Tampereen ammattikorkeakoulu

Turbogenerator Stator Problems and Fault Categorization

Veeti Korpelainen

BACHELOR'S THESIS
APRIL 2024

Degree Programme in Electrical Engineering
Electrical Power Engineering

TIIVISTELMÄ

Tampereen ammattikorkeakoulu
Tampere University of Applied Sciences
Sähkö- ja automaatiotekniikan tutkinto-ohjelma
Sähkövoimatekniikka

KORPELAINEN, VEETI:
Turbogeneraattorin staattorin ongelmat ja vikakategorisointi tekijöiden perusteella

Opinnäytetyö 56 sivua, joista liitteitä 2 sivua
Huhtikuu 2024

Työssä tunnistettiin ja kategorisoitiin turbogeneraattorin staattorin yleiset vikamekanismit tekijöiden, kuten valmistajan, vuosimallin, tai napaluvun perusteella. Työn tilaaja oli TGS Finland Oy.

Työ on luonteeltaan tutkimuksellinen. Kirjallisuuskatsauksessa esitellään turbogeneraattorin rakenne sekä yleisiä vikaantumismekanismeja. Vikamekanismien tekijöiden tunnistamiseen käytettiin vuosien 2010-2022 välillä suoritettujen kunnonvalvontatarkastuksien ja mittausten raportteja.

Työn keskeisenä tuloksena tunnistettiin, että katastrofaaliset vahingot eivät rajoitu vain käytössä kuluneisiin koneisiin, vaan myös uusissa generaattoreissa vikamekanismit voivat johtaa nopeasti vaurioihin ja yllättävään voimantuotannon pysähtymiseen.

Lisäksi havaittiin että 2000-luvulla valmistetuissa koneissa ilmeni suhteellisesti enemmän ongelmia kuin muilla vuosikymmenillä valmistetuissa. Ongelmia ilmeni valmistajasta tai koneen mallista riippumatta.

Asiasanat: turbogeneraattori, staattori, ongelmat, kunnonvalvonta

ABSTRACT

Tampereen ammattikorkeakoulu
Tampere University of Applied Sciences
Degree Programme in Electrical Engineering
Electrical Power Engineering

KORPELAINEN, VEETI:
Turbogenerator Stator Problems and Fault Categorization

Bachelor's thesis 56 pages, appendices 2 pages
April 2024

The aim of the thesis was to recognize and categorize the common failure mechanisms of turbogenerator stators based on factors such as manufacturer, model year or number of poles. The commissioner of the thesis was TGS Finland Oy.

The type of thesis was a research. The literature research presented the construction of a turbogenerator and the common failure mechanisms. To identify the factors related to the failure mechanisms, the reports of condition monitoring inspections and measurements from years 2010 to 2022 were analyzed.

As the key result of the study, it was identified that catastrophic damages were not limited to machines worn in use, but also appear in new generators, where failure can quickly lead to damages and sudden stoppage of power generation.

In addition, it was found that the machines manufactured in the 21st century had relatively more problems than those manufactured in other decades. Problems appeared regardless of the manufacturer or the model of the machine.

Key words: turbogenerator, stator, problems, condition monitoring

ACKNOWLEDGEMENTS

I would like to extend my gratitude for DI Osmo Koponen for mentorship and feedback throughout the thesis process. Additionally, I am thankful to thesis supervisor MEng Sami Heikkilä for his genuine interest in the subject matter.

CONTENTS

GLOSSARY

AVR	Automatic Voltage Regulator
DC	Direct Current
DE	Drive-end
GVPI	Global Vacuum Pressure Impregnation
IAEA	International Atomic Energy Agency
IEA	International Energy Agency
IHA	International Hydropower Association
IPB	Isolated Phase Bus
kV	Kilovolt
MVA	Megavolt-Ampere
NDE	Non-drive-end
PMG	Permanent Magnet Generator
VPI	Vacuum Pressure Impregnation

1 INTRODUCTION

Traditional power generation is going through a change. Fossil fueled power generation such as coal and gas powerplants are being driven down and being replaced by renewable generation. Fifth of coal plant fleet in European Union is predicted to close by 2026, and gas-powered generation reduction is expected to follow (Ember 2024, 13-17).

While renewable production is replacing conventional fossil fueled thermal power generation, general electricity demand in Europe is predicted to increase 60 % by the year 2030 (European Commission 2023). Electricity demand seems to be at a turning point, as electrification is seen as a key method to reduce emissions. Even though energy-intensive industries decline in Europe, there is a significant increase of consumption in areas such as heat pumps and electric mobility. In developed countries data-centers have also emerged as a new driver for electricity demand by the ongoing artificial intelligence boom (IEA 2024, 31). Hydrogen production via electrolysers may also affect electricity demand significantly in the future.

Increase in inverter-fed generation such as wind and solar raises concern in power grid stability. Historically system inertia has been provided mostly by synchronous rotating machines such as hydro- and turbogenerators. As conventional thermal power is being decommissioned, the amount of rotating machines in grid declines, and so does the kinetic energy provided.

However the urgent need for low emission power generation has sparked new interest in stable generation such as nuclear power (IAEA 2023) and hydropower (IHA 2023). Rotating machinery from coal and gas plants are also being retrofitted as synchronous condensers to provide system stability, and hydrogen-ready gas turbines are being developed and provided (IEA 2024, 57). These developments would suggest that turbogenerators will continue to be an important component in the power grid, and should be maintained accordingly.

This thesis was commissioned by TGS Finland Oy. TGS is an expert organization which provides turbine and generator services with a focus on Northern Europe.

The purpose of the thesis is to investigate common failure mechanisms appearing in turbogenerators and to categorize these problems.

In this work first a literary research is performed as an introduction to the constructional features of a turbogenerator and common fault mechanisms. Then the analysis of material generated by condition monitoring reports from past 13 years are reviewed and detected problems are categorized, with example case studies.

The literary research focuses heavily on turbogenerator’s stator, and other components such as rotor and excitation are introduced just very shortly. The terminology used is mostly North American, due to the reference literature.

2 CONSTRUCTION AND DESIGN OF TURBOGENERATOR

Constructional principles of electric rotating machines such as turbogenerators are basically the same whether the power generated is large or small. The basic physical constructional features include:

- Enclosure
- Stator body and winding
- Rotor body and winding

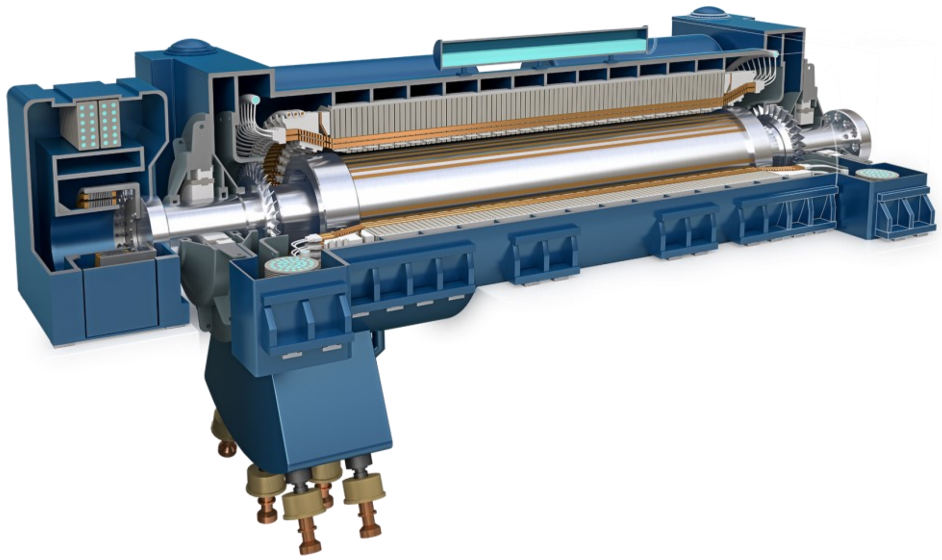

FIGURE 1. General construction of a turbogenerator (GE Steam Power).

In addition, turbogenerators require auxiliary systems such as lubricating oil, sealing oil, space heaters, temperature sensors, excitation, cooling and protection.

2.1 Generator enclosure

The generator enclosure consists of few major components; the casing and stator frame, heat exchangers, electrical connections, bushings and bearings.

The main task of the stator frame is to provide support for the stator core and shield the generator from the environment and contaminations. The frame may also act as a pressure vessel for the possible hydrogen cooling gas. (Klempner & Kerszenbaum 2004, 39).

Turbogenerators employ usually either air or hydrogen as the internal cooling medium of the machine. Air is used in smaller generators, but hydrogen has been recognized as the most effective gas for ventilating a rotating machine and is used in the larger machines to achieve higher power ratings. (Klempner & Kerszenbaum 2004, 82). In addition to providing significantly better heat transfer than air, the hydrogen also suppresses partial discharges with the added pressure inside the generator. The heat transfer capability of hydrogen is approximately 14 times better than air. (Klempner & Kerszenbaum 2004, 92). Heat exchangers for the cooling system of the machine are mounted on the enclosure or are a part of it. They vary from simple finned casing for convective heat transfer to air to more complex water-cooled systems (Tavner, Ran, Penman & Sedding 2008, 26).

On the outside of the frame enclosure there is footings and frame mounts to secure the generator to a foundation. These mounts are required to carry the weight of the generator and withstand the rotational forces from the magnetic fields in the generator (Klempner & Kerszenbaum 2004, 39). The mount design needs to take in account forces in normal operation and the possibility of very high dynamic forces in short-circuit fault situations.

Electrical connections are made to the stator windings via copper busbars or cables that leave the machine enclosure through bushings into a terminal. The busbars can be lightly insulated to protect them against the environment (Tavner et al. 2008, 26), or have a totally enclosed design as in isolated phase bus system (IPB) to reduce the external magnetic field induced by large currents flowing in the busbars (Timperley 2021).

The terminals are subject to high losses which generate heat and in large units must be force-cooled. The cooling is usually done either by the internal cooling gas in the generator casing or by water-cooling as a part of the possible winding cooling water system. The three phase lead terminals are rated at the nominal voltage of the generator. They are insulated conductors and therefore have generally same requirements as stator windings. (Klempner & Kerszenbaum 2004, 63).

In addition to the high-voltage three phase terminals, there are three neutral terminals that make up the connection point (the “star” point) at the neutral ends of the stator winding phases. While these are essentially at ground potential and under less load stress, they do carry the full stator current that the high-voltage terminals carry and so must be given the same cooling (Klempner & Kerszenbaum 2004, 63).

2.2 Stator core and windings

2.2.1 Stator core

The stator core is made up of thin sheets of electrical grade steel. These sheets are commonly referred as core laminates. The core build is segmented, generally from 10 to 24 laminates are laid side by side to form full 360 degree ring layer. Each lamination is insulated on both sides with compounds such as varnish or an layer of oxidation. The purpose of interlaminar insulation is to confine any induced eddy currents to a path along the same lamination where it is induced. This is to reduce eddy currents by reducing their magnitude to prevent associated losses and temperature rise. (Klempner & Kerszenbaum 2004, 35).

Figure 2 presents the confinement of eddy currents (marked in red) with interlaminar insulation, where B is the magnetic flux.

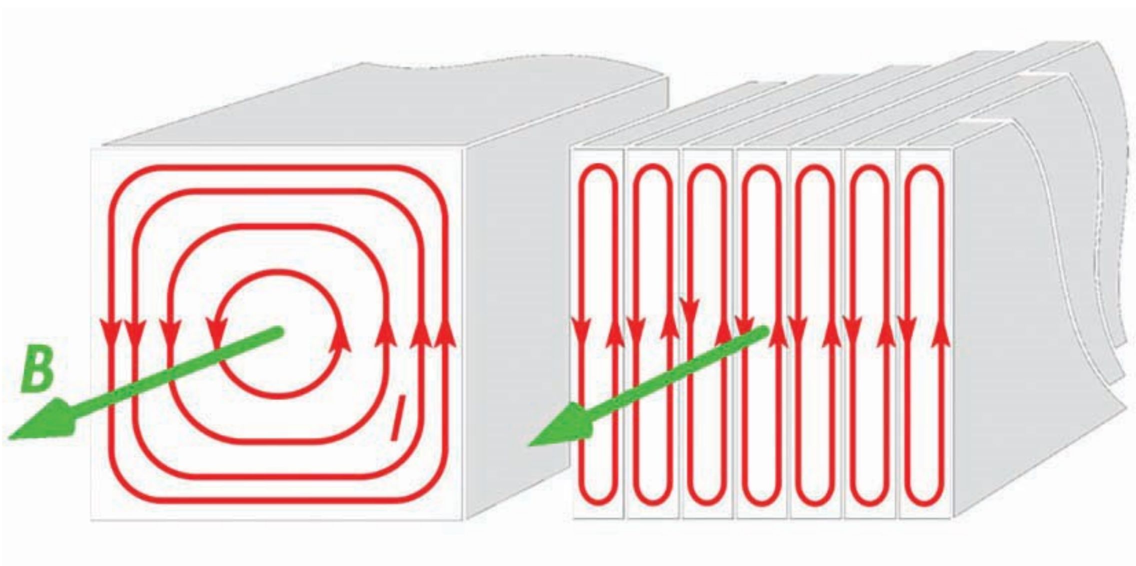

FIGURE 2. Confinement of eddy currents with interlaminar insulation (NETA World technical journal)

To ensure mechanical integrity necessary to transmit load torque and have low levels of vibration when carrying the magnetic flux, the core laminations are firmly clamped between end-plates at both ends of the generator. The end-plates are secured to a cylindrical frame which into the core is keyed. On larger machines, the clamping plates are tightened axially by large bolts. On smaller generators interlocking keys or welds are used to secure the plates, or the core itself may be welded or cleated (Tavner et al. 2008, 18).

The stator core concentrates the magnetic field from the rotor on the copper conductors in the coils as the magnetic steel acts as a low-reluctance path for the magnetic fields, and also prevents most of the stator winding magnetic field from escaping from the ends of the stator core. This prevents any unwanted current-flow in near conductive material (Stone, Boulter, Culbert & Dhirani, 2004. 8).

The construction of stator core includes ducts for cooling gas to flow through the core, enabling transmission of the heat conducted from the winding to the core.

2.2.2 Stator winding

The stator winding of a turbogenerator is generally made up of insulated copper conductor bars around the inside diameter of the stator core. The bars are constructed in equally spaced slots in the core to ensure symmetrical flux linkage with the magnetic field produced by the turning rotor. Generally each slot contains two bars, one on top and one under. These bars are referred as top and bottom bars. Top bars are nearest to the air gap, under the wedges. The core areas between the slots is usually referred as core teeth (Klempner & Kerszenbaum 2004, 52).

Example structure of a stator slot with windings is presented in figure 3.

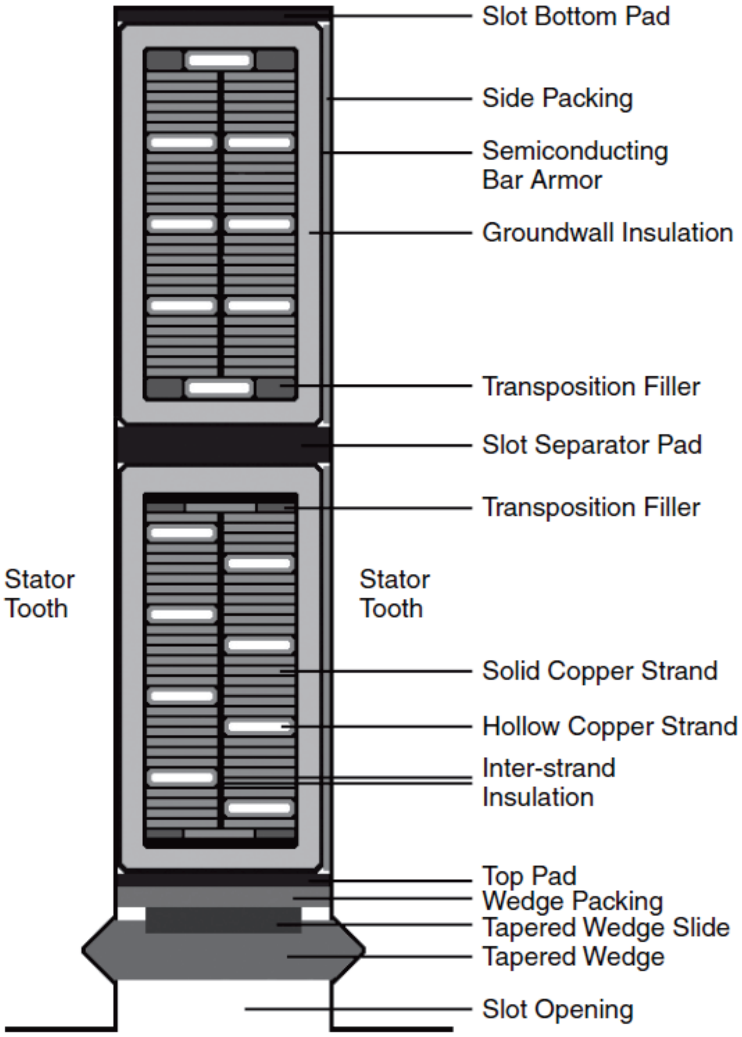

FIGURE 3. Example of winding bars inside stator core slot (Energiforsk)

Stator winding is divided to three phases which are wye connected. The top bars on one side of the stator bore are connected to the bottom bars on the other side of the bore. (Klempner & Kerszenbaum 2004, 52). The amount of slots separating the connected bars is referred as the “coil-pitch”. The connected bars form a single coil.

Windings of smaller turbo generators are often made of multi-turn coils instead of bars. One coil side is on top of stator core slot, and the other coil side on the bottom of another stator core slot, separated by the coil-pitch. The coils are connected to each other in one end of the machine to form three phase winding.

As the turning rotor and the magnetic field induced passes through these windings, the “plus” and “minus” of the rotating field induce opposing polarity current flow to each side of the coil.

To reduce the effect of eddy currents and heat losses, the stator bars can be built from many copper strands, similar to the core being built of laminations. The strands are insulated from each other but eventually connected at the end of the bar. The reason for stranding the conductor bar from an electrical design point of view is that via stranding, the skin effect (current tends to flow on the periphery of the conductor) that would affect the cross-sectional area of the conductor can be negated, which reduces the heat losses in the conductor. (Stone et al. 2004. 14).

Also to reduce the effect of circulating currents on each bar, conducting strands can be transposed into “Roebel-bar” structure as seen in figure 4.

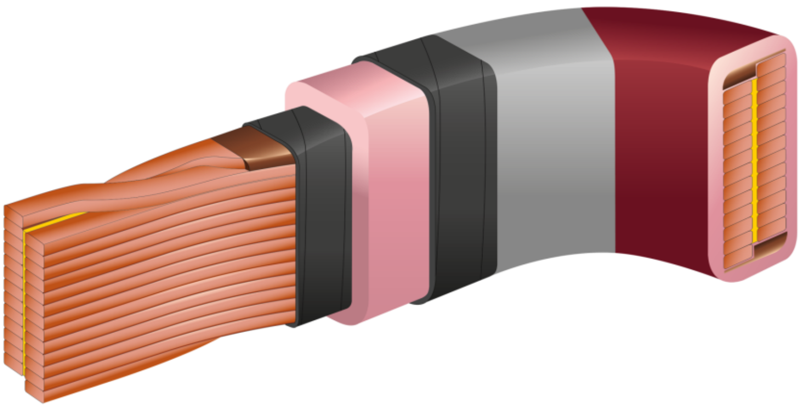

FIGURE 4. Roebel transposition (Krempel)

In large machines designed for high power rating, the stator bars are equipped with ducts or hollow strands which enable direct hydrogen- or water-cooling of the winding in order to increase stator current carrying capacity via better heat transfer. This complicates the construction of the generator especially in case of direct water-cooling of conducting bars. Liquid cooling requires external system and components such as heat exchangers, water pumps, filtering and de-ionizing (Klempner & Kerszenbaum 2004. 57).

To restrict movement of the winding in the slots, the conductor bars are wedged in to position. Usually also some side- or depth-packing filler strips are inserted in to slot to increase mechanical support and fill any extra space as seen in figure 5. In large machines, “ripple springs” can be used. The ripple spring is an laminated material which is not fully flat, and can expand if the slot contents shrink (Stone et al. 2004. 27). In addition it is possible to glue the bars into the slot using varnish or epoxy for example.

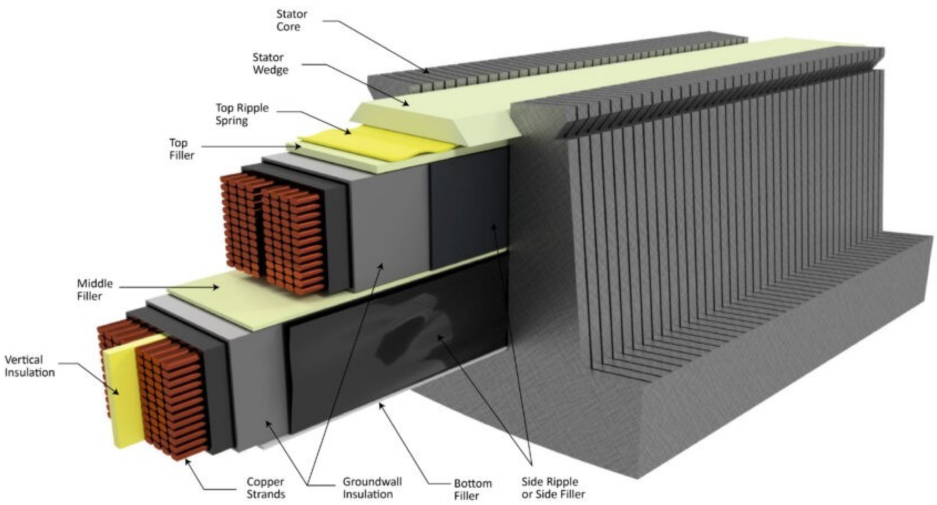

FIGURE 5. Winding bars wedged into stator core slot. (The Gund Company)

The winding exits the core slots to the end-winding area for electrical connections of the bars. These connections potentially at both ends of the machine must be well away from the stator core, which is in ground potential, to prevent problems at the insulated connection points. On large two-pole machines, the end-windings can reach up to two meters away from the core (Stone et al. 2004. 29).

To prevent end-windings from movement and vibrations, the end-winding must be supported well. Usually this supporting structure consists of support ring(s), in which winding is lashed in to. The support ring material can be for example insulated steel, fiberglass or epoxy-glass laminate. (Stone et al. 2004. 29).

The final part of stator winding is the connection rings, where the windings are connected phase-by-phase to line and neutral terminal busbars. The connection between busbars connecting the generator to grid are often build from flexible, laminated or braided copper connectors for vibration-insulating purposes.

2.2.3 Stator winding insulation

The primary purpose of the insulation in the electrical windings is to prevent short-circuits between conductors and/or the ground potential. The stator winding insulation system contains several components which ensure that these shorts do not occur, and that the heat losses are transmitted to a heat sink. The basic stator insulation system components are strand-, turn-, and groundwall insulation (Stone et al. 2004. 14).

The conducting strands must be insulated from each other to prevent short-circuits between strands. Similar to this, the turns in the coil must also be insulated to prevent shorts between the turns.

Groundwall insulation is the component that separates the conductors from grounded stator core in the slots. This insulation is also key component in transmitting the heat losses from the conductors to the stator core, as depicted in figure 6. This requires the insulation to have a high thermal conductivity as possible, while being free of any voids, in which air would block the flow of heat. Air pockets in insulation also enable partial discharges which may erode the insulation. (Stone et al. 2004. 19). The groundwall insulation also increases the mechanical strength of the winding against vibrations caused by magnetic forces.

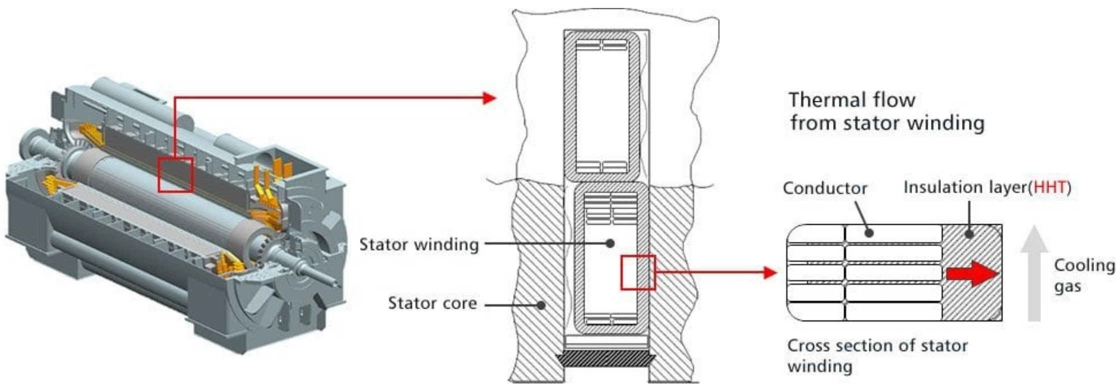

FIGURE 6. Thermal flow from stator winding (Mitsubishi Power).

Modern groundwall insulation material is typically mixture of epoxy resins and mica paper. The insulation is applied to winding bar by taping and is impregnated by applying pre-wetted semi-cured epoxy-resin in a process called Resin Rich or by vacuum pressure impregnation (VPI) (Draper, Ramsauer, Lemesch 2018).

The VPI-process may be applied to individual coils or even whole winding system in a process referred as global vacuum pressure impregnation (GVPI). The method consists of taping the winding bars with dry mica-tape, then applying a vacuum cycle in a sealed tank, which removes humidity and other volatile material, then impregnating the winding with resin by pressure. After impregnation and cooling, the resin is cured in oven (Draper et al. 2018).

In stators rated at above 6 kV nominal voltage, an voltage stress relief coating system is applied to prevent partial discharges in slots or in end-winding near the stator core. Common components of an stress relief system are presented in figure 7.

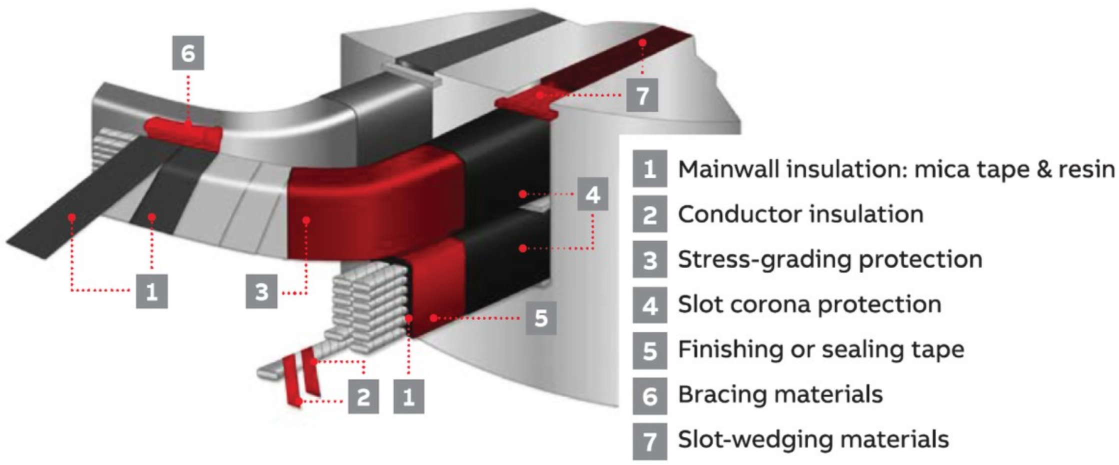

FIGURE 7. Stress grading protection (ABB)

In order to prevent partial discharges on the winding surfaces, the coil/bar is coated in the slot area with partly conductive coating. This coating is usually a carbon-black-loaded paint or tape. This “semiconductive coating”, generally referred also as slot corona protection, is in contact with the stator core along the length of the slot. As there is a contact to the grounded core, the voltage in the potential gap between winding and core is essentially zero, and no partial discharges should occur (Stone et al. 2004. 24).

For clarification, the term “semi-conductive” is generally used in North America, and the term “conductive” is used in Europe, when discussing the slot corona protection electrode.

The slot corona protection usually extends a few centimeters beyond each end of the slot to the end-winding area. If the coating would end abruptly, it would form an localized high voltage electric field in the end-winding area which would enable partial discharges. To prevent this, an special silicon carbide coating – “stress grading” is applied to the end of the slot protection coating. Silicon carbide is an material which has special property: as the electric stress increases, it’s resistance decreases. This stress grading makes the electric field more uniform and the stress is reduced below an critical 3 kV/mm voltage threshold which would initiate partial discharges (Stone et al. 2004. 26).

2.3 Rotor body and windings

The body of a turbogenerator’s rotor is a cylindrical piece of solid steel. Modern rotors are generally forged from a single piece of magnetic steel. The main body has machined slots for rotor winding. Unlike stator winding’s wedging, the rotor wedges are invariably made of stronger material like metal, for example steel or aluminum alloy. (Stone et al. 2004. 36). This is because the centrifugal forces from the high rotating speed.

The rotor winding is installed in to the slots machined to the main body, and distributed symmetrically around the rotor between the poles. Turbogenerator rotors are two-, and four-pole designs.

Comparison of two- and four-pole rotor flux patterns are presented in figure 8.

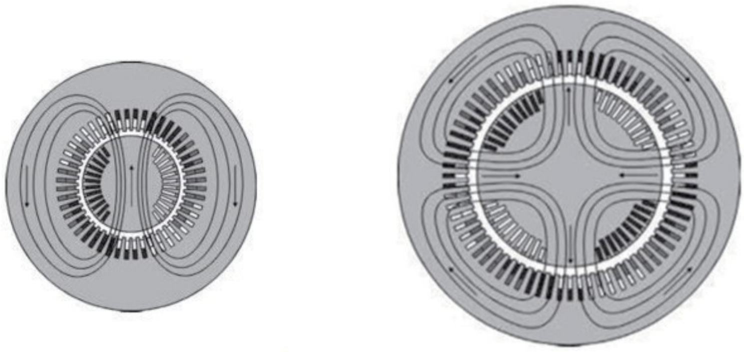

FIGURE 8. Comparison of two- and four-pole rotors flux patterns (Energiforsk)

Turbogenerator rotor design is generally non-salient pole (cylindrical pole). Two-pole rotors are without exception cylindrical, but some four-pole turbogenerators employ salient pole design. Comparison of these rotor designs are presented in figure 9.

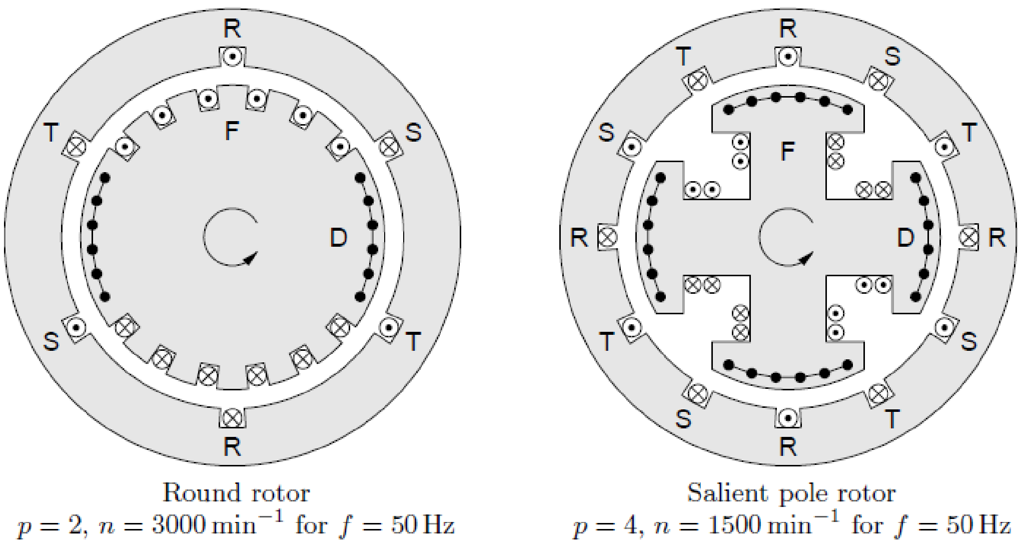

FIGURE 9. Comparison of salient and non-salient pole rotor design (IEEE)

Rotor winding is insulated in similar design to stator windings, to prevent short-circuits between conductors or rotor body. However since the excitation voltage of the rotor is low, generally a few hundred volts in direct current, and the mechanical stress on the winding is high, the materials and structure of the rotor insulation system is very different from the high voltage stator insulation systems.

2.4 Excitation

The rotating magnetic field is not generated on its own, it requires excitation. Excitation system provides a magnetizing current to the rotor winding. The basic excitation system types used for turbogenerators are static and brushless.

Static excitation uses an external power source to supply alternating current to an excitation transformer. The transformer output is then fed to a rectifier bridge for direct current conversion, which is fed to the main rotor winding via slip-rings, controlled by AVR (automatic voltage regulator).

Brushless excitation system typically consists of a high-frequency alternating current generator with a rotating diode bridge for rectification, an external AVR for excitation control, and a power supply. The alternating current supply power is generated usually with an shaft mounted PMG (Permanent Magnet Generator) or with an transformer for backup supply. The exciter is generally attached as extension of the generator shaft (Klempner & Kerszenbaum 2004, 106). The key feature in PMG use for power supply is in operational safety; if the shaft is not rotating, no excitation current is provided.

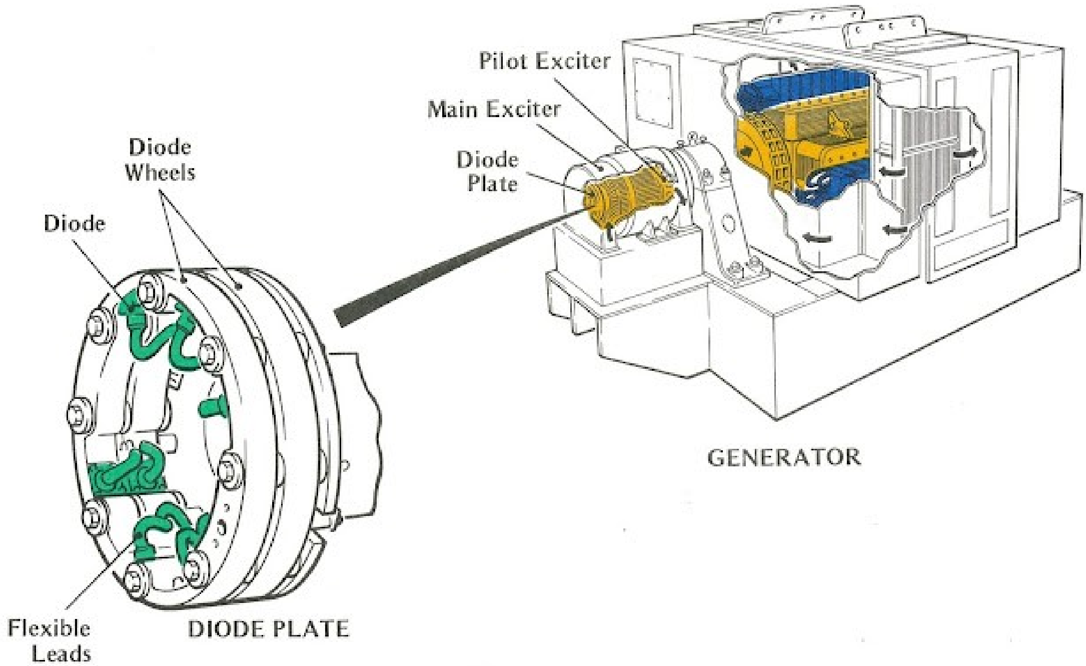

FIGURE 10. Brushless excitation system (Engineering Search Engine)

3 ROOT CAUSES AND FAILURE MECHANISMS OF STATORS

This chapter presents some common recognized failure mechanisms in generator stators and the potential root causes.

3.1 Stator winding problems

3.1.1 Thermal Deterioration

Thermal deterioration and the problems caused by thermal aging is one of the most common reasons for stator winding to fail.

In air-cooled machines which employ epoxy-mica as insulation material, high operating temperatures lead eventually to chemical reaction where chemical bonds of the insulation break. The insulation becomes more brittle and has lower mechanical strength. The reduced bonding strength leads to separation of the mica tape layers, resulting in delamination (Stone et al. 2014. 172).

Delaminated insulation may initiate partial discharges, which will eventually erode a hole through turn- or groundwall insulation, leading to short-circuiting or ground fault.

Another possible cause for winding failure is that when the mechanical strength of the insulation lessens, the conductor strands are held together less tightly. Eventually the conductors may vibrate against each other and lead to strand-, or turn faults. This leads to hotspots in the winding and eventually decompose the insulation, which leads to turn- or ground fault. Multiturn coils are more susceptible to this failure as less layers of insulation need to fail. (Stone et al. 2014. 173).

If the generator load is increased suddenly, the winding conductor temperature will rise faster than stator core, and lead to thermo-mechanical stresses. The temperature variation cycle from low to high is generally referred as thermal cycling. This cycling may gradually fatigue and crack the winding insulation and conductor strands. Thermal cycling may also affect stator wedges, stator core, gaskets and frame support systems in a deteriorating manner.

The main root cause for thermal deterioration is operation at high temperature, which might occur because of many reasons such as poor design or manufacturing, overloaded operation, voltage imbalance between generator phases, loss of cooling, or operating the machine under-excited (Stone et al. 2014. 175).

3.1.2 Loose coils in slot

Loose coil induced failure is common in modern generators. This failure mode is generally associated with form-wound stators using thermoset bars manufactured in other way than GVPI-process, although not entirely without exception.

Loose coils in stator slots leads to vibration and movement of the winding bars. Magnetic forces will affect the bars mainly radially, and the bars will bounce up and down against the slot wall. This leads to abrasion of the semiconductive coating and groundwall insulation.

At first the vibration may lead to contact sparking during operation, as the bar moves away from grounded core. When the slot corona protection coating has abraded, partial discharges will initiate on the surface of the bar, in the airgap between the bar and core. This will accelerate the deterioration of the groundwall insulation in addition to the vibration and movement, eventually leading to ground fault (Stone et al. 2014. 186).

The potential root cause for coil looseness is that the coils were originally installed too loose, as the slots lack sidepacking or wedging due poor design or manufacturing. It is also possible that initially tight insulation has shrunk due aging. This kind of shrinkage typically takes decades, and may be prevented with the use of ripple-springs. Some ripple-springs as well as wedging can loosen over time due stator core movement or oil contamination. Loose wedging may then eventually lead to loosening of the coils in the slot (Stone et al. 2014. 188). This mechanism is further inspected in chapter 4.1.

3.1.3 Semiconductive coating failure

Semiconductive coating - the slot corona protection, may fail even without mechanical vibration. This failure mechanism is referred as “electrical slot discharge”. Weakening conductive function leads to partial discharges in the small gaps between the coils and the grounded stator core. Partial discharges will mitigate the groundwall insulation and may even bore an hole through, resulting in ground fault.

This failure mechanism appears more likely in air-cooled machines, since hydrogen suppresses potential discharges. Partial discharges can produce ozone in air-cooled machines. This may lead to chemical deterioration, as ozone will form nitric acid when combining with nitrogen and humidity in air. Nitric acid will affect especially steel, oil, epoxy, polyester and rubber compounds. This chemical attack will accelerate the deterioration as semiconductive coating weakens and leads to further partial discharge activity and ozone (Stone et al. 2014. 191).

Nitric acid formation expands the problem beyond the stator as it will affect heat exchangers and bearing lubrication oil for example. Also if ozone escapes the enclosing of the generator, it is a potential health threat.

In case the stress grading overlapping the slot corona protection coating at the ends of the bars, near the slot exit area, has degraded or was manufactured insufficiently, it may lead to partial discharges in the slot exit area. Examples of erosion and dusting from this type of discharge activity is presented in chapter 4.4 and appendixes 1 and 2.

The root cause is mainly poor manufacturing procedure. The general process happens when a capacitive current flows from conductor copper through the groundwall insulation to the stator core via the coating, because of an deviant surface resistance (surface resistance is too high in some areas). Some of the capacitive current will flow laterally on the coil surface, which leads to heat losses. This local heating can oxidate the coating and deteriorate the semiconducting function (Stone et al. 2014. 192). It is also possible that if small air pockets exist between the groundwall insulation and the coating, potential occurrence of partial discharges will deteriorate the semiconducting function of the coating.

3.1.4 Chemical deterioration

In addition to nitric acid mentioned before, other contaminations like solvents, water, oil or gases may lead to chemical deterioration of insulation. Contaminations can soften or swell the insulating material and thus weaken the mechanical integrity.

The root cause for such contamination may be for example lack of maintenance, or operational issue such as oil extractor impairment.

3.1.5 Electrical tracking

In addition to thermal and chemical deterioration, winding contamination can lead to electrical tracking.

In failure mechanism called electrical tracking, contaminated winding surface enables currents to flow over the insulation. The material can be for example dirt, ash or carbon dust from brushes which will mix with moisture or oil to form a conductive coating on the winding.

In form-wound stators the failure mechanism occurs usually in the end-winding area. Generally the process includes two points of differing phases, for example two coils next to each other, and a contaminated path between for small current to flow. If the contamination resistance is high, it will lead to high voltage and eventually partial discharges, which may carbonize and degrade the underlying resin and tapes. As the electric stress moves along the region as carbonization makes the surface conductive, the result is an electrical track which may appear as black branches on the surface. The discharges will eventually bore in to the groundwall insulation and may lead for example to phase-to-phase failure (Stone et al. 2014. 212).

3.2 Stator core problems

Core lamination problems may occur from variety of recognized failure mechanisms such as thermal-, electrical-, and mechanical deterioration.

3.2.1 Thermal Deterioration

Stator core thermal deterioration generally occurs if the designed thermal rating is exceeded in operation. Overheating will lead to accelerated aging of the core insulation. A key process in thermal aging is the drying of varnish used in insulation, which will eventually break down. This leads to interlaminar shorts and eddy currents in laminations. Eddy currents then lead to heat losses which accelerate the deterioration, and may even melt the core.

Example of eddy current across core laminations is presented in figure 11.

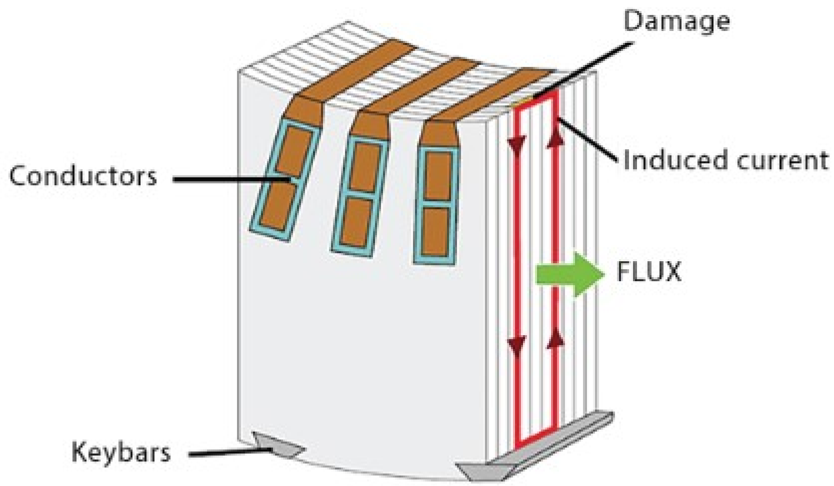

FIGURE 11. Eddy current across laminations due damaged stator core (NETA World technical journal)

Overheating may occur in the general core or locally in parts of the core. In addition to thermal deterioration of the insulation, general overheating may also cause core looseness due thermal expansion of the core steel and possible shrinkage of organic components. (Stone et al. 2014. 286). Core looseness then may lead to abrasion of the interlaminar insulation which then accelerates the general fault process.

The root cause is generally loss of cooling which may occur for various reasons, such as loss of cooling water, high ambient operating temperature, blockages of air flow or operation at reduced hydrogen pressure (Stone et al. 2014. 286).

3.2.2 Electrical Deterioration

Electrical deterioration may occur across the core lamination by magnetic fluxes, electromagnetic forces and high currents. Generally in addition to faults between the winding and core, the root cause for electrical deterioration is excessive fluxes caused by under-, or over-excitation may result in overheating of the core.

Operation in under-excitation may lead to elevated eddy currents especially at the end of the core, induced by the leakage fluxes caused by currents in stator and rotor end-windings and discontinuities at the stator and rotor surfaces (Stone et al. 2014. 291). The eddy currents may lead to generally higher temperature which can deteriorate the interlaminar insulation.

Over-excitation of the rotor will lead to higher magnetic flux. Higher magnetic flux then leads to increased heat losses in the core, which will generally raise the temperature of the core, especially in the area behind the slots, as there is less ventilation than in the core-teeth area. Elevated temperature increases the risk of interlaminar breakdown and possible mechanical stresses, and eventually may even lead to fusing of laminations (Stone et al. 2014. 292).

Additionally winding insulation faults such as sparking can damage the interlaminar insulation of the core, and lead to shorts and local overheating. Grounding fault may even melt and fuse the core laminations if the energy and heat produced by the flowing current are high.

3.2.3 Mechanical Deterioration

Common causes for mechanical deterioration in stator core are lack of core pressure, vibration, and back-of-core looseness.

If core laminations loosen, they may move from vibration or electromagnetic forces, which then may lead to abrasion of the interlaminar insulation. Degradation of the insulation may lead to shorts and current flow as mentioned before. Degradation of the core teeth may also lead to fatigue cracking of the laminations and thus loose debris inside the generator that can cause further damage. (Stone et al. 2014. 296).

Core vibration can be cause or result of core looseness. Cause for looseness could be for example inadequate support for the core in the frame or end-windings, causing vibrations.

3.3 End-winding vibrations

End-winding vibrations may occur if the winding support is inadequate. This problem is likely in large turbogenerators rated in hundred megawatts, as these sort of machines have long end-winding. Generally if winding-ends lack support, the bars begin to vibrate due magnetic forces generated as current flows through the conducting copper.

If the bars are tightly wedged in slots, the vibrations may fatigue and crack the bar insulation just outside the slot, leading to ground fault. This may happen even if the individual bars are tightly supported in the end-winding, if the whole end-winding system is vibrating (Stone et al. 2014. 224).

If the winding support blocks are loose, bars may vibrate against each other or the support structure, which leads to deterioration of the insulation. The effects of vibration may be seen visually near the abrasion as light-colored dust, or if oil is present to potentially mix with dust, black grease-like substance.

End-winding vibrations are also able to break conducting copper strands. If a single strand breaks, it will increase the current flow on other strands. This will lead to process which increases temperature and accelerates the cracking of strands. Eventually as more strands break, the conducting bundle may melt and lead to catastrophic failure (Stone et al. 2014. 225).

The main root causes are poor design and manufacturing. It has been recognized that especially natural frequencies at twice the rotational frequency cause resonation and thus vibration. These frequencies must be avoided in design of the end-winding support. It is also possible that end-winding is affected by actions in operation, such as load cycling or out-of-phase synchronization. Contamination such as oil may affect the winding support with deteriorating effect, and act as an lubricant in support structures, leading to abrasion. Operation in high temperature also accelerates thermal aging of the insulation, and may cause support materials to shrink (Stone et al. 2014. 226). Failure resulting from end-winding vibrations is futher presented in chapter 4.3.

3.4 Electrical connection faults

There are many electrical connections in a standard stator winding. The connections between copper conductors in coils/bars are generally brazed and the bus bar or cable connections are bolted. If the resistance of the connections is too high, the heat losses from currents will lead to overheating. Continuously increased temperature of the copper will lead to oxidation, which accelerates the temperature rise. Eventually the temperature will degrade insulation and may lead to melting of the winding or connection. Even if the overheating will not lead to melting, serious deterioration of winding insulation will increase risks related to contamination and lack of insulation (Stone et al. 2014. 232).

The general root cause is poor manufacturing of the connections, such as inadequate brazing or poor bolt connections. The connections may also be affected by possible end-winding vibrations which can fatigue the connections, which may lead to cracking of the conductors and thus a process which will accelerate the overheating process. Electrical connection failure is further presented in chapter 4.2.

4 FAULT CATEGORIZATION

This chapter presents the results of generator condition monitoring analysis and fault categorization. The fault categorization was done by analyzing data generated by condition monitoring reports.

4.1 Data overview

The condition monitoring data is based on 970 inspection reports from years 2010-2022. The reports are divided to Major- and Minor-overhauls, offline measurement reports from safety checks and reports from performed online-measurements.

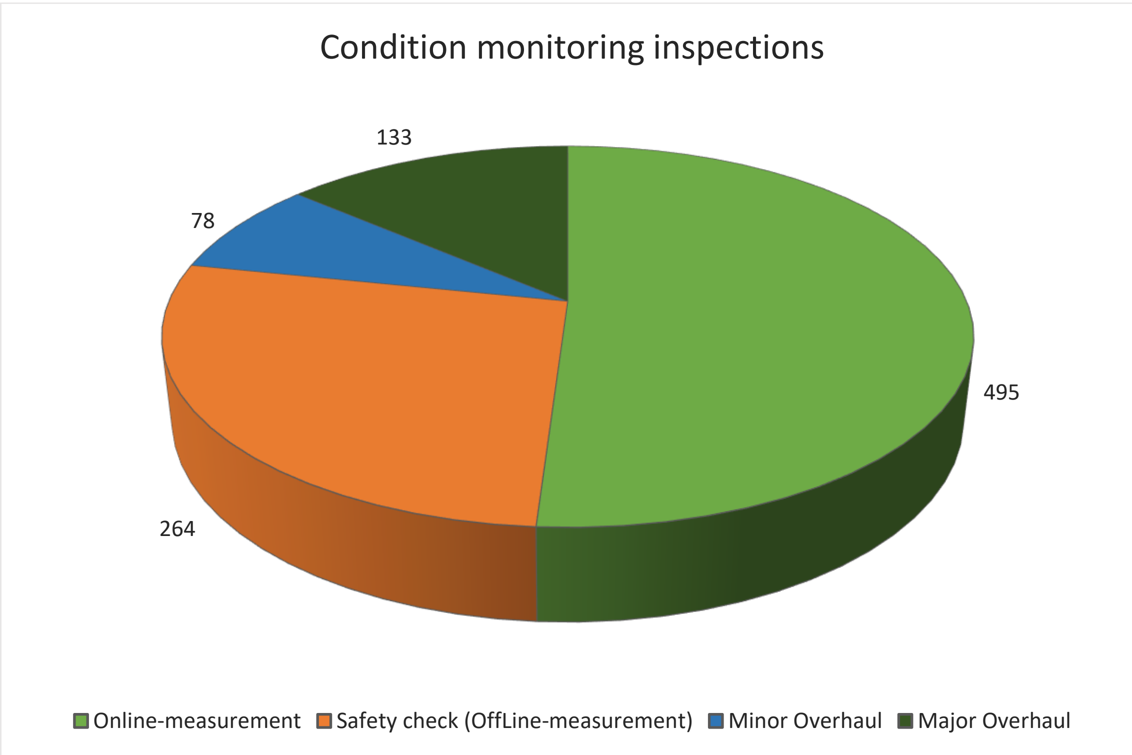

FIGURE 12. Distribution of condition monitoring inspections

Many of the generators included have been monitored online during operation yearly or more frequently, with the addition of offline inspections and safety checks during overhauls.

The generators included were manufactured between years 1952 and 2019. Majority of the machines are from 1970's to 2010's as seen on figure 12.

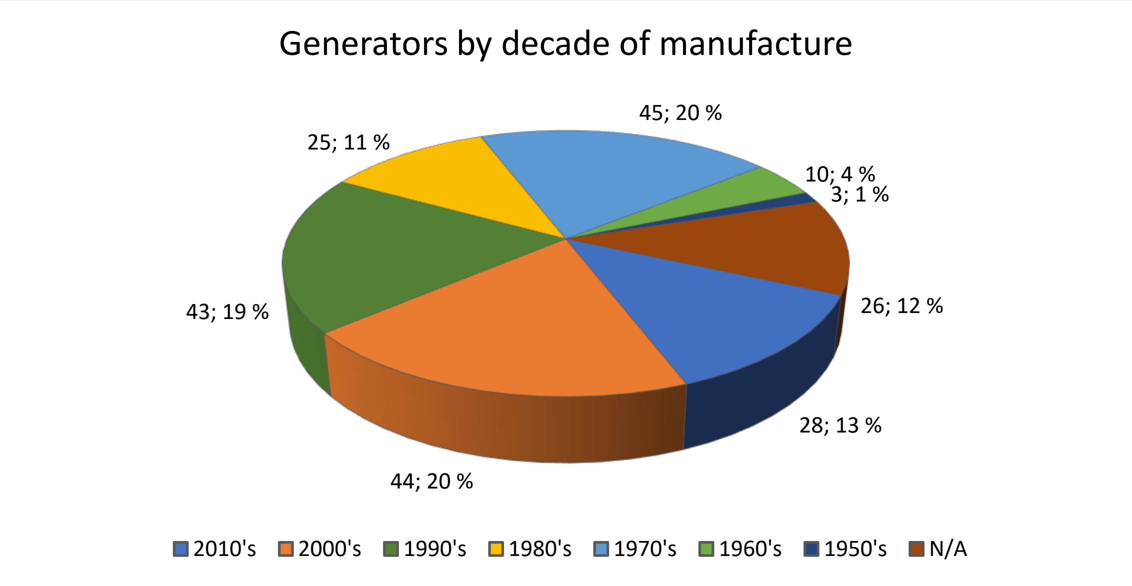

FIGURE 13. Generators by decade of manufacture

The material consisted of 226 generators from 33 different manufacturers. The manufacturers with most generators included are numbered from 1 to 14 and their share of the material is presented in figure 14. The remaining manufacturers are presented in the "Other" category.

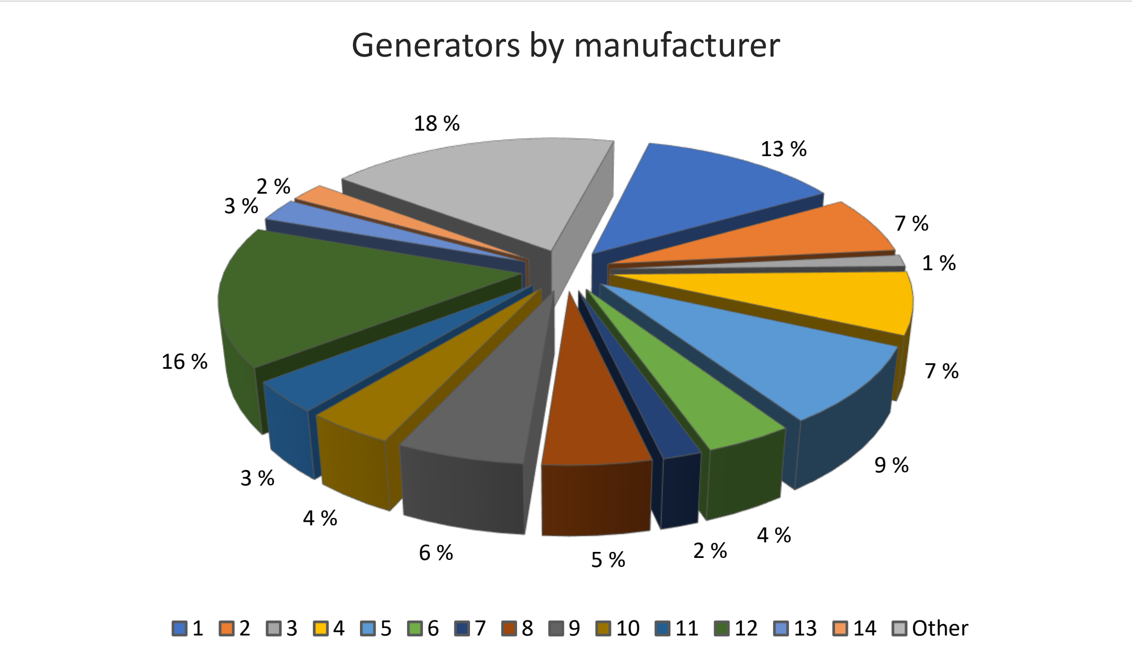

FIGURE 14. Generators by manufacturer

The material consists of two- and four-pole generators, majority being two-pole machines with 3000 rotations per minute rotating speed, with the share of 71%. Out of 226 generators, 62 is four-pole machines and 160 two-pole machines. For the remaining 4 machines the data was not available. The distribution of the machines by number of poles and rotating speed is presented in figure 15. All included generators operate in frequency of 50 Hz in the electrical grid.

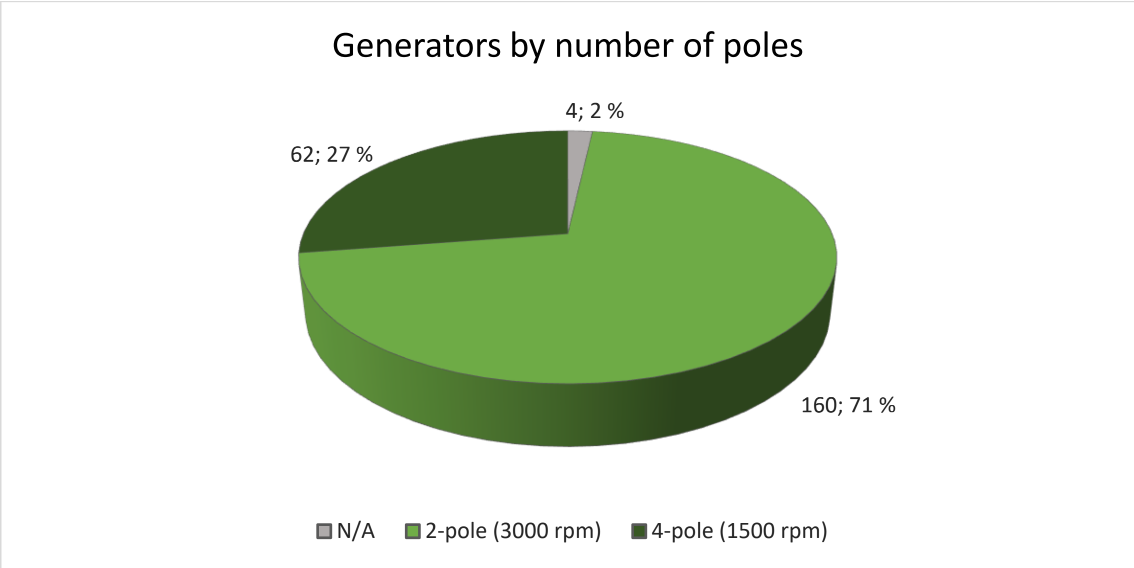

FIGURE 15. Generators by number of poles

Majority of the generators included are powered by steam turbines with a share of 67%. Out of the 226 machines, 151 was powered by steam turbine and 53 by gas turbine. Data for 22 machines was not available. Distribution of turbine types is presented in figure 16.

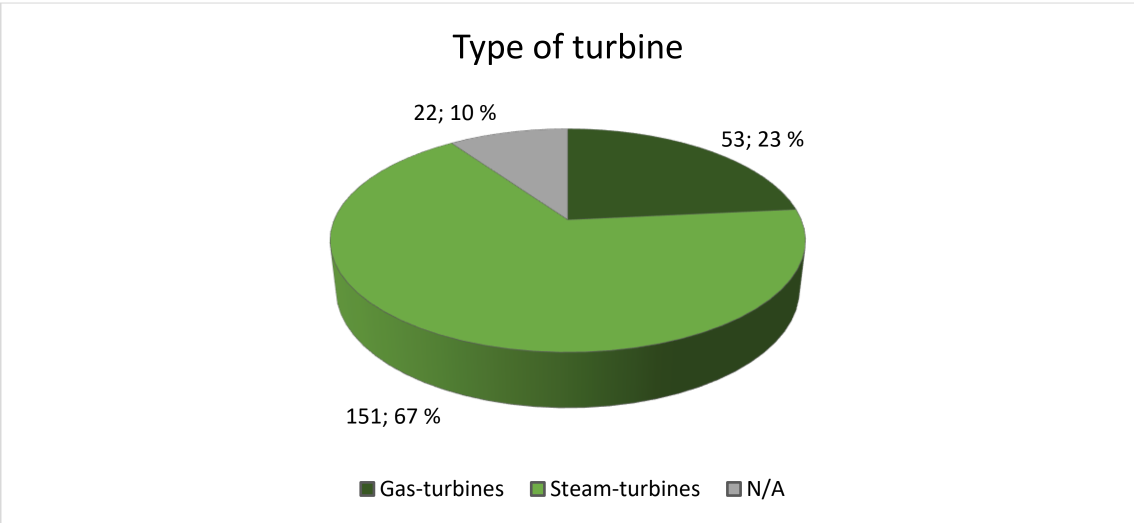

FIGURE 16. Type of turbine powering the generator

Generators included were rated in 20 different voltage levels, most of them between rated voltage of 6,3 kV to 15,75 kV. The share of generators with the common rated nominal voltages are presented in figure 17.

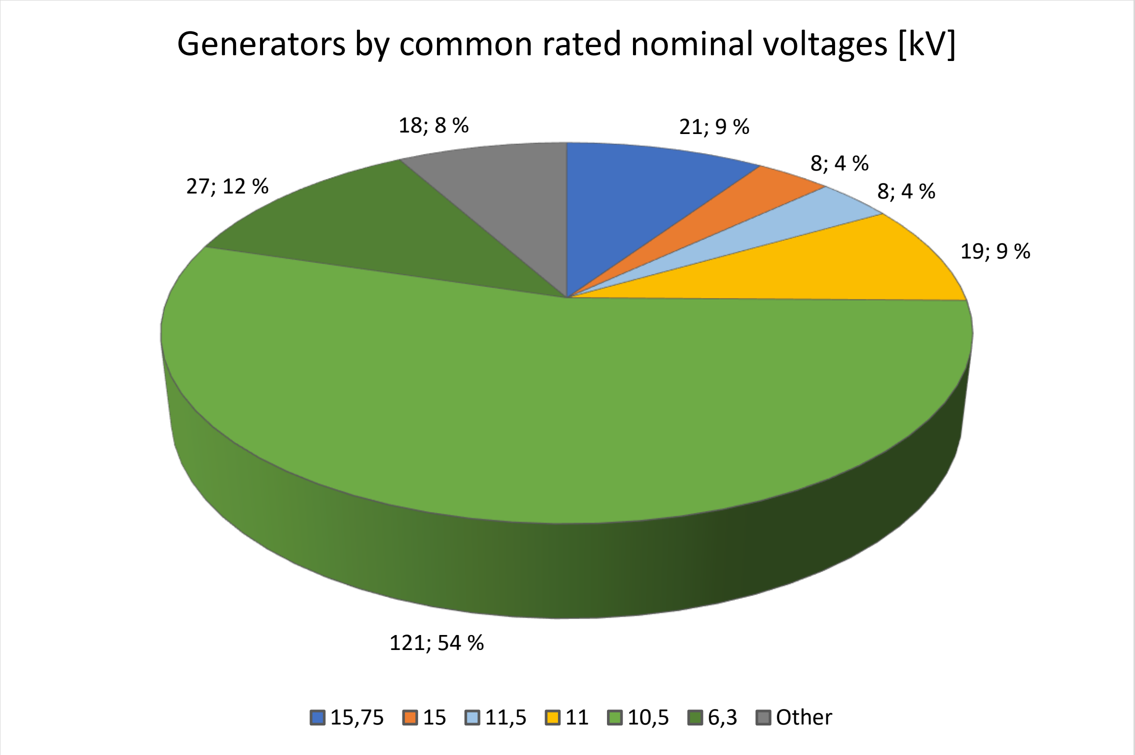

FIGURE 17. Generators by common rated nominal voltages

Majority of the generators are rated at 10,5 kV nominal voltage with the share of 54%.

4.2 Detected faults

Out of the 226 generators included, 66 was found to be affected by a recognized failure mechanism, as presented in figure 18.

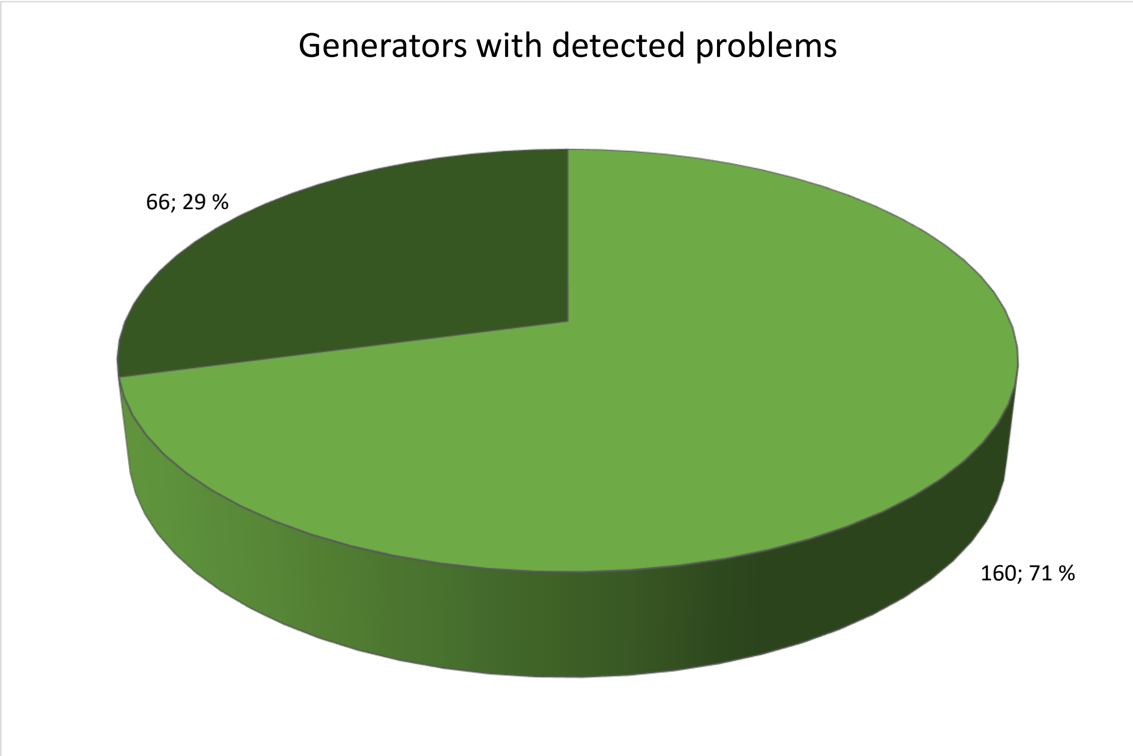

FIGURE 18. Generators with detected problems

Out of the 66 machines with detected faults, in 6 generators the failure mechanism led to ground fault, representing 9 percent of total detected problems. Some of these are further inspected in chapter 4.

Figure 19 presents the distribution of detected faults according to the decade of manufacture.

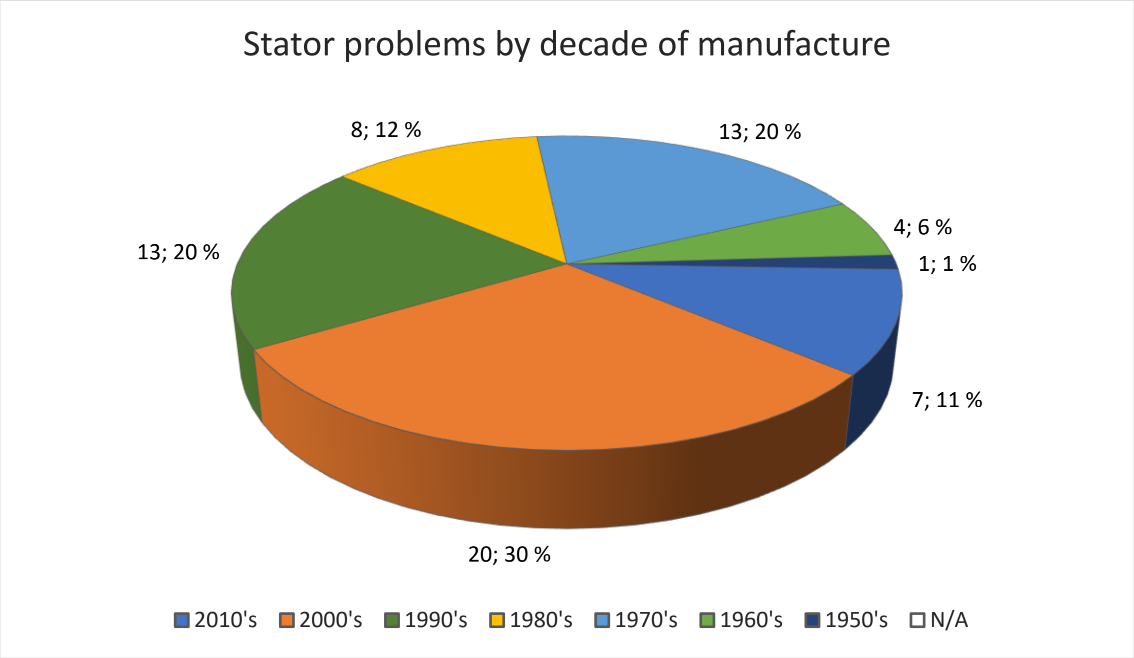

FIGURE 19. Stator problems by decade of manufacture

In figure 20 is presented the comparison of detected problems by decade to total number of generators included from each decade.

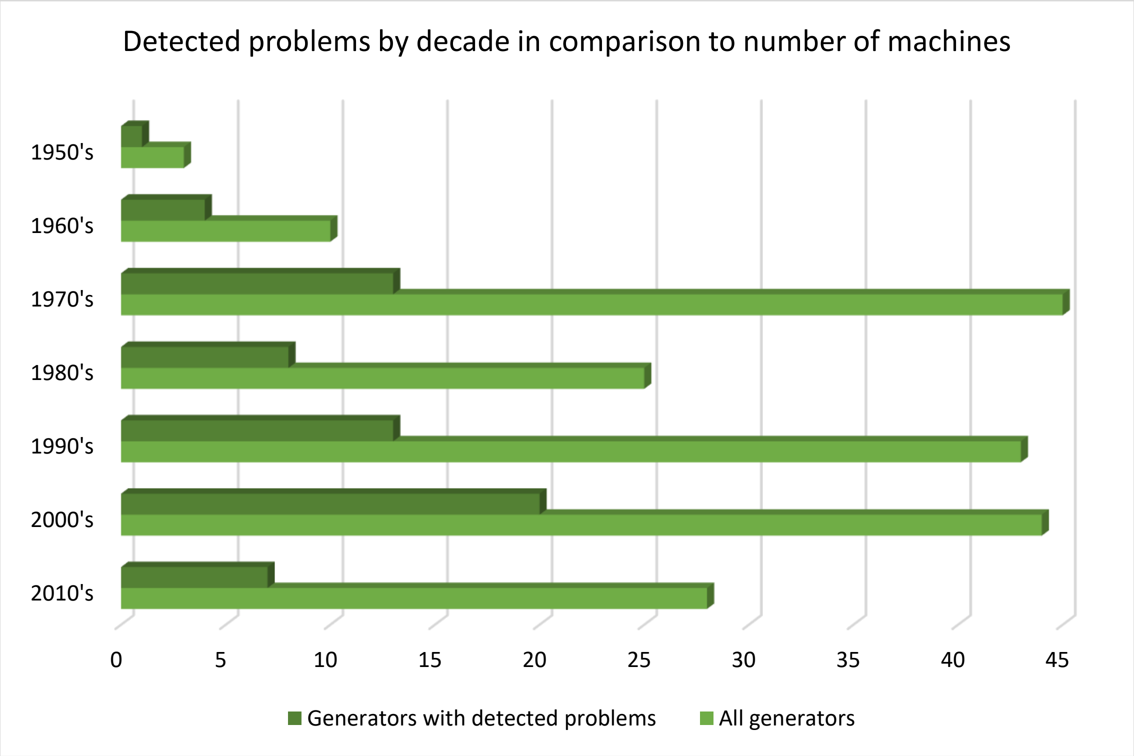

FIGURE 20. Detected problems by decade in comparison to number of machines

Figure 21 presents the generators with detected problems by manufacturer.

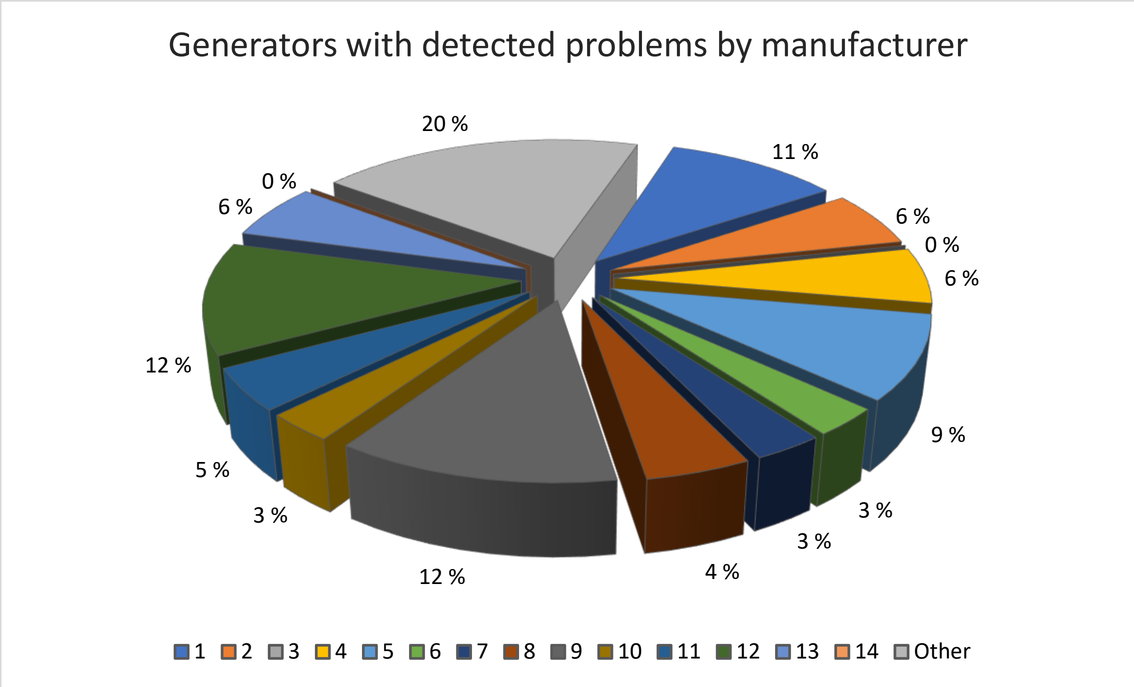

FIGURE 21. Generators with detected problems by manufacturer

In figure 22 is presented the comparison of generators with detected problems to total number of generators by manufacturer included.

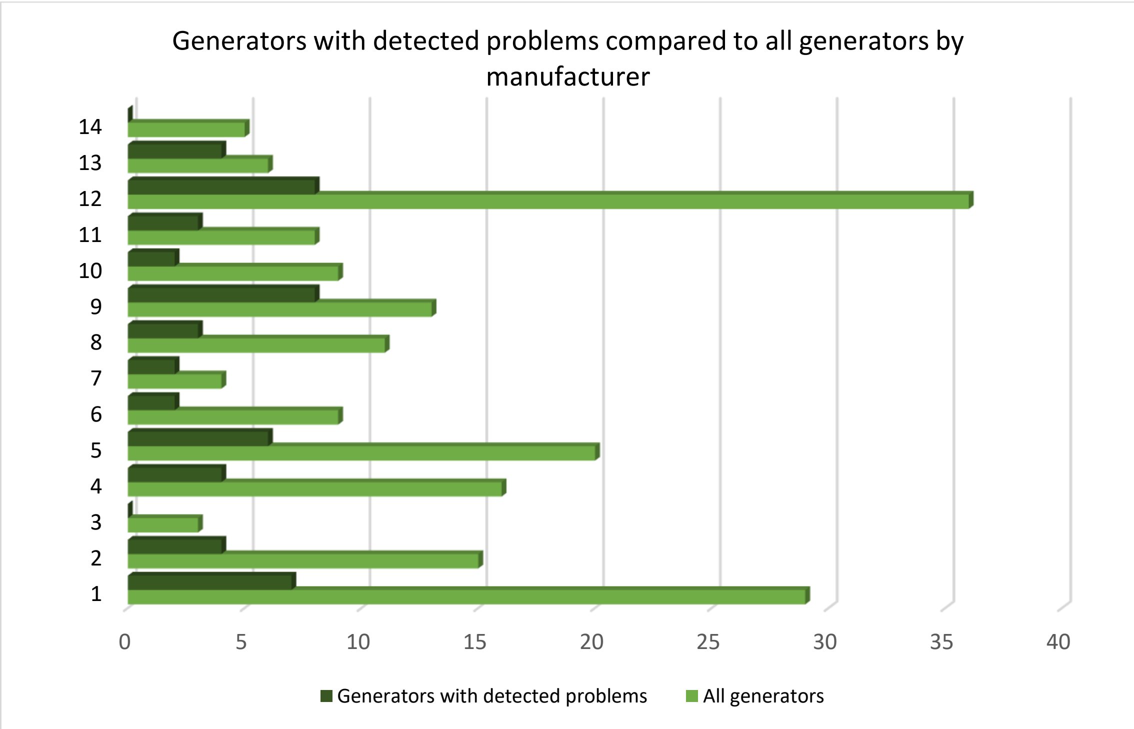

FIGURE 22. Generators with detected problems compared to all generators by manufacturer

In figure 23 is presented the generators with detected problems by number of poles and rotating speed.

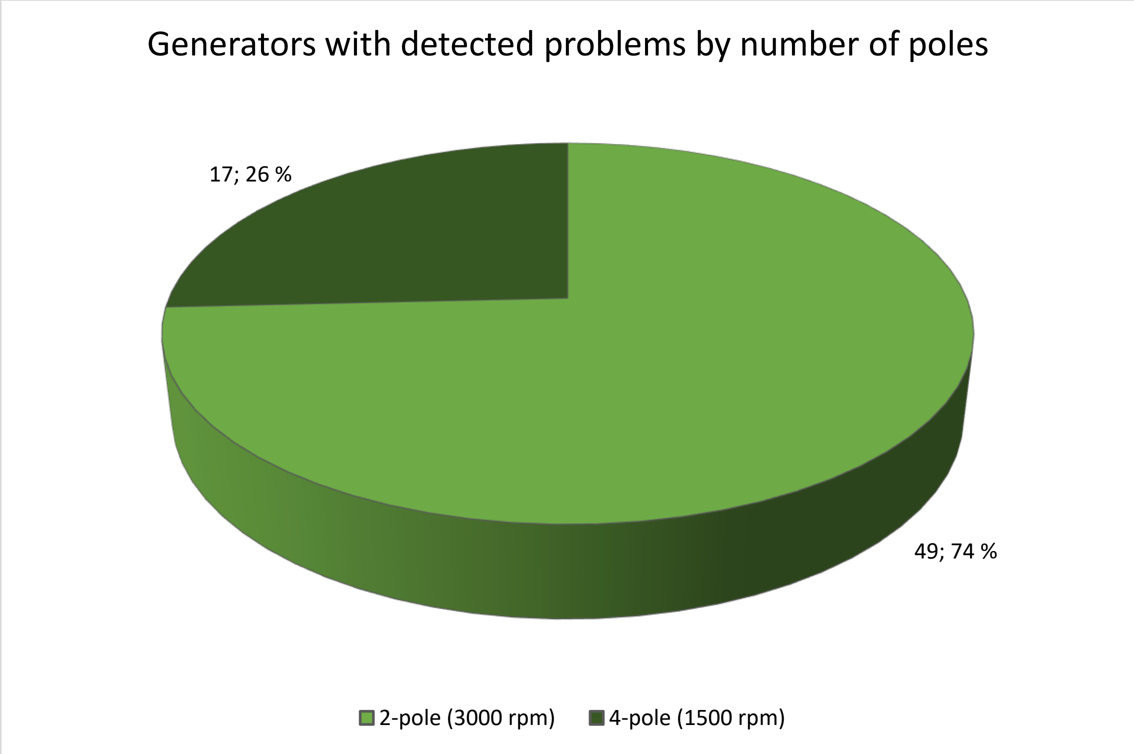

FIGURE 23. Generators with detected problems by number of poles

In figure 24 is presented the generators with problems by common rated voltages.

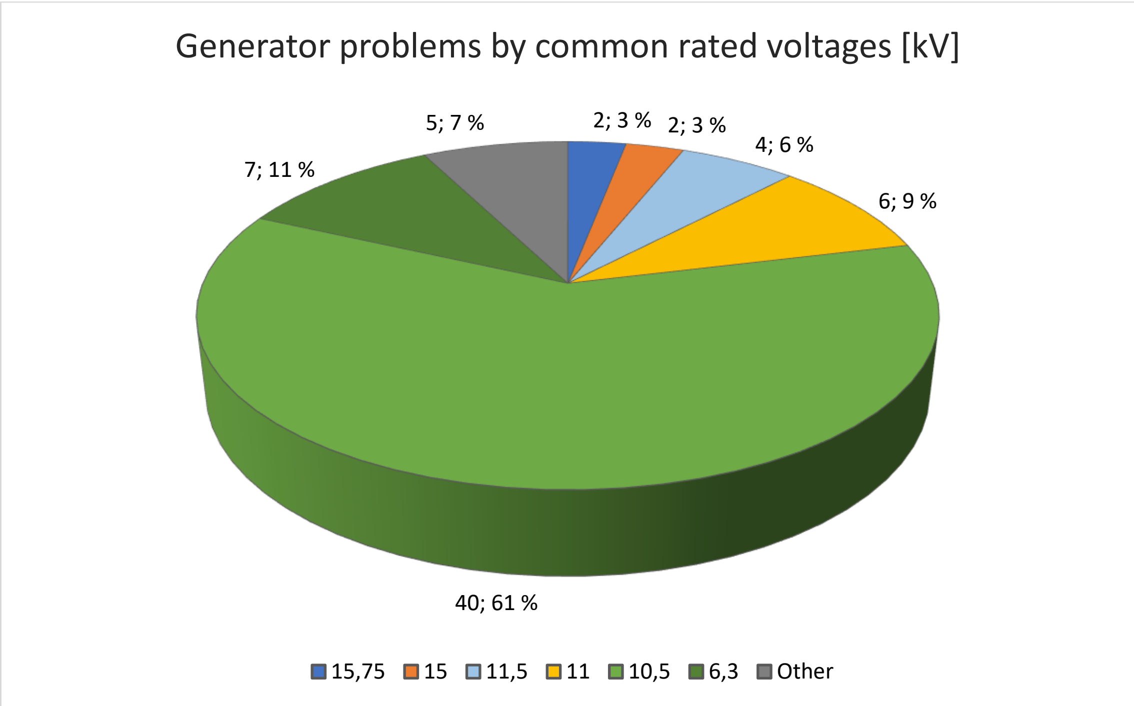

FIGURE 24. Generator problems by common rated voltages

4.3 Common detected failure mechanisms

The common detected failure mechanisms detected in the data represent the majority of problems detected. The common failure mechanisms include wedge looseness, core- and slot faults, and end-winding area vibrations and discharges. The distribution of these failure mechanisms are presented in figure 25.

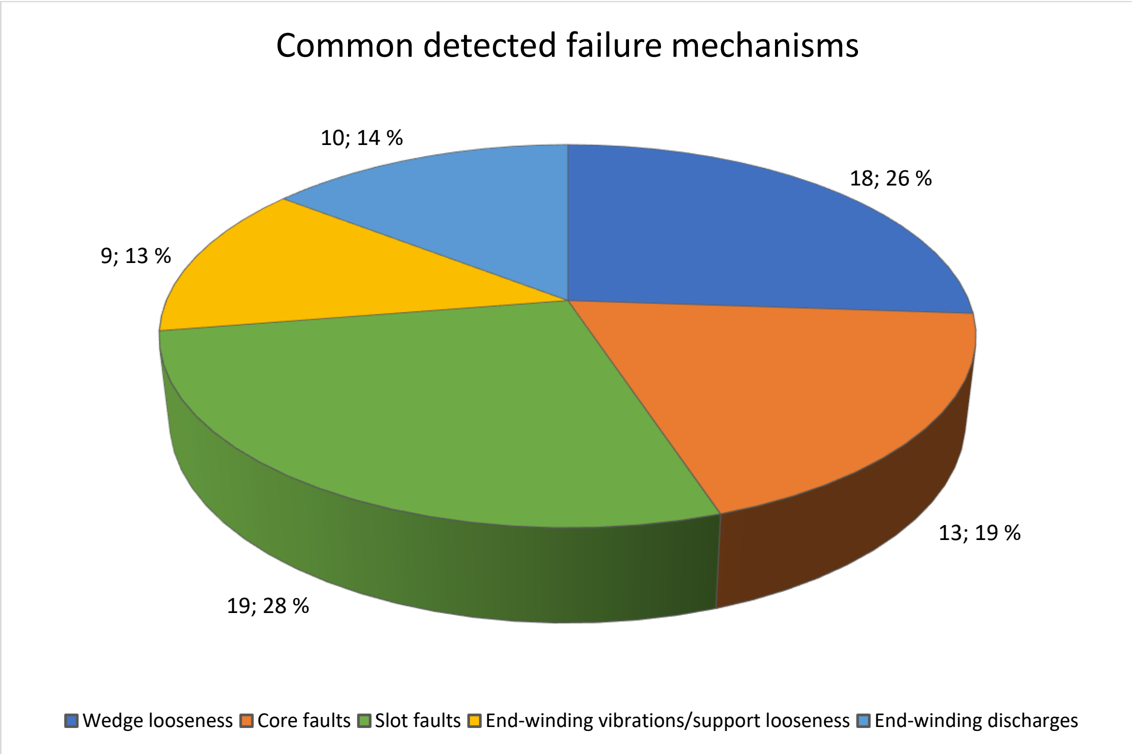

FIGURE 25. Common detected failure mechanisms

Core faults include problems such as deterioration of lamination insulation and core looseness. Slot faults include problems detected in slot area, such as discharges, bar vibration, and winding insulation deterioration.

In figure 26 is presented the common detected problems distribution in two-pole generators.

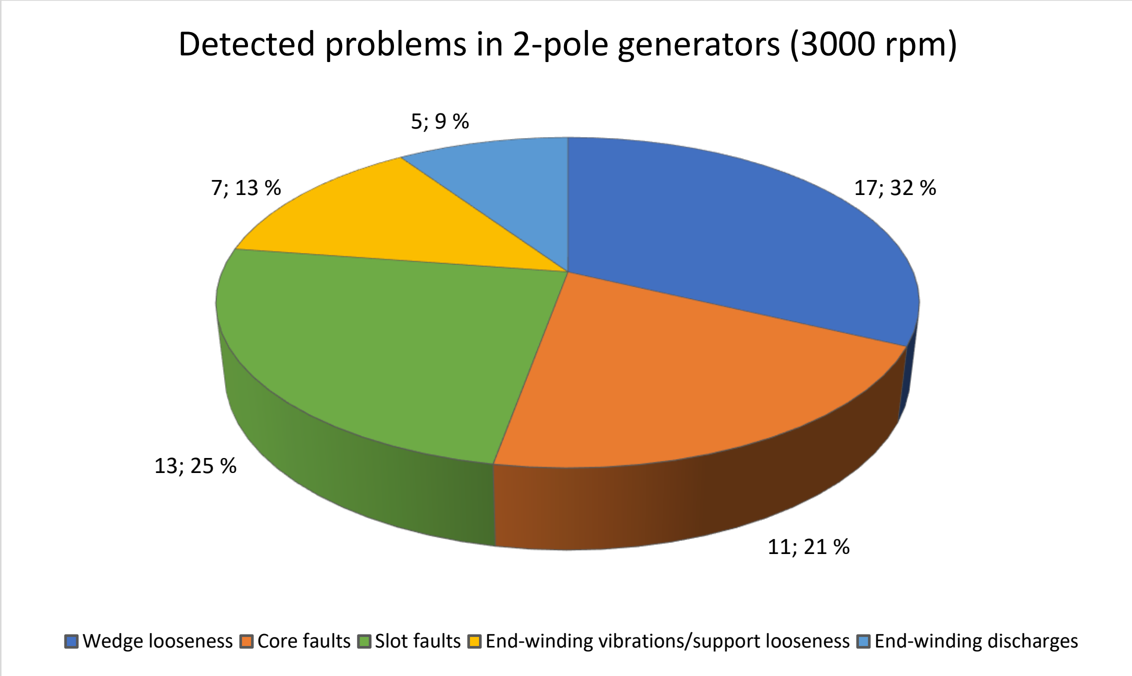

FIGURE 26. Detected problems in 2-pole generators

In figure 27 is presented the distribution of common detected problems in four-pole generators.

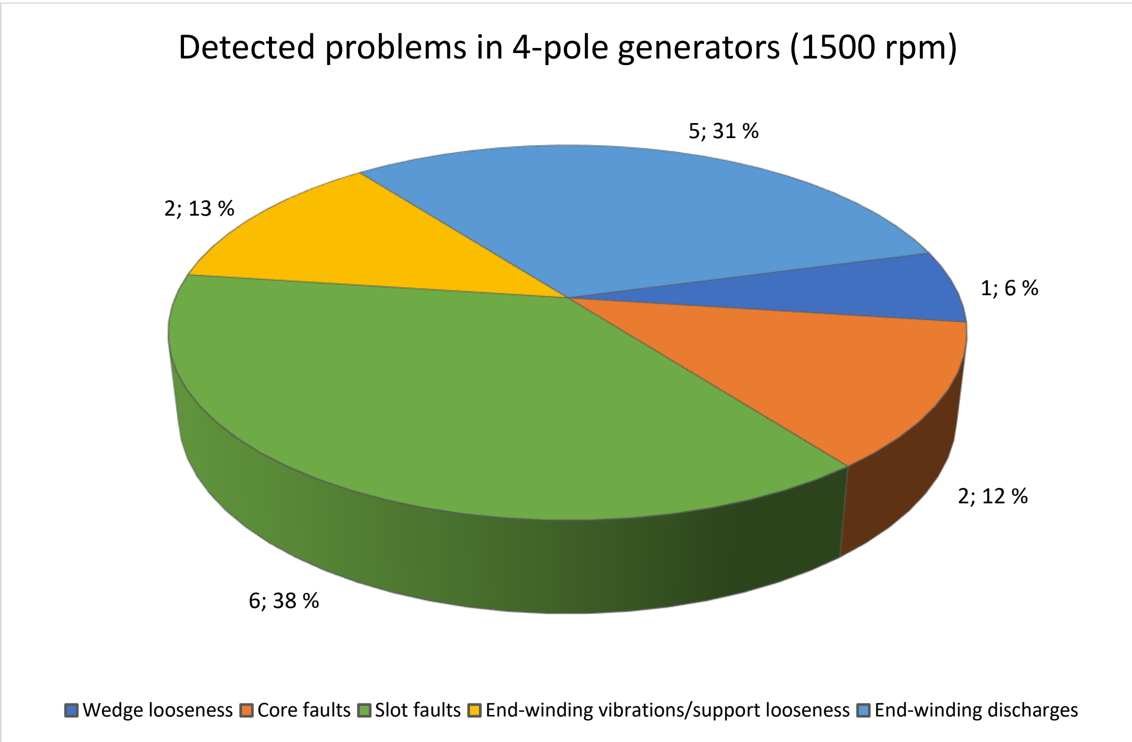

FIGURE 27. Detected problems in 4-pole generators

Comparison of the detected problems between two- and four-pole generators would suggest that the major distinction is occurrence of wedge looseness in two-pole generators, as 32 percent of the problems detected were loosening of wedges, in comparison to just 6 percent appearance in four-pole generators.

Four-pole machines seem to be more susceptible to problems in slot area and end-winding discharges, as majority of detected problems were found in these categories. However it is good to acknowledge the smaller portion of problems detected in four-pole generators, as the total share of problems detected in four-pole generators was 17 percent out of all generators included.

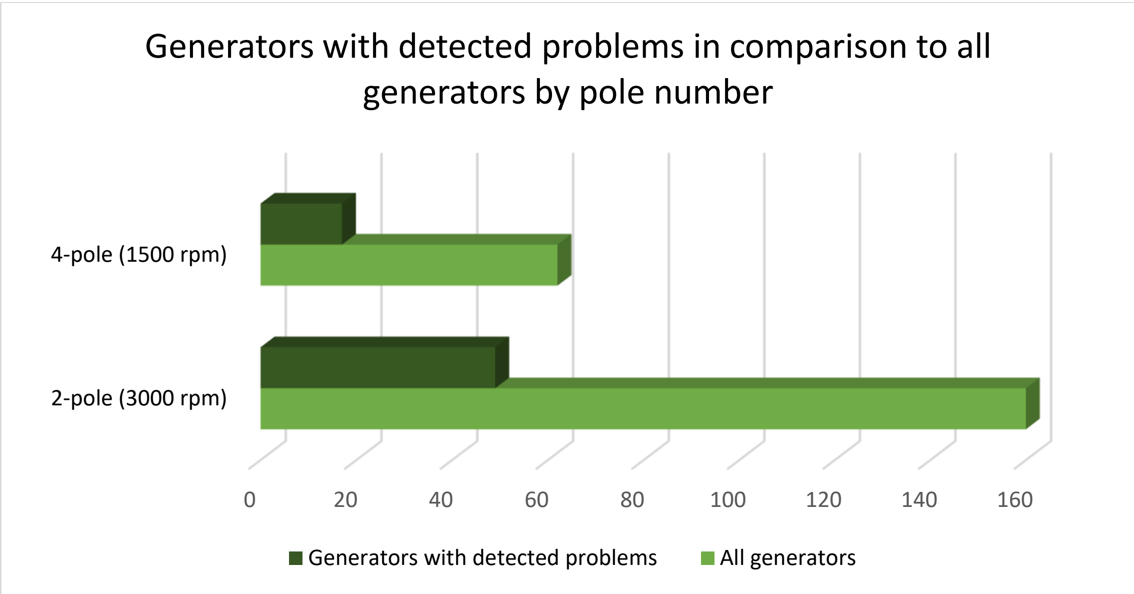

FIGURE 28. Comparison of generators with detected problems in comparison to all generators by pole number

In comparison, there was problems detected in 34,7 percent of four-pole generators and 38,8 percent of two-pole generators.

5 CASE STUDIES OF FAULT MECHANISMS

This chapter presents some case studies of generators in which fault mechanism led to ground fault. These case-examples are to present previously mentioned problems in reality.

5.1 Case 1: Radial vibration of winding bars – Bar Bouncing

The generator of case 1 is a 233 MVA air cooled generator, operated at rated voltage of 15,75 kV. The generator was manufactured in 2009.

In 2014, after protection relay tripped the generator, it was found by measuring that there was a low resistance ground fault. After pulling out the rotor for proper inspection, a main insulation puncture in a top bar was discovered. The surface of the whole bar was seriously damaged by abrasion caused by vibration and erosion caused by partial discharges. In addition two other bars with signs of vibration was discovered. The damaged winding bar is presented in figure 29.

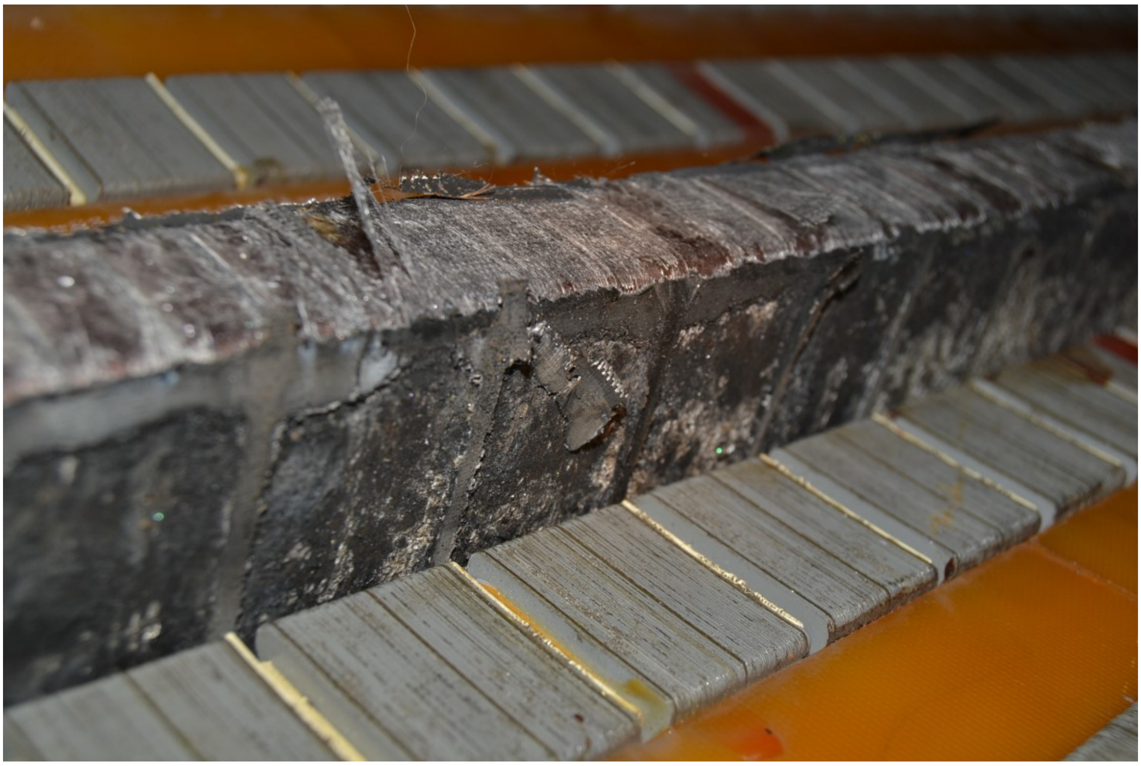

FIGURE 29. The damaged winding bar partially pulled out of slot (Osmo Koponen, 2014)

The damaged bar was in such a position of the winding where voltage stress to the ground is approximately 60 % of the rated phase-to-ground voltage. The position of the damaged bar then indicated that the root cause for the damage was not in inadequate performance of the slot corona protection, stress grading or insulation system of the bar as otherwise the damage would have started in bars with higher voltage stress.

Evidence was found of that the bars had been vibrating in the slots up and down by electromechanical forces because of inadequate support in the slot. The vibrating bars had not been subject to any higher forces than other bars of the stator winding.

The damage caused to the winding bar by abrasion and sparking can be seen in figure 30. The main insulation was damaged from the whole length of the bar.

FIGURE 30. Abrasion damage on the bar surface (Osmo Koponen, 2014)

The likely root cause of the failure was poor design and manufacturing, as the failure occurred only 5 years after commissioning. The bars were not properly supported in slot, probably because of loose fitting, which prevented good gluing in VPI-process. As the bars were not well supported, the electromagnetic forces affecting the bars were able to vibrate and move the bars in the slot. This vibration led to abrasion of the surface in the bar, either directly by mechanical contact to core, or by electrical contact sparking. There was also some loose steel particles found, which might have accelerated the erosion, but were not alone sufficient root cause for the damages. Thermal cycling might have also contributed to the process by further weakening the adhesion of the bar to the slot.

The abrasion led to the erosion of the slot corona protection and main insulation, and eventually electrical breakdown of the insulation and grounding failure. The crater-like erosion can be seen in figure 31.

FIGURE 31. Erosion on the surface of the bar (Osmo Koponen, 2014)

The damaged bar was replaced and the slot-wedging improved, but it was not possible to fully repair the failure mechanism as vibrations continued. The stator winding was eventually rewound about 7 years later, in 2022.

5.2 Case 2: Electrical connection breakdown

The generator of case 2 is a 121 MVA air cooled generator, operated at rated voltage of 10,5 kV. The generator was manufactured in 1994.

In 2021, protection relay tripped the generator due earth fault. After the generator was opened, there was a discovery of melt copper and major contamination of soot. Inspections revealed that a 10 centimeters long piece was missing from a conductor in a connection to a ring busbar, as seen on figure 32.

FIGURE 32. Melt copper connection (Pasi Lehtiniemi, 2021)

The earth fault which alerted the protection relay was in phase W, which was a result of molten copper dripping into the W phase connection bushings below the fault spot in the V phase. The molten copper had probably connected the conductor to ground.

Although the fault spot was destroyed completely, inspections were performed to five similar connections for root cause analysis. It was found that in these connections there was a gap between the two parts, when they should be brazed together. Further inspections revealed pores in other brazed connections as well.

FIGURE 33. Gap between the two parts (Osmo Koponen, 2021)

The likely root cause for the faulting is breakdown of the high voltage connection because of poor manufacturing related to the brazing. There had been increasing vibration problems detected before the breakdown which might have further deteriorated the poor connection, although none were detected before in the NDE (non-drive end) end-winding. The light arc which melt the connection also damaged winding around the fault spot significantly and led to soot contamination.

The copper plates of the connection might have been held together by the insulating system even without the proper brazing. It is possible that as the top bar has come off, the flowing current of the connector has gone through only the bottom bar, which has led to local overheating and eventually breakdown and a light arc, which then has melt the connector and near insulating system.

The construction of another damaged winding-turn connection above the fault spot is presented in figure 34. The insulation of the connector had partially melt.

FIGURE 34. Construction of another damaged connection (Pasi Lehtiniemi, 2021)

The rotor of the generator was also contaminated with soot and had very low insulation resistance values, and had to be transferred to workshop for cleaning and repair.

The damaged bars were rewinded with new bars and support structures. Other affected parts were reconditioned.

5.3 Case 3: Two-phase winding short circuit

The generator of case 3 is 84,9 MVA, air-cooled turbogenerator operated at rated voltage of 10,5 kV. The generator was manufactured in 2006.

In 2022, the generator protection system activated the differential protection function of phases V and W. This means that the current values measured with current transformers from the star point side and the line side did not match. As the difference was detected, the protection relay system shut down the generator. Approximately 20 milliseconds later the system detected also an stator earth fault.

After the shutdown the generator was opened and rotor removed. Visual inspection revealed fault spot on the outer perimeter of the NDE (non-drive end) end-winding, as seen in figure 35.

FIGURE 35. Outer perimeter of the end-winding (Ville Holmstrom, 2022)

The location of the fault spot was inspected to be between two winding bar ends, as seen on figure 35. The bars were found to be the first bar of the phase V line-end and the second bar in phase W line-end. This means the voltage between these bars was at least near the nominal 10,5 kV rated voltage, and the voltage stress was at highest level compared to anywhere else in the winding.

FIGURE 36. Fault spot on the end-winding (Ville Holmstrom, 2022)

Insulation on both bars was found to be punctured and some conducting copper had melt from both bars and was missing, which referred to high current short circuit. The windings near the fault spot were dirty and contaminated with soot, which had resulted in earth faulting. A large melted object was found inside the stator winding-end area below the fault spot, which was analyzed in laboratory to be almost pure copper, which then would suggest no foreign metal object was included in the failure. It was also confirmed by measuring the winding resistance that in comparison to phase U, there was copper missing from phases V and W.

The performed root cause analysis came to conclusion that the most probable root cause was failure caused by a loose component in the winding end support system. In order for a short circuit to occur between the bars, the insulation of the winding bars had to been punctured on both sides. It was found that there had been a winding support block exactly in the middle of the fault spot, as seen on figure 37.

FIGURE 37. Remains of a support block in the middle of the fault spot (Osmo Koponen, 2022)

A possible cause for the puncture would be that the support block between the bars had vibrated and thus eroded the insulation material on the surface of the bar. The support block is made of materials like glass and polyester, which are not magnetic and therefore not affected by the strong magnetic fields present. It is possible that the support block was not properly tightened by GVPI-process and was then affected by the strong cooling air flow created by the fans on the rotor, which caused movement of the block. It is also possible that some hidden weak spot had affected the windings. The generator was eventually renovated and a new stator was installed.

5.4 Case 4: Winding insulation erosion by partial discharges

The generator of case 4 is a 27 MVA, air-cooled turbogenerator operated at rated voltage of 10,5 kV. The generator was manufactured in 2016.

In 2022, protective relay detected an earth fault in phase V. Measurements confirmed a grounding fault in the stator winding, and the rotor was pulled out for further inspections. The fault spot was located in the DE (drive-end) slot exit area, near line-end of the winding. Visual inspection revealed that the insulation of the winding had been damaged by erosion caused by partial discharges. The fault spot is presented in figure 39.

FIGURE 38. Fault spot in the bottom bar slot-exit area (Sami Lehtola, 2022)

The surface of the insulation is visibly damaged with a black burning mark and evidence of significant discharge activity. The fault spot was confirmed by applying 2 kV DC pulse to the coil which resulted in visible spark.

In addition to the grounding fault spot, further inspections revealed multiple similar spots with signs of partial discharges. Approximately 20 spots were found on both NDE and DE winding ends, in the top and bottom bar slot-exit areas, as presented in figure 39.

FIGURE 39. Signs of partial discharge activity in the slot-exit area (Sami Lehtola, 2022)

The likely root cause is poor design, or error in manufacturing process of the discharge protection system, especially in the slot corona protection. There was many spots with traces of partial discharges and multiple spots where discharges had eroded the surface insulation significantly, but no signs of vibration. This would suggest the erosion was from electrical deterioration, which is not normal for a generator that has been in use for just 5-6 years.

The generator was rewound. The original winding was manufactured with GVPI method, and the new winding was manufactured with Resin Rich coils.

6 CONCLUSIONS

Key result of the study was to recognizing that for the generators included, the catastrophic failures due fault mechanisms were not limited to older generators which have worn in use, as there was occurrences of power generation interrupting damages in newer machines. Some contribution to the matter may be in modern operating of the generators, as the generation is optimized for fast changes in electricity price and as the rise in the use of inverted-fed generation from renewables has changed the need for use of rotating machines for grid frequency- and stability-control. These factors may result in continuous thermal cycling, which takes its toll on the machine condition.

The machines built in 2000's also had relatively more problems detected than other decades, as 30 percent of generators included from that era had detected problems. It is also possible that the machines built in 2010's are also more prone to similar problems, which are still to occur or have not been yet detected. The root cause might be changes in modern manufacturing technology, as the general trend lately has been to lower manufacturing costs, which then may have led to deterioration of the manufacturing quality. This has been noted in other similar studies as well, such as VGB database evaluation in 2016, where machines built in 2000's represented approximately 45 percent of machines with detected problems (Bomba, 2016).

However the problems detected had no clear dependency on any generator manufacturer, as problems were detected from all manufacturers and types of generators. One manufacturer (manufacturer 9) did stand out slightly, as in 8 out of 13 (61,5 %) machines included, there was detected problems.

It was observed that two-pole generators had notably higher share of wedges loosening, as the wedge problems represented 32 percent out of all problems detected. This is not surprising as the higher rotating speed results in more stress to the wedging. Loosening of wedges was highlighted in older two-pole machines which have been worn in use. For example, in two-pole machines built in 1977, there was loosening detected in 5 out of 7 generators. Contribution to the matter may be that in this material, the four-pole generators included are small in rated power when compared to the two-pole machines, which reduces the stress to wedging. In smaller machines the currents in winding are lesser, and therefore so are the forces affecting the winding bars.

The collection of condition monitoring data should be continued to gain more experience of common failure mechanisms. Further study could also focus on contribution of different insulation designs (Resin Rich versus GVPI) and cooling gases (air versus hydrogen).

REFERENCES

Ember. 2024. European Electricity Review 2024. Read on 29.2.2024
https://ember-climate.org/insights/research/european-electricity-review-2024/

European Commission. 2023. Actions to accelerate the roll-out of electricity grids. Press release. Read on 1.3.2024.
https://ec.europa.eu/commission/presscorner/detail/en/ip_23_6044

International Energy Agency. 2024. Electricity 2024. Read on 1.3.2024.
https://www.iea.org/reports/electricity-2024

International Atomic Energy Agency. 2023. Nuclear Innovations for Net Zero. News article. Read on 5.3.2024.
https://www.iaea.org/newscenter/news/2023-scientific-forum-nuclear-innovations-for-net-zero

International Hydropower Association. 2023. International community sets new ambition for hydropower to enable sustainable growth. News Article. Read on 5.3.2024.
https://www.hydropower.org/news/international-community-sets-new-ambition-for-hydropower-to-enable-sustainable-growth

GE Steam power. Gigatop 4-pole generator. Referenced 27.11.2023.
https://www.ge.com/steam-power/products/generators/gigatop-4-pole

Krempel GmbH. Roebel transposition. Referenced 21.12.2023.
https://krempel.com/en/solutions/energy/generators

Klempner, G., Kerszenbaum, I. 2004. Operation and maintenance of large turbo-generators. Hoboken: A John Wiley & Sons, inc. Publication.

Tavner, P., Ran, L., Penman, J., Sedding, H. 2008. Condition Monitoring of Rotating Electrical Machines. London: The Institution of Engineering and Technology.

Timperley, J. 2021. Preventing failures in isolated phase bus. Iris Rotating Machine Conference. Read on 22.11.2023.
https://irispower.com/learning-centre/preventing-failures-in-isolated-phase-bus/

Öettl, F. Lachance, M. 2023. Electromagnetic Imperfection Measurements for Stator Core Condition Assessment. NETA World technical journal. Referenced 6.2.2024.
https://netaworldjournal.org/electromagnetic-imperfection-measurements-for-stator-core-condition-assessment/

Stone, G., Boulter, E., Culbert, I. Dhirani, H. 2004. Electrical insulation for rotating machines: Design, Evaluation, Aging, Testing and repair. 1st edition. Hoboken: A John Wiley & Sons, inc. Publication.

Engvall, K., Csaba, G. 2019. Nordic Nuclear Power Generator Stator Vibrations. Energiforsk. Referenced 7.2.2024.
https://energiforsk.se/program/vibrationer-i-karnkraft/rapporter/nordic-nuclear-power-generator-stator-vibrations-2019-621/

The Gund Company. Turbine generator stator insulation. Referenced 27.11.2023.
https://thegundcompany.com/generators/

Mitsubishi Power. High Heat Transmission. Referenced 27.11.2023.
https://power.mhi.com/products/generators/technology/large-capacity-technology

ABB. Insulation System for Rotating Electrical Machines Brochure. Referenced 5.12.2023.
https://library.abb.com/d/9AKK108467A2886

IEEE Region 5. Generator Basics. Referenced 8.2.2024.
https://r5.ieee.org/houston/wp-content/uploads/sites/32/2016/10/2016-09-27-2-Generator-Basics-1.pdf

Engineering Search Engine. Generator Excitation and Voltage Control. Blog post. Referenced 24.2.2024.
https://emadrlc.blogspot.com/2013/01/chapter-3-generator-excitation-and.html

Draper, R., Ramsauer, F., Lemesch, G. 2018. Insulation Comparison: VPI produced versus Resin Rich. Iris Rotating Machine Conference. Read on 20.11.2023.
https://irispower.com/learning-centre/insulation-comparison-vpi-produced-versus-resin-rich/draper-insulation-system-comparison-vpi-versus-resin-rich/

Stone, G., Boulter, E., Culbert, I. Dhirani, H. 2014. Electrical insulation for rotating machines: Design, Evaluation, Aging, Testing and repair. 2nd edition. Hoboken: A John Wiley & Sons, inc. Publication.

Koponen, O. 2014. Internal report. TGS Finland Oy.

Lehtiniemi, P. 2021. Internal report. TGS Finland Oy.

Holmstrom, V. 2022. Internal report. TGS Finland Oy.

Lehtola, S. 2022. Internal report. TGS Finland Oy.

Bomba, R. 2016. New design criteria for the life time of turbogenerators. VGB KELI Conference. Presentation.

APPENDICES

Appendix 1. Surface erosion in slot exit area

FIGURE 40. Surface erosion from discharges in slot exit area (Veeti Korpelainen, 2023)

Appendix 2. Surface damage in winding slot-exit area

FIGURE 41. Major surface damage in winding slot-exit area (Veeti Korpelainen, 2023)