding the procedure to stack the core. One should postulate that the lamination thickness is 0.5 mm, which gives about 1,900 layers per meter after adjustments for the inbuilt radial cooling ducts in the core. For a generator with an active length of 7 meter, this gives about 13,000 layers. The segments are stamped out of a sheet roll and normally the thickness is greater in the middle of the roll which will impact on the overall thickness in each segment. Even a small thickness variation of just 1 micrometer results in a variation of 13 mm of the core length if the deviation is oriented to the same area of the segment. In reality, the variation will be about 5 micrometer, but measurements larger than that cannot be excluded.

This phenomenon, or fact must be taken into account in order to produce a core with a uniformly distributed pressure over the whole surface. If this criterion is not fulfilled, extremely severe failures can result, especially on the air gap surface. Yet even an anomaly of the pressure in the area in the core back can result in disturbances of the operation. The conclusion from this is the need for careful manufacturing of the segments and a stacking procedure to secure the uniformity of the core pressure.



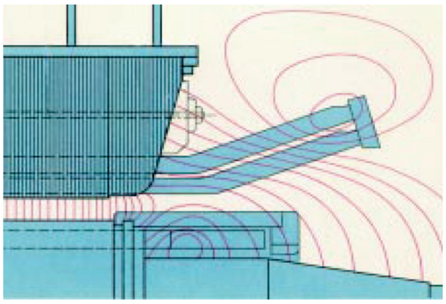


Figure 19 Core end with shields

Figure 20. Pressure ring of stator laminations

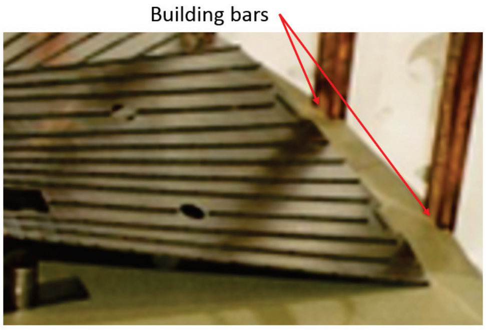
3.2.2 Frame

The main mission for the stator frame is to keep the core in position and finally to connect the forces from the core to the turbine foundation. The frame constitutes also the casing for the active parts of the generator and will also form the path for the cooling gas/air. If the cooling media is hydrogen, the containment must be gas-tight and sustain normal and abnormal gas pressures, without leakage. The connection between the core and frame can either be rigid, as in figure 21, or flexible, as in figure 22. In both cases, the fixation and positioning of the core must be sustainable in all normal and abnormal operation conditions.

The reason for using a flexible connection is to reduce the vibration level in the frame and, more specifically, in the connections to the turbine foundation. This reduction can also be managed with the use of beams between the stator feet and foundation, which are flexible in a horizontal direction. By this, one can conclude that the rigid coupling requires a lower core vibration which produces a larger core back diameter and a slightly heavier core.

The frame is made of welded steel plates and must be dimensioned to manage and take care of the forces, where the connection point to the foundation is the most stressed part, due to the exceptional forces at a short circuit scenario. Even the freedom of eigenfrequencies close to the excitation modes created by the core and rotor must be avoided. The stiffness from the frame will create a large impact on the bending mode shapes for the core, but produce a very limited impact on the ring-related stiffness and modal modes in this direction in the core.

Added to these requirements the frame must also be designed to make it possible for lifting and transportation of the complete stator.



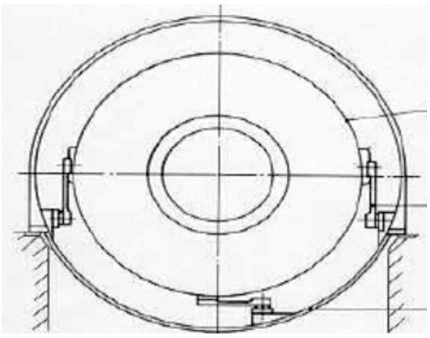


Figure 21. Rigid connection between core and frame

Figure 22. Flexible connection core and frame

3.2.3 Winding

If we consider a metaphor for a generator "body", the cardiovascular system is synonymous with the magnetic circuit, and the stator winding the muscles, while the heart is the rotor with the magnetic field. This metaphor is just to illustrate the relationship of the main parts in the generator. Nevertheless, the stator winding shall be able to deliver the required apparent power for the unit which consists of the active and the reactive power, but the praxis is to use the apparent power and the cos fi, which will be the same. The power will be formed by the production of the voltage and the current in the stator winding. It is common knowledge that losses will always occur and this even occurs in the stator winding. The generated losses are coupled to the current in square and therefore it is useful to strive for a high voltage level in the winding, which will result in lower losses.

On the other hand, high voltage requires more insulation and there will be an optimum of the most useful voltage where the insulation thickness don’t get in conflict with the conducting area of winding bars. And for the commonly used insulation based on mica this level will stay below 26 kV.

For large generators, this is a question of insulation materials and the ability to cool the winding. Figure 23 shows different types of directly cooled stator bars, where the hollow parts are for the cooling media, which normally is water, although the one with the large ducts uses hydrogen.

As can be seen in the same figure, the conducting area is divided into quite small parts or strands which are all insulated from each other, except at the ends where all of them are coupled together. The reason for this design is to avoid or reduce eddy currents in the conductor. To produce a useful conductor, all the strands must change position over the active whole core length which will be done with a systematic twisting: a so-called Roebeling (named after the inventor). Without the twisting of the parts, there will be a circulating current within the bar between the strands, which would result in extra losses and a higher temperature.

Figure 23. Cross section of stator bars for large generators

The main insulation of the stator bars is made of epoxy bounded mica flakes and dimensioned to sustain the rated voltage for a minimum period of 40 years. The bars are formed to be coupled together to a complete winding for each of the three phases. Figure 25 presents a good overview of the end-winding where it is easy to understand the coined name for this: end basket.

The active part of the winding (see chapter 3.2.1 Stator core), the straight part, is placed and fixed in the stator slots with the aim of sustaining forces from normal and abnormal operations (see Figure 24). The insulation of the bar must also have a suitable electrical contact to the slot walls in the winding slot to sustain the large voltage field. Even the insulation surface in the end-windings must be treated to sustain the electric field. The end-windings must be designed with the same focus to take care of the forces from normal operations as well as from abnormal. The forces also perform between the bars as in a radial and tangential direction. All of the forces will be 10 to 15 times larger in a short circuit scenario. To be able to manage this, the end-windings must have a well braced structure with a stiffness to sustain the forces from these operation conditions.

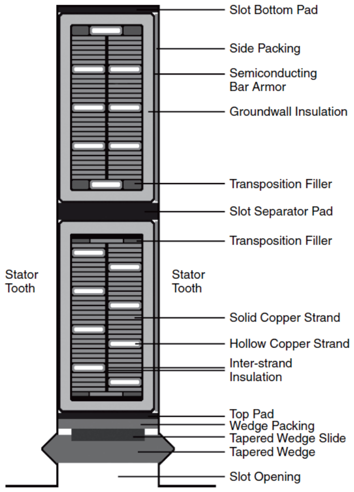
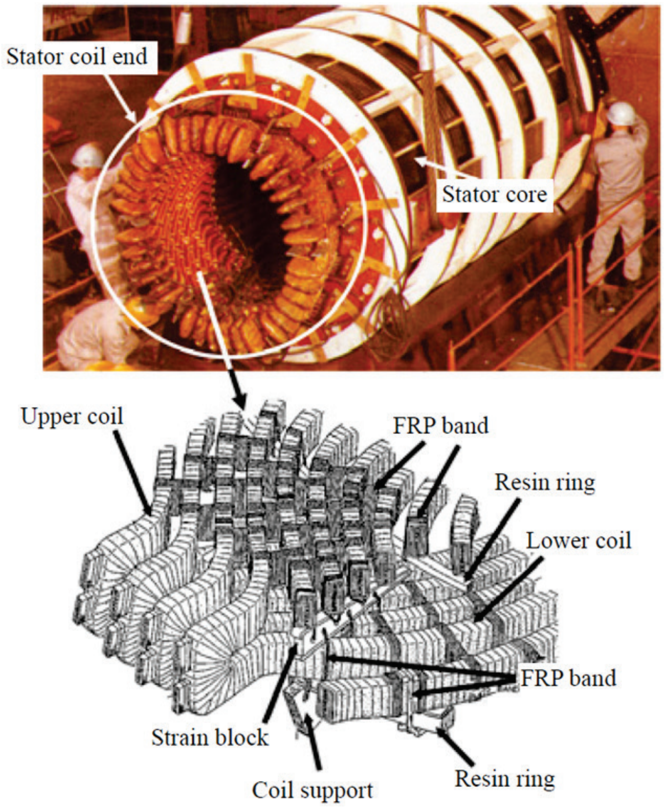


Figure 24. Stator slot with winding

Figure 25. End-winding [2]

The end-winding bracing structure must be built of non-magnetic and electrically nonconductive material. A commonly used material is glass-reinforced epoxy lamination which will even be glued to produce a solid and sustainable structure. Figure 26 shows the typical components of a bracing structure. The structure must also consist of blocking parts between the bars which will be fitted with epoxy soaked felt, as well as elements with a tensile strength to avoid the separation of the blocked parts. Together, this will produce a structure which is sustainable against the forced elastic displacements of the end-winding structure. However, a negative scenario can occur if the tensile elements lose their prestress forces. Such will result in a vibration wearing and a change in the intended dynamic requirements. There are several specific concepts to realize the bracing, two common solutions for which can be seen in Figure 27



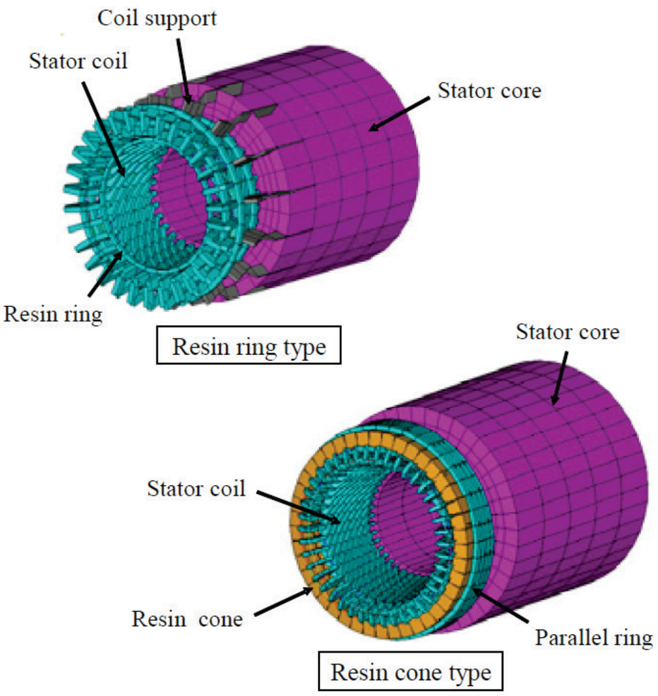


Figure 26. Examples of bracing designs

However, the bracing is not only a question of taking care of forces between bars and in the whole end-winding basket. Even the vibration dynamics are essential to manage in a successful way with the aim of achieving reasonable vibrations of the end-windings.

As previously mentioned, the strong magnetic field from each pole in the rotor will produce an elastic deformation of the core which will follow the rotation of the rotor. These are mode shapes which always will be excited from the core, due to the more or less rigid coupling between the core and the winding; added to this is even the rocking or 2 node mode (Figure 28 below).

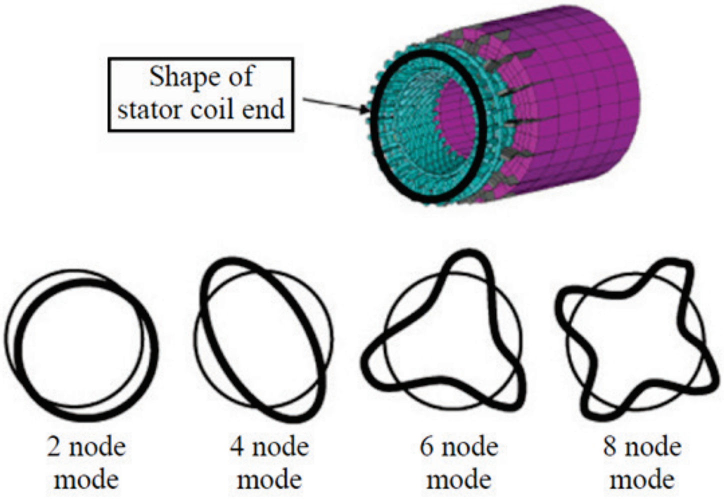


Figure 27. Mode forms for the end-windings

In the design of the support or bracing system for the end-windings, it is essential to avoid natural frequencies twice the rotational frequency for a 2-pole generator and four times the rotational frequency for a 4- pole generator. Otherwise the bracing structure will be in resonance with high and destructing vibrations. The support system can either be dimensioned to be weak, with the dangerous mode shape below the excitation, or stiff, with this mode above the excitation from the core. Both concepts can deliver the same level of vibration during operation.

Advantages with the weak system are that it would have more resistance against any deterioration of the parts between the bondings in the bracing structure compared to the stiff system. In other words, the weak system tends to enlarge the distance to be in resonance and the stiff will move in to the resonance, when the structure becomes weaker from the deterioration. Alternatively, a disadvantage with the weak system is the needs for an additional bracing to take care of the short circuit forces.

However, a well-designed system will produce reasonable and sustainable vibrations independent of the principle, and both are equally resistant to a short-circuit scenario.

The design of the end-winding supports previously involved a scaling of the used system for medium-sized generators and an additional fix to make it useable. Nowadays, it is easier to design the support system, since it has been possible to modulate and use FEM technology to calculate the dynamic for the braced end-windings. Calculated results will normally be well in line with the real realized end-winding structure (see Figure 30).

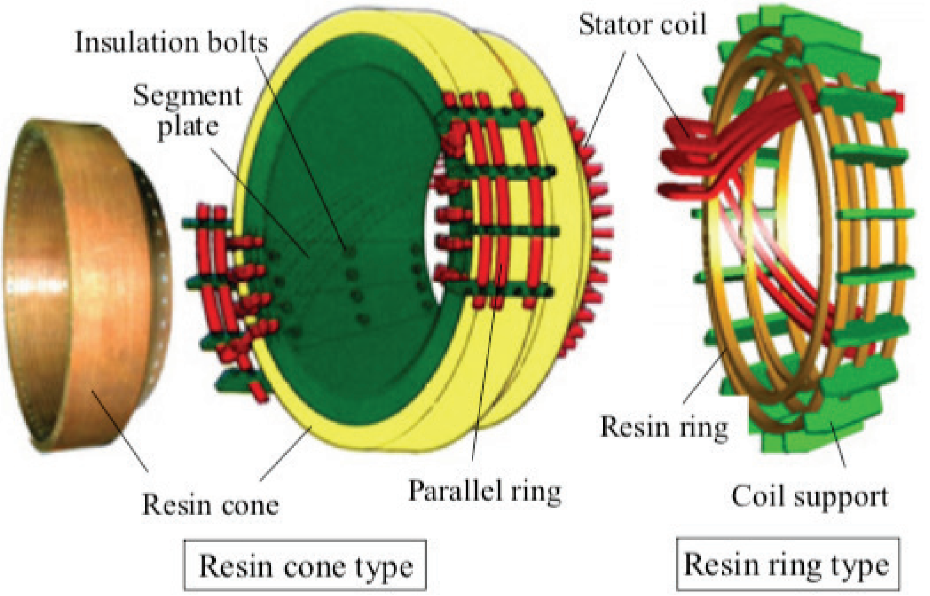
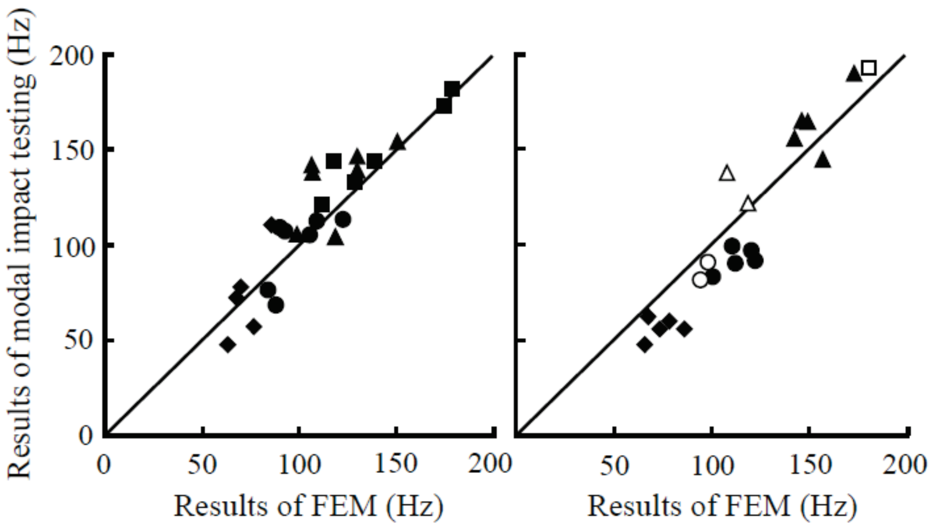


Figure 28. Type of bracings related to the analysis [2]

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	-	□



(a) Resin ring type

(b) Resin cone type

Figure 29. FEM calculation results vs results from modal impact test [2]

One can conclude from the results shown in figure 30 that FEM is a powerful tool for dimensioning of the bracing of the end-windings. This is not only a question of natural frequencies, as even the real impact from vibrations can be calculated which will create the ability to predict the sustainability to a short circuit event. The very killing point for a vibration level in normal operations, as well as at a short circuit, is the stresses in the stator bar at the slot entrances into the core. Severely large stresses will start to delaminate the main insulation of the bar which in a short period of time will result in an earth fault.

The results from the calculation and modal test on the manufactured stators shown in figure 30 also illustrate the major difference between the ability to brace a 2-pole generator compared to a 4-pole generator. The 4-pole generator produces the critical mode shape, the 8-node, which is far (200Hz) from the excited frequency 100 Hz and results in low vibrations and a sustainable structure due to that.

However, the 2-pole generator is trickier, where the most critical mode shape, the 4-node, will either be just above or just below the excitation frequency of 100 Hz, which results in higher vibrations and makes it more difficult to build a sustainable bracing structure. An active decision must even be made regarding where to place the 4-node: either above or below the excitation frequency.

A commonly used solution for end-winding bracings with the 4-node above the excitation frequency, i.e. the stiff design, is to build, in some type of adjustable wedge, elements to enable retightening, to increase the stiffness and eigenfrequency if the stiffness of the bracing structure degenerates. The other solution, i.e. the weak design, with the 4-node below the excitation frequency, the structure tends to be more sustainable and even degenerated, and a decreased stiffness will not place the 4-node in to resonance. On the other hand, this solution needs to have some type of stiffer short circuit supports, which only operate in the event of a short circuit. If the end-winding touch those supports in a normal operation, the stiffness can be increased and bring part of the structure in resonance.

3.2.4 Round Connections

The final main part of the stator winding is the so-called round connections, where the connections between the winding groups and connection lead to the neutral and the connection coupling to the line. Those connection leads are formed as a unit and will be located at the coupling end of the stator and radially outside the end-winding. The conductors have to be cooled with either water or hydrogen, which is in principle with the same requirement for the mechanical and dynamic design as for the end-windings (see Figure 31).

Depending on the end-winding design, it is necessary to analyze the interacting dynamics and forces between the end-winding and the round connections with a focus on the electrical connections between them. There have been several failures with fatigue cracks and broken connections in the past. Even the connection flags to the line and the neutral side must be controlled to produce reliable vibrations for the braids.

Figure 30. Round connection conductors between winding and round connection marked with red

3.3 SUMMARY ABOUT TURBO-GENERATOR DESIGN

The technology or knowledge about large Turbo Generator design, operation and manufacturing has developed tremendously since the first steps in the 1970s. All the experiences which led to this development came from failure events, trial and error actions, and of course FEM technology, which can be used for mechanical stresses, modal analysis, electromagnetic dimensioning and close to all of the complex cooperation between several technologies in a Turbo Generator. Nevertheless, a well-designed Turbo Generator will manage the intended mission for at least 30 years without the necessity for replacing any specific part. However, the realization of the design will be the bottle neck for the true survivals and most probably there will be inbuilt weak points which have the potential to cause a disturbance of operations.

This is the main argument for using monitoring in combination with inspections for the early detection of such weak points.

4 Excitation and Dynamics

As mentioned previously, the Turbo Generators will always vibrate, which is normal. The magnitude of the vibration is a result of the relation between the excitation forces and mode forms and the stiffness and natural frequencies for the stator main components. These relations are clearly demonstrated when comparing vibrations in 2-pole with 4-pole Turbo Generators. The 4-pole has significant lower vibrations. However, the level and shape of the vibrations can be destructive for the whole structures or several components. The overall sources are based on rotation, magnetic- and electrodynamic- forces, which means that also rotating components such as the generator and turbine rotors in some cases have an impact on the stator vibrations.

This in general terms regarding vibrations in the stators. Upcoming sections want to treat vibrations in more detail especially in end windings and to some extent also the core that has a direct connection to the vibrations in the end windings.

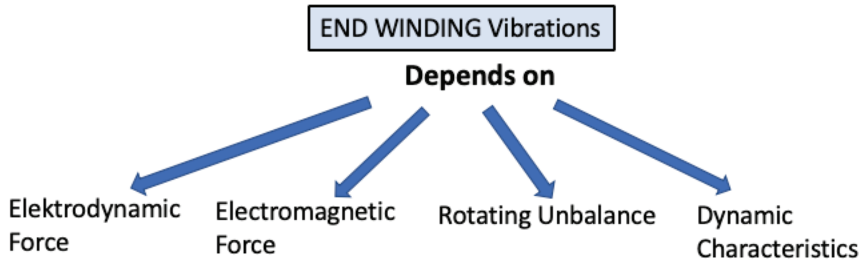


Figure 31.End-winding vibrations

4.1 SOURCES FOR THE VIBRATION

As described in section 3, the magnetic field from the rotor poles creates a forced elastic deformation of the core which will follow the rotation of the rotor. This excitation from the electromagnetic forces will start as soon as the rotor winding is energized and the magnitude is coupled to the actual rating of the excitation current. The whole winding is of course forced to follow this deformation.

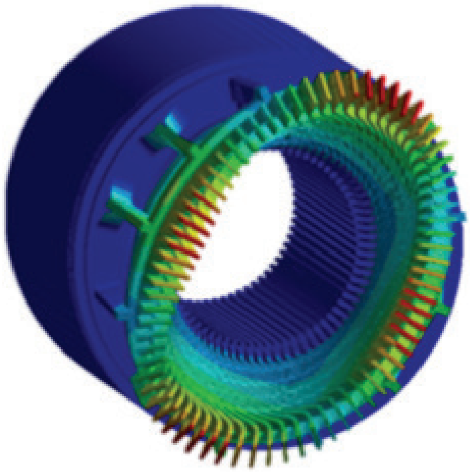


Figure 32. Electromagnetic deformation

When the stator winding is connected and loaded from the line or grid, the actual current in the stator winding will result in electrodynamic forces acting in the winding slots, but even more powerful in the end-windings, together with the flux from the end parts of the rotor (see figures 19 and 20). These load coupled electrodynamic forces will also impact on the electromagnetic field in the air gap and make a twist or phase shift of the electromagnetic forces acting between rotor and stators active parts. In other words, these magnetic forces will act on the rotor with the aim of counteracting to the rotor magnetic forces,

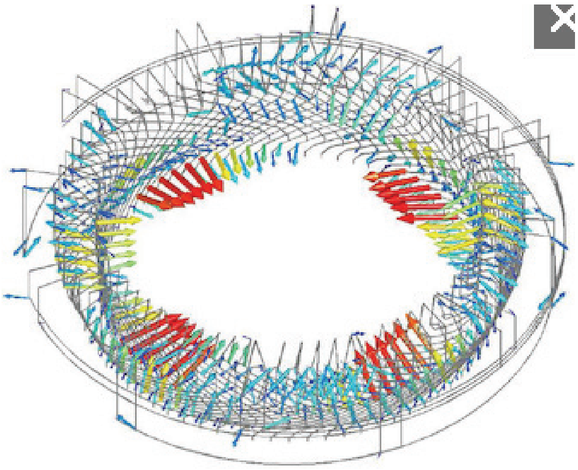


Figure 33. Electrodynamic deformation

Even with mechanical unbalance vibrations in rotating parts, the generator rotor will excite vibrations in the stator structure, directly via the end shield bearings or from the foundation when pedestal bearings are used. The two first sources will excite mode shapes and frequencies related to the number of poles and the rotation speed or frequency for the rotor.

For a 2-pole generator, this is the 4-node mode/ovalization with the frequency of twice the rotor speed, i.e. 100 or 120 Hz. For a 4-pole generator, the mode shape is the 8-node mode, a four-pointed star, with the frequency of four times the rotor speed, i.e. 100 or 120 Hz.

The rotating mechanical unbalance forces will cause a rocking mode in the end-windings with the frequency equal to the rotor frequency, i.e. 50 Hz for a 2-pole and 25Hz for a 4-pole generator. The magnetostriction effect will not have any impact on the end-winding vibrations, but will most probably excite the core in axial directions.

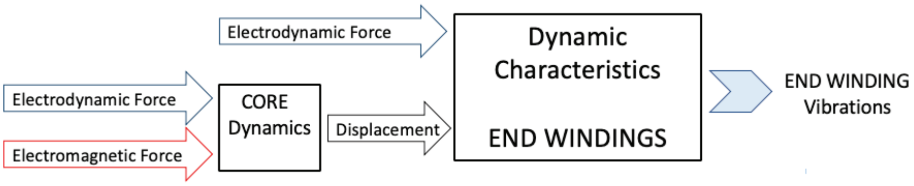


Figure 34. End-winding vibrations [18]

4.2 MODE SHAPES AND DAMPING CONDITIONS

Natural frequencies for modal forms within or near the forms from the excitation sources are essential to know in order to avoid and bring the designed structure in to resonance. In practice, however, it can in some cases be hard to realize the intentions to get the required span between the excited and natural frequencies. Figure 36 gives a good view of the transmissibility at a different ratio to the resonance frequency and even the impact from different damping conditions.

The natural frequencies for a structure can either be changed by an increase or decrease of the stiffness of the structure, or by changing the mass of it. The very simplified formula below gives the principle coupling between the stiffness and mass of the structure.

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

Figure 35. Basic formula for natural frequencies

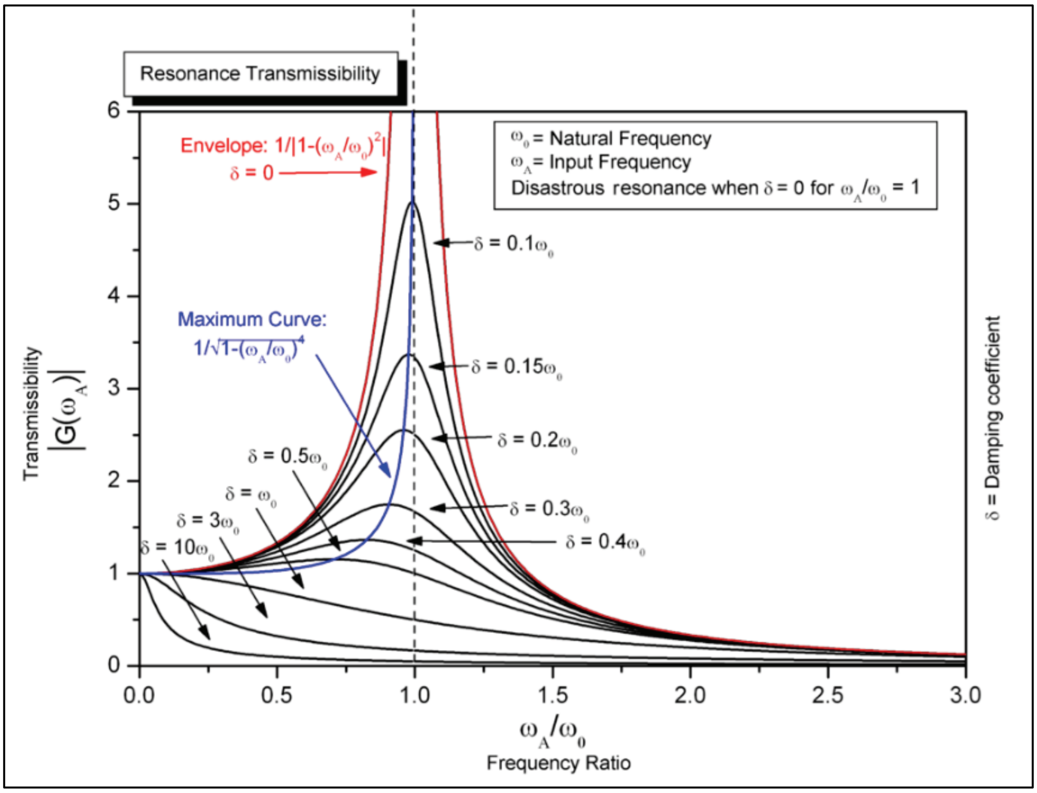


Figure 36. Transmissibility.

To obtain some know-how and a better insight of the stator, the mode shapes for the stator core should be expanded on. As mentioned in section 3, it is necessary to keep a well-controlled and sustainable pressure between the lamination sheets to achieve the necessary stiffness of the core in a radial direction.

For a 2-pole generator the natural frequency for the 4-node mode in the core will be above the four-node excitation frequency i.e. 100 or 120 Hz. In an axial direction, there will be a lot of modes, with no or very low impact on the end-winding vibrations, but with one exception which is the “pringle” mode shape (see Figure 38) in the core ends at 100/120 Hz. Such a mode will amplify the end-winding vibration.

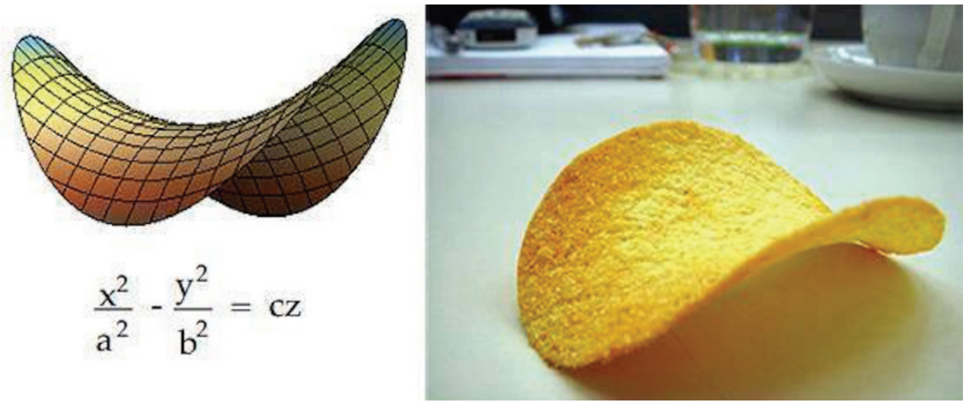


Figure 37. Example of the pringle mode shape

For a 4-pole generator the natural frequency for the 8-node mode in the core will be far above the 8-node excitation frequency, i.e. 100 or 120 Hz. This will give the core a quite low vibration level. The damping conditions for the core are very close to solid steel which means very low damping. Nevertheless, the vibrations in the core are decided at the design phase and will be very hard to change, and this will be the base excitation for the end-windings.

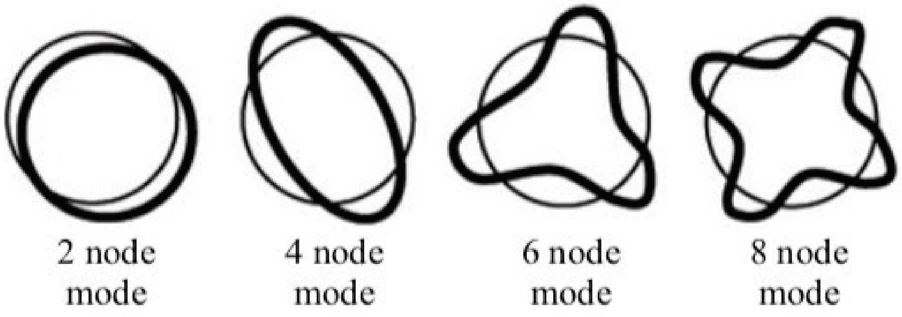


Figure 38. Mode forms of end-winding

4.3 VARIATION OF VIBRATION LEVEL

The amplitude and phase angle for the end-winding vibrations will variate as a result of the different power modes of the generator. Also the temperatures of all the material involved within the end-winding bracing structure will have an impact on the stiffness of the structure. The stiffness will either be stiffer or lighter, which then changes the natural frequencies (see formula in figure 36). Figure 40 give a more comprehensive view of how these different influences are correlated, but without any figures and the grading of the different impacts. Figure 42 presents a simplified overview of the main forces.

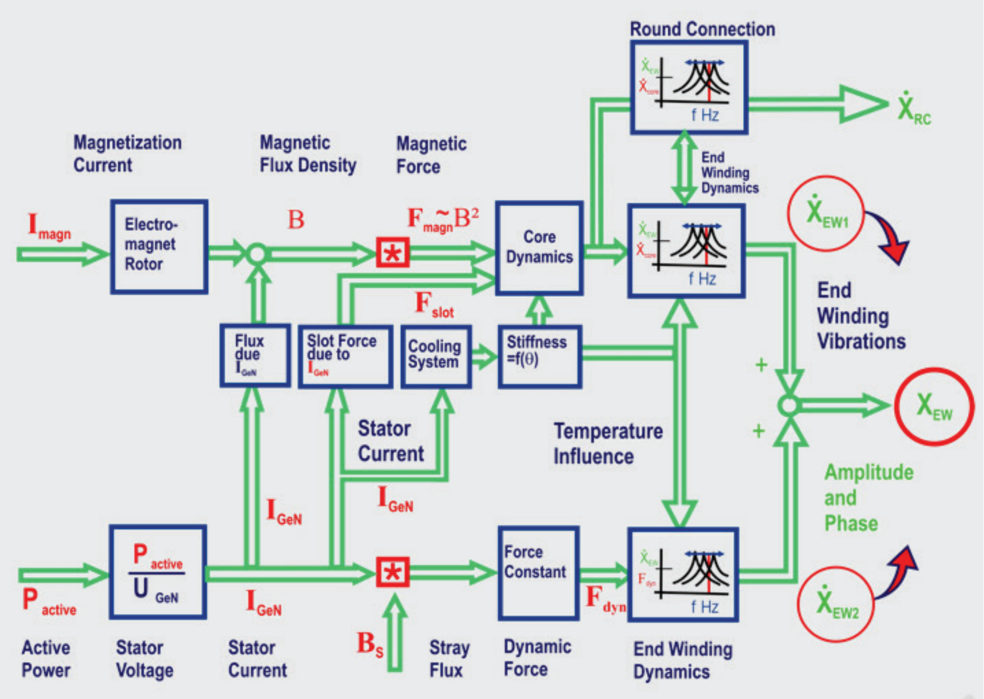


Figure 39. Block diagram for end-winding vibrations [18]

Starting with the simplest excitation, which is to get the rated voltage in the stator winding without connection to the grid, the magnetic forces from the rotor field Fmag will bring the core to an elliptic mode shape following the rotor rotation. This will indirectly excite the end-windings with the same mode shape with a frequency of two times the rotation speed for a 2-pole and four times for a 4-pole generator. When the stator winding is connected to the grid, there will also be a direct excitation created by fore Fdyn , which is a result of the interaction of the flux created by the stator current through the stator winding and the flux created by the field current through the rotor winding.

The stator current will as earlier mentioned be an antagonist which produces the armature reaction in the air gap, which reduce the radial impact from the Fmag on the stator core. The magnitude of the vibrations in the end-windings and round connections can be approximated as a relation to the flux from the rotor and from the stator winding which produces the principle formula:

$$v \sim \vec{P} \cong \frac{1}{2\mu 0} * \overrightarrow{B_{magn}} * \overrightarrow{B_{dyn}}$$

The principle formula can be quite well represented by a simpler formula:

$v \cong v0 + k * Ifield * Iarmature$

v = Vibration level for a certain load point in mm/s

P = Pressure wave amplitude in kilo Pascal, kPa

μ0 = Permeability of air in Vs/Am

Bmagn = Magnetic flux density created by the rotor winding in Weber /m2

Bdyn = Magnetic flux density created by the stator winding in Weber /m2

v0 = Core vibrations, when the stator winding is excited to rated voltage but not connected to the grid in mm/s

k = Correlation factor which can be estimated to be in the range of 2 – 5 e-8 ,(mm/s /A*A)

I field = Current in rotor winding in amps, A

I armature = Current in stator winding, A

The result is quite linear, but tends to overestimate the vibration level which probably is a result of the armature reactions on the stator core vibrations, and this cannot be used for under excited reactive power modes. The capability diagram in Figure 43 gives a good view of the different operation modes and the limitations for them, while figure 41 shows the expected relative vibration levels for some different load cases; and the load cases are as follows:

1. Stator winding is excited to rated voltage but not connected to the grid.
2. Stator winding is connected to the grid and loaded with 50% of the rated apparent power, over excited reactive power.
3. Stator winding is connected to the grid and loaded with 95% of the rated active power and with quite a low level of over excited reactive power.
4. Stator winding is connected to the grid and loaded with 90% of the rated active power and about a third of the rated over excited reactive power.
5. Stator winding is connected to the grid and loaded with 100% of the rated apparent power, i.e. 100% active and 100% over excited reactive power.
6. Stator winding is connected to the grid and loaded with 100% of the rated active power and 100% under excited reactive power.

Figure 40. Correlation between load and vibration

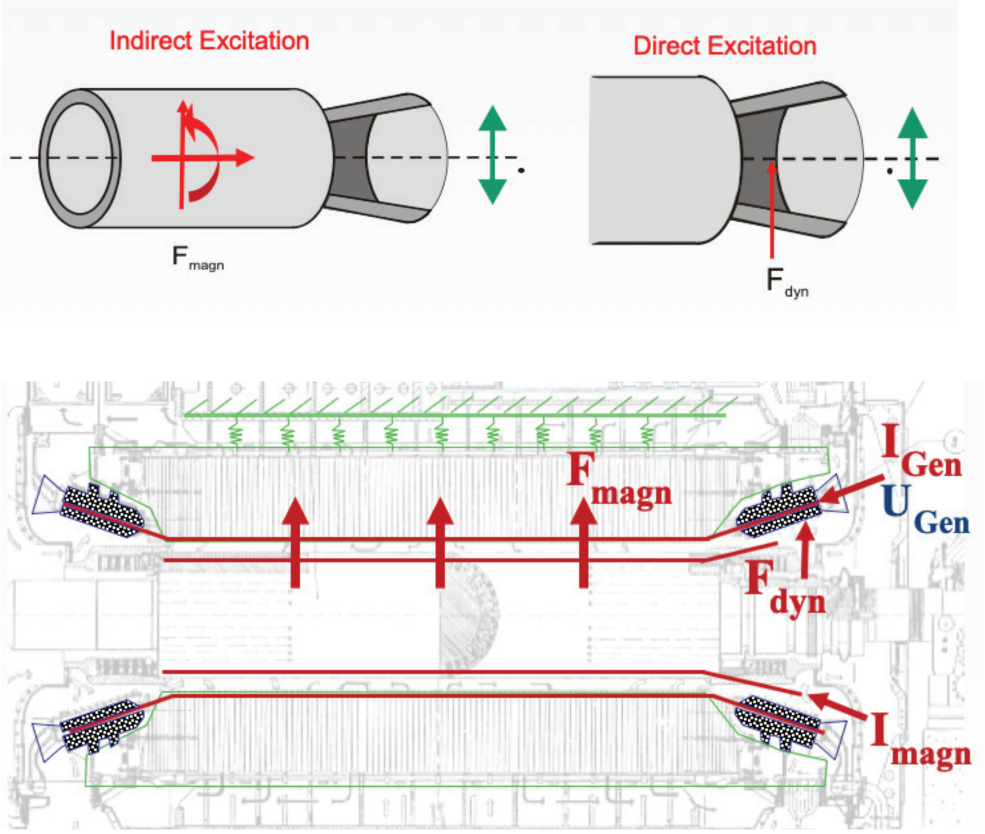


Figure 41. Simplified view of indirect and direct excitation. [18]

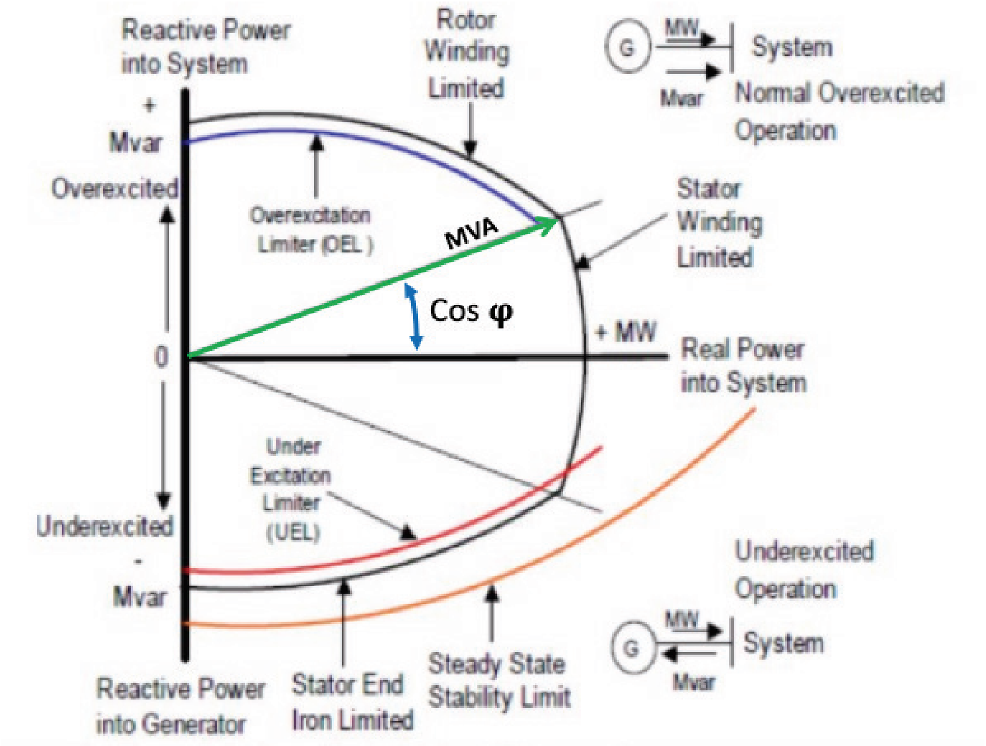


Figure 42. Capability diagram for generator

Added to the impact of different power modes will also produce a variation of temperatures of all material in the end-winding structure, but also changes of mechanical contact requirements between the core and frame will impact on the end-winding vibrations.

The magnitude of the thermal impact is strongly connected to the relation between natural frequencies and the frequency of the excitation. Figure 37 presents a good view of that relationship and one can imagine that very narrow relations will result in large changes of vibrations. One can easily see the difference to moving in to the resonance or away from it.

Normally the temperature impact will result in a weaker structure with lower natural resonances and the impact of the changes depends on whether the natural frequencies are above or below the excitation frequency. In cases with very close relations, even normal deviations from the stated grid frequency may impact on the vibration level. Additional contact points between end-winding structure and the core, can even change the vibrations but this is only applicable to weak structures with natural frequencies below an excitation frequency.

Even a loss of fixation forces of the bar in the winding slot will impact on the vibrations which will be concentrated to the 2 end wedges in each end of the core, and this may impact on the rocking and ovalization modes. The rocking mode (see 2 node form in figure 39) will variate with the magnitude of vibrations from an unbalance in the rotor.

4.4 VIBRATION LEVEL MONITORING

Generally, generators are inherently reliable and will operate for several years without any problem and at a minimum of maintenance. The absolute main part of a well-fitted maintenance for generators is diagnostics to get a view of the real condition. To make these diagnostics reliable, structured and complete, data must be available, which will be collected in operation, measurements at stand still, inspections with rotor in-situ and even when the generator is dismantled. All this complementary data will give the best view of the real condition and can be used to form additional inspections and measurements.

Monitoring of stator vibrations in end-windings, as well as in the core will provide a good background to form detailed inspections, measures and measurements based on these readings. Such maintenance will avoid surprises and unplanned outages, and a planned action will always be shorter than an unplanned one, especially for large turbo generators. One should keep in mind that 6 sensors per end-winding can probably only catch a global deterioration of the structure. Local deterioration will be more difficult to catch, but with continuous monitoring trends are possible to identify and inspections at a planned stop can identify the real condition for even local defects.

Figure 44 gives a general view of the main types and rates of failure in generators, while figure 45 illustrates the different growth phases for a failure, from the starting point to the breakdown, and gives even a reflection on detectability and optimal intervals for inspections

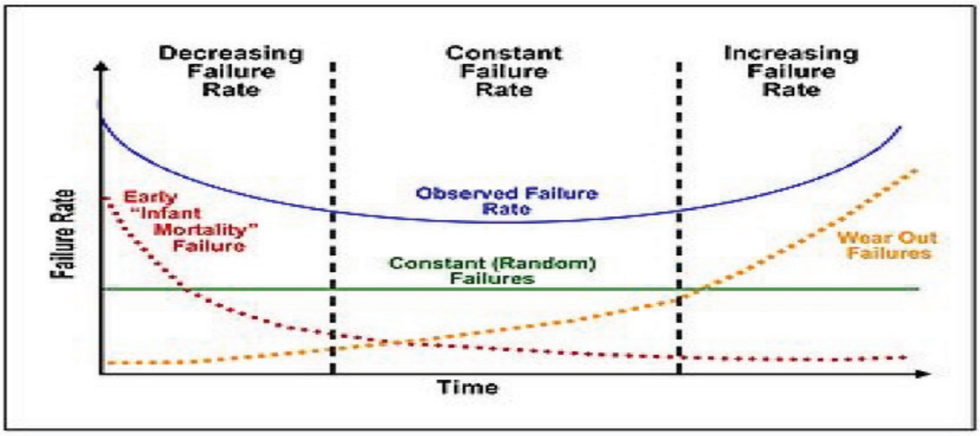


Figure 43. General view of failure rate for generators

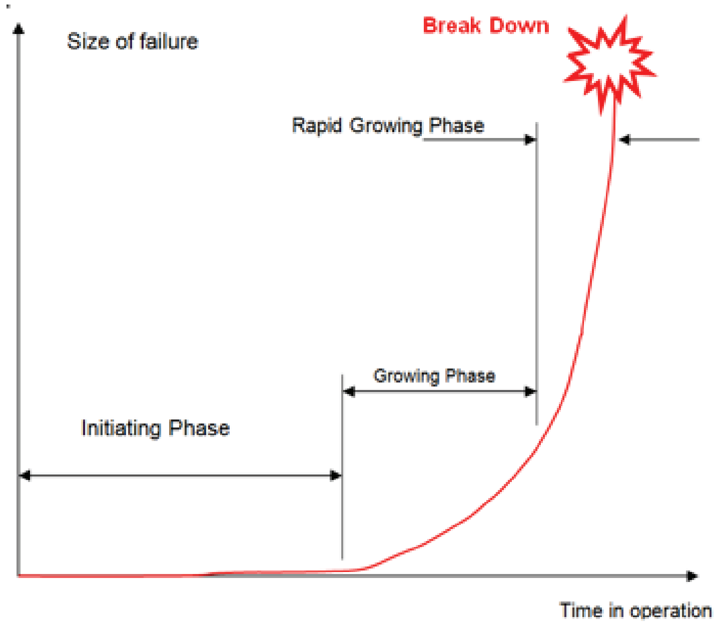


Figure 44. Development and detectability of failures

4.5 END-WINDING VIBRATION MEASUREMENTS

First, some basic information about vibration measurements in Turbo generator stators is required. As previously mentioned, the frequency of the vibrations in the stator are related to the rotor revolution and the double grid frequency, both of which are even sinusoidal. However, even vibrations with stochastic frequencies can occur if sensors or stator parts miss the fixation and become free or lost, though these types of vibrations can be seen as extreme and hopefully unusual.

For the 4-pole generators this will result in 25 or 30 Hz, and 100 or 120 Hz, depending on the grid frequency, while for the 2-pole generators this will be 50 or 60 Hz and 100 or 120 Hz based on equal reasons. The vibrations can be expressed and measured as displacements, velocity or as acceleration, where the use of displacement and velocity is the most commonly used.

The vibration signal or data are nowadays filtered at the revolution and double grid frequencies together with an unfiltered signal. Those constellations will give a quick and good overview of the vibration conditions with the ability to find even unusual conditions.

Some simple information about the sinusoidal wave form vibrations and the correlation between the used types of ω measurement.

$$Displacement \qquad z = Z * \sin \omega t$$

$$Velocity \qquad v = Z * \omega * \cos \omega t$$

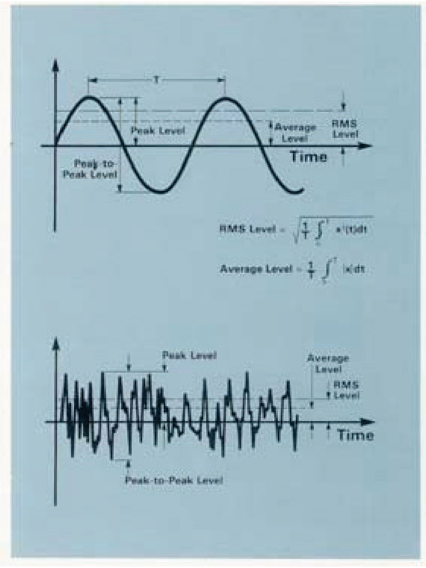
$$Acceleration \qquad a = Z * \omega^2 * \sin \omega t$$

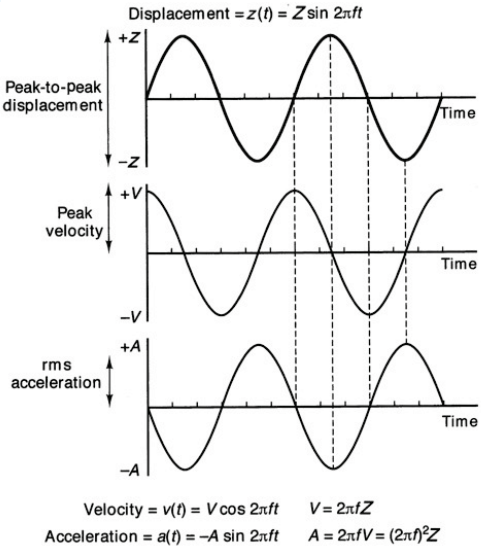
z = displacement/amplitude, current time value in meter, m
Z = displacement/amplitude, peak value in, m
v = velocity current time value in meter per second, m/s
(maximum when the cos value = 1)
a = acceleration current time value in meter per square second, m/s2
(maximum when the sin value = 1)
ω = angular frequency in radian per second, rad/s = 2*π*f
f = frequency in Hz i.e. revolution per second or sinusoidal periods per second

The root mean square (RMS or rms) is defined as the square root of the mean square, which for a sinusoidal wave forms produces the relations between peak amplitude and the rms value = $\sqrt{2}$. This can be compared to the phase voltage used in the wall socket at home, 230 Vac, which produces a peak value of 325 Vac. The rms value gives the same output as dc voltage of the same value. The RMS value is the most relevant measure of amplitude because it both takes into account the time history of the wave and gives an amplitude value which is directly related to the energy content, and therefore the destructive abilities of the vibration.

In practice, there are two or maybe three main values used to provide information of the stator vibrations. These are:

- Peak to peak value, which are the most commonly used in the US. Used units are either recorded in mills (one thousand of an inches or 25,4/1000 mm) or micrometers (one thousand of a millimeter or 1/1000mm).
- Peak value, where the most common unit are in micrometers.
- RMS amplitude value, where the most common unit are in micrometers.
- Velocity, where the most used common value is mm/s rms.

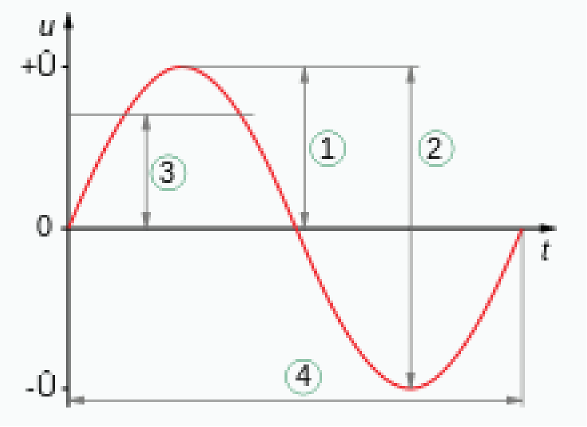




The following ratios can be useful in order to convert between units and indicators

- Peak to peak value in mills to micrometer.
  1 mills = 25,4 µm (micrometer/microns)
- Peak value is 1/2 of the peak to peak value
- Peak rms converted to peak will be RMS peak value * √2

- The conversion of velocity rms value to peak value will depend on the frequency of the vibration.
  - × Velocity rms 50 Hz * 4,5 produces the peak value. ʻ
  - × Velocity rms 60 Hz * 3,76 produces the peak value.
  - × Velocity rms 100 Hz * 2,25 produces the peak value.
  - × Velocity rms 120 Hz * 1,88 produces the peak value.



A sinusoidal curve

1. Peak amplitude
2. Peak-to-peak amplitude
3. Root mean square amp
4. Wave period (not an amplitude)

5 Problems/failures caused by vibrations in stator

5.1 FAILURES IN STATOR END-WINDINGS CAUSED BY VIBRATIONS

As mentioned in the design section, the intention with the end-winding design is to create solid ring structure with natural frequencies far away from the excitation mode frequencies. Added to this, the structure must sustain a short circuit event without destruction.

Relations between excitation and natural frequencies will be quite different for a 2-pole generator compared with a 4-pole one. This relation is about a factor two for the 4-pole generator. For the 2-pole it is typically a span of 0.7 to 1.3. This will in general result in more unsustainable solutions of the end-winding support for 2-pole generators.

To ensure a long-lasting function for the end-winding structure fulfilling the intended requirements, it is necessary to give the structure stable properties. It must be sustainable for all excitation forms for the whole range of the operation conditions, including the whole range of operation temperatures, and added to this is the impact from abnormal events on the grid.

To realize all of these it is necessary for the following:

1. Dimensioning to place the natural frequencies as far away as possible from excitation frequencies.
2. The shape of the end parts of the bar must be well within the theoretical shape for the cross section at the evolvent bended form.
3. Bracing blocks or parts between bars in the top and bottom layer must be well fitted with the use of a sustainable material.
4. Bracing block or parts between the bottom and top bars must be well fitted with the use of a sustainable material. Prestressed compression elements must even be added to take care of forces acting between the top and bottom bars.
5. Tangential support blocking in the outermost part of the end-windings must be well fitted with use of stable material. Added to this it is even necessary to create radial forces on this blocking pieces with aim to compensate for settlement in the glued joints and the blocking material.

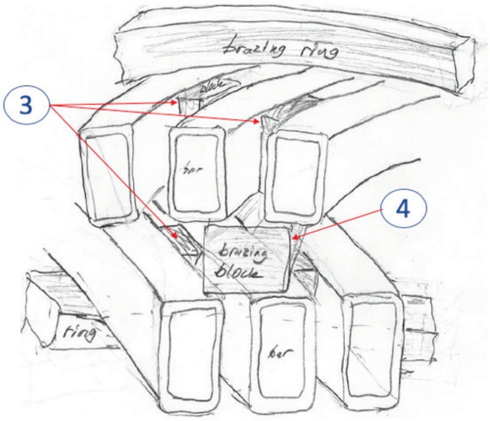


Figure 45. Bracing blocks in end-winding

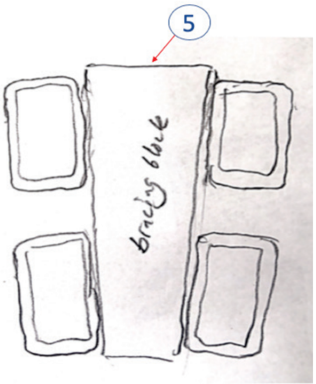


Figure 46. Tangential bracing block

The fulfillment of these fitting requirements depends on the material selection, the workmanship to fit and finally to realize and get the right prestress conditions after curing of the structure.

Use of too much polyester-felt for the fitting work will result in a less sustainable structure. Unproper prepressed structure will even that result in that.
One can easily understand that it is more complicated to fit support blockings between bars which all have an individual shape and dimensions.

Anomalies in these requirements will create a separation or cracks between bars and bracing parts which will impact on the natural global frequencies of the end-winding or in local locations.
This will most likely result in increased vibrations and the unbound surfaces will slide toward each other, resulting in an abrasive process creating flour or powders and the gaps will grow larger, and the process will must probably accelerate.
This will result in an abrasion of the bracing material and the main insulation of the bar, see figures 48 – 56.

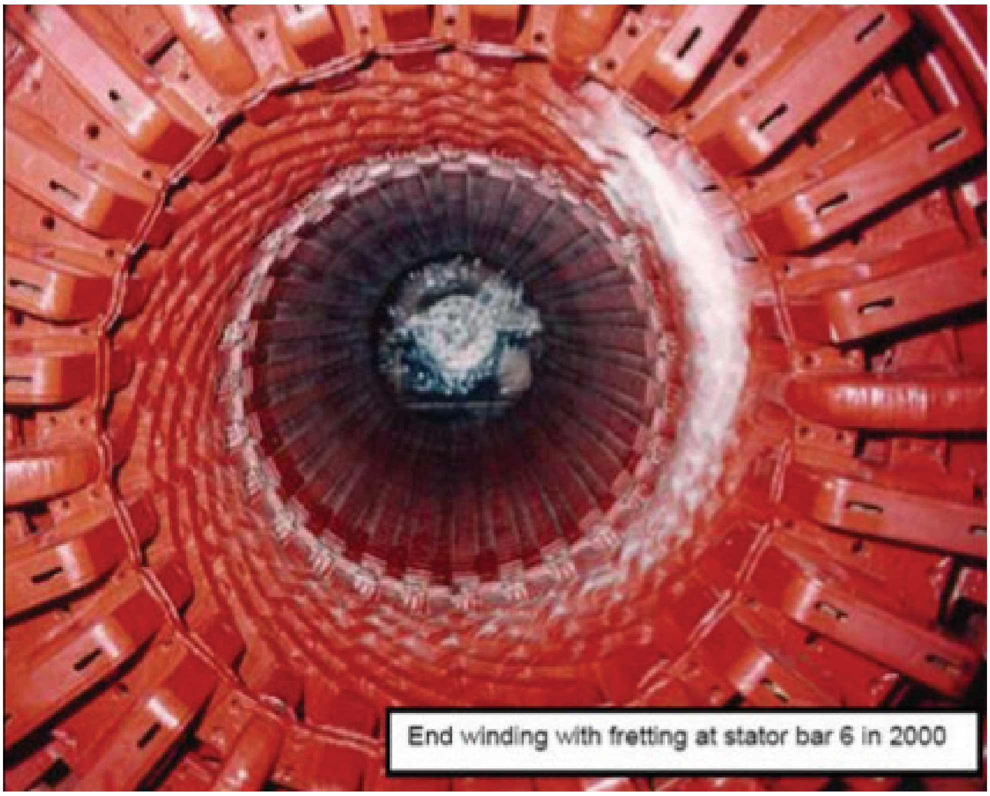


Figure 47. End-winding with fretting wear, abrasion flour

Figure 48. Fretting wear and Abrasion flour in broken contact surfaces

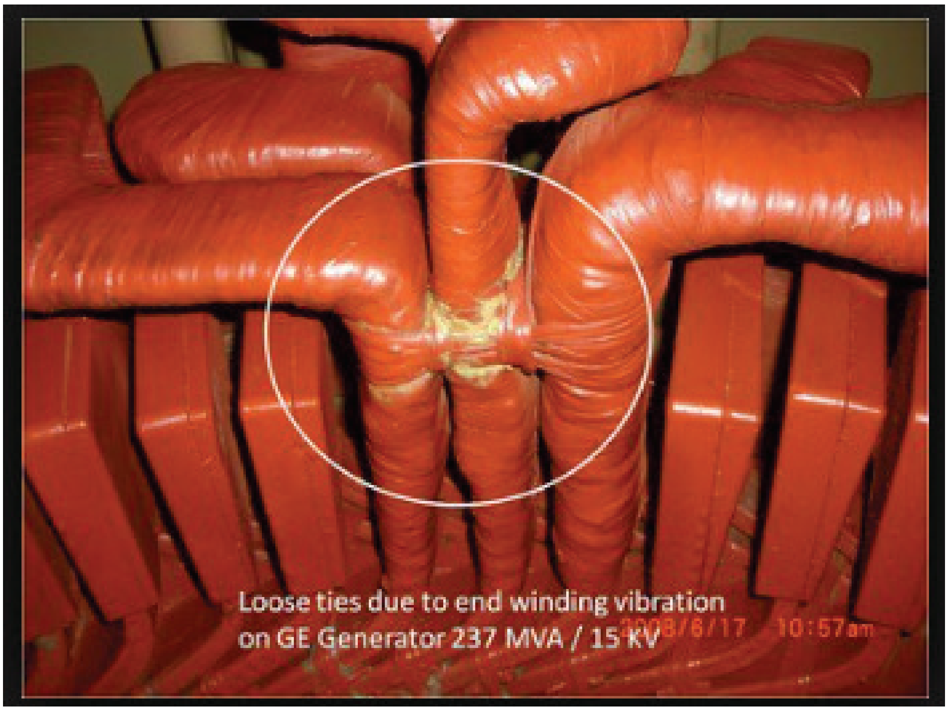


Figure 49. Fretting wear in tied connection points

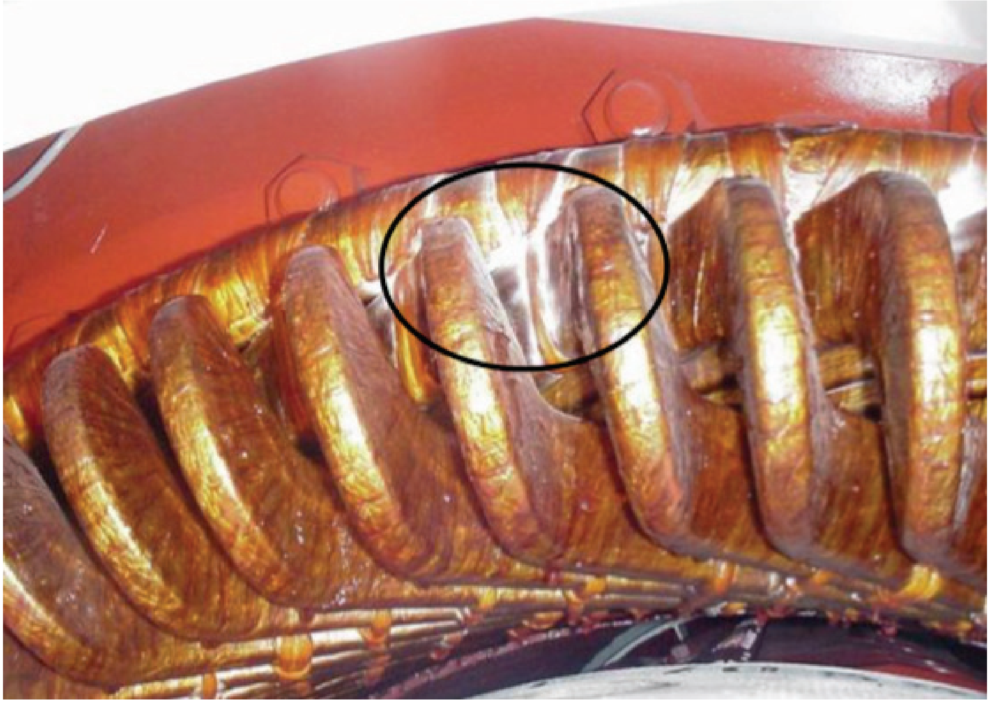


Figure 50. Fretting in tangential blocking between bar knuckles

Figure 51. Tangential blocking with degenerated prestress forces causing cracks and abrasion dust

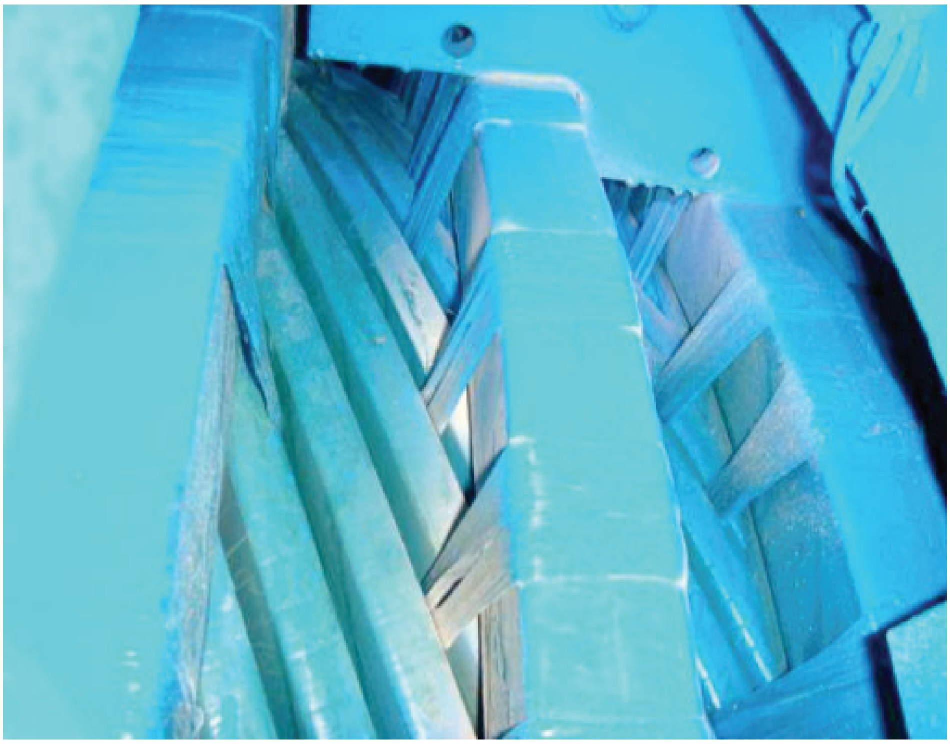


Figure 52. Lost prestress tension in fixation bandage between bars and support rings. In stator of resin ring type se figure 28

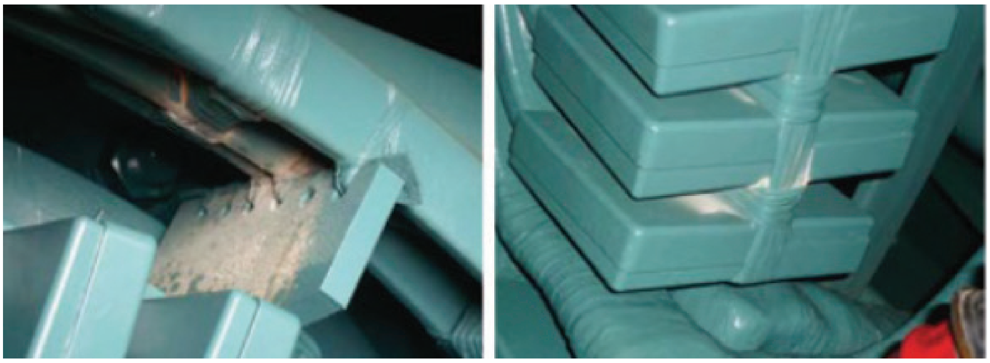


Figure 53. Fretting in round connections, left, and between knuckles, right

Figure 54. Fretting in round connection

Figure 55. Vibration fretting of main insulation in slot parts

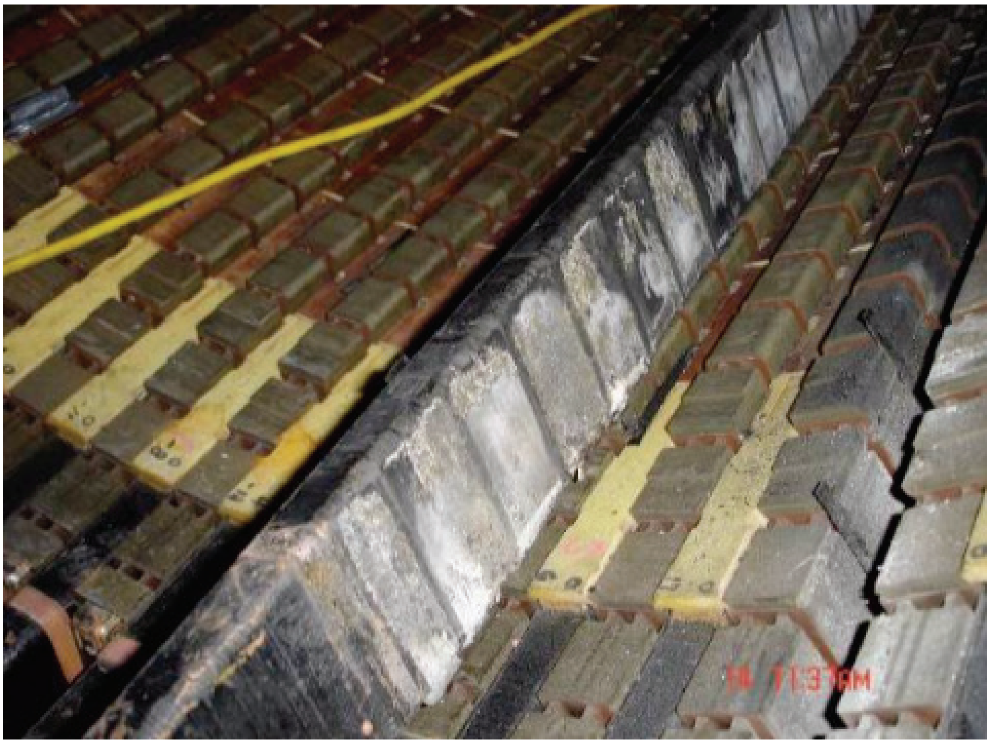


Figure 56. Vibration sparking on bar at neutral of the winding

Figure 57. Broken connection between corona protection at slot portion and end-winding

Even more severe failures as fatigue cracking in copper strands or connection braids to bus bars can occur as a result of increased vibrations. These types of failure are often found in the connections between the end-winding and round connections (see figure 56,57 and 58).

Figure 58. Broken connection between end-winding and round connection, caused by vibration

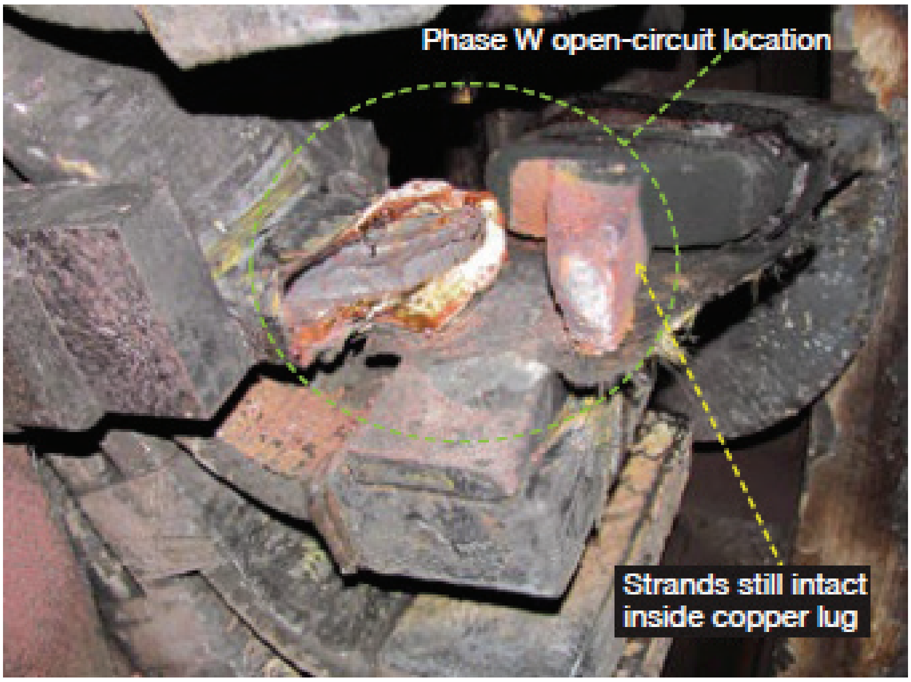


Figure 59. Another example of broken connection between end-winding and round connection, caused by vibration

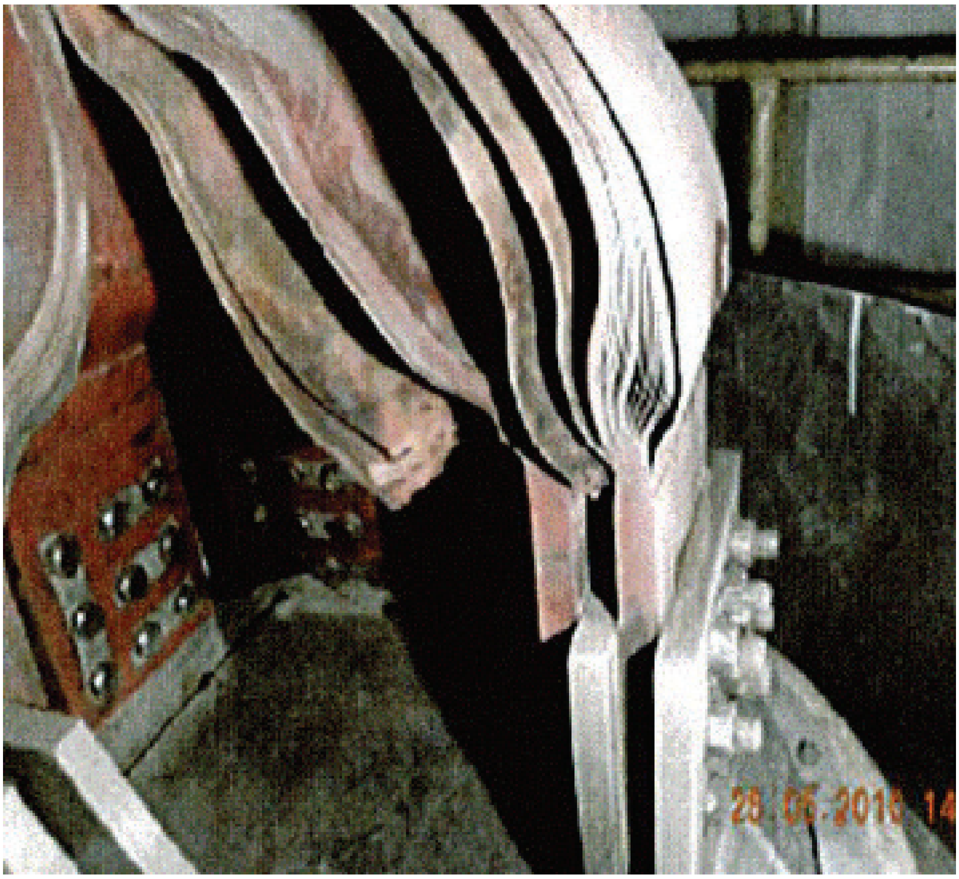


Figure 60. Partly broken braid between winding and bus bar

However, the worst case may be delamination's of the main-insulation at the slot entrance, which will result in an earth fault, most probably for the main part of the bars. Such failures will occur for vibrations which result in stresses from about 300 micro-strains in the main insulation.

Figure 58 shows signs of separation, lost electrical contact, between the corona protection for the slot part and the end winding part. One can speculate that this can be the first signs of destructive vibration levels with potential to soon delaminate the main insulation.
Severe end-winding vibrations will impact on the overall vibrations in stator-core, frame and connected details as manifold tubes and coolers.

The inside containment of a turbo generator is very sensitive for contamination and/or pieces of metall. And extremely sensitive is end winding region where even as small particles less than a grain of rice have potential to penetrate the main insulation.

With impact of the strong magnetic field metallic particles brings to rotate and act as a "drill" which very quick will "drill" through the insulation. Induced current from the he magnetic field will even varm up all metallic particles.

There are several examples of lost details due to pour fixation. Lost details moved in to the end winding structure will very soon create an earth fault or a short circuit. But even larger pieces of insulation material are able to destruct the main insulation or cooling components due to vibration abrasion.

5.2 FAILURES IN CORE, FRAME AND END COVERS CAUSED BY VIBRATIONS

Three main types of failures can occur in a stator core. Foreign object in the air, partial loss of axial core pressure and lost contact between core back and frame. All these three main causes are together with vibrations able to create failures with a severe impact on the power production.

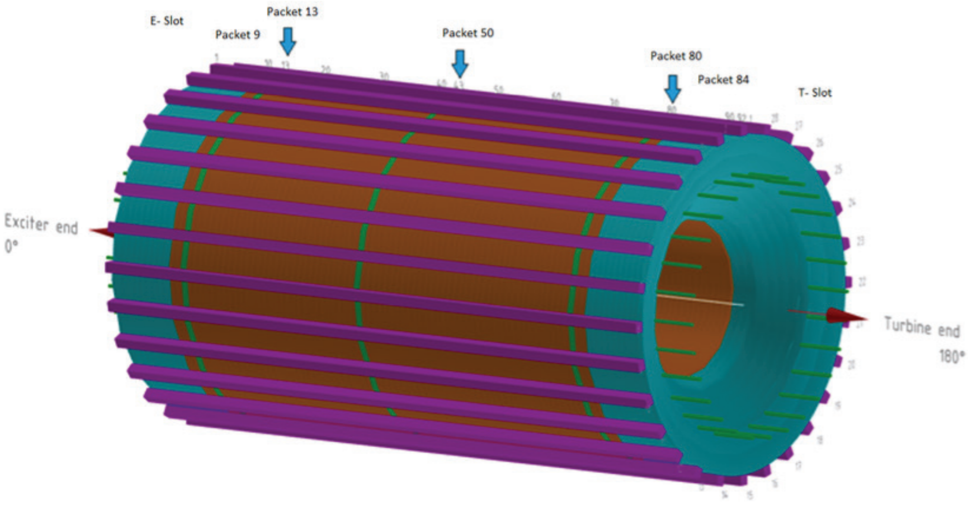


Figure 61. Stator core

Foreign objects

The first example is quite trivial, yet a potential trouble maker and is coupled to the requirement of the freedom of non-conducting pieces of any type in the air gap. Pieces or details made of magnetic steel have the largest potential to create failures since it also will interact with the magnetic field of the rotor. There are several examples of forgotten tools, lost screws, etc., creating more or less severe meltdown scenarios of the stator core.

Figure 62. Partial meltdown of the core air gap surface.

Partially lost (axial) core pressure

The next type of failure is lost core pressure. The minimum overall axial pressure in the core must be 0.1 MPa. At a lower pressure, the segments start to have relative motions, the insulation varnish will be worn out and the core will be totally destroyed. Yet even a partial loss of needed pressure will cause local destruction of the core. Even such minor destruction can produce severe disturbances in the power production. Repair actions may involve partly restacking the core which also includes a complete rewind.

An example of such locally lost pressure is shown in figure 63. With the missed needed pressure, the laminations will start to vibrate and fatigue cracks will develop. This failure will also get magnetic lamination pieces in to the air gap and even more damages on the core.

The main cause for this failure is an uneven and improper pressure created in the stacking procedure in manufacturing. The commonly used core pressure of 1 MPa is chosen to produce a margin for the settlement in the core due to all the contact surfaces and the comparable rough surfaces from the insulation varnish. Therefore, an uneven distributed pressure creates a risk for such events as in figure 64.

Yet even a lack of pressure in the core back, se figure 65, can impact on the power operation ability, even if the airgap pressure is in order. The most probable impact may be on the bending mode of the core and frame, but even axial mode forms could be impacted by the axial core pressure.

A frequency shift of the “pringle” shaped mode may create an impact on the end-winding vibrations, especially if the end-winding and the pringle mode have corresponding mode forms close to 2 times the net frequency. Such an event may be possible to recognize or identify with vibration monitoring.

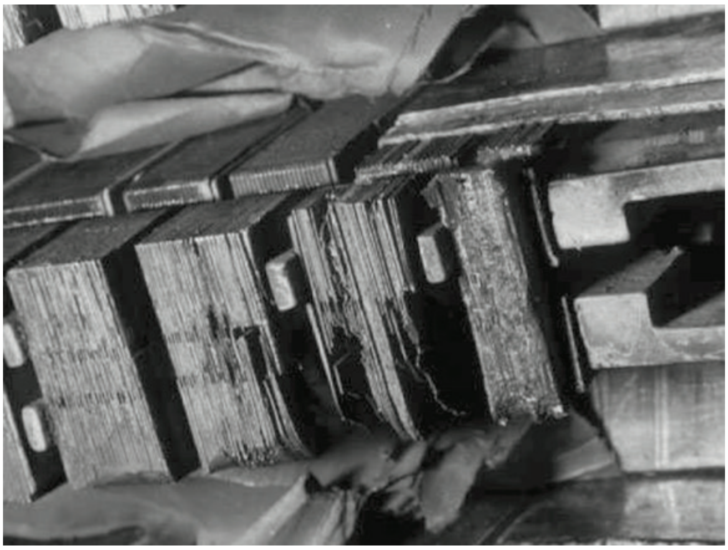


Figure 63. Failure in on air gap side caused by lack of pressure

Figure 64. Lack of pressure in the core back

Lost contact between core and frame

The third type of failure is lost mechanical and electrical contact between the building-bars and core. As mentioned in the design section, it is necessary to take care of the induced currents from the core back flux. For that reason it is necessary to achieve a good contact between the building bar and the core back. A bad contact will result in arcing and partly a meltdown of the core, especially in the core ends.

Figure 66 shows an early stage of such an event. The melted particle from the core back will be forced to rotate with the flux, especially in the end-winding region, and there is a potential risk of penetrating the stator winding main insulation. A changed contact condition might even impact on the axial and bending mode of the core and frame.

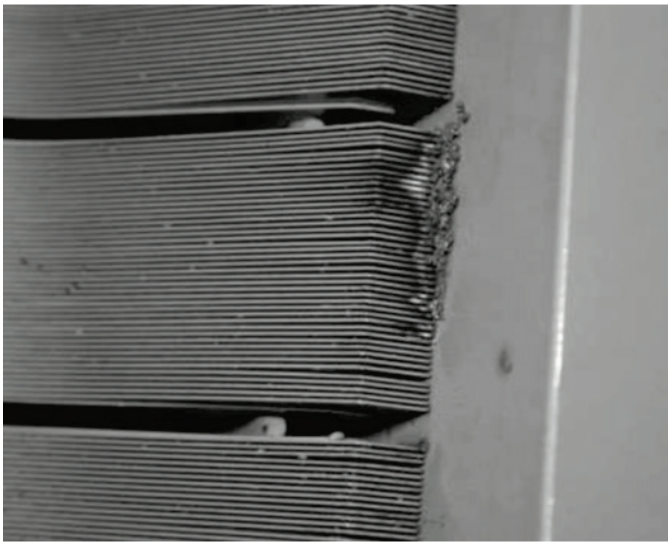


Figure 65. Failure in the core back

Improper design of generator containment or degenerated contact requirements between different parts.

Common to this fault is a structure with the dynamic condition close or in resonance with the excitation frequency. Such a condition can easily generate fatigue cracks in the structure.

Figure 66. Generator containment

Before the time where finite elements modelling was commonly used as a tool for the dimensioning of stresses and dynamics, more simple calculations were performed with the support of experiences from similar applications. Looking at the generator containment shown in figure 67, one can understand that such a design result not was an easy match to predict. That, together with a manufacturing result, even added more uncertainty to the real conditions, especially on the dynamic conditions.

Based on this, it is more than only odd examples of different mitigation actions to bring the structure in an operable condition; such actions as stiffening rings and beams or different types of tuning weights adopted to the structure to get a dynamic condition usable to run without large vibrations and risk for fatigue cracks. Yet there can still occur such vibration events in this structure, especially if the natural frequencies are close to resonance, coupled with the fact that the damping factor is very low in this structure made of welded steel.

An explanation for this could be improperly mounted screw joints, not fulfilling requirements for contact forces between the feet of the foundation and the foundations. Even large end-winding vibrations can be seen on the containment.

Failures in gas/air coolers.
Destructive vibrations in the inbuilt gas or air coolers are not an unusual event in turbo generators, where the excitation vibrations frequency is the 100/120 Hz. It is essential to design the cooler to achieve freedom from natural frequencies close to the above-mentioned frequency and realize this with a sustainable design. The failure modes are either related to the bracing condition of the tubes or the frame of the cooler (see figure 68), both of which can result in fatigue cracks in tubes and the frame which ends up with a water leakage.

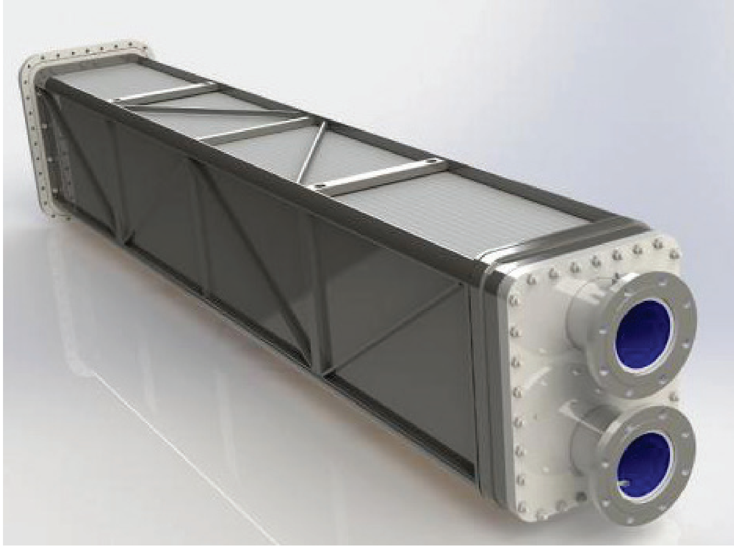


Figure 67. Gas or air cooler

<u>Failures in manifolds or ring tube manifold and piping in and outside of the generator containment.</u>
Also the manifolds and all piping, on the outside of the generator containment as well, must be braced to avoid a frequency close to 100/120 Hz, and usually the bracing points for the manifolds are electrically insulated from the containment. The sustainability is an essential requirement for all these bracing parts, and all screws must be locked in a safe way (see figure 69) with the larger manifolds for connection to the stator bars. A failure event can be fatigue cracks in the manifold and a water leakage, but a lost screw can cause more severe failures if it drops into the end-winding basket. The outside piping can be checked with periodic vibration measurements, but the inside must be visually inspected at planned outages.

Figure 68. Manifolds with fixation supports

6 Study of 4-pole Generator Stators

6.1 4-POLE GENERATORS IN OSKARSHAMN 3 AND FORSMARK 3

6.1.1 Design concepts for the main stator parts and expected properties

The generators in Oskarshamn 3 and Forsmark 3 are the GE/Alstom, type GIGATOP 4-pole. The generator rotor is cylindrical with four poles and the rotor winding, as well as the stator core and the rotor body are directly cooled with hydrogen. All active parts of the generator operate inside the pressurized and gas tight enclosure at about 5 bar gas over pressure. The stator winding is directly water-cooled.

The natural frequencies for the 8-node modes excited by the rotor field are well above the excitation frequencies, both for the stator core as for the end-windings. This results in normally low vibrations in the core as well as in the end-windings. Results from the impact test produce natural frequencies for the end windings at the following ranges:

8 node mode 200 – 250 Hz

6 node mode 140 -170 Hz

4 node mode 75- 100 Hz.

The Generator stator is equipped with 22 sensors to monitor the vibration conditions of the stator.

<u>6 sensors</u> are placed in the end-winding at the drive end to measure radial vibrations.

<u>6 sensors</u> are placed in the end-winding at the non-drive end to measure radial vibrations.

<u>6 sensors</u> are placed at connection bar braids.

<u>4 sensors</u> are placed in the core back to measure radial vibrations.

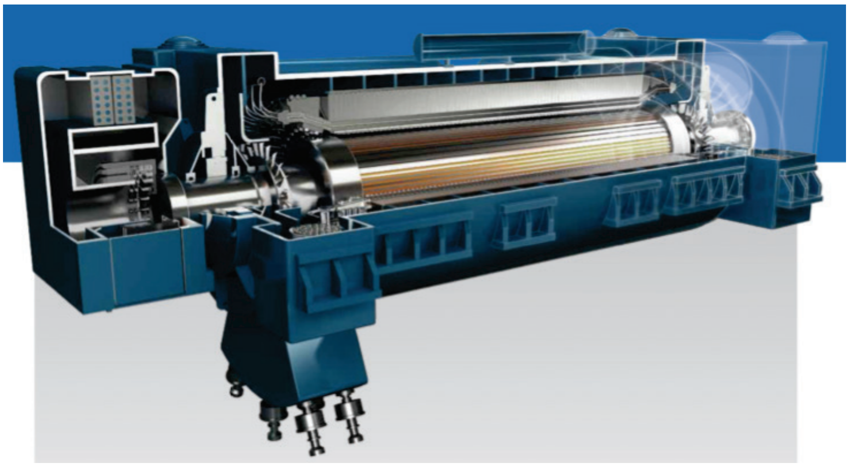


Figure 69. GIGATOP 4-pole generator. [4]

6.1.2 Identifying potential parts for malfunctions with impact on operation

Deterioration or degeneration of the bracing structure for the end-windings will result in placing the natural frequencies for the eight-node mode form closer to the excitation frequency, 100 Hz, which in theory will result in an increased vibration level. Most probably, the global structure will be sustainable, but one cannot exclude a locally oriented degeneration of bracing elements which can produce a larger impact on the vibrations in that area.

6.1.3 Systematization and a brief evaluation of real cases

A typical stator vibration in Forsmark 3 is for:

- Drive end-winding of about 2 mm/s with a maximum level of 7 mm/s.
- Non-drive end-winding of about 1 mm/s with a maximum level of 4 mm/s
- Connection bar braids of about 4 mm/s with maximum level of 7 mm/s.
- Stator core of about 2 mm/s.

One can expect a stable condition without major changes over time, but a systematic long-term collection and evaluation of vibration data is important in order to identify changes in the structure for end-winding bracing and the connection bar braids.

6.2 STUDY OF THE 4-POLE GENERATOR STATOR IN OLKILUOTO 3

6.2.1 Design concepts for the main stator parts and expected properties

The generator in Olkiluoto 3 is a Siemens 4-pole generator, type: SGen 4000 W. The generator rotor is cylindrical with four poles and the rotor winding, as well as the stator core and the rotor body are directly cooled with hydrogen. All active parts of the generator operate inside the pressurized and gas tight enclosure at about 5 bar gas over pressure. The stator winding is directly water-cooled.

The natural frequencies for the 8-node modes excited by the rotor field are well above the excitation frequencies, both for the stator core and the end-windings. This result in normally low vibrations in the core as well as in the end-windings.

Natural frequencies of the end windings can be expected at the following ranges:

8 node mode >150 Hz

6 node mode ≈ 100 Hz

4 node mode > 50 Hz.

The Generator stator is equipped with 12 sensors to monitor the vibration conditions of the stator.

<u>6 sensors</u> are placed in the end-winding at the drive end to measure radial vibrations.

<u>6 sensors</u> are placed in the end-winding at the non-drive end to measure radial vibrations.

Figure 70. Siemens 4-pole generator, type: SGen 4000 W

6.2.2 Identifying potential parts for malfunctions with impact on operation

Deterioration or degeneration of the bracing structure for the end-windings will place the natural frequencies for the 8-node mode form closer to the excitation frequency, 100 Hz, which in theory will result in increased vibration level. Most probably the global structure will be sustainable, but one cannot exclude locally oriented degeneration of bracing elements which can create a larger impact on the vibrations in that area.

6.2.3 Systematization and a brief evaluation of real cases

Currently, this unit has not been in commercial operation yet.

7 Study of 2-pole Generator Stators

7.1 THE EVOLUTION STEPS OF THE WATER-COOLED TURBO GENERATORS OF ASEA, TYPE GTD

The intention of the ASEA strive was to develop an all water-cooled 2-pole Turbo Generator, which means that the core, rotor body, the stator windings and the slip rings would be cooled by water without any use of hydrogen or forced circulation of air. The only exception to fulfilling the intention was the need for cooling air to complete the cooling of the core ends; see figure 69 below, showing the water-cooled parts.

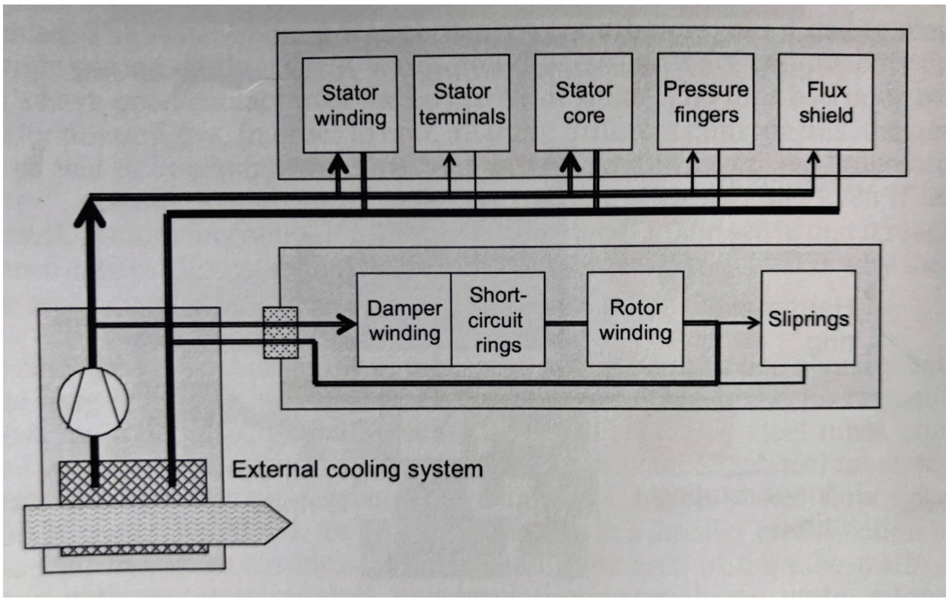


Figure 71.Cooling water flow of the GTD Generator [1]

Figure 73 shows the very first generation of the GTD generator. The concept was developed for active rotor diameters of 1150 and 1250 mm, which still is the commonly used diameters on large generators, where 1250 is the maximum diameter that can be used, due to material strength limitations.

The following is a brief view of the development, and further changes of the GTD generator concept will be described. Several problems with leakage in rotor windings and a struggling water device occurred, together with surprisingly high vibrations in the end-windings and high temperatures in the flux shield rings. Here, only the evolution of the stator design will be mentioned in more detail, and the evolution of the rotor concept will not be considered in this paper.

The end-winding vibrations in the Stator were solved with a quick fix solution with the use of stiff support studs, marked red in Figure 73. As a result of the unexpectedly high-end-winding vibrations, a concept to continuously monitor these vibrations was developed and has been used since that time. This concept consists of accelerometers attached in a safe way on the end-winding baskets. Yet even the core was measured with fixed sensors in the core back, which was established as the standard solution for larger generators.

The reason to equip the core with vibration gauges, was due to a design criterion for stator core radial vibrations with a displacement or amplitude of less than 15 micro meters. This requirement was set to a non-excitation vibration to the foundation. If the requirement is not fulfilled, the core must be flexibly connected to the frame, spring suspended, or the frame should be flexibly mounted to the foundation.

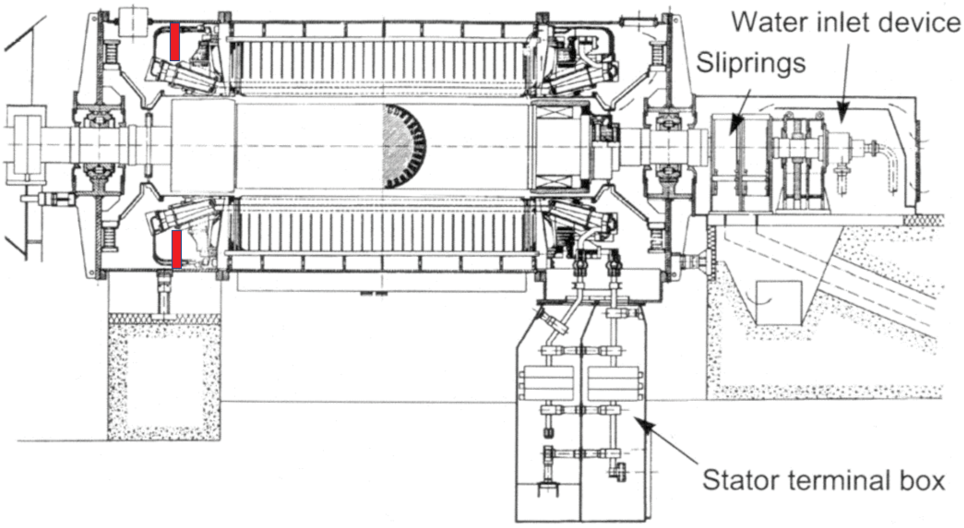


Figure 72. Longitudial section of the first generation GTD generator [1]

Trouble shooting together with a minor step development for existing generators influenced the next generation stator design and construction. The main focus for the changes was the core and bracing of the end-windings. The water-cooling concept for the core was replaced with air cooling. The water-cooled core was glued together with simple pressure fingers to achieve a solid core. The new design with ventilation ducts and solid steel rings was used to realize a solid core and suitable core.

A lot of attention was spent on the end region of the core to produce permitted operation temperatures within the IEC standards. To manage this, a flux ring was placed on the pressure ring together with a copper screen on the cone tip of the ring. All these parts were directly water-cooled with the use of in built stainless tubes in those parts. Added to this, was a forced cooling of the two outermost placed core packages, which including cooling with water via the spacer and the addition of air. The new end-winding support was designed to be stiffer with the aim of placing the eigenfrequency for the end-winding above the excitation frequencies 50 and 100 Hz.

Several other improvements were established, but without any impact on the vibration conditions; Figure 74 shows the new developed concept.

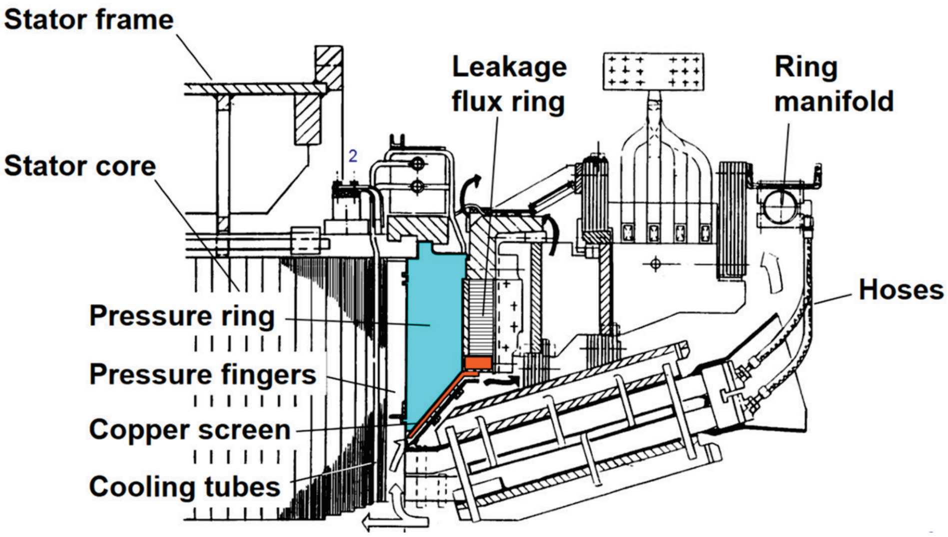


Figure 73. End part of the next generation of GTD stator design [1]

The improvements were not completely successful in terms of vibration behavior. Also the end regions of the core did not fulfil the expectations of operation temperatures and was limiting the power rating. Together with the very high cost to realize the complicated cooling of the flux screening, a new development started with the aim of finding a better design concept for the core. The work resulted in a completely new design with solid pressure rings built up of stator lamination steel segments which are glued together to a solid ring (see Figure 75).

Another improvement was the forced coupling between the core back and the building bars of copper (see figure 73). This solution produced a sustainable mechanical and electrical coupling between the stator frame and core, resulting in sustainable vibrations in those parts.

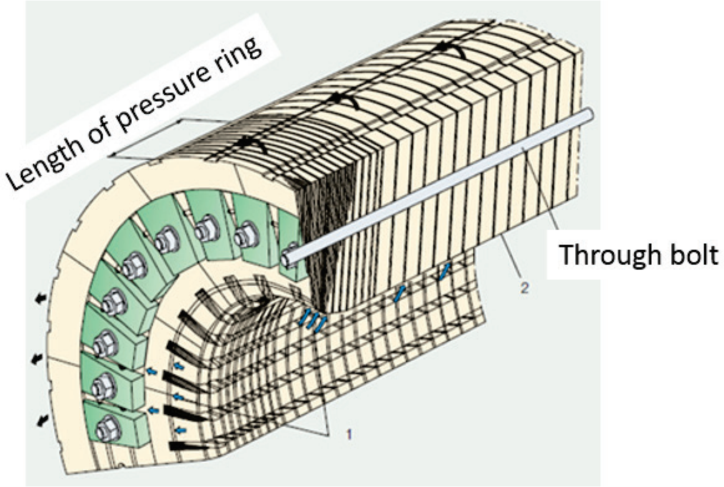


Figure 74. Cut out view of the latest design of the core [3]

Figure 75. Building bar of copper

To produce sustainable vibrations in the end-windings, the design concept was changed from a stiff to a weaker version with the ovalization modes below 100Hz. The requirement to sustain a short circuit scenario was met with the use of rigid supports which only acts in such an event. The new design is shown in Figure 77 and in Figure 78.

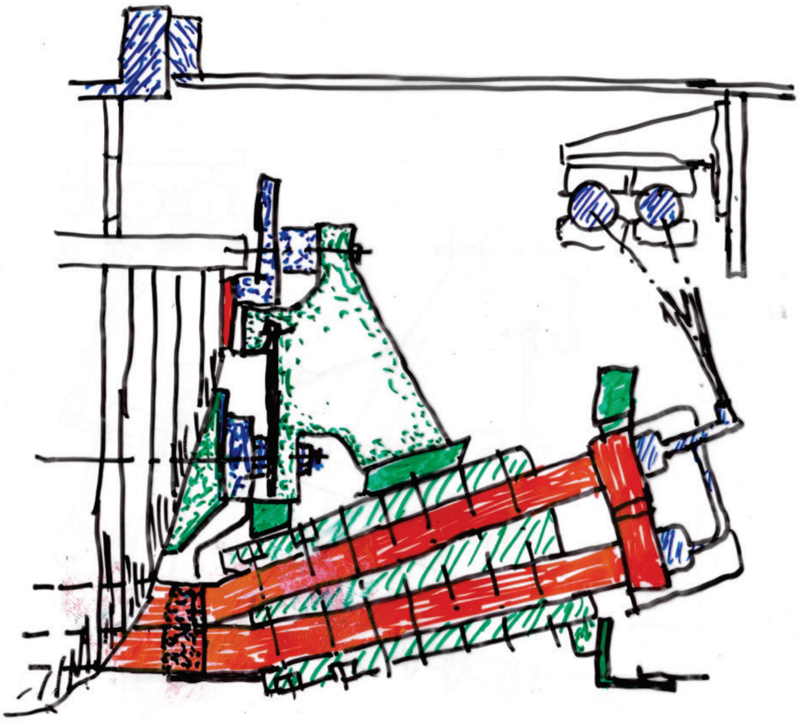


Figure 76, End-winding of latest design

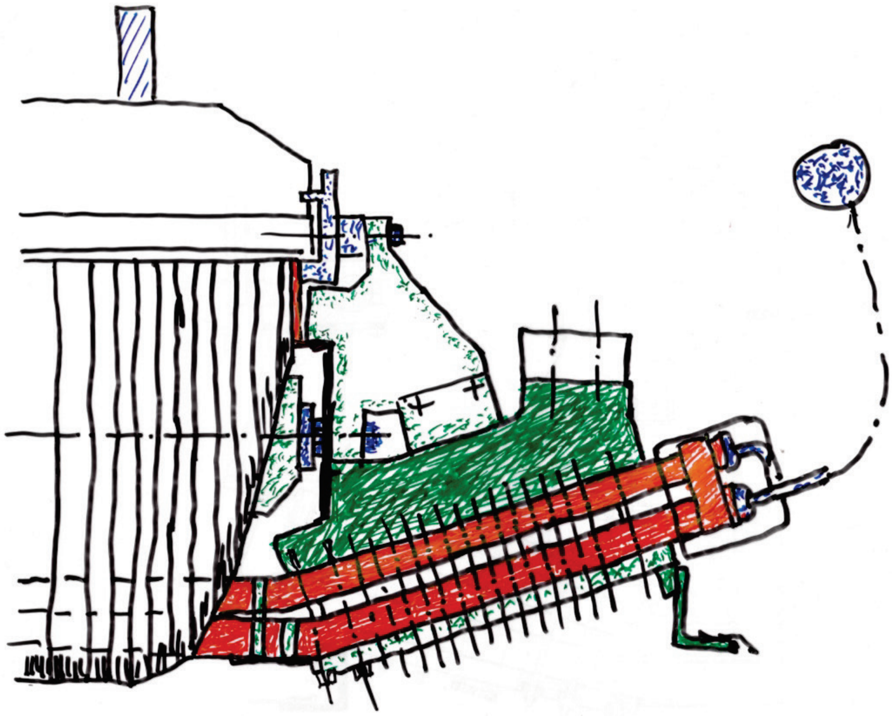


Figure 77. End winding of latest design, above 1000MVA

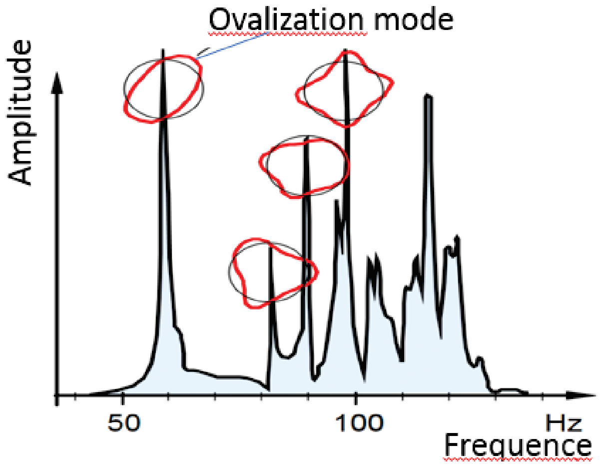


Figure 78. Eigenfrequencies for new design

7.2 STUDY OF 2-POLE GENERATOR STATORS IN FORSMARK 1&2 AND RINGHALS 3&4

7.2.1 Design concepts for the main stator parts and expected properties

The generators in Forsmark and Ringhals are Alstom, type GTD 2-pole all water-cooled generators. Both rotor and stator windings are directly cooled with water. The stator core and rotor body are air-cooled by force and the generator enclosure is open to the atmospheric environmental conditions and pressure. All the ordinary stators in Forsmark and Ringhals are of the latest design, as described in section 7.1 and in figure 75; only the spare stator is of the predesigned type, which is close to that in figure 71.The end-winding bracing is of the "resin ring type" (see figure 27).

The natural frequency for the 4-node modes in the end-windings and round connections are below the excitation frequency, 100 Hz, created from the magnetic field from the rotor. The tilting modes are below as well as above the excitation frequency, 50 Hz, created by unbalance in the rotor. The stator is equipped with sensors as in the end-windings, and round connections, as in the stator core. Also connection flags to the busbars have in some generator's optical sensors for vibration measurements.

The sensors are applied as follows:

6 radial sensors in the end-winding drive end

6 radial sensors in the end-winding non-drive end

6 radial sensors in the round connection

6 radial sensors in the stator core back

6 axial sensors in the stator core back

6 sensors on generator terminal

6 sensors on water manifold. Only on Forsmark TA 21

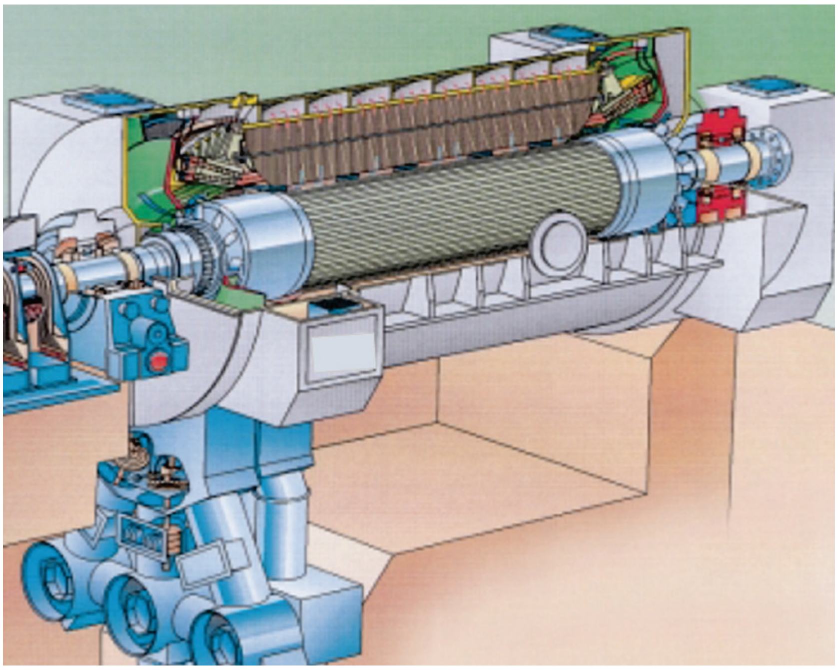


Figure 79. GTD generator all water-cooled [1]

7.2.2 Identifying potential parts for malfunctions with impact on operation

Normal vibration levels for end-windings are about 10 mm/s, with maximum levels of about 15 mm/s. The end-winding basket will most probably be sustainable, based on the design with through-going screws and with the ovalisation mode below the excitation. Changes in the structure stiffness will most probably not be global, but even individual changes can develop to potential scenarios with an impact on the operation ability. Eight areas are identified as possible places where such an event have the potential to occur and they are shown in figure 81 and described on next page.

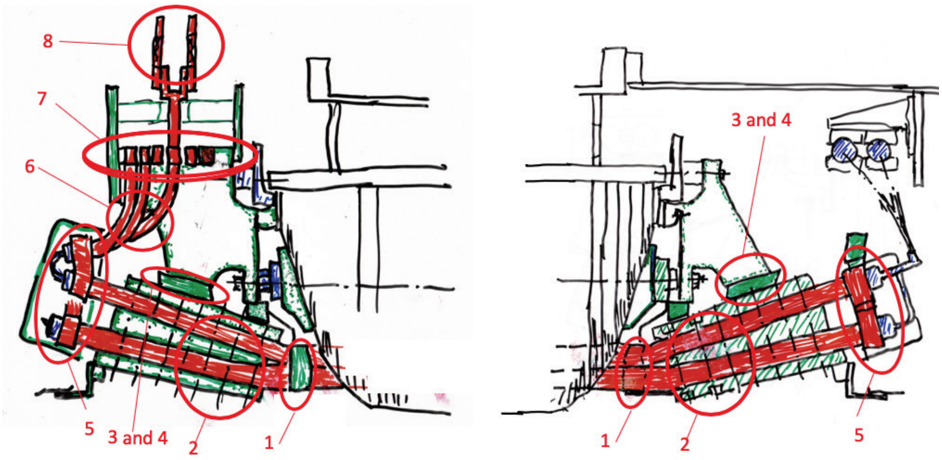


Figure 80. Probable places where problem events can occur

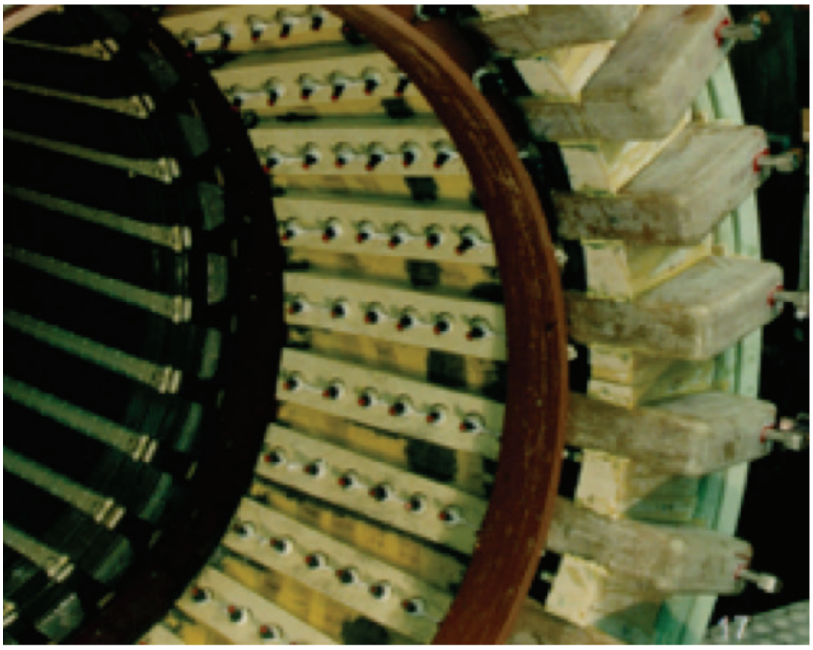


Figure 81. End winding

The eight are:

1. Bracing between bars just outside core ends
   The probability for destruction is low, but even a single failure can result in the destruction of the end corona protection. Requires a visual inspection.

2. Bracing structure for the end-winding baskets
   Will most probably not be changed even after a short circuit scenario.

3. Connections between outer support beams and solid ring
   This is a prestressed connection essential to keep the structure solid. Should be periodically inspected.

4. Gap between solid ring and short circuit supports
   Closing the gap will result in a partially increased stiffness, which most probably will increase the vibration level. A growing gap will increase stresses in a short circuit scenario. The vibration monitor will catch such an event.

5. Bracing blocks between knuckles
   Perhaps this is the trickiest part of the bracing structure where the solid couplings between the knuckles mostly are related to gluing joints between these parts. The ambition to build in some number of prestresses is not easy to achieve. One can therefore expect more or less cracks between these elements. Changes will be seen in vibration monitoring.

6. Connections between end-winding and round connections
   All these connections are more and less solid copper leads which are then fitted to the geometry of the round connections. Each one is fixed with supports to avoid local resonance frequencies. The required mechanical conditions are mainly based on glued connection joints, with a small part of prestress forces. Forces from thermal and mechanical cycling may impact on these fixing connections, which can result in cracks and will be a starting point for vibration fretting wear. This can develop to severe disturbances of the operation. Most probably the vibration monitoring will catch such an event as local trend changes.

7. Round connections
   The round connections consist of leads built of copper strands, similar to the stator bars. All phase and inter connection leads are built together with glued and partly prestressed connection joints to realize the required stiffness and natural frequencies. Forces from mechanical and thermal cycling may influence this joint to be a starting point for vibration fretting. Such defects will be detected as small trend changes in vibration monitoring.

8. Flexible connection leads between RC and bus bar connections
   These connections are designed to take care of vibrations and relative movements between connections from round connections and the bus bar connections. Each connection from the round connection is formed and

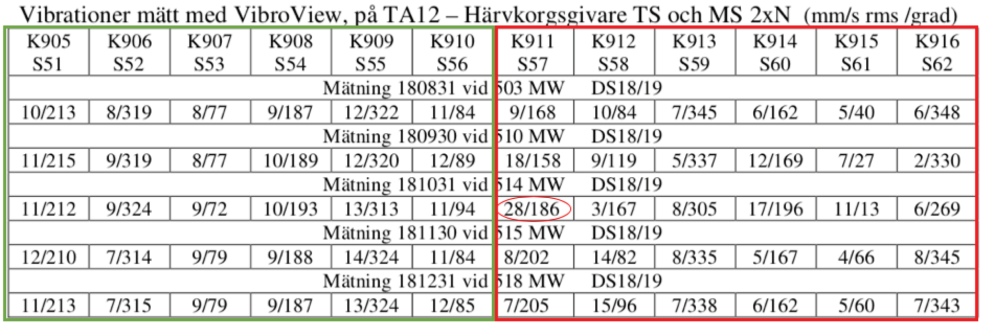
supported to get the right mechanical and natural frequencies. The sustainability for these support joints relies on glues and some prestress forces. Thermal and mechanical cycling may have an impact and make the starting condition for cracks and vibration fretting. Such changes can result in growing vibrations which are able to cause fatigue cracking of the flexible leads. Such defects will be detected as small trend changes in vibration monitoring.

Other parts can also have failure scenarios, but they are already described in chapter 5.

7.2.3 Case study: Changed vibrations in Forsmark TA 12

Case from Forsmark with changed end-winding vibrations.
Figure 83 shows a table with vibration trends for the end-windings. Sensor K911 shows three times higher vibrations in a time frame of about two months, but even sensors K914 and K915 have significant changes, though vibrations at DE are stable. It was decided to stop the unit for inspection and be prepared for any necessary reconditioning. The root cause for the changed vibrations was cracks and fretting wear in the bracing details between the knuckles (end caps). All the cracks were injected with epoxy molds through a drilled hole in the crack. The result of the corrections can be seen in the table (see figure 83). The levels are close to the same amount as before the changes started.

One comment on the trend measurement is that it will be easier and more powerful to use continuous readings. Nevertheless, the reconditioning was made in an early stage and limited reconditioning work was quite easy to do. A good example of the power of vibration monitoring is shown in figure 88.



Vibrationer mätt med VibroView, på TA12 – Härvkorgsgivare TS och MS 2xN (mm/s rms /grad)

K905 S51	K906 S52	K907 S53	K908 S54	K909 S55	K910 S56	K911 S57	K912 S58	K913 S59	K914 S60	K915 S61	K916 S62
Mätning 180831 vid 503 MW DS18/19											
10/213	8/319	8/77	9/187	12/322	11/84	9/168	10/84	7/345	6/162	5/40	6/348
Mätning 180930 vid 510 MW DS18/19											
11/215	9/319	8/77	10/189	12/320	12/89	18/158	9/119	5/337	12/169	7/27	2/330
Mätning 181031 vid 514 MW DS18/19											
11/212	9/324	9/72	10/193	13/313	11/94	28/186	3/167	8/305	17/196	11/13	6/269
Mätning 181130 vid 515 MW DS18/19											
12/210	7/314	9/79	9/188	14/324	11/84	8/202	14/82	8/335	5/167	4/66	8/345
Mätning 181231 vid 518 MW DS18/19											
11/213	7/315	9/79	9/187	13/324	12/85	7/205	15/96	7/338	6/162	5/60	7/343

Figure 82. End-winding vibration trend. DE in green square, NDE in red square.

Figure 83. Cracks and fretting powder in bracing outside knuckles

7.2.4 Case study: Changed vibrations in Ringhals G32 and G41

Ringhals unit G32 and G41 with changed end-winding vibrations.
In Ringhals, the stator-vibration trends are checked and analyzed one time per working shift. At the two mentioned units, a change in the vibration was observed at several occasions. For unit G32 the event occurred only 2 months after the commissioning date, 2010. The reason for the change was a loss of all the tuning weights in the end-winding.

The same type of failure-event occurred later in unit G41 in 2017 as for the G32. Secondary damage was created by missing tuning weights, which resulted in fretting wear on the cooler as well was on the water manifolds. The event in G41 was observed as minor increased changes of the end-winding vibrations two years before the opening and identifying the failure event.

Figure 84. Tuning weights after reconditioning

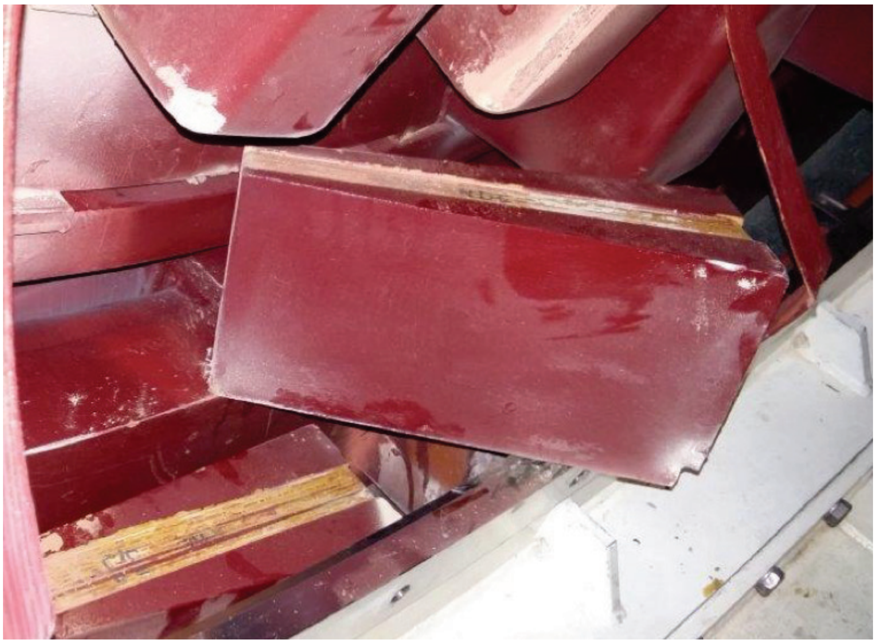


Figure 85. Lost tuning weight

Figure 86. Wear marks on manifold

Mitigation actions have involved maintaining a more sustainable fixation of the tuning weights, but on G32 it was concluded that it was possible to run without any tuning weights in the end-winding. The basis for such a decision was the result from a performed Modal Analyze Bump test.

The use of trend analysis is a powerful tool to identify these types of failures. One conclusion from the G41 case was that a deeper analyze of the monitoring data would have given arguments for an inspection at the planned stop in 2016.

With the deep wear marks on the manifold it was very close to a forced outage of the unit, caused by water leakage from the penetrated wall of the manifold tube.

At analysis, it is important to get answers to all changes of the vibrations. In this case the tuning weight might have acted as a dynamic damper, before it became totally loose?

Currently, three units operate with tuning weights and one without.

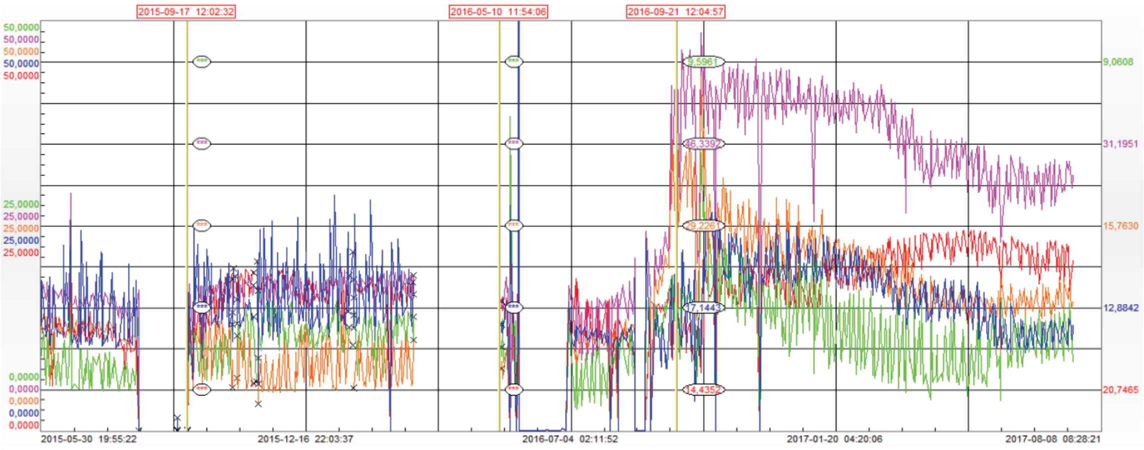


Figure 87. Vibration trends which was the background of the decision

Bending mode vibration in the stator frame /core in unit G42

At the commissioning 2009 of this unit, it was concluded that the radial core vibration, with a magnitude of 17 mm/s, was well above the stipulated requirement and guarantied level of 10 mm/s.

The mode analysis showed that the bending mode for the unit frame and core was close to the resonance frequency. The mode shape was a simple bending mode with the maximum amplitude in horizontal direction in the middle of the stator.

The OEM decided to add tuning weights outside, and in the middle, located on each side of the frame where the lifting lugs are placed. The tuning weights were built up of several numbers, 11 pieces, thick steel plates, which then were screw-joined to each other and to the frame. In total, nine tons were applied to each side of the stator frame, see Figure 89 .

The diagram in Figure 90 shows the impact from at assembling the weights where the number represents the applied weight. The bending mode frequency was moved down and the level of the vibration decreased to be within the guarantied value. The action was unfortunately not long-lasting for long-term operations. The screw joints tend to relax the prestress due to a settlement in the surfaces between the thick plates.

After some unsuccessful trials to increase the long-lasting conditions for fixation of the weights it was decided to remove the weights and operate at slightly higher vibrations.

This is a good example of the variation of dynamic conditions for a generator of the same design. The frame and core for generators in Forsmark F11-F22 and Ringhals G31-G42 are of an identical design, as are the manufacturing documents. Perhaps the largest difference is the manufacturing. The Forsmark stators were manufactured in Västerås and the Ringhals stators in Wroclaw. There is one stators in Forsmark (also manufactured in Wroclaw) with remarks on core vibrations, but also stator G41 in Ringhals is close to the G42 in vibration levels.

Structures made of steel, welded, or with good contact conditions, even for other joints, can be sensitive to small differences of the frequency if the mode forms are close to the 100 Hz excited ones. The reason for this is the very low damping and the transmissibility may be close to the maximum curve (see figure 37).

A similar but much worse case was in Olkiluoto on the stator containment structure. Stator S3, the number 3 with equal designs, started to vibrate during commissioning. Several actions were made to mitigate the vibration conditions, and some made this better though others even worse, see chapter 7.3.3.1 for more details.

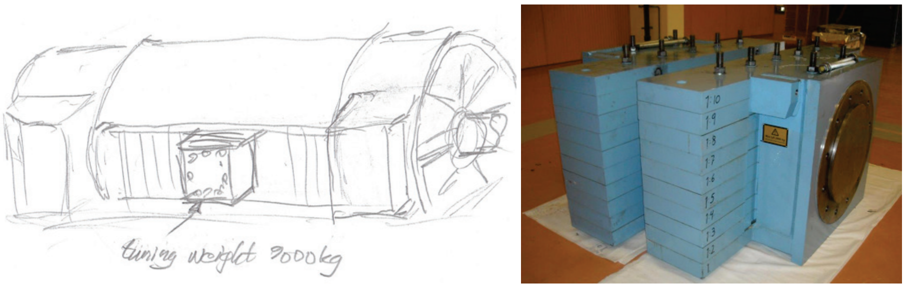


Figure 88. Stator frame with adopted tuning weights. **Tuning weights**

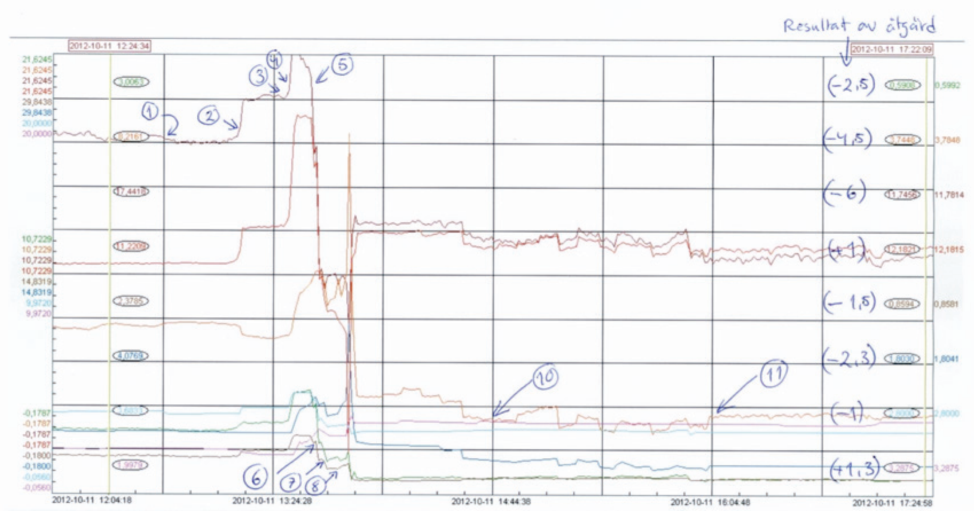


Figure 89. Vibration readings at assembly of the weights

7.3 STUDY OF THE 2-POLE GENERATOR STATORS IN OLKILUOTO 1 & 2

7.3.1 Design concepts for the main stator parts and expected properties'

The generators in Olkiluoto are Alstom type GTD 2-pole generators. Both rotor and stator windings are directly cooled with water. The stator core and rotor body are air-cooled by force and the generator enclosure is open to the atmospheric conditions and pressure. The ordinary stators in Ol1 and 2 are of the latest design, as described in section 7.1 and in figure 78, while the spare stators are of the pre-design, which is close to that in figure 74. The end-winding bracing is of the "resin cone type" (see figure 27) and the end-winding bars are fixed to the cone with use of glass-reinforced screws which are thread-joined to the solid cone (see figure 78).

Each of these screws is prestressed to ensure a long-lasting stable structure.

The natural frequency in radial directions for the 4-node modes in end-windings and round connections will be below the excitation frequency, 100 Hz, created from the magnetic field from the rotor. To sustain a short circuit scenario, an additional stiffer support structure must be in action at the SC, but without any connection at normal operation.

The round connection structure is built together with the end-winding support cone with the aim of dynamically acting together with the end-windings as one structure.

The reason for this design was due to some bad experiences from earlier designs (stator S2.2) where the round connections acted as a dynamic damper. Axial modes in the round connections may be not so far from the excitation frequency. The tilting modes will be below as well as above the excitation frequency, 50 Hz, created by unbalance in the rotor.

The stator is equipped with sensors in the end-windings, round connections as well as in the stator core.

Figure 90. Generator in Olkiluoto 1 and 2

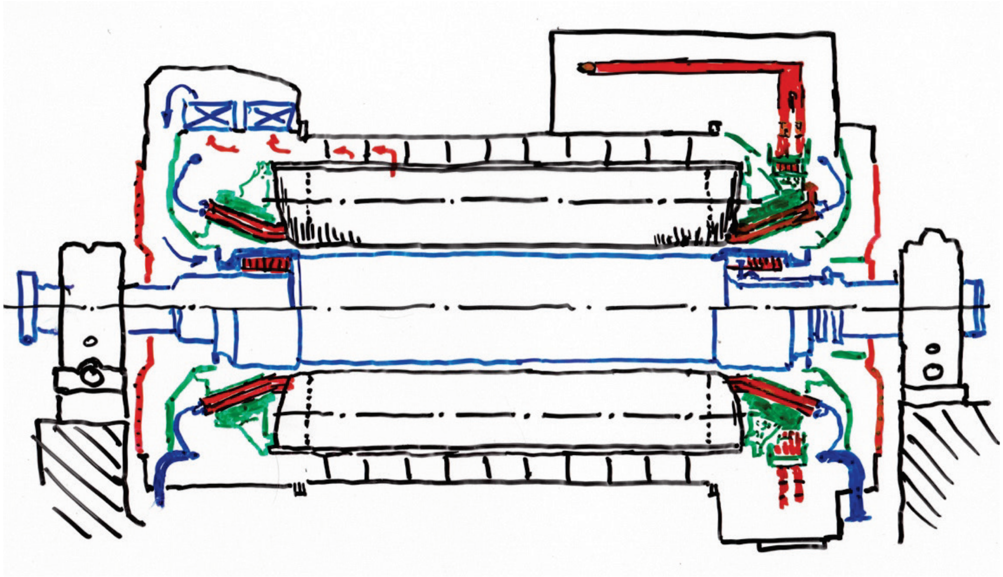


Figure 91. Longitudinal section of the GTD generator for Olkiluoto 1 and 2.

The sensors are applied as follows, (see figure 81):

OL1

6 radial sensors in the end-winding drive end

6 radial sensors in the end-winding non-drive end

6 axial sensors in the round connection

6 radial sensors in the stator core back in packages: 13, 50, 80

6 axial sensors in the stator core back in packages: 13, 80

4 tangential sensors in stator core back in package 9

5 tangential sensors in stator core back in package 84

2 radial sensors in stator frame on package 50

8 sensors in stator cooling tubes

Total amount of sensors:67

OL2

6 radial sensors in the end-winding drive end

6 radial sensors in the end-winding non-drive end

6 axial sensors in the round connection

6 radial sensors in the stator core back in packages: 13, 43, 80

<u>6 axial sensors</u> in the stator core back in packages: 13, 80

<u>8 sensors</u> in stator cooling tubes

Total amount of sensors:56

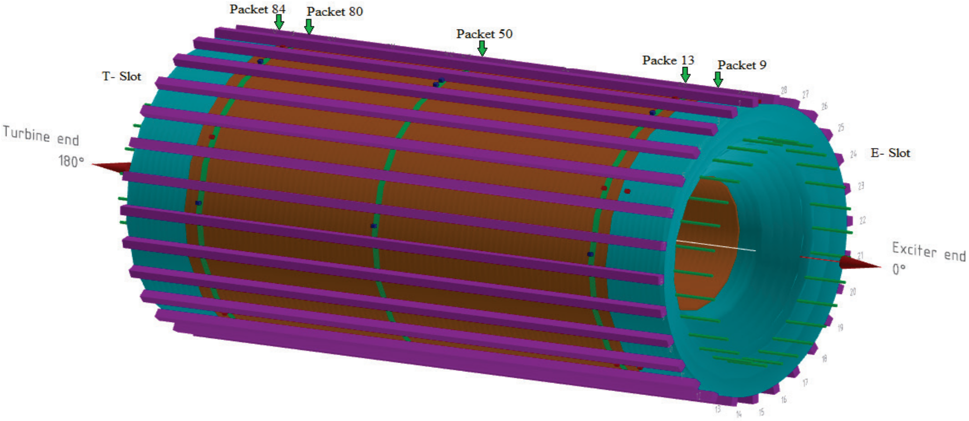


Figure 92. Location of vibration sensors in core back

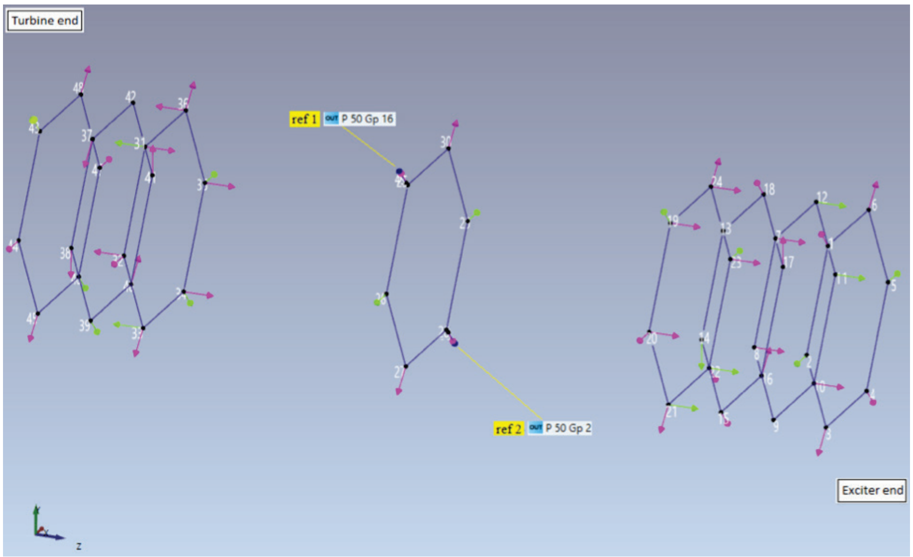


Figure 93. Configuration of vibration sensors

7.3.2 Identifying potential parts for malfunctions with impact on operation

Nine areas are identified as possible places where such events have the potential to occur and which are shown in figure 95 below and described on next page.

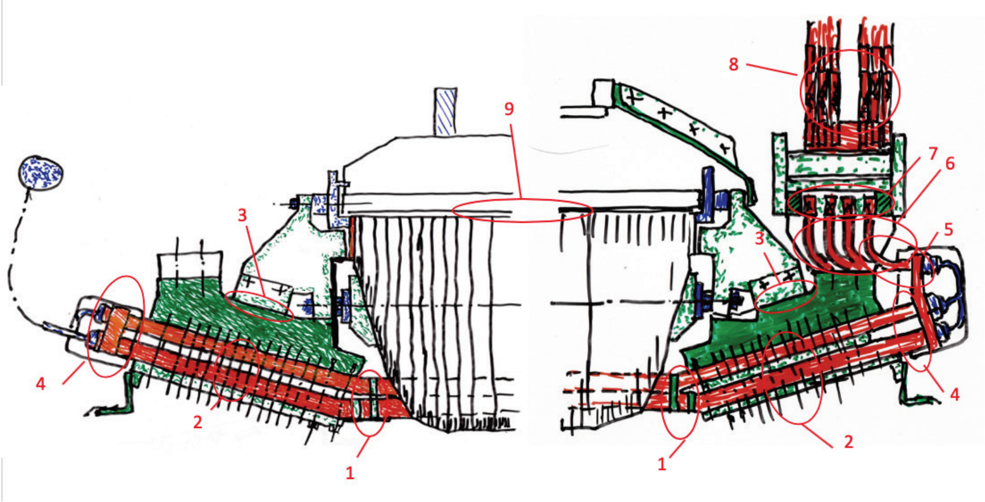


Figure 94. Probable places where problem events can occur

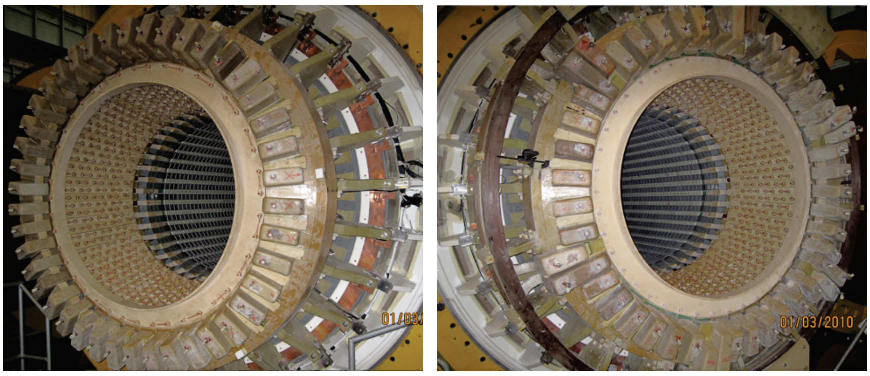


Figure 95. End-windings, left DE, right NDE

The nine areas are:

1. Bracing between bars just outside core ends
   The probability for destruction is low but even a single failure can result in the destruction of the end corona protection. Visual inspection detects such types of defect.

2. Bracing structure for the end-winding baskets
   The glass-reinforced epoxy screws may be the weakest part, and if the prestress forces are relaxed, the solid structure will not be as stiff as it should be to get the required dynamic conditions.
   This type of failure has a very low probability to occur based on the large number of screws, about 700 per end-windings.
   Malfunction of some singular randomly oriented screws will not have any impact on the structure stiffness, and will even sustain a short circuit scenario, without any additional defects.
   To result in a destructive scenario, many screws within a certain area must lose their prestress forces. Such a scenario will be detected with the use of

vibration monitoring, and the other scenarios will be found with visual inspections at planned outages.

3. Gap between solid ring and short circuit supports
   As mentioned earlier, there must be a gap here to produce a solid structure with stated dynamic requirements. The short circuit supports as well in radial direction as in tangential. Closing the gap will result in a partially increased stiffness which most likely will increase the vibration level, and a growing gap will increase stresses in a short circuit scenario. The vibration monitor will catch the event of a closing gap, but it is necessary to inspect the condition of the gaps at planned outages.

4. Bracing blocks between knuckles
   Perhaps this is the trickiest part of the bracing structure where the solid couplings between knuckles mostly are related to gluing joints between these parts. The ambition to build in a level of prestresses will in fact not be easy to realize. One can therefore expect more or less cracks between these elements. Changes will be seen in the vibration monitoring, and easy to see at a visual inspection.

5. Connections between end-winding and round connections
   All these connections are more and less solid copper leads which then are fitted to the geometry of the round connections. Each one is fixed with supports to avoid local resonance frequencies. The required mechanical conditions are mainly based on glued connection joints, with a small part of prestress forces. Forces from thermal and mechanical cycling may impact on these fixating connections, which can result in cracks and will be a starting point to vibration fretting wear. This can develop to severe disturbances of the operation. Most probably the vibration monitoring will catch such an event as local trends change.

6. Connection stud support blocks between the end-winding support cone
   To obtain the required stiffness between the support cone and round connections there are several stud blocks between them. These stud blocks are as well screwed to both of the structures together with two solid insulation rings shrunk up on the stud blocks.
   The details of the design can be seen in figure 94.
   It is essential not to lose these contact conditions which will result in change dynamic conditions and fretting wear in contact surfaces. Such a failure event will be detectable by vibration monitoring.

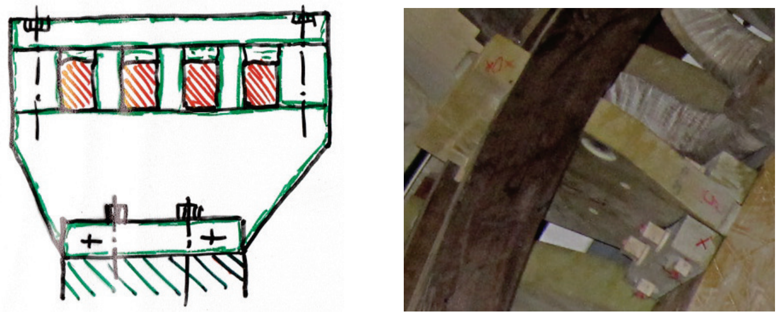


Figure 96. Connection stud support blocks between support cone and round connections

7. Round connections
   Round connections consist of leads built of copper strands, similar to the stator bars. All phase and inter connection leads are built together with glued and partly prestressed connection joints to realize the required stiffness and natural frequencies. Forces from mechanical and thermal cycling may influence this joint to be a starting point for vibration fretting (see figure 52), which is an event from an Olkiluoto generator. Such defects will be detected as small trend changes in vibration monitoring. Visual inspections will easily catch this failure.

8. Flexible connection leads between RC and bus bar connections
   These connections are designed to take care of vibration and relative movements between connections from round connections and the bus bar connections. Each connection from the round connection is formed and supported to achieve the right mechanical and natural frequencies. The sustainability for these support joints relies on glues and some prestress forces. Thermal and mechanical cycling may impact and make the starting condition for cracks and vibration fretting. Such changes can result in growing vibrations able to cause fatigue cracking of the flexible leads, which will be detected as small trend changes in vibration monitoring.

9. Core back
   The reason to identify this area as a possible failure event region is the missed core back pressure in the stacking procedure. The most inhomogeneous end of the core is where the stacking procedure was finalized. Stators S4 and S5 have the inhomogeneity end in NDE and DE, respectively, depending on the different start ends in stacking (see figure 98). Mitigation activities were implemented to produce a more solid core back, but the sustainability will most probably be limited in time. Relaxation of the core back pressure can either create axial vibrations in the core with a risk for fret wearing between core and building bars which will result in degeneration of the prestress forces between core and frame. Such changes will most probably impact on the core vibrations, but the degeneration of the solidity in the core can perhaps even create an impact on the natural frequency for the pringle mode shape in the core ends. If this mode shape comes close to resonance, it will impact on the end-winding vibration, especially on the NDE with an axial mode shape in the round connections close to 100 Hz.

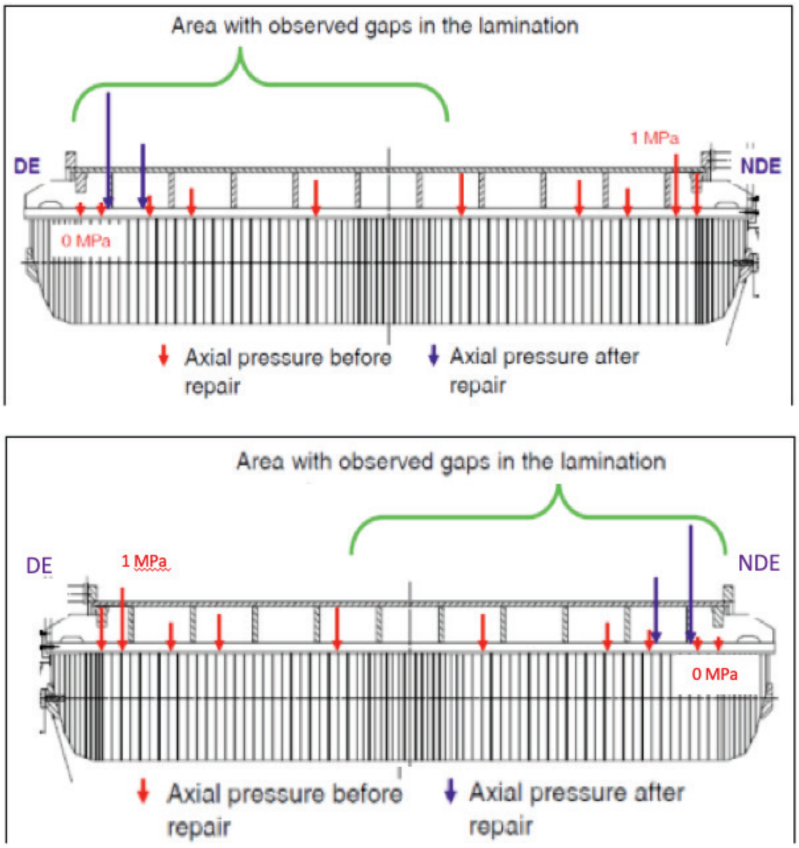


Figure 97. Cores for stator S4 and S5.

Other parts can also have failure scenarios, but they are already described in chapter 5.

7.3.3 Case Study: Historical vibration case in the old stator S3

Following the commissioning of the new stator S3 it was concluded that there were high vibrations, especially at the end cover at NDE. The vibration resulted in cracks in the end cover and in the cabinet within the connection to the busbars. Even the manifold connections received cracks and water leakage. To stop the development of the fatigue cracks, stop holes were drilled and tuning weights were mounted in the compartment gables and on the connection tubing. OEM made several investigations and an analysis to obtain better knowledge in order to understand why this stator had such a bad dynamic behavior. In essence, this stator was a copy of the two first and only some improvements have been implemented on end-windings and the end cover; the stator frame was manufactured in Portugal rather than in Västerås.

Several hypotheses were created together with extensive work for examination and validation, performed by the OEM as well as expertise from Olkiluoto.

The emergency solution to make the stator useable was to adopt tuning weights on the stator, shelves, see figure 96. The work continued for more than two years and a lot of trials were implemented to mitigate the dynamic conditions. One most comprehensive of these was to remove a pivot stop for the core which was inside the containment, while another was to release the end cover from the stator frame. Unfortunately, none of those resulted in the anticipated success; the released cover even created additional cracks in the frame structure. The final action was to add masses to the stator frame which was supported by the earlier actions and an extraordinary modal analysis where the impact nocks were done with the help of a 4 meter long rail way beam.

This case is a good example that even small deviations can result in a really complicated condition. The other learning point is the ability to perform a usable modal analysis on heavy structures. Perhaps the use of Operational Modal Analysis would have been an efficient tool if it had been available at that time.

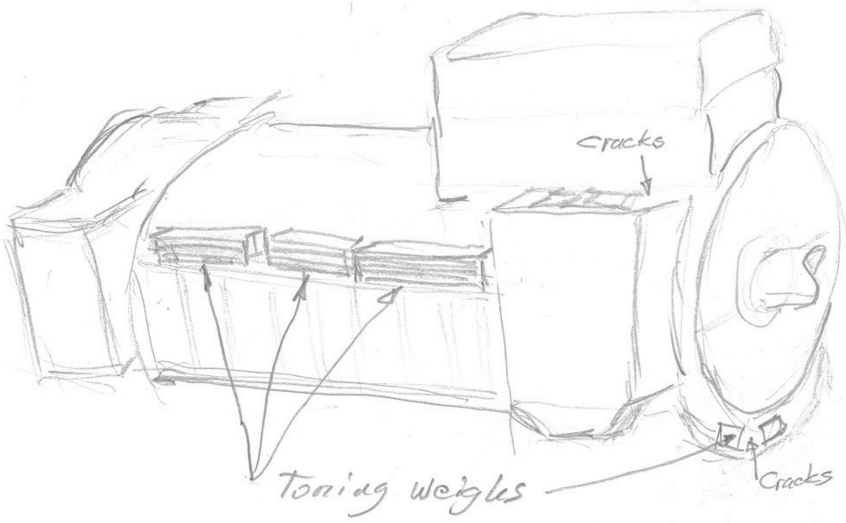


Figure 98. Stator S3 with emergency tuning weights

7.3.4 Case Study: Changed vibrations in Stator S4 2018-2019

1. Change of vibrations in stator S4

a. Findings from vibration reports

The location of vibration sensors is shown in figure 93. One thing that should be noted is that packet 9 and packet 84 are located at respective laminate press plates of the turbine end and exciter end. The laminated press plates, seen in blue are consolidated using a VPI process before stacking the core.

Changes in vibration have been seen on several sensors located at the exciter end of the generator. A load change (perhaps due to a valve test) was done on January 25th, 2019 and changes can be seen since then; see the following pictures from the vibration report, where the trend graphs shows vibrations recorded between Oct 7, 2018 until Feb 28, 2019.

What can be seen is that some vibrations have increased, especially R slot 13, from ~2 to 14 mm/s, and some have decreased a little bit, such as E slot 06. However, what can also be seen is that since the end of January 2019 the vibrations are fluctuating on several sensors, which is clearly notable.

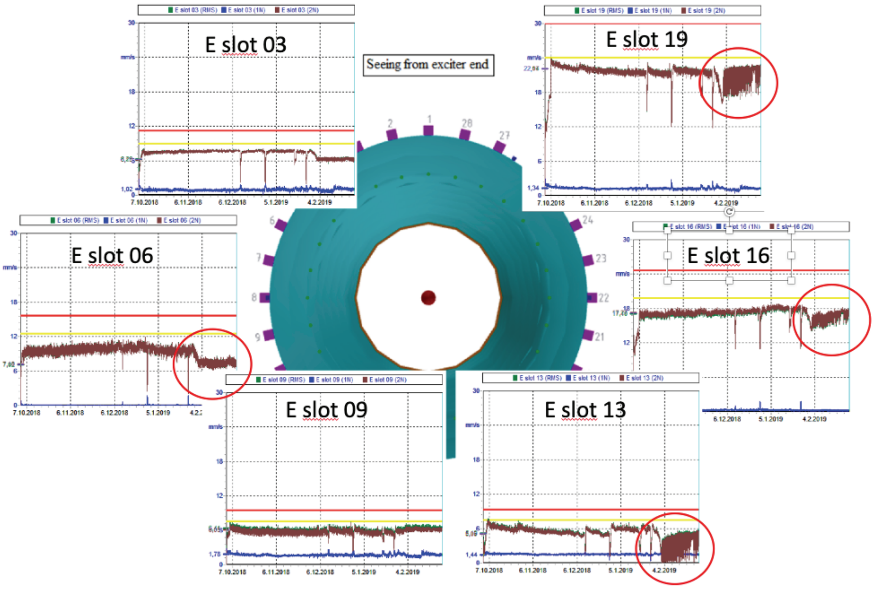


Figure 99.Exciter end-winding vibrations. Changes after load change are noted in red circles.

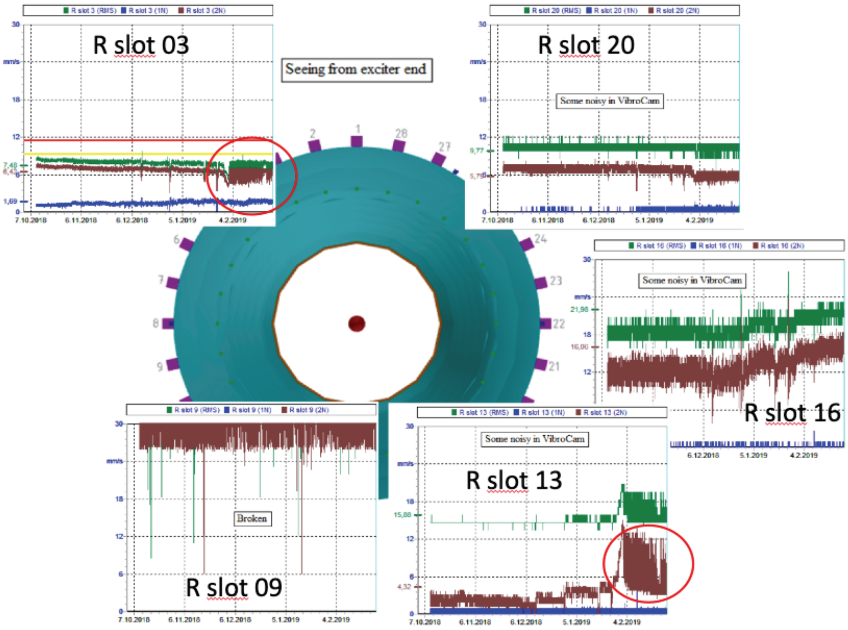


Figure 100. Round connection vibrations in axial direction (exciter end). Changes after load change are noted in red circles.

The sensors at the core also show the changes where, for example, P13 Gb 1-2 Ax has an increased vibration level from ~20 mm/s to ~25 mm/s since the end of

January 2019. It can also be seen there, and on other sensors as well, that the fluctuation has increased.

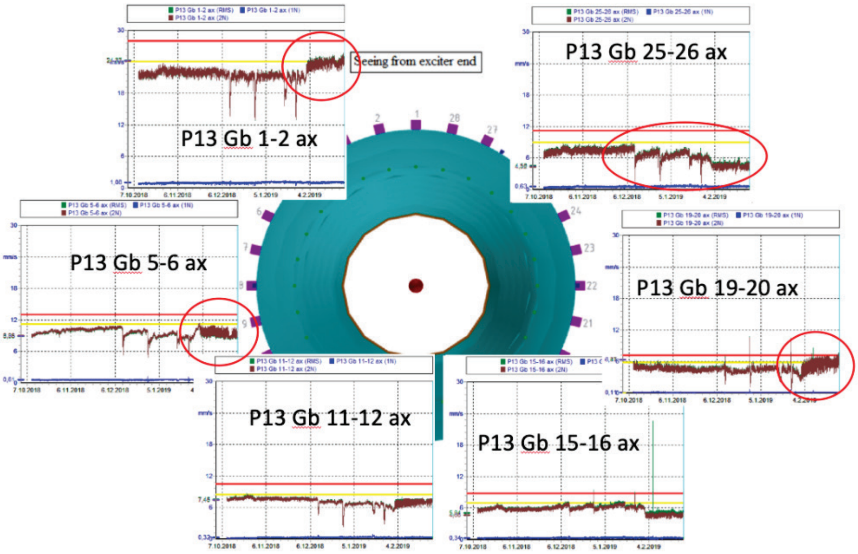


Figure 101.Axial vibrations of the core at packet 13, exciter end.

Changes in vibration and increased fluctuation can even be seen at the other end of the generator, on sensors located on the turbine end of the core.

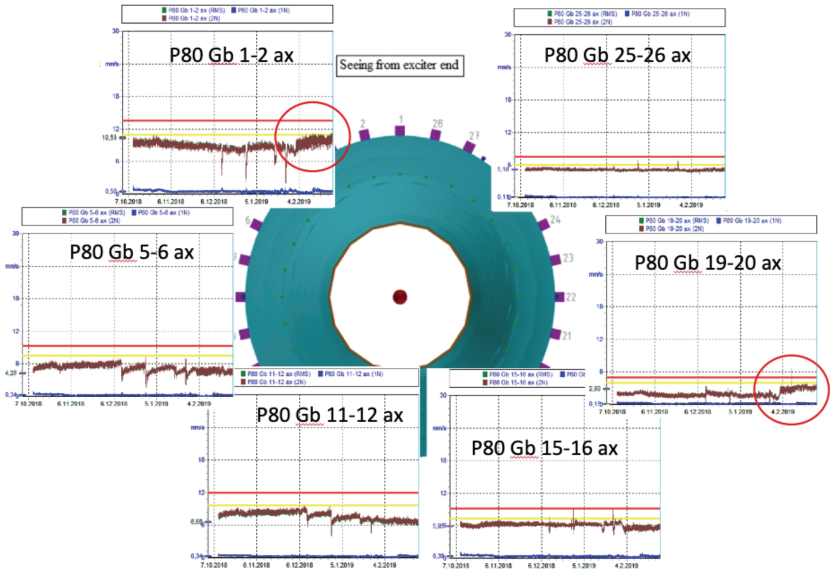


Figure 102.Axial vibrations of the core at packet 80, turbine end

All these changes in vibrations, as shown in figures 100 – 103, indicate that something has happened. Most changes are on the exciter end of the generator, but the vibration changes also show that whatever has happened is significant enough to be seen on vibration sensors at the other end of the generator.

2. *Analysis of findings*

a. *Notes from the history of stator S4.*

Before the stator was installed, it was discovered that stacking the core was not done correctly when manufactured. In 2012, work was done on the stator in the Olikluoto warehouse to improve the core pressure. Compensation was made on the DE/Turbine side at first packages only. After the start-up and some running of the generator with the S4 stator, the axial vibration levels were between 4 – 12 mm/s at DE package 80, and 7 – 10 mm/s at NDE package 13. These levels were recorded in the end of 2013. For the future evaluation of axial core vibrations, the following risk levels were estimated:

1. Base Risk <18 mm/s
2. Increased risk 18 – 25 mm/s
3. Medium high risk 25 – 50 mm/s
4. High risk >50 mm/s

Potential root causes and actions, depending on risk level, are coupled to the different risk levels.

Another note from the history of stator S4 that is worth pointing out is that cracks in the NDE end-winding supports between caps were discovered at the outage in 2013. In addition, supports at round connections were loose or cracked. All of this was corrected, but without a definition of the root cause.

3. *Potential causes for change in vibration and risk evaluation*

The findings show vibration changes in axial direction in the core and round connections. The end-winding vibration at the exciter end is measured perpendicularly to the support cone, so there is an axial as well as radial component. At this stage only, a hypothesis can be given until further inspections have been made.

a. *Potential root cause: changed core back pressure.*

One can expect that some settlement would follow the consolidation in 2012, before the stator was installed. The measured core pressure at that time is given in figure 86. If this settlement has occurred, or if, for instance, inserted wedges have come loose, it can well explain the changes in vibrations on the core. To find out more, a longer time trend is necessary.

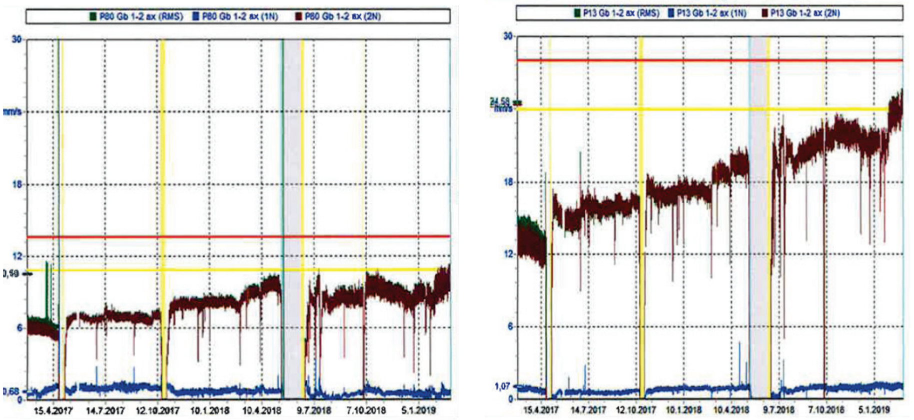


Figure 103. Three-year axial vibration trend at packet 80 and packet 13. Observe the vibration increase from 6 to 10 mm/s at packet 80 (DE) and 11 to 25 mm/s at packet 13 (NDE).

Over this three-year period, clear changes can be observed. In accordance with defined risk levels, the axial vibrations of the core now move from level 2 into level 3. Although it is only one sensor that has this high vibration, the recommendations must be to make inspections of the core back at both ends-

b. Potential root cause: changes at end-winding and round connections, exciter end

Cracks were found in this area in 2013. It can well be that new cracks have occurred in the same places or in new places. This could explain changes in these vibrations. The root cause can be from the manufacturing of the stator, but it can also be a consequence if the core vibrations increase that this effects the end-windings as well. For this, it is recommend to visually inspect end-winding supports between the caps and the supports in the round connections.

c. Another potential root cause: contact between end-winding basket and short circuit support brackets.

Such contact or coupling gives a stiffer "basket" with natural frequencies closer to 100 Hz than the design was intended to be (70 Hz). This was discovered by an impact test and a visual inspection of stator S5 at OL2 at the planned outage in 2013. At this inspection there were even observed cracks and wearing in the support blocking between the end caps. There is a strong recommendation to inspect that there is a clearance between the short circuit supports and the end-winding basket.

d. Another potential root cause: for the vibrations in NDE winding and round connection can be loose tuning weights at the terminals

Tuning weights at the terminals have come loose, or perhaps fixation of conductors for the phase connection flags has been degenerated. If either one of these components has come loose, it can affect vibration levels locally, but most likely not globally. Therefore, it is recommended to inspect the round connection close to the S1 flag, to find any imperfections in the structure. Additionally, the braids on the S1 flag must be inspected to see signs of wearing of the threads in the braids

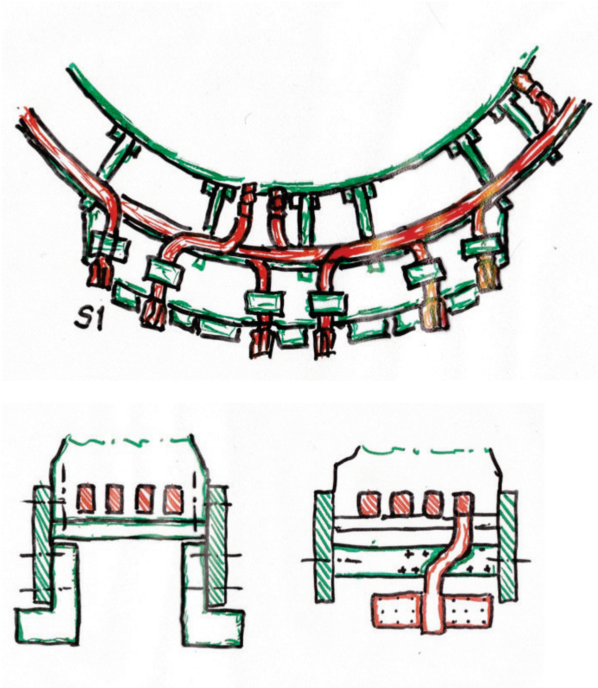


Figure 104. Connections to the bus bar

4. Conclusions

The analysis of the data shows that there have been changes in vibrations on the core in an axial direction, as well as at the end round connections on the phase side (S1). Some of these changes have been occurring for at least three years and some can be resent and observed after a load change in January 2019.

The conclusion is that the changes in vibration are real and most likely due to changes in the stator as well. The potential root cause can be a loosening of the core back pressure and potentially a loosening of support in the round connection structure. There could be other root causes as well. For all these observed changes of vibration the risk classification is on the way to a red level.

5. Recommendations

The recommendation is that the core back pressure at both ends of the stator should be checked, i.e. visually inspected as well as by measuring the pressure using pressure tubes in the ventilation channels. To access these areas, all four inner coolers must be removed (see picture below). The area of the vibration sensors closest to the laminated press plate (packets 80 and 13) are easily accessible when the coolers have been removed. In addition, areas further towards the middle are accessible through ventilation holes in the frame.

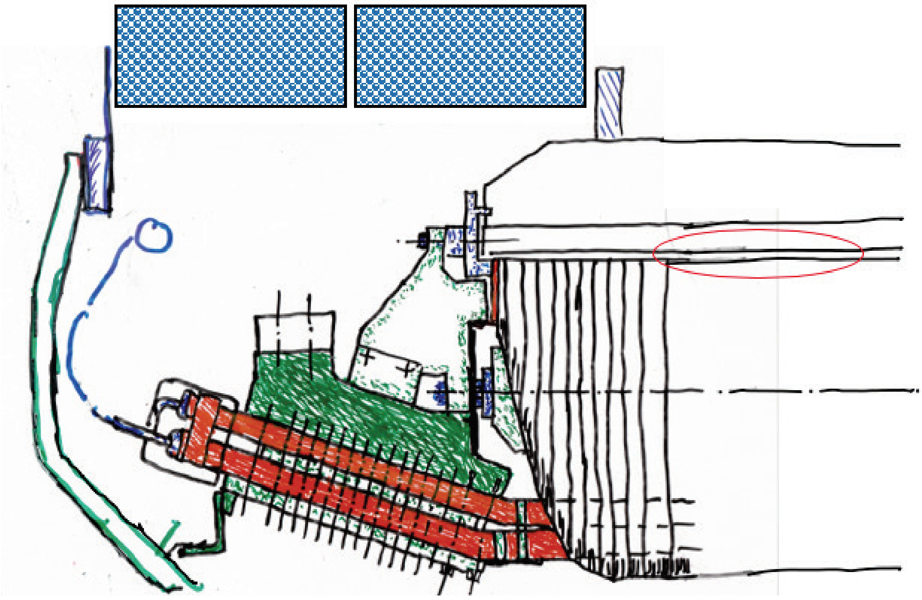


Figure 105. End winding on DE

It is also recommended that a visual inspection is conducted of round connections with the focus on the area around the S1 connection, but it is also important to inspect the end-winding in this area (see figure below). The aim of such is to find evidence for looseness or cracks.

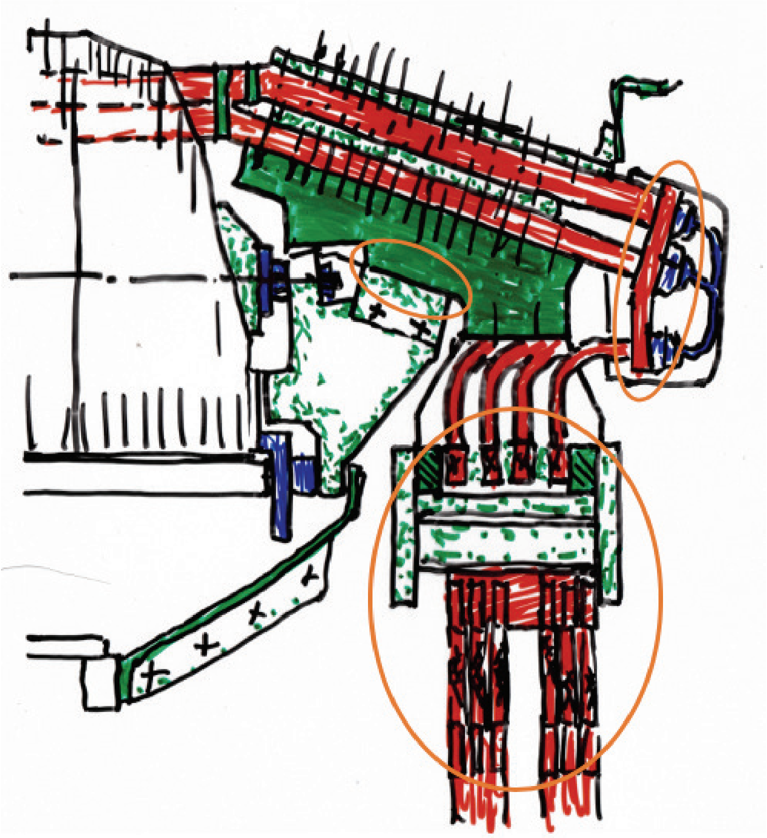


Figure 106. Critical areas

Depending on the outcome of these inspections, there can be several actions to restore the condition of the stator core. For the round connection, it is recommended to prepare the reconditioning of cracks in the bracing area and enable a complete change of the braids for the S1 flag. If the braids are partly damaged by vibration wear, it's necessary to make a decontamination or cleaning of copper dust and pieces of broken braid threads.

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

8.1 MANAGE VIBRATION READINGS/TROUBLE SHOOTING

Monitor the vibrations in stator, end-windings, round connections and the core will provide good opportunities to obtain an early indication of changes in these structures. It will even be possible to see how different load and thermal conditions influence the vibrations. There will be an essential difference between vibrations and vibration behavior in a 4-pole generator compared to a 2-pole one, where the 4-pole produces low and stable vibrations due to the great span between excitation and natural frequencies.

Vibrations from the 2-pole generator are more sensitive for everything which may impact on the stiffness condition and so even for any variation of the excitation conditions. The reason for this is the much closer span between excitation and natural frequencies.

Nevertheless, 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 therefore essential to combine vibration monitoring with visual inspections at planned outages. Even small changes in vibration readings can be a severe failure developing. Readings from a 2-pole generator will be more animated, but even here a more “concealed” failure can occur. Nevertheless, there will be more data to evaluate and make decisions from.

A common goal for monitoring stator vibrations is to avoid disturbances of the operation, which for a large unit is related to large income losses. Normally the vibration readings are used as a condition information with some form of alert alarm for abnormal changes. It is very rare connect high stator vibration signal to an automatic trip of the unit, causing a forced outage. How to form the alert alarm may be related to historical experiences or based on OEM information.

Nevertheless, the analysis work will at least start after passing the alarm level, or even unexpected changes to a lower vibration level can be a sign of a developing failure event. With more reading points in the structure such scenarios may be easy to observe and identify.

To realize high quality data for decision making, the analysis work may include the following 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.

For the vibration data and correlating data for optimal analysis, the vibration data shall consist of:

- Type of vibration gauges and sensitivity
- Location and direction of all vibration gauges
- All over unfiltered signal
- 1 x n with phase angle
- 2 x f with phase angle
- Time stamped
- Active load
- Reactive load
- Voltage
- Temperature in stator winding
- Temperature in cooling air/gas

Added to this, is an all over view of the whole stator design and the running mode for the end-windings and round connections (below or over critical frequencies) from OEM recommended long-term and maximum allowable vibration levels.

8.1.1 Influences evaluation of monitor readings

Assume that some of the reading points of the monitoring survey show increased vibrations above the alert level. This will then be a starting point for evaluation and analysis work.

1. **Confirmation that readings is generated by vibration in the stator structure.**
   What is the dominate frequency range for the signal: Unfiltered, 1 x n/ 1 x f, or 2 x f, where f stands for the frequency of the net/grid.

   A major content of 1 x f may depend on the malfunction of the screening of the signal cable. Beware if a single gauge shows a high content of 1 x f.

   If the content of the unfiltered signal is dominant, it can be a sign that the fixation of the gauge has been broken and the gauge becomes loose; even gauge failure can generate such a signal. Nevertheless, a study of the frequency content in the unfiltered signal will confirm the true condition.

2. **Form hypotheses and identify how to confirm or reject these**
   When the readings are confirmed to be true, the next step will be to use the data to get a picture of how the structure vibrates, the mode form.

   - Is the vibration "global" to the whole end-winding?

   - Or strict local?

   - How is the interaction between the end-winding and round connection?

   - How is the interaction between the axial vibrations in core ends?

   - Are there any changes of vibrations in frame and/or core?

   Use of a software tool to animate the mode forms together with a good view of the stator structure will be powerful in the process to identify a probable hypothesis. Normally there will be more than one probable hypothesis and it is necessary to identify actions for confirmation or rejection. Such actions can be, for example:
   - change of excitation level
   - change of temperature in winding
   - change of temperature in cooling air or gas
   - small variation of the grid frequency, which may in some cases produce usable information

3. **Evaluation of most probable hypothesis**
   With the help of the additional information from actions to confirm or reject the hypothesis, there may be the possibility to identify the most possible hypothesis. In cases where the level of uncertainty is still too high, use of the Operation Modal Analysis tool may present additional information which can reduce the uncertainty.

4. **Analysis of the most probable impact and ranking of the risk level to impact on the production availability.**
   If a red level is identified, then that means an emergency case. The decision will not be a part of this study, but it is necessary to deliver a risk analysis which is as good as possible and to that the most possible failure scenario, together with reconditioning actions and time. For that, it is necessary to have competence of turbo generator design together with relevant information of the detailed design of the complete stator.

8.1.2 Reconditioning and mitigation actions

If severe faults occur, such as fatigue cracking of bars or connection leads, the damaged parts have to be replaced. The worst scenario is delamination of main insulation in the slot exit of the core. This will result in a complete rewind of the stator.

However, the main parts of the failures will be related to destruction of the solid end-winding structure. This can depend on badly fitted bracing blocks, too much fitting felt, or non-cured epoxy. However, even missed prestressing conditions in details require that to get the expected stiffness condition. Such elements include rings or screws, see Figure 77.

For end-windings designed to run with critical modes below main excitation frequency, if noncontact zones change to be in contact, the result can be that the structure comes close to resonance. These cases with changed contact condition must be reconditioned to produce the original clearances which most probably need some type of machining activities.

The first step in the reconditioning or mitigation actions is to inspect and document the failed details or structure, together with a bump test to get a view of the natural frequencies. The next step will be to decide how to recondition the structure. Minor cracks can be injected with an epoxy mass to restore the required contact conditions. Most probably the end-winding structure will be weaker after reconditioning which will create a lower eigenfrequency. For an end-winding intended to run with the critical modes above the main excitation frequency, this can result in a resonance condition of the end-winding. Based on experience, it is always hard to build a stiff structure, but with use of tuning weights it can be possible to get lower eigenfrequencies fitted to be below the excitation frequency.

Making a bump test after the reconditioning or mitigation actions will produce information about the mode forms and frequencies, but it is necessary to use the optimal excitation forces to not overestimate the stiffness.

One key element in the analysis of a bump test is to review the obtained mode forms in combination with the excitation forces that are acting during operation. The mode forms that cannot be excited during operation should not be considered in the evaluation.

8.1.3 CMA, Classic Modal Analysis "Bump test"

The bump test is an efficient tool to check the dynamic condition before and after reconditioning actions, but one must keep in mind that un-linearity stiffness and temperature dependent conditions must be taken into account at the final analysis. There are several companies that are more or less competent to make an analysis on Turbo Generators.

Modal testing is the form of vibration testing of an object whereby the natural (modal) frequencies, modal masses, modal damping ratios and mode shapes of the object under test are determined. A modal test consists of an acquisition phase and an analysis phase. The complete process is often referred to as a Modal Analysis or Experimental Modal Analysis.

There are several ways to do modal testing, but impact hammer testing, a so-called "BumpTest", is nowadays a commonly used method for the testing of stator end-windings, core, and even the complete stator structure. In the past, use of shaker testing was more common. In both cases energy is supplied to the system with a known frequency content. Where structural resonances occur, there will be an amplification of the response, clearly seen in the response spectra. Using the response spectra and force spectra, a transfer function can be obtained. The transfer function (or frequency response function [FRF]) is often curve fitted to estimate the modal parameters. However, there are many methods of modal parameter estimation and it is the topic of much research.

An ideal impact to a structure is a perfect impulse, which has an infinitely small duration, causing a constant amplitude in the frequency domain; this would result in all modes of vibration being excited with equal energy. The impact hammer test is designed to replicate this; however, in reality a hammer strike cannot last for an infinitely small duration, but has a known contact time. The duration of the contact time directly influences the frequency content of the force, with a larger contact time causing a smaller range of bandwidth. A load cell is attached to the end of the hammer to record the force. Impact hammer testing is ideal for small light-weight structures; however as the size of the structure increases, issues can occur due to a poor signal to noise ratio.

8.1.4 OMA, Operational Modal Analysis

Ambient modal identification, also known as Operational Modal Analysis (OMA), aims at identifying the modal properties of a structure based on vibration data collected when the structure is under its operating conditions, i.e., no initial excitation or known artificial excitation. The modal properties of a structure include primarily the natural frequencies, damping ratios and mode shapes. In an ambient vibration test the subject structure can be under a variety of excitation sources which are not measured but are assumed to be 'broadband random'. The latter is a notion that one needs to apply when developing an ambient identification method. The specific assumptions vary from one method to another. Regardless of the method used, however, proper modal identification requires that the spectral characteristics of the measured response reflect the properties of the modes rather than those of the excitation.

The question is if this method can be useful on large Turbo-Generators and without getting into a deep discussion of the method this seems to be possible. Testing on large Turbo Generators have proven that it is possible to estimate the modal parameters, even if the harmonic component was placed in the vicinity of the mode. For some amplitudes of the harmonics, the detection was not properly indicated. Nevertheless, it was easy to obtain a visual view of the harmonics.

The conclusion is that OMA can be a powerful tool for trouble-shooting vibrations in a Turbo Generator stator, especially in heavy structures and structures with unilinear stiffness and damping conditions, which can variate with the operating temperature and degree of deflection or deformation. To acquire a deeper view of OMA for large rotating machines see the report in [5]

Advantages with OMA:

- The degree of excitation is on the true level, which can produce quite a different answer than from a common bump test (CMA Classic Modal Analysis), as in the case with the old stator S3 in Olkiluoto. Most probably the way to find the solution should become easier and much faster.
- Simplified measurement when the generator can be in operation.
- Most probably, troubleshooting will be faster and more adequate. Without the need to interrupt production for the test and better data for decision making it has the potential to save money.
- As previously mentioned, the operation conditions will prove the results for the modal analysis.

Disadvantages with OMA:

- Need for specialized hardware and software for these measurements and analysis
- Specific competence to manage the OMA analysis.
- Eigen modes very close to main excitation frequency can be difficult to identify due to the presence of the core ovalization by the magnetic field.

9 Experiences from other plants

Contents in paper [7] to [14] provide a good view of Turbo-generator stator problems in other plants with some focus on the US-Canada market. One can conclude that most of the described events are related to new gas turbine plants with mostly air-cooled generators.

In [3] it is mentioned that end-winding failures are the largest cost for insurance companies, due to the repair time and loss of production. However, several failures occur also in the winding slots, either related to vibrations or improper condition or wrong requirements on the corona protection system. In addition, it is remarkable to see figure 2 in [11] which gives a surprising view of high PD levels for 9 manufacturers versus the year of the stator's manufacture.

Several of the papers are quite comprehensive of 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. One paper [14], shows the temperature impact on the end-winding modes.

Altogether those papers provide comparable information with this paper for Energiforsk, with one exclusion, which is the focus on Partial Discharge. Paper [13] can be especially interesting to the Alstom fleet owner due to the problems described and the root cause investigation for a winding with the slot fittings with the use of the Round-packing concept. The generator in the article is most probably of the GTL type delivered from Alstom in Västerås. The contents in [8] and [12] provide a good overview of different types of failures and repairs.

Paper [6] provides a good summary of permitted levels for end-winding vibrations, and even mention of excitation and dynamic.

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	

9.1 USEFUL ARTICLES MADE BY EPRI

The abstracts below give an impression of useful articles to acquire knowledge from other users or operators of turbo generators. The full article can be obtained with some form of EPRI membership.

Generator Stator End-winding Vibration Guide: Tutorial

Electric generators have not changed much since their invention and yet today are being pushed to their limits in step with the rest of the plant equipment.
As a result, depending on the design applications, the industry has experienced and continues to experience problems with various components of the generator, particularly the stator and stator windings. These are the subject of this tutorial. Such problems can be prevented and corrective action taken only with a proper understanding of the machine designs and the phenomena that affect them under both normal and abnormal conditions throughout the life of the machine.

This guide documents applicable electric generator principles so that the reader—presumably an owner or operator of one or more generators—can have a useful tool to make proper decisions for his or her equipment. The report describes the design of the machine, the forces, trends and problems, and the steps necessary to prevent or solve those problems.
The following topics are covered: recommended maintenance and monitoring of operating parameters, stator construction, vibration phenomena, thermal phenomena, failure mechanisms, preventing failures, and repairing a stator after a failure.

Theoretical Limits of Generator Stator End-winding Vibration: Analytical Basis

The purpose of this report is to provide an analytical basis for the important parameters that may define vibration limits for reliable operation of generator stator end-windings. A number of geometric variations of end-windings have been studied to provide end-winding vibration limits for a wide range of end-winding designs.

The range covers 2-pole Turbo Generators, from small air cooled units rated at 100 MW to large water-cooled units rated at 800 MW or greater. Results are summarized in a table of four generic designs.

There are design details of various manufacturers that can affect the vibration limits that cannot be considered in the scope of this study.

Operators must confirm vibration limits with the OEM to assure that all parameters that may affect the vibration limit have been accounted for, and that appropriate action is taken to address abnormal vibration levels.

Theoretical Limits of Generator Stator End-winding Vibration – Analytical Basis: Part 2 Connection End with Phase Leads Between Coil Ends and Parallel Ring Conductors

This report presents Part 2 of research to examine an analytical basis for generator stator end-winding vibration limits. The first study was of the non-connection end. This second study is of the connection end, the end with the conductors that collect the phase currents and connect through the outside of the machine through the main leads to the isophase bus.

Three geometric variations of end-windings have been studied with finite element models to postulate theoretical end-winding vibration limits for a range of end-winding designs.

The range covers 2-pole Turbo Generators, from small air-cooled units rated at 100 MW to large water-cooled units rated at 800 MW or greater.

Results from this study of the three design variations are summarized and included in a table in the report. These are provided for information only. Among other variables, there are design details of various manufacturers that can affect vibration limits that were not within the scope of this study.

Among other actions, operators must always confirm vibration limits with the original equipment manufacturer to ensure that all parameters that can establish or affect a vibration limit have been accounted for and that appropriate action is taken to address abnormal vibration levels.

9.2 MAINTENANCE PHILOSOPHY

As previously mentioned, generally, generators are inherently reliable and will operate for several years without any problem, and at a minimum of reconditioning or replacement of components. This can give the wrong conclusion that a generator will “survive” without any structured and ongoing maintenance actions. However, one should have an open mind and stop comparing the maintenance of a generator to that of a turbine, which includes a lot of reconditioning and replacement of worn parts.

Maintenance actions for generators consist of diagnostics.

The aim of that is to get a view of the true condition of the complete structure and, as early as possible, to identify possible failure events and the risk of disturbances to production. In addition, one should keep in mind that an early mitigation action will most likely be negligible compared to a forced outage and the lost production costs before the unit is corrected and connected back to the grid again.

- <u>Vibrations</u>
  To realize those aims one can understand from this paper is that the vibration condition of the stator is one of the most necessary tasks to perform, and to perform this in a way in order to obtain as much information as possible to evaluate. For this purpose, it is necessary for the continuous monitoring of end-windings, round connections and the core. In parallel to the vibration readings one need to have information about the actual load parameters, temperatures in winding, core and gas or air ventilation.

To this monitoring should also periodic measurements by hand be added on parts and components which not are included in the monitoring. This could for instance be the generator containment, coolers, grid and neutral compartment, tubes, etc.

A good example how to do such periodic measurements is described in [15]. Result from measurements and analysis can be seen in [16]. Added to this are all individual deviations which may exist.

- Partial Discharge PD
  One can understand from the experiences abroad that partial emissions PD is a quite common failure event for several stator windings. Background to these PD based failures have several causes, there even lost knowledge is a reason.

  From paper [11] one can conclude that more than one OEM have forgotten how to produce an optimal protection for partial discharge, as well in the slot part as in the end-windings.

  This type of failure will be easy to find early but a developed failure will result in long-term forced outage.
  PD can either be contentiously monitored or measured periodically in operation or at planned outages. Both are able to catch changes of the PD level.

- Visual inspections
  It is essential to perform a visual inspection of all major and minor components inside the generator compartment.
  With help of vibration and PD readings, special attention can be focused on areas with question marks.
  It is necessary to start the inspection work in parallel with the dismantling work. That to don´t miss any useful information's from instance anomalies in contact surfaces. A tap test of stator slot wedges will be a part of this inspection

- Diagnostic test of stator winding

- Ring loop test of the stator core laminations.

There can be different suppliers of those actions, but to make the analysis of a single measurement as well as a merged one with the use of combined data from all the tests, one needs to have experience and quite a deep knowledge of turbo generators

10 References

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NORDIC NUCLEAR POWER GENERATOR STATOR VIBRATIONS

This report provides broad support for handling vibrations in the stator of a turbo generator, with the emphasis on 2-pole generators with a focus on end windings and the stator core.

The foundation for this support is basic knowledge of dimensioning and design requirements with regard to the main components of the stator. To this has been added basic knowledge about excitation and vibrational dynamics, as well as methods for data collection, evaluation and risk assessments.

Actual events are described for the 2-pole generators included in the study as well as adequate and comparable events from external power plants.

Finally, the design of generator maintenance is described with the aim of being able to make adequate and conscious decisions based on the production safety that is sought with identified risks.

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