OULUN AMMATTIKORKEAKOULU

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FAILURE MECHANISMS OF TURBO GENERATOR ROTOR

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Opinnäytetyön tavoitteena oli tutkia ja perehtyä 2- ja 4-napaisten turbogeneraattoreiden roottorien vikaantumismekanismeihin ja luoda kategorisointi, jonka avulla roottoreiden vikaantumistapauksia pystytään tarkastelemaan mm. generaattorin tehon, jännitteen, napaluvun, valmistajan, valmistusvuoden tai käyttötavan mukaan.

Työ oli rakenteeltaan tutkimusmainen. Työssä perehdytään sähkön tuotantoon, turbogeneraattorin rakenteeseen, roottorin kunnonvalvontaan, vikaantumismekanismeihin, sekä käydään läpi kiinnostavimpia esimerkkitapauksia. Työ pohjautuu pääasiassa alan kirjallisuuteen ja TGS Finland Oy:n sisäiseen materiaaliin.

Turbogeneraattorin roottorilla on useita eri vikaantumismekanismeja ja niiden seuraaminen ja tunnistaminen on elintärkeää generaattorin luotettavan toiminnan takaamiseksi. Roottorin, ja sitä kautta generaattorin elinikään ja toimintavarmuuteen voidaan vaikuttaa säännöllisellä kunnonvalvonnalla, jossa havaitut vikaantumismekanismit tunnistetaan ja korjataan.

Asiasanat: generaattori, roottori, kunnossapito, kunnonvalvonta

ABSTRACT

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Author: Juho Hussa
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The aim of the thesis was to investigate and become familiar with the failure mechanisms of the rotors of 2- and 4-pole turbo generators and to create a categorization, with the help of which the cases of rotor failure can be examined e.g. according to generator power, voltage, number of poles, manufacturer, year of manufacture or usage.

The thesis was research-like in structure. In the thesis, we familiarize ourselves with electricity production, the structure of the turbo generator, condition monitoring of the rotor, failure mechanisms, and we go through the most interesting example cases. The work is mainly based on the literature of the field and TGS Finland Oy's internal material.

The rotor of the turbo generator has several different failure mechanisms, and monitoring and identifying them is vital to guarantee reliable operation of the generator. The lifetime and operational reliability of the rotor, and thus the generator, can be affected by regular condition monitoring, where the detected failure mechanisms are identified and repaired.

Keywords: generator, rotor, maintenance, condition monitoring

ACKNOWLEDGEMENTS

The thesis was commissioned by TGS Finland Oy. Engineer Sami Lehtola has acted as examiner of the thesis. Principal lecturer Ensio Sieppi from Oulu University of Applied Sciences acted as supervisor of the thesis and lecturer Marjo Heikkinen acted as language instructor. I would like to thank all of them, as well as other TGS's specialists, from whom I have received advice during my thesis.

In Oulu 13 December 2023

Juho Hussa

CONTENTS

ABBREVIATIONS

Hz	Hertz
LI	Limited inspection
MO	Major overhaul
MVA	Megavolt ampere
NDT	Non-destructive testing
PI	Polarization index
PMG	Permanent magnet generator
RFM	Rotor flux measurement
RPM	Rounds per minute
RSO	Recurrent surge oscillograph
SC	Safety check
TWh	Terawatt hour
µm	Micrometre

1 INTRODUCTION

The commissioner of the thesis was TGS Finland Oy, whose services include, among others, turbine and generator service, maintenance, and condition monitoring. The purpose of the thesis was to investigate the failure mechanisms of 2- and 4-pole turbo generator rotors over the past 13 years and to create a categorization of problems occurring in rotors. The categorization was done so that the material can be viewed, e.g., in terms of the generators power, year of manufacture, manufacturer, number of poles, voltage or type of use.

At the beginning of the thesis, electricity production in Finland and the world, the structure of turbo generators and their maintenance and condition monitoring are discussed, which includes electronic condition monitoring measurements and inspections of the rotor. After this, the different failure mechanisms of the rotor and how they affect the operation of the rotor are presented. At the end, a categorization of faults occurring in generator rotors is presented and a few interesting example cases are reviewed.

2 ELECTRICITY PRODUCTION IN THE WORLD AND IN FINLAND

Fossil fuels continue to be the primary contributor to electricity production on a global scale. As of 2021, coal comprised around 35 percent of the overall power mix, with natural gas following closely at 24 percent. In the same year, China, India, and the United States were responsible for the largest share of coal utilization for generating electricity. Figure 1 shows electricity production in the world by energy source in 2021. (1).

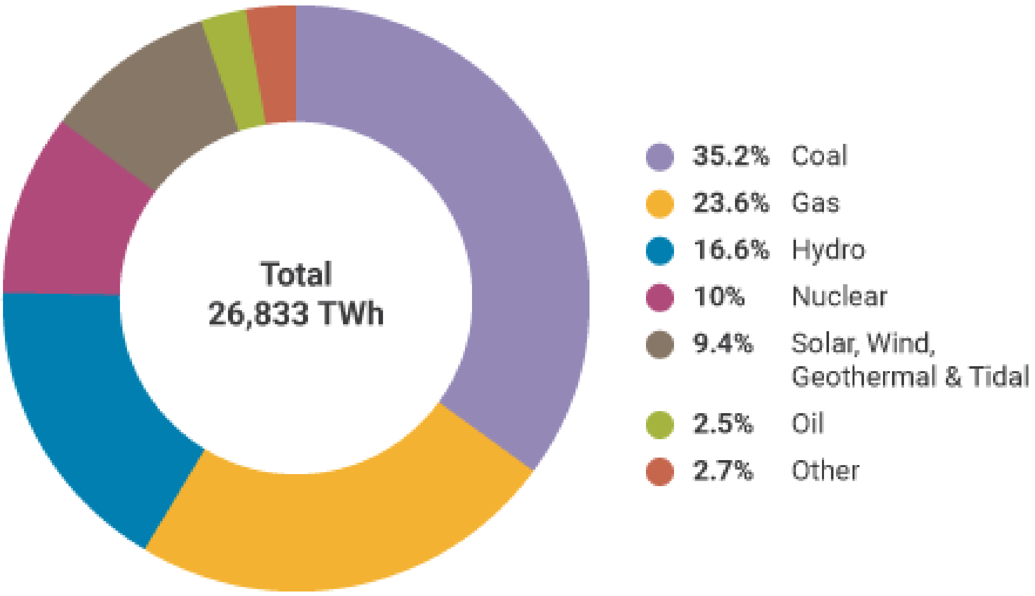


FIGURE 1. Electricity production by energy source 2021 (2)

However, despite the dominance of fossil fuels, there has been a noteworthy increase in the proportion of renewable energy sources in the global electricity sector. This growth can be attributed to the concerted efforts of governments to combat climate change and the declining costs associated with renewable energy technologies. Projections suggest that by 2035, renewables will surpass fossil fuels as the leading power source. (1).

When it comes to electricity consumption, China takes the lead as the world's largest consumer, requiring a staggering 7,800 terawatt-hours annually. It is crucial to note that while China's economy is robust and its population substantial, its per capita electricity consumption is nearly ten times lower than that of Iceland. However, Iceland's power stems predominantly from clean energy sources. (1.)

In Finland there are approximately 120 electricity producing companies and about 400 power plants, more than half of which are hydropower plants. In addition to this, electricity is also imported from the Nordic markets, mainly from Sweden and Norway. Almost a third of Finland's energy production takes place in cogeneration power plants, where the heat generated during electricity production can be used as district heating. In this way, the efficiency is as high as possible. (3.)

In Finland, electricity is produced in a variety of ways using different forms of production, the largest of which are nuclear power, hydropower, biomass and wind power. A versatile and distributed electricity production structure increases the security of electricity procurement. The share of hydropower in electricity production depends on annual water situation. Figure 2 shows electricity production in Finland by energy source in 2022. (3.)

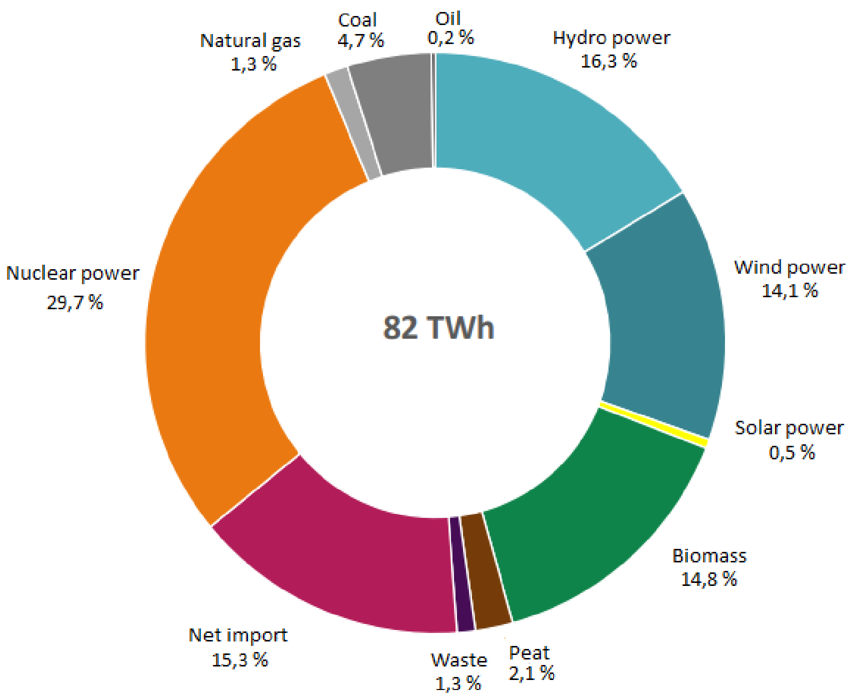


FIGURE 2. Electricity production in Finland by energy source 2022 (4)

Electricity production and consumption must constantly be in balance, because electricity cannot yet be stored on a large scale with current technology. For this reason, a regulating power is needed that is able to react to fluctuations between production and consumption. In addition, the regulating power enables preparation for possible disruptions in production. Most of Finland's regulating power is produced by hydropower or imported from other Nordic countries that have easily adjustable hydropower production. (3.)

3 TURBO GENERATOR STRUCTURE

In a power plant, the actual part that produces electricity is the generator, which in this case is rotated by a steam or gas turbine. Turbine-generator combinations produce almost all of the consumed electrical energy. A turbo generator is a general name for a synchronous generator whose power source is a steam or gas turbine.

Turbo generators are generally used in nuclear, bio and fossil fueled power plants (figure 3). Hot gases, the Sun or geothermal energy can also be used as an energy source. The size of the generator varies from small generators of a few megawatts to generators of up to 1900 megawatts. (5, p. 33).

FIGURE 3. Turbo generator header (4)

3.1 Turbine

A turbine is a rotating machine that converts the kinetic energy of a flowing substance into rotational energy. In a steam turbine (figure 4), the steam produced in a steam boiler pushes the turbine blades under pressure, making the turbine rotate, while in a gas turbine (figure 5), the mixture of air and fuel is compressed and burned at a very hot temperature, producing hot gas. The hot gas flows under pressure through the turbine blades, causing the turbine to spin. In all modern gas turbines, the pressurized gas is created by the burning of a fuel like natural gas, kerosene, propane or jet fuel. (7).

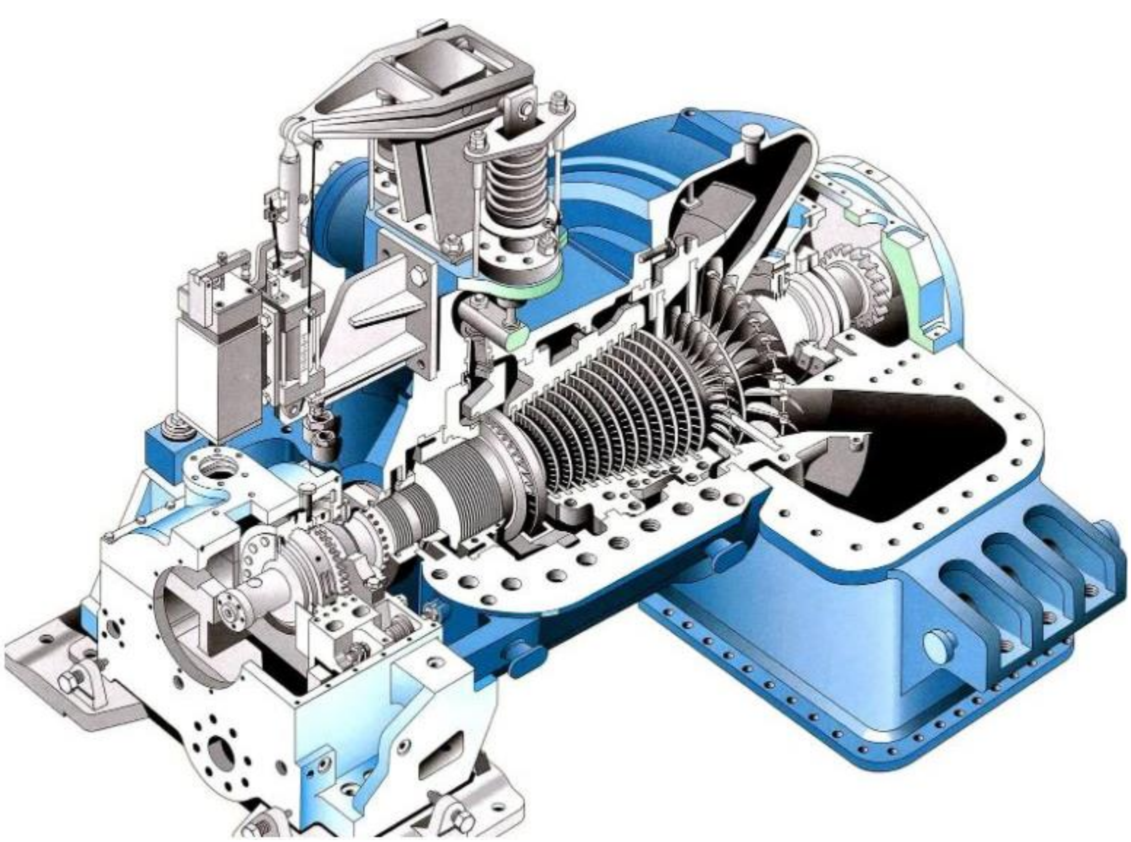


FIGURE 4. Steam turbine cross-section (8)

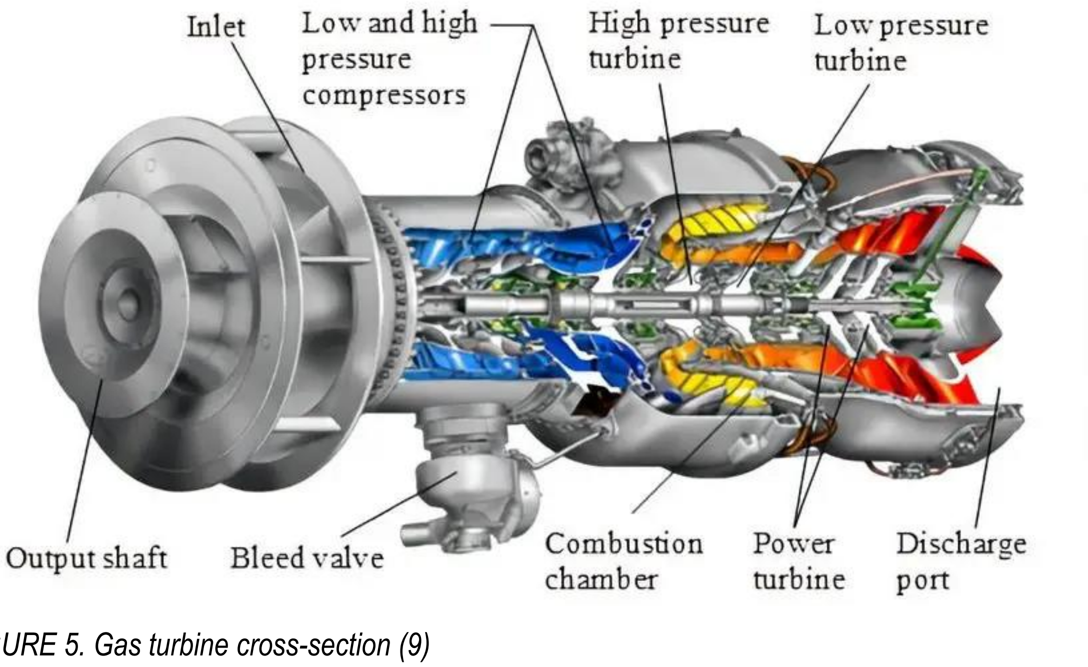


FIGURE 5. Gas turbine cross-section (9)

3.2 Synchronous generator

A Synchronous generator (figure 6) is a machine that converts mechanical kinetic energy into electrical energy. The generator consists of two main components, the stator and the rotor. The rotor of a synchronous generator is made to rotate with the help of an external power machine, in this case a steam or gas turbine. When direct current is fed to the magnetizing coil of the rotor using brushes or slip rings, a magnetic flux develops in the machine. As the rotor rotates, the magnetic flux lines intersect the stator winding coils, causing a sinusoidal three-phase voltage to be induced in the stator winding. (10, pp. 19-21).

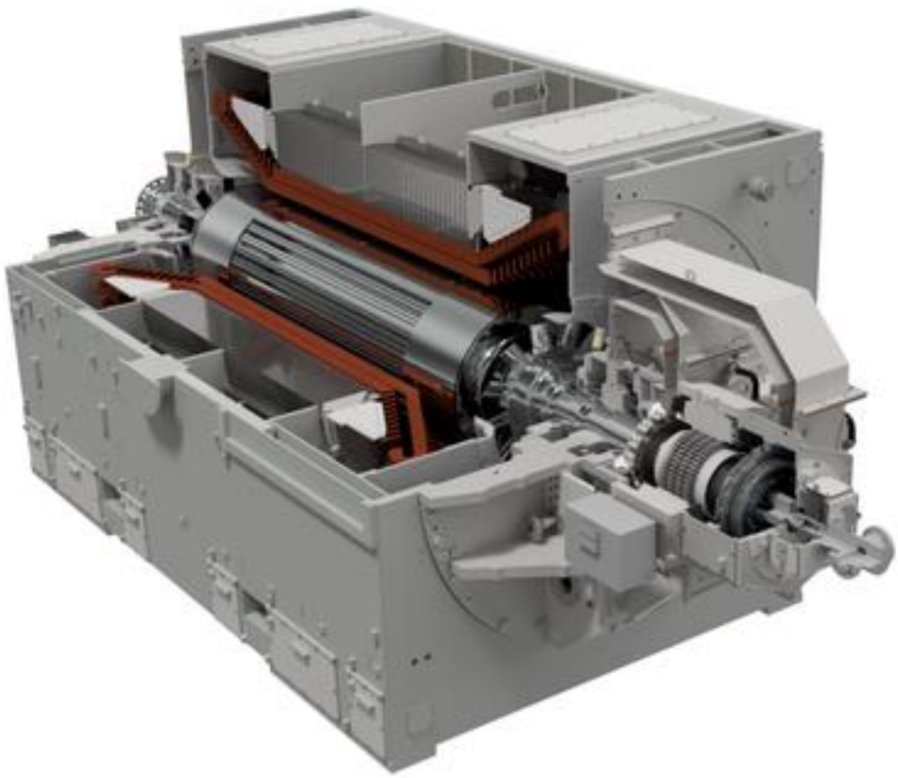


FIGURE 6. Synchronous generator cross-section (11)

3.2.1 Stator

The stator of the generator consists of three main components, which are the frame, stator winding and stator core.

The purpose of the stator frame (figure 7) is to support the iron core and act as a pressure vessel in hydrogen-cooled generators. The frame must be able to withstand the weight of the generator, the force caused by the rotating movement and the network and generator faults that can momentarily cause very large forces. It must also be able to move with the thermal expansion and contraction of the iron core. (5, p. 39).

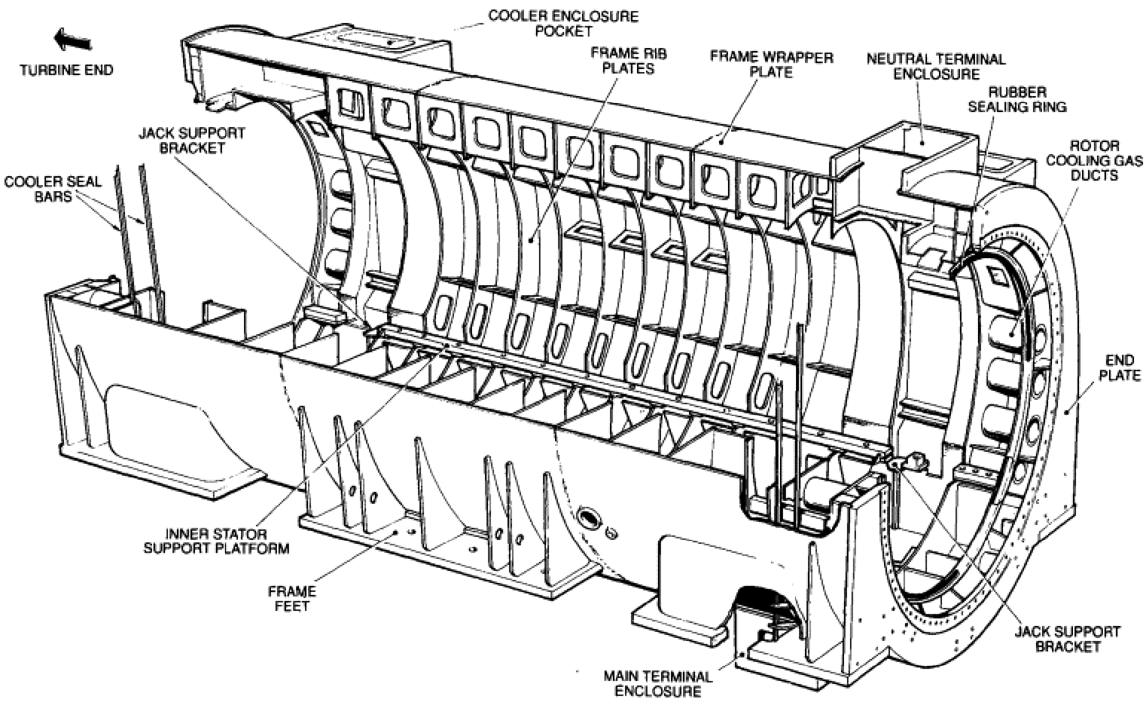


FIGURE 7. Stator frame (12)

The stator winding consists of winding bars or coils (figure 8) made of copper. The winding is placed symmetrically in the grooves in the stator core. Each groove has two bars or coils on top of each other. To reduce eddy currents and iron losses, the winding bars consist of several copper strands isolated from each other and not one large copper rod. In winding bar, the copper strands are usually connected to each other at both ends of the bar, unlike in winding coils, where the strands are kept separate from each other. (5, pp. 35-40).

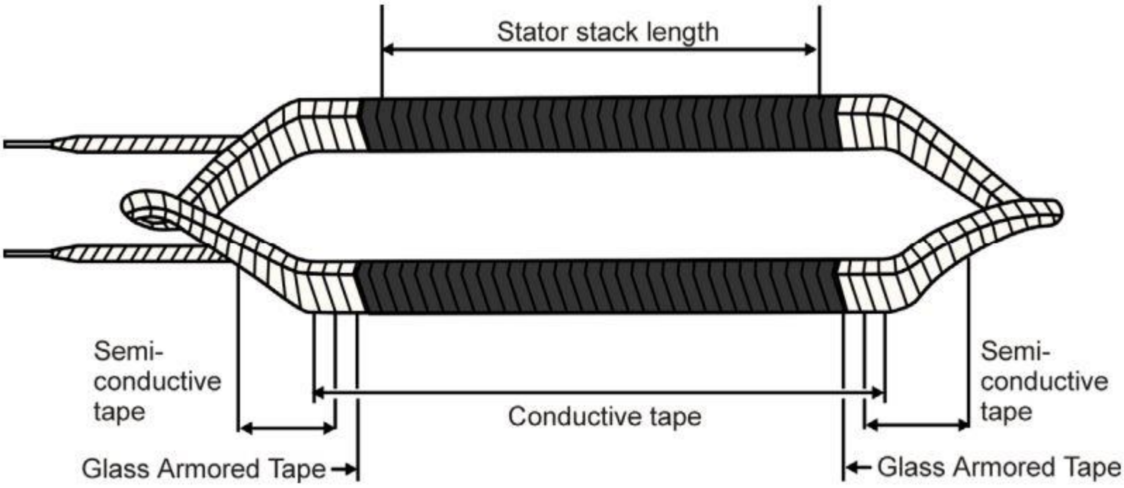


FIGURE 8. Stator winding coil (13)

The purpose of the stator core is to hold the winding in place in its grooves and conduct the magnetic flux. The full circumference consists of several segmented steel plates (figure 9), which are usually 10–24 pieces. This is affected by whether the generator is two- or four-pole. (5, pp. 35-40).

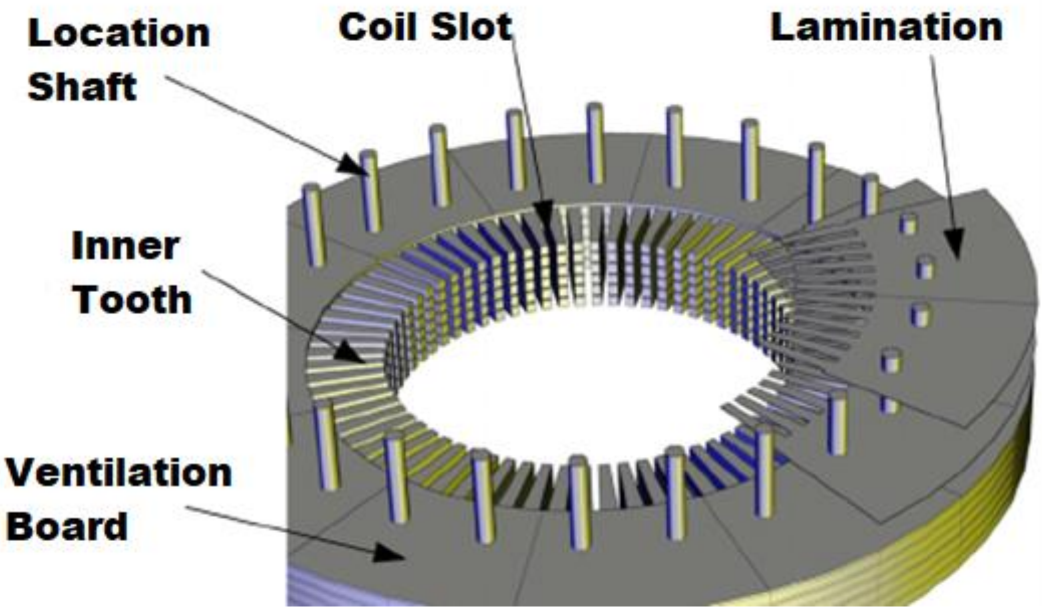


FIGURE 9. Stator core laminations (14)

3.2.2 Rotor

Synchronous generators can be divided according to rotor type into two categories: salient pole and cylindrical pole generators. The rotor of a salient pole machine (figure 10) consists of separate poles around which the magnetizing winding is wound. The rotor winding of a cylindrical pole machine (figure 11), on the other hand, is placed in the rotor slots. Turbo generators are almost without exception two- or four-pole machines, and their rotation speeds at a frequency of 50 Hz are 1500 rpm with 4 pole machines and 3000 rpm with 2 pole machines.

More often than not turbo generators are cylindrical 2-pole machines, while multi-pole synchronous generators, such as low-speed hydroelectric generators, are salient pole machines. In addition to the previous ones, especially in wind turbines, other types of rotor structures are also used. (10. pp. 19-21).

FIGURE 10. Salient pole rotor (15)

FIGURE 11. Cylindrical pole rotor (16)

3.2.3 Magnetizing

In order for the generator to produce electricity, magnetizing current must be supplied to its rotor winding. The voltage regulation of the generator is done by changing the magnitude of this current. This is provided by the excitation system. By adjusting the magnetizing current, the terminal voltage of the generator is affected and thereby also the power factor and reactive power when the generator is connected to the power grid. (5, p. 106)

Based on the method of magnetization synchronous generators can be divided into three different groups: static (solid state), brushless (shaft mounted) and rotating (generator driven or independent). Each method of magnetization has its own advantages and disadvantages, and the choice depends on the purpose and power requirements of the generator. (5, p. 104).

In static magnetization, the components related to the production and regulation of the magnetizing current remain in place. The equipment needs a separate magnetizing transformer, with the help of which the energy obtained from the external voltage source is changed to suit the magnetizing equipment. The magnetizing current is fed with help of carbon brushes to the rotor slip rings, which are connected to the rotor winding. (5, p. 104).

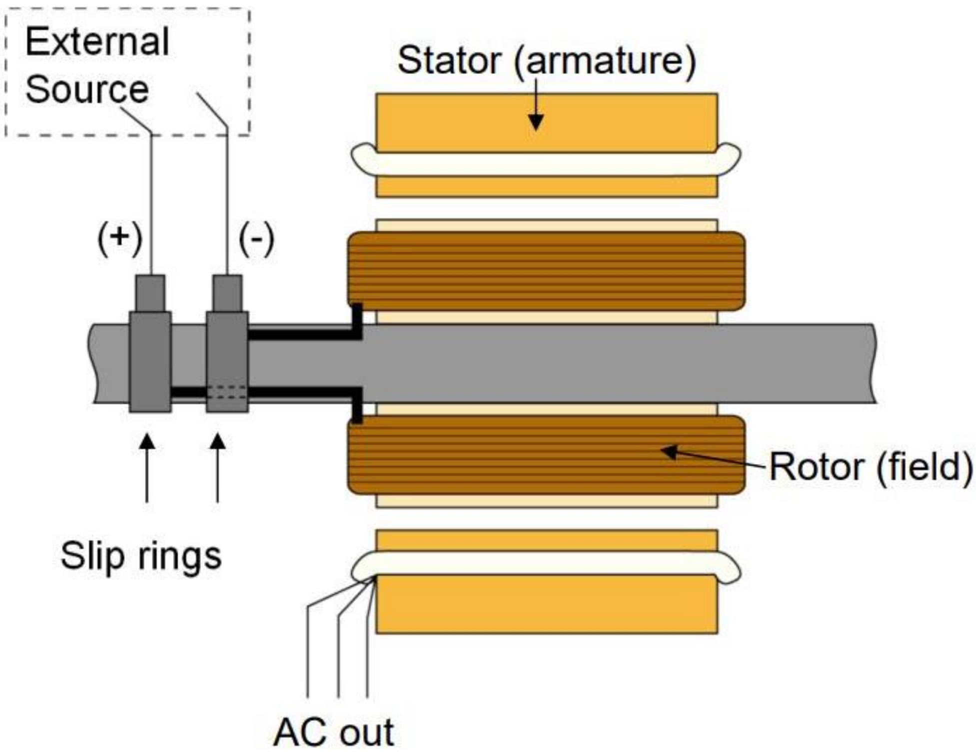


FIGURE 12. Static magnetization (16)

Brushless magnetization is the most common and efficient way to magnetize higher power generators such as turbo generators. In brushless magnetization, the magnetizing current is produced by an external electrical source, or another generator connected to the same shaft and fed to the rotor without carbon brushes or a slip ring. (5, pp. 103-106).

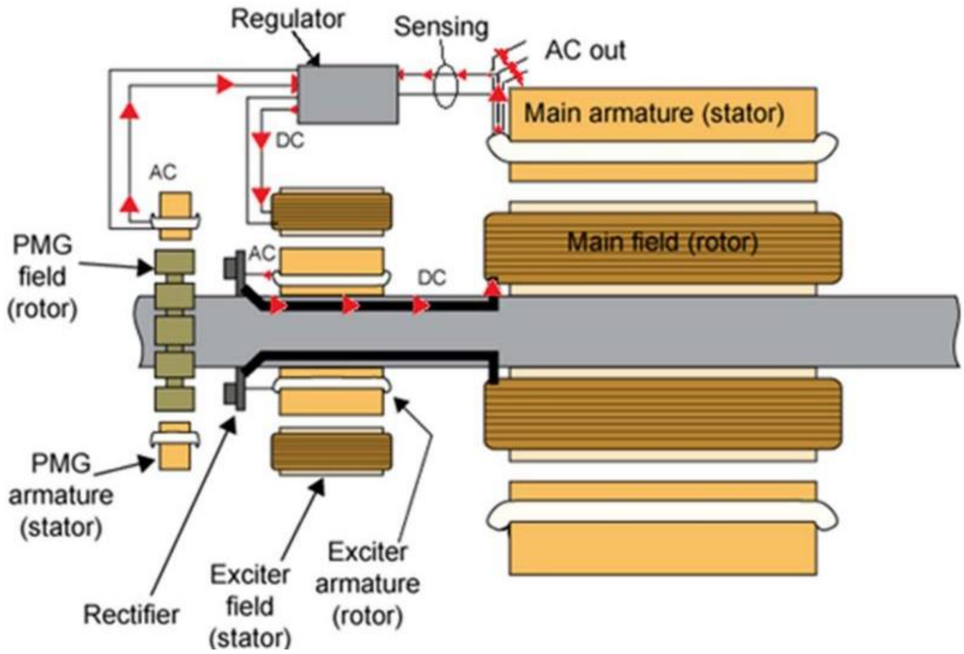


FIGURE 13. Brushless magnetization with permanent magnet generator (PMG) (16)

In rotating magnetization, the magnetic field of the generator is produced by means of a rotating rotor. This technique is commonly used in both brushed and brushless generators. In rotating magnetization there is also an exciter machine on the same shaft, with which the current needed by the magnetizing machine is produced. (5, p. 104).

4 ROTOR CONDITION MONITORING MEASUREMENTS

Condition monitoring of the generator is extremely important to ensure its functionality and reliability. Regular condition monitoring helps detect potential damage, problems or signs of wear in time, before they cause serious damage. This helps to avoid unexpected expensive repairs or even complete failure of the generator.

Generator condition monitoring also helps to optimize its performance and efficiency. For example, regular inspection and cleaning can prevent contamination that can impair cooling or cause components to overheat. Generator offline inspections can be divided into three different levels based on scope: Safety Check (SC), Limited Inspection (LI) and Major Overhaul (MO).

Safety checks are performed in the internal between major overhauls. Safety check consists of removing inspection hatches and visual inspection of accessible parts. (17.)

Limited inspection should be performed about one or two years before the planned major overhaul to prepare and plan the activities needed. Safety check consists in addition to the above removing the bearings upper half, end gables and winding covers. In addition, less extensive diagnostic testing of electrical circuit integrity and insulation is performed. (17.)

Major overhaul is the most important part of the maintenance plan. It enables comprehensive inspection and diagnosis of all critical components and cleaning and renovation. Major overhaul consists of removing bearings, winding covers, rotor and cooler. All parts are checked visually, and diagnostic tests of critical components are performed. (17.)

Figure 14 shows that major overhauls can identify 80% of the failure modes and detect an additional 15%. The remaining 5% can only be identified during operation. A limited inspection can identify 25% and detect an additional 5% of the failure modes. The remaining 70% are not detectable by a limited inspection. A safety check can only identify 15% and detect an additional 10% of the failure modes. The remaining 75% are not detectable by a safety check. (17.)

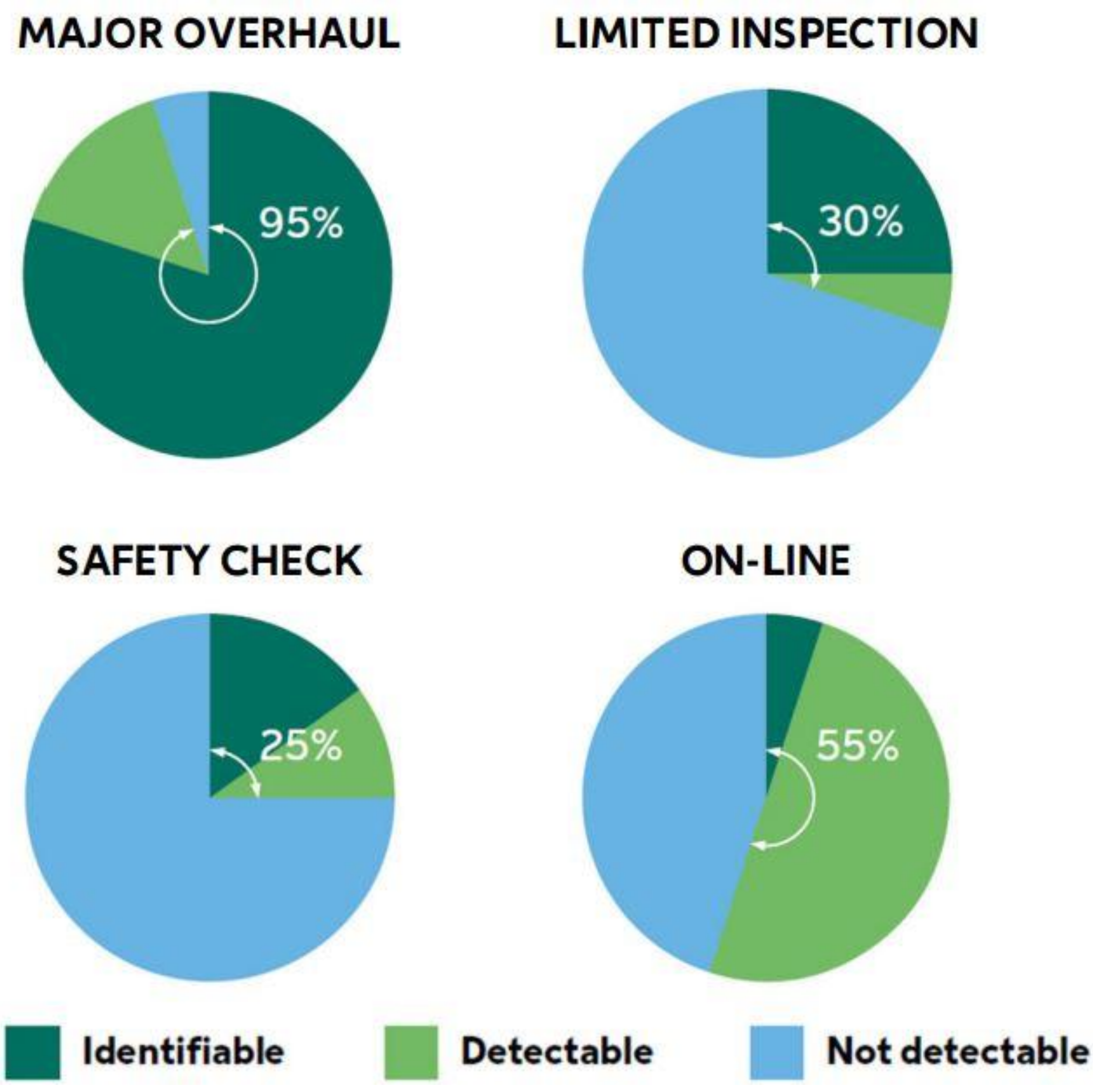


FIGURE 14. The ability of Inspection level to detect and identify failure modes (17)

4.1 Online measurements

Online measurements are performed on a running generator connected to the grid. Those can be used to monitor the condition of the generator regularly without interrupting production. With continuous or periodic data collection, trend monitoring can be performed, which can be used to predict and monitor developing failure situations. One of the most important variables in online measurements is the driving situation of the generator at the time of measurement. With the help of high-quality trend monitoring, temperature and load dependence in the driving situation can also be determined. (18.)

4.1.1 Rotor flux measurement

The purpose of rotor flux measurement (RFM) is to detect possible turn-to-turn fault in the main rotor winding, i.e. conductive connection between the turns of the winding. Turn-to-turn fault occurs in the rotor when the insulation between the windings fails and the windings touch each other. It can be caused by damage to the insulation of the winding, loosening of the winding in the grooves, deformation of the end winding, dirt or even a foreign object. To carry out the measurement, a coil acting as a sensor is permanently installed in the air gap between the stator and the rotor, and the rotor pole induces a voltage in it. Installing the sensor requires pulling out the rotor. In the measurement results, the magnetic fluxes caused by each winding coil of the positive and negative pole of the rotor appear as separate voltage spikes (figure 15).

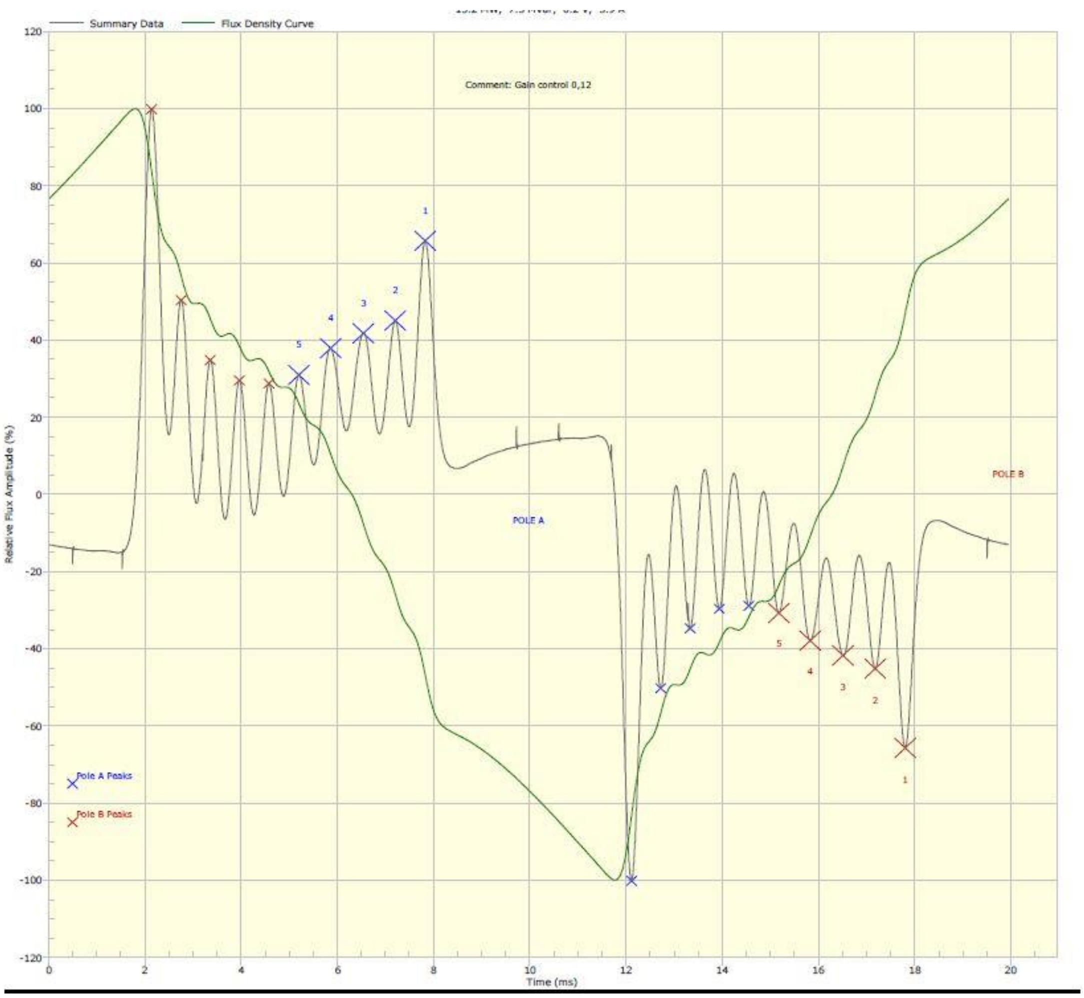


FIGURE 15. RFA measurement results (19)

Usually, coils that have peak to peak difference larger than 3% compared to the same coil on another pole, may be considered to have shorted turns. A rotor-specific threshold limit can also be calculated for the rotor using formula 1. (20.)

$$\frac{100\%}{n} * 0{,}6 \qquad \text{(FORMULA 1)}$$

in which

n is the number of winding turns in coil

4.1.2 Shaft voltage measurement

In synchronous machines, the mutual asymmetry of the phase windings, the eccentricity of the rotor air gap, turn-to-turn fault of the rotor winding or magnetizing equipment power electronics fault can induce a voltage between the ends of the rotor shaft (21, p. 405).

The purpose of shaft voltage measurement is to ensure that the bearing insulation and the shaft grounding system work as planned. When the generator is running, a voltage is generated on the rotor shaft, and if the rotor is not grounded, the current passing through the rotor's bearings to the ground can increase (figure 16). Too high shaft voltage is harmful if it grows too close to the break-down voltage of the oil film. (18.)

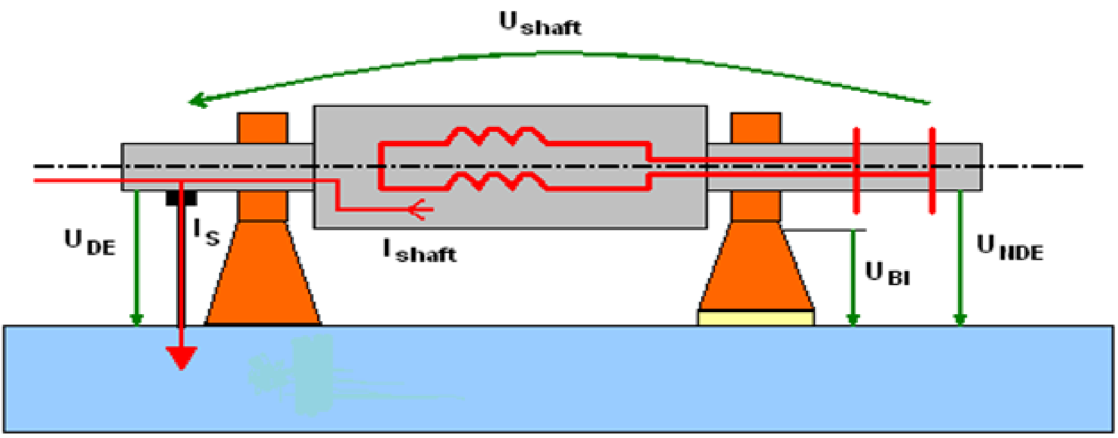


FIGURE 16. Generator's basic arrangement of the shaft mechanism (17)

The rotor shaft is grounded with the help of grounding carbons. The ground carbon is normally placed in a rack between the turbine and the generator on the rotor shaft, and its other end is connected to the power plant's ground rail. The condition of the grounding is determined by measuring the voltage across the grounding carbon and the current passing through it. It is also possible to install online measurement in the earthing carbon, so that the condition of the earthing can be continuously monitored from the control room. (18.)

4.2 Offline measurements

Offline measurements are performed on a stopped and disconnected generator. The advantage of offline measurements is that they can be used to inspect generator's condition more accurately that online measurements. The benefits of offline measurements are also the lack of interference compared to online measurements. Disturbances from outside the generator do not affect the measurement, because the generator is disconnected from the power grid. Offline measurements also enable a much wider visual inspection. However, the measurement method is significantly slower and more expensive. This is mainly due to having to run the generator down from production. Some measurements also require disassembling the generator and pulling out the rotor. In addition, some measurements require an external voltage source and portable measuring equipment. (18.)

4.2.1 Resistance measurement

The purpose of the resistance measurement is to determine that there are no breaks or bad connections in the winding. Depending on the machine structure, the measurement can be performed for the main stator, the main rotor, the stator and rotor of the magnetizing machine, and the stator winding of the permanent magnet generator (PMG). (18.)

The measurement is usually performed using a four-wire DC resistance meter. In order for the results to be comparable, the obtained measurement results are reduced by formula 2 to the temperature of the factory measurement results, usually 20 °C. When comparing measurement results, a 2% change is considered a significant change. (18.)

$$\rho = \rho 0(1 + \alpha \Delta \mathrm{T}) \qquad \text{(FORMULA 2)}$$

in which

$\rho 0$ is the original resistivity

α is the temperature coefficient of resistivity (3.9×10^{-3} in copper)
ΔT is the temperature change

4.2.2 Insulation resistance measurement

The purpose of the insulation resistance measurement is to determine that the rotor winding is not, for example, due to a break in the main insulation in a ground or phase fault, and that the winding is not damp or dirty. Depending on the machine structure, the measurement can be performed for the main stator, the main rotor, the stator and rotor of the magnetizing machine, and the stator winding of the PMG. (18.)

The measurement is carried out by applying DC voltage to the winding of the measured object with an insulation resistance meter. The rotor measuring voltage is usually applied for 1 minute, from which 15 s and 1 min values are recorded. (18.)

In evaluating the results of insulation resistance measurement, the normal range depends on the type of winding and the measurement conditions. The polarization index is calculated from the measurement results with formula 3. (18.)

$$PI = \frac{60s}{15s} \qquad \text{(FORMULA 3)}$$

in which
60s is the insulation resistance value at 60 seconds
15s is the insulation resistance value at 15 seconds

The polarization index of the rotor winding should be more than 1,3 for clean and dry insulation. (17.)

4.2.3 Impedance measurement

The purpose of the impedance measurement is to reveal a potential turn-to-turn fault in the main rotor winding, i.e. a conductive connection between the turns of the winding. The measurement results are affected by whether the rotor is inside or outside at the time of measurement. (18.)

The measurement is performed by feeding alternating current through the rotor winding, and at the same time the voltage acting across the winding is measured. The current is increased step by step to its maximum and brought back to zero with similar steps. From the measurement results, impedance is plotted as a function of current (figure 17). (18.)

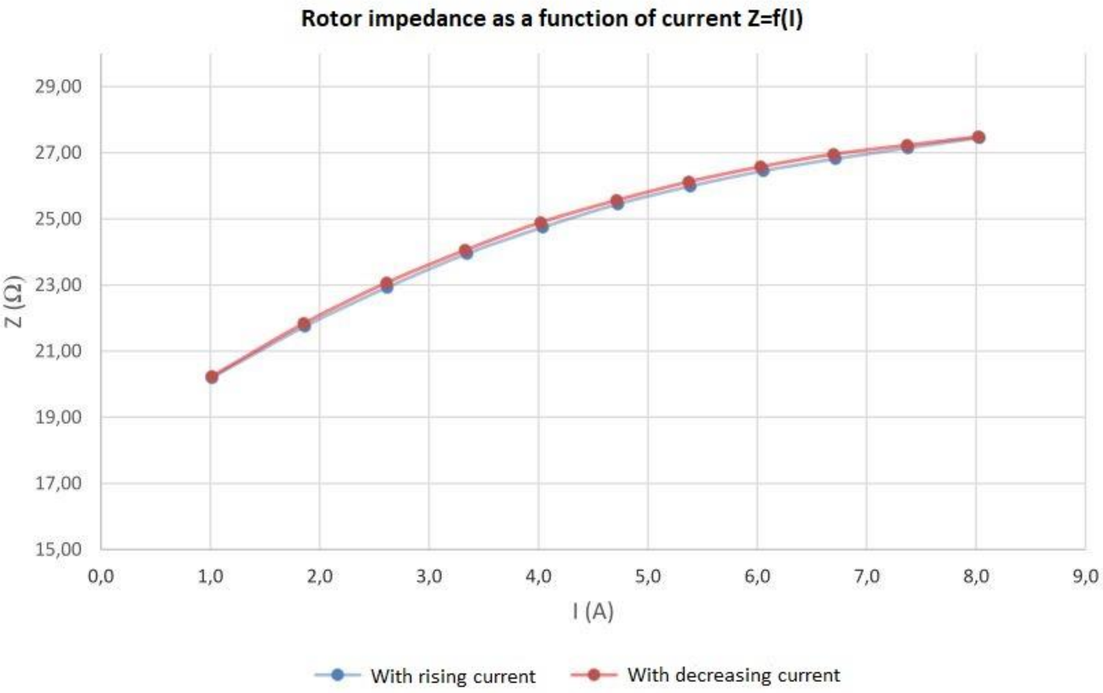


FIGURE 17. Impedance of the rotor in good condition as a function of current (19)

The method is based on the assumption that the fault impedance of a possible turn-to-turn fault is not stable, but depends on the magnitude of the voltage acting at the fault location, as well as the heating effect of the current passing through the fault. In case of fault, step changes or other types of value variation occur in the measurement result, while in a completely healthy winding, the curves measured with rising and falling current run either next to each other or on top of each other without significant variation. (18.)

Impedance measurement can also be performed per pole, where alternating current is fed to the rotor winding and the voltage acting across each pole is measured separately. With the help of the obtained measurement results, a mutual comparison can be made between the poles.

4.2.4 Impedance measurement as a function of rotational speed

In the measurement of impedance and insulation resistance as a function of rotation speed, the aim is to find out the turn-to-turn and earth faults of the rotor winding, which are caused by the movement of the rotor structure when the rotation speed changes. In the measurement, the alternating voltage is fed to the rotor winding, after which the voltage, current and insulation resistance are measured as a function of the rotation speed. The impedance curve is continuous on a machine in good condition, either decreasing or increasing depending on the characteristics of the damping coil. (18.)

4.2.5 RSO measurement

As in impedance measurement the purpose of the RSO measurement is to reveal a potential turn-to-turn fault in the main rotor winding, i.e. a conductive connection between the turns of the winding. Also the RSO measurement can be performed with the rotor inside or outside the machine. (18.)

In the measurement, voltage pulses with a fast rise time are fed to the winding of the main rotor. Pulses are fed alternately to both ends of the winding, and the resulting response is registered with an oscilloscope. The responses of pulses fed from different ends are compared by superimposing the curves. Normally, there should be no significant difference, a significant difference in the curves (figure 18) indicates a turn-to-turn fault of the winding or other asymmetry of the winding. (18.)

FIGURE 18. Direct turn-to-turn fault detected by RSO measurement (22)

Turn-to-turn faults are sometimes more difficult to detect in completely offline measurements, because when the rotor is rotating, the centrifugal forces presses the winding turns more tightly against each other, so the fault appears more easily than when the rotor is stationary. In some cases, turn-to-turn faults are not detectable at all by resistance measurement when the machine is turned off.

Both RSO measurement and impedance measurement measure the same thing with two different methods, and the measurements support each other well. (18.)

4.2.6 Diode bridge

Inspection measurements are performed on the rectifier diodes of the magnetizing machine, the purpose of which is to find failed or failing diodes in order to replace them, or to determine that the diodes are still in reliable working condition. (18.)

In the forward emission voltage measurement, the DC voltage that causes the diode to conduct is measured. In the leakage current measurement, usually 100-200 V DC voltage is connected to the blocking direction of the diode and the leakage current released by the diode and the insulation resistance are measured. (18.)

4.2.7 Visual inspection

Visual inspection with a trained eye is an important information-gathering tool and its purpose is to look for signs of physical damage, wear, corrosion, vibration, dirt, oil leaks, loose connections, or overheating. Visual inspection can help you spot obvious defects or deviations that may affect the performance or safety of the machine. Some defects are usually noticed first by a visual inspection, before they show up in the measurements. Observations made during visual inspection and condition monitoring measurements support each other well.

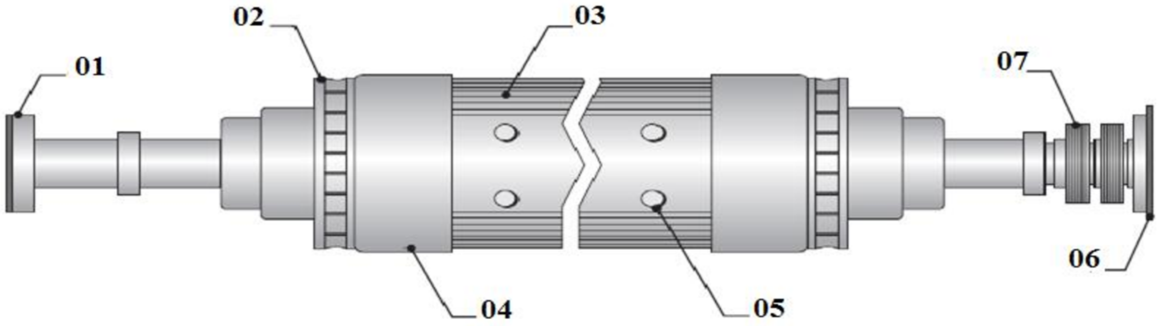
When performing rotor inspections, particular attention should be paid to the following things: (23, p. 521).

- Windings should be inspected for insulations cracking and pole winding bulging for insufficient support.
- Winding top and bottom washers should be inspected for cracking and migration movement.
- Damper winding bars and interconnections should be inspected for cracks, fracture, and migration movement of laminations.
- Interpole connections should be inspected for conductor cracking and insulation failure.
- Interpole V-braces should be inspected for looseness and cracking.
- Possible slip rings should be inspected for pitting, grooving and fingerprinting.

- Insulation on the leads between the slip rings or brushless exciter and field winding should be inspected in visible parts.
- Bolts in strip-on-edge type of machine, with bolted-on pole tips, should be inspected for looseness and cracking.

5 ROTOR FAILURE MECHANISMS

The failure of the turbo generator rotor can be caused by several different reasons. In this chapter, some of the most common causes and their effects are discussed. It is important to note that a failure of the rotor can lead to a malfunction of the generator and the end of electricity production. Failure can be detected in addition to measurements, for example, by observing the generator's performance, sounds, vibrations and other unusual symptoms. Figure 19 shows some main components of the rotor of a cylindrical pole turbo generator.



01.	COUPLING	**05.**	BALANCING PLUG
02.	FAN	**06.**	COLLECTOR FAN
03.	COIL SLOT	**07.**	COLLECTOR RING
04.	RETAINING RING		

Figure 19. Main components of a cylindrical pole rotor (24)

5.1 Damp or dirty insulation

The cleanliness of the generator is important, not only to guarantee the proper operation of the machine, but also to allow visual observations to be made properly. Dirt can hide cracks on the surfaces of critical components such as wedges, retaining rings, fans, the forging itself and the damper windings bars' connection to the short-circuiting rings in salient pole machine. (25, pp. 97-98).

5.2 Retaining rings

The retaining rings (figure 19, part 4) in cylindrical pole rotor are used to restrain the centrifugal force of the rotor winding end turns. The retaining rings are the most critical component in the rotor and usually the most highly stressed rotor component. These rings are critical in the sense that mechanical damage to them always has catastrophic consequences for the physical integrity of the machine. (25, p. 98)

There is a one retaining ring at each end of the rotor shrunk-fit onto the main rotor forging. Retaining rings require always some form of locking arrangement to prevent axial movement. The material of the ring is very critical because it is exposed to extremely heavy stress. Figure 20 shows a damaged locking ring.

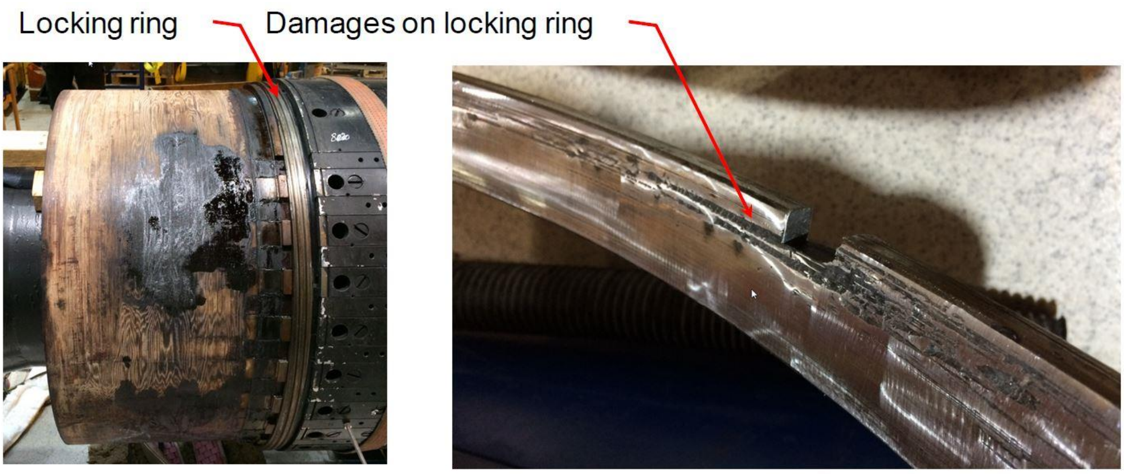


FIGURE 20. Damages on locking ring (19)

Both magnetic and non-magnetic materials are used in the manufacture of rings, but non-magnetic materials are more common in large turbo generators because of their electromagnetic high reluctance. The most common material used is 18 Mn - 18 Cr. The advantages of this material are its durability against corrosion pitting and cracking. The second most commonly used non-magnetic material is 18 Mn - 4 Cr or 18 Mn - 5 Cr. However, there are problems with these materials when moisture contamination is present. There have been a couple of reported cases of pitting or cracks being found in these rings. (5, pp. 74-77).

The NDT (non-destructive testing) (figure 21) inspection examines whether there are cracks, inclusions or other deviations in the retaining rings.

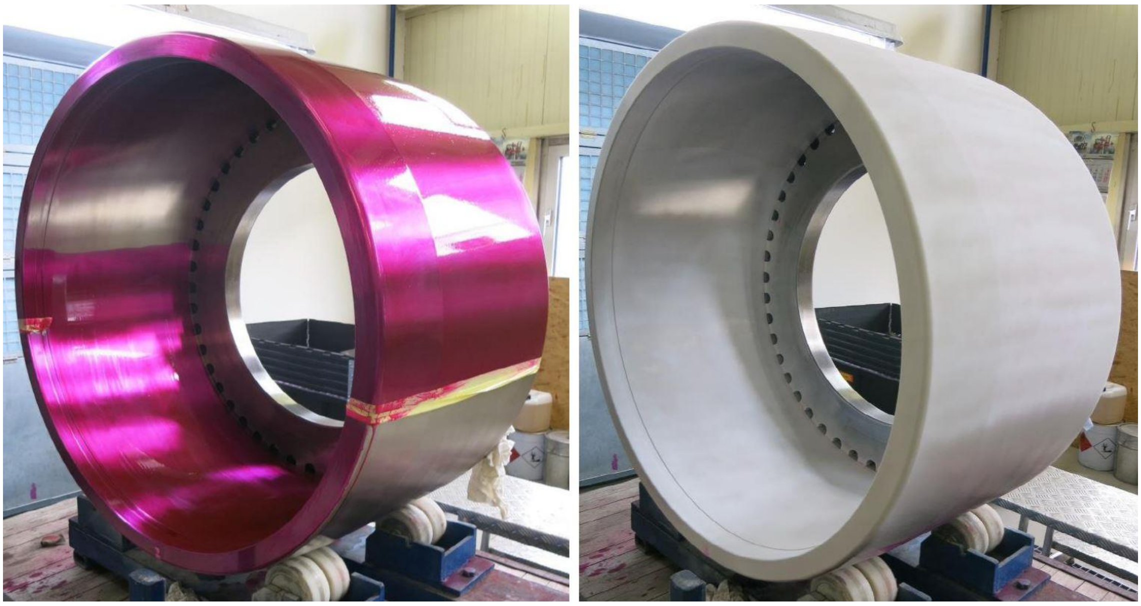


FIGURE 21. NDT-inspection of the retaining ring (19)

If the retaining rings are made of crack-sensitive material, usually the recommendation is to replace them with new ones made of a different material, for example 18 Mn - 18 Cr.

5.3 Winding

The end windings of the rotor are subjected to a strong centrifugal force and forces caused by temperature changes. However, a properly designed rotor allows relatively free movement of the entire coil in the axial direction. Regardless of the movement of the entire end winding, it is important that the distances between the individual windings under the retaining rings are maintained. (25, p. 111).

However, due to the age of the machine, the type of use, structure of winding and possible abnormal use situations, the end windings of the rotor tend to deform. If the distortion is too great, i.e. the individual windings are not aligned in each coil, they are prone to shorted-turn faults. Excessive deformation can also cause cracks or breaks in the coils, especially at 90 degree angles (figure 22). (25, p. 111).

Figure 22. Deformed winding end with cracked soldering joint (19)

One of the most stressful procedures for the integrity of the turbo generator rotor winding is prolonged slow rotation of the rotor with a turning gear. This measure is designed to prevent permanent bending of the rotor shaft due to prolonged standing still. Slow rotation, however, leads to constant bumping of the winding, especially in the winding head area due to their own weight. This problem gets worse if the clearances between the winding and the insulation are excessive. This constant pounding causes copper dust that can lead to short circuits in the winding or even a ground fault in the slot area. (25, pp. 111-112).

Chapter 7 presents an example case related to this failure mechanism.

5.4 Insulation

In addition to moisture and dirt, the deterioration of the condition of the winding is caused by copper losses in the rotor winding and iron losses in the rotor forging, which cause the temperature of the rotor components to rise. Due to thermal expansion, the physical location of the components in the rotor changes. When the generator is turned off, the rotor components cool down and return to their original shape, if the copper has not been stretched beyond the elastic limit, and their movement is not restricted. The movement of the copper tends to rub the winding insulation, especially against the ends of the rotor slots. (26, p. 238).

Depending on the cause that led to the damage, the weakening of the insulation can lead to, for example, shorted turns, ground faults, damage to slot insulation or damage of interturn insulation. The most likely scenario for an insulation burn is an electrical fault, such as short circuit between winding turns or to ground. (26, pp.341-342). Figure 23 shows signs of a possible turn-to-turn fault in two winding bars observed during a visual inspection.

Figure 23. Signs of shorted turns in two coils observed during visual inspection (19)

5.5 Wedges

The function of the rotor wedging is to restrain the rotor coils in the slot against centrifugal forces. The rotor wedges should be checked for cracks and looseness. In particular, wedges made of aluminium alloy may have warped or lost their original mechanical properties when overheated. When using aluminium or brass wedges, special attention must be paid to the points where the mechanical stress is greatest. Inspection of these wedges can only be performed with the end wedge and at least one retaining ring removed. If the wedges are discoloured, it means that the machine has been used in abnormal conditions. (25, p. 110). Figure 24 shows the end wedge of the rotor with marks caused by an external object.

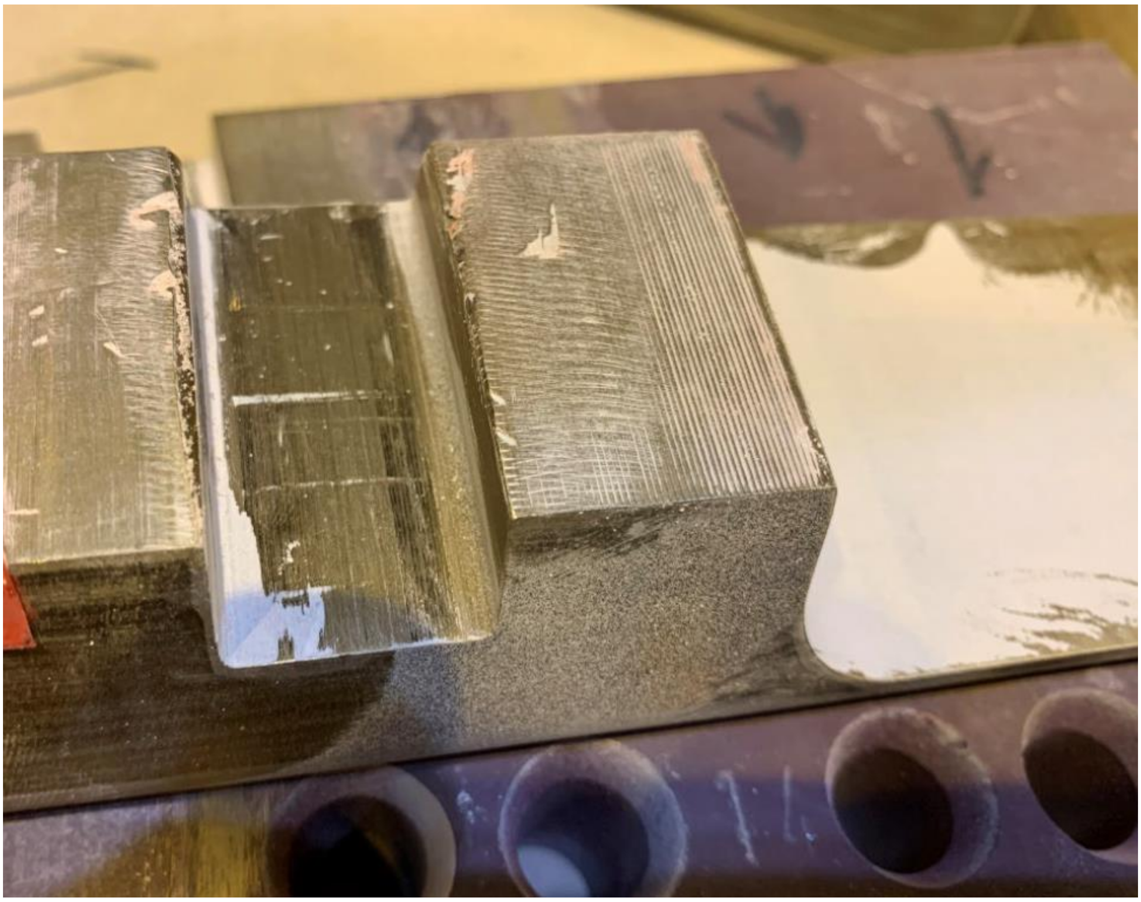


FIGURE 24. Marks on the rotor end wedge (19)

5.6 Damper winding

A typical damper winding consists of short-circuit bars that in the cylindrical rotors share the slots with the field windings, and in the salient pole rotors are located in the dedicated slots on the surfaces of pole shoes. The purpose of the damper winding is to protect the rotor winding from transients in connection with rapid changes in the magnetic flux of the air gap. (19). Figure 25 shows the damage of a certain 4-pole rotor damper winding.

FIGURE 25. Burning marks on the shorting rail, damping rods and pole plate (19)

Damage to damping bars and rails is caused by the generator being exposed to such large transients that the damping coil is overloaded. (19).

5.7 Leads and connections

Damage to the rotor leads and connections can be caused by, for example, mechanical forces, loosening of connections or overcurrent, as a result of which the copper burns across.

Damaged connections and their insulation can be replaced without disturbing the winding. Before repairing it is important to determine why the failure occurred. It may be necessary to improve the connection structure to prevent the recurrence of the defect. (26, p. 262). Figure 26 shows a broken pole connection point in a 4-pole salient pole rotor.

Chapter 8 presents an example case related to this failure mechanism.

FIGURE 26. A break in the connection point of the rotor pole of salient pole rotor (19)

5.8 Fan hubs and blades

The means of cooling gas (air or hydrogen) circulation is accomplished by the use of a blower or rotor fan (figure 19, part 2). There can be one or more fans inside the generator. Usually, however, there is a fan at both ends of the rotor. (5, pp. 84-86).

In 2- and 4-pole rotors, the fan blades are attached to fan-rings shrunk onto shaft. Interference fit stresses and centrifugal forces induce mechanical stresses in rotor fan elements. It is very important to examine the condition of the blades and the soundness of their attachment. (25.) Rotor fans can easily affect rotor balance as well (5, p. 86).

Failure of the rotating fan inside the generator can cause serious damage to critical parts of the machine. The stored rotational energy in a fan will typically destroy the stator winding, or damage the stator core and cause damage to other rotor components such as the rotor winding, retaining rings and the rotor forging. Figure 27 shows a fan with a detached blade and figure 28 shows the damage to the stator winding caused by the detached fan blades.

FIGURE 27. Missing blades on the fan (19)

FIGURE 28. Damage in the stator winding caused by the detached fan blades (19)

5.9 Slip-collector rings and brush gear

In static magnetization, the rectified magnetizing current is led to the slip rings (figure 19, part 7) attached to the rotor windings, usually with the help of carbon brushes made of graphite. The polarity of the adjacent slip rings is opposite, as one carries current to the rotor and the other away from the rotor. With brushed magnetization, adjusting the magnetization is faster, but the carbon brushes and slip rings wear out and produce carbon dust when they rub against the slip ring and thus require regular maintenance. (7, p. 41-42).

Premature wear or even damage of the sliding rings can be caused, for example, by too high a temperature of the sliding rings, moisture and impurities such as dust, oil and dirt (26). Figure 29 shows a slip ring with a piece broken off from the edge.

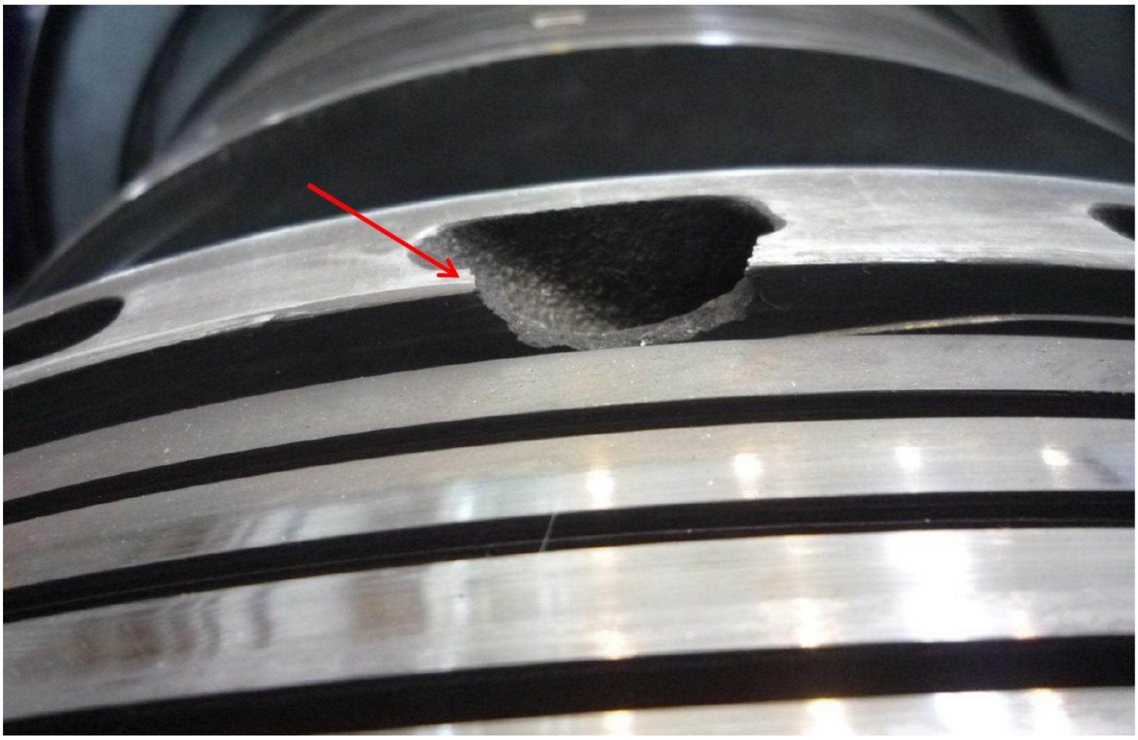


FIGURE 29. Damage on the slip ring (19)

5.10 Exciter

A generator exciter can fail for a number of reasons. A fault can be caused by, for example, loss of power to the excitation transformer, faulty firing circuit board, solid-state power rectifier, diode, capacitor in the power circuit, breaker or short circuit on the AC or DC side of the excitation. (26).

The most common fault is a short circuit of only one diode. This can be caused by overvoltage or overcurrent, which is usually caused by an external current spike, such as a lightning strike, but also when voltage is applied to the poles of the brushless generator while it is at rest. After the diode is short-circuited, it burns open, if no other fault occurs first. There may also be a broken or loose connection outside the diode, which has the same effect as an open diode. One open diode overloads other diodes and the rotor winding of the exciter, but usually does not cause the regulator to fail. (27).

If several exciter diodes fail simultaneously, it is unlikely that the Generator will be able to maintain open circuit voltage. If the generator is not immediately shut down in the event of a fault, it leads to almost certain exciter rotor failure. With several open diodes it is unlikely that the generator can maintain rated voltage at no load. (27).

If all the exciter's diodes fail simultaneously, the generator's terminal voltage will collapse. If the generator is shunt excited, this collapse in generator terminal voltage will result in a loss of input power to the voltage regulator shutting off excitation. If the generator is equipped with a PMG or other form of excitation support system, the voltage regulator will go to full forcing. If the voltage regulator is equipped with an over excitation feature, it should trip on over excitation, which may occur fast enough to prevent damage to the exciter rotor. (27).

5.11 Balance weights and bolts

In large turbo generators, balance weights, nuts and bolts (figure 19, part 5) are subjected to intensive centrifugal forces. For example, the centrifugal force of a 50 g nut attached to the rotor rotating at 3000 revolutions per minute is more than 45 kg. In addition, constant vibration and thermal cycles usually loosen these. When a bolt, nut or balancing weight comes off, it can cause serious damage to critical parts of the machine. (5).

5.12 Bearings

The generator bearings must rotate freely with as little friction as possible and without vibration. (5, p. 81). Bearing failure is usually progressive but ultimately its effect upon the machine is catastrophic. Failure is accompanied by a rising temperature at the bearing surface, in the lubricant and in the bearing housing, which are detectable by temperature sensors. (28, p. 56).

Electrically insulated bearings are used in generators to prevent the flow of electric current from the rotor through the bearing to the ground. Sliding bearings with an insulating oil film between the rolling surfaces are mostly used in synchronous machines. Sparking through the oil film damages the metallic sliding surfaces of the bearings. The insulating ability of the oil and the thickness of the film affect how much shaft voltage is required before breakthrough happens (21, p. 405). The 100-200 μm film formed by pure oil can withstand a voltage of about 50-100 V peak, but impurities mixed in the oil can lower the breakdown voltage considerably (18.) Figure 30 shows what sparking through the oil film can do to the surface of the bearing.

FIGURE 30. Marks on bearing surfaces caused by sparking through the oil film (19)

5.13 Forging

The rotor forging (figure 31) is usually a one-piece solid steel forging, but there are also rotors built from sections and locked together with a spigot type arrangement. The material used in rotor furnaces is made of highly permeable magnetic steel to carry the flux produced by the rotor winding. Since the rotor is a dynamic component that rotates at high speed, the materials are very stressed, because they have to support the copper winding and withstand high mechanical and thermal stress. (5, p. 64).

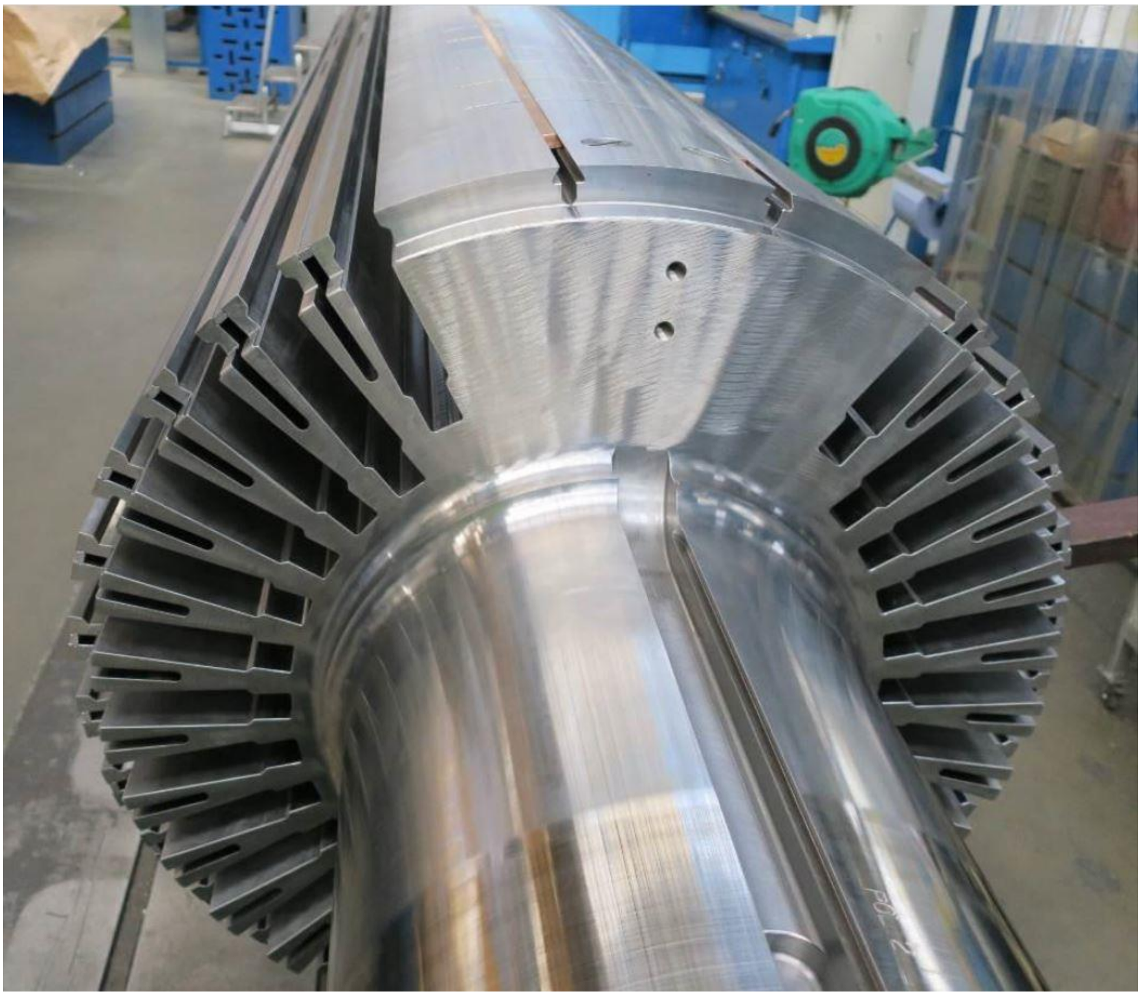


FIGURE 31. Cylindrical pole rotor forging (19)

The best thing would be to find a crack in the forging before it goes into a runaway situation. In the worst case, the crack opens quickly, and there is not enough time to shut down the machine before a catastrophic failure. A crack can be caused, for example, by high bending stress in long, thin rotors, defects in the rotor's bore surface, bore hole or becoming unstable. (26).

6 FAILURE CATEGORIZATION

In the years 2010-2022, TGS has performed approximately 500 online measurements, 260 safety checks, 80 minor overhauls and 130 major overhauls on a total of more than 200 turbo generators. Figure 32 shows the percentage of all generator manufacturers inspected. Numbers 1-14 have been used instead of manufacturers' names.

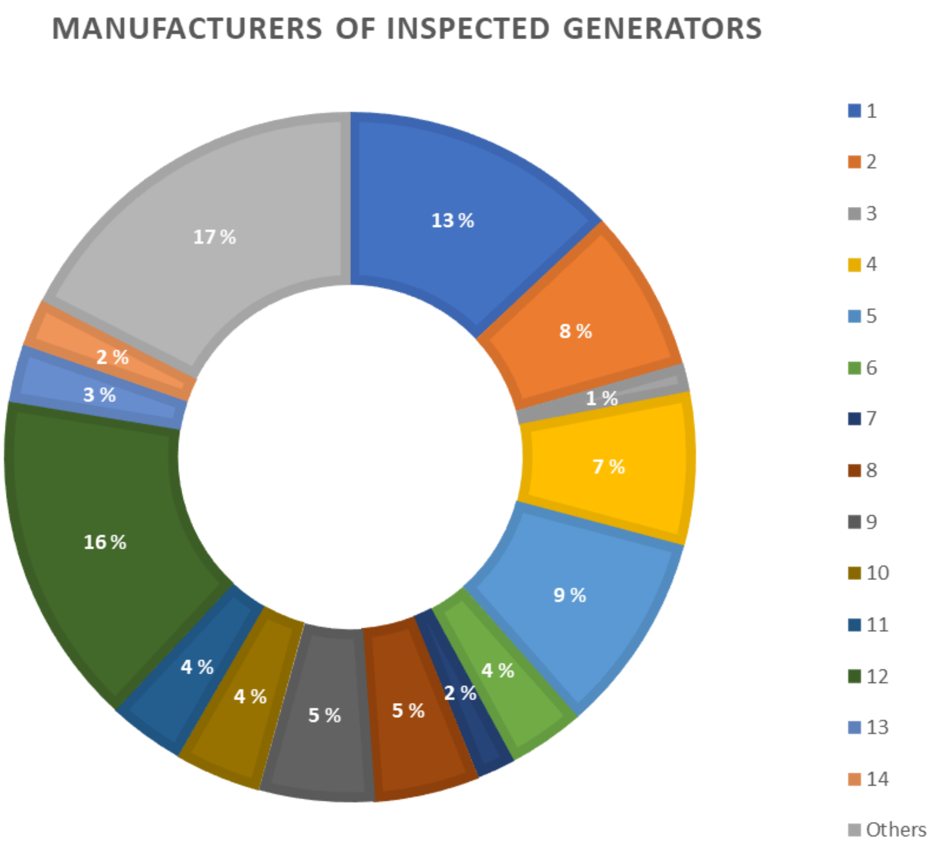


FIGURE 32 Manufacturers of inspected generators

6.1 Manufacturer

Figure 33 shows the number of generator rotor failures based on the manufacturer. The rotors of generator manufacturer 12 had the most defects in relation to the number of generators inspected, while the rotors of manufacturer 3 generators did not show any failure at all during the review period.

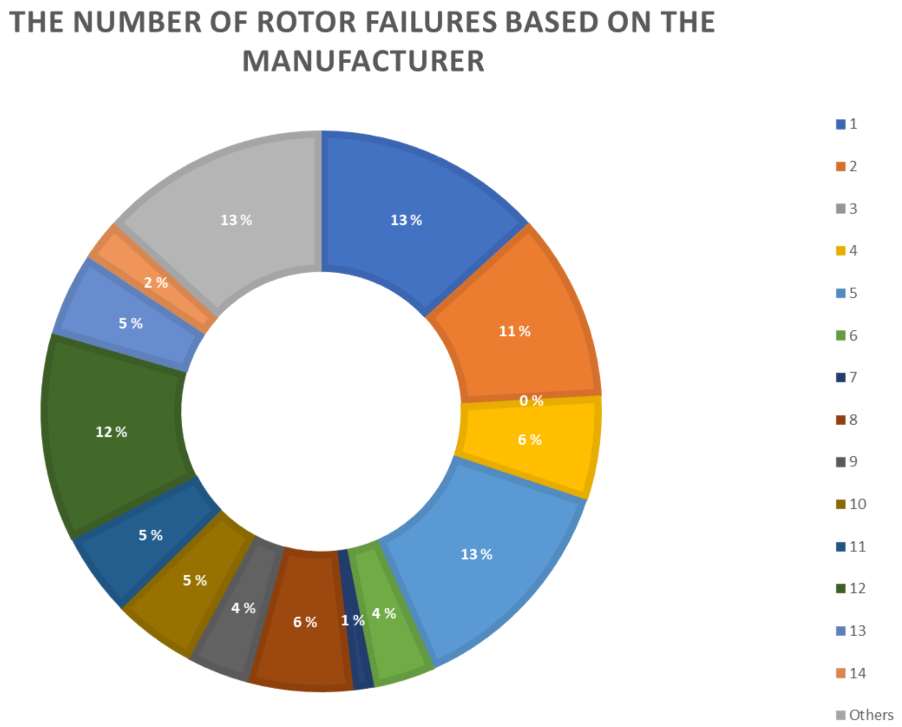


FIGURE 33 The number of rotor failures based on the manufacturer

6.2 Power

More than a third of breakdowns leading to rotor damage have occurred with 100-199 MVA generators, while the 200-499 MVA machines had the least amount of faults. Figure 34 shows the number of generator rotor failures based on the power of the generator. The results are in proportion to the number of generators inspected.

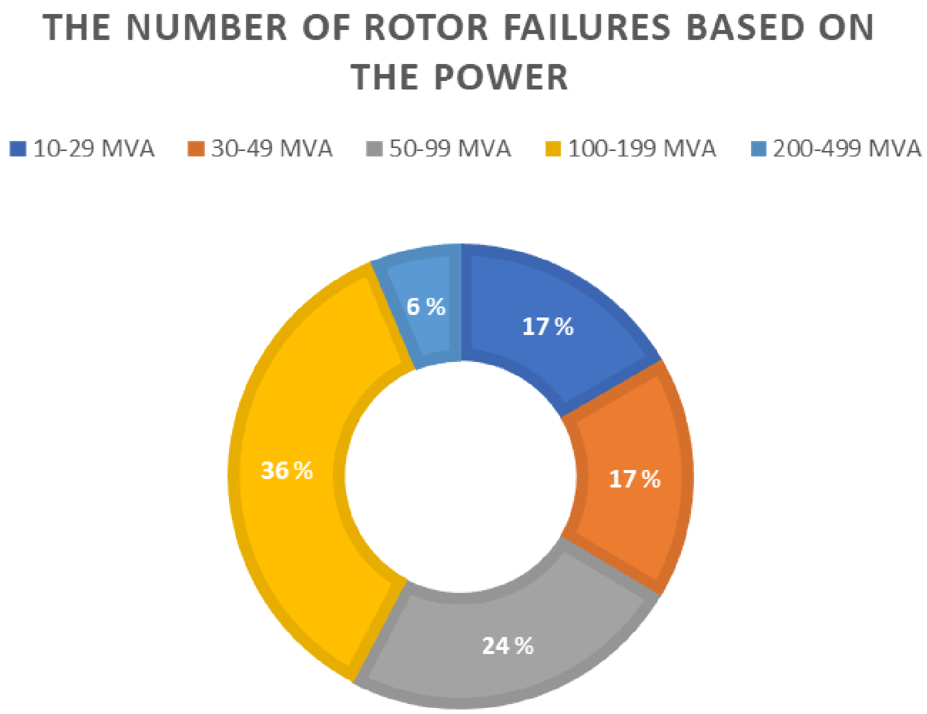


FIGURE 34. The number of rotor failures based on the power

6.3 Voltage

More than half of the failures leading to rotor damage have occurred with generators with a voltage of 10.5 - 11.5 kV. Figure 35 shows the number of generator rotor failures based on the voltage of the generator. The results are in proportion to the number of generators inspected.

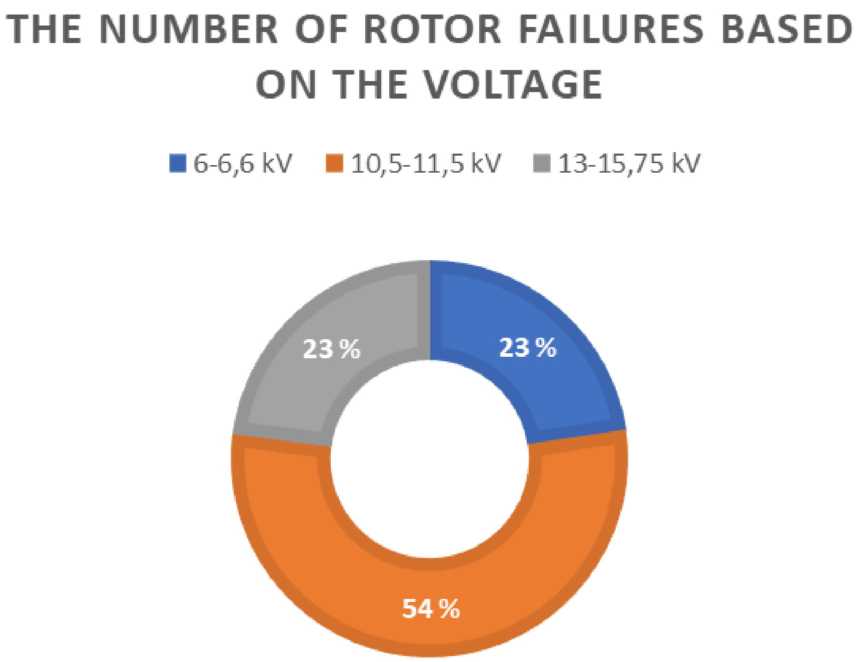


FIGURE 35. The number of rotor failures based on the voltage

6.4 Number of poles

About 70% of rotor failures occur in 2-pole cylindrical pole machines. This is at least partially influenced by the greater centrifugal force of the rotor spinning at 3000 revolutions per minute. Centrifugal force is proportional to the square of the angular velocity (and correspondingly the peripheral velocity), which means that if the rotor rotates at twice the speed, the outward pulling force is four times compared to a 4-pole rotor rotating at 1500 revolutions per minute. Figure 36 shows the number of generator rotor failures based on the number of poles. The results are in proportion to the number of generators inspected.

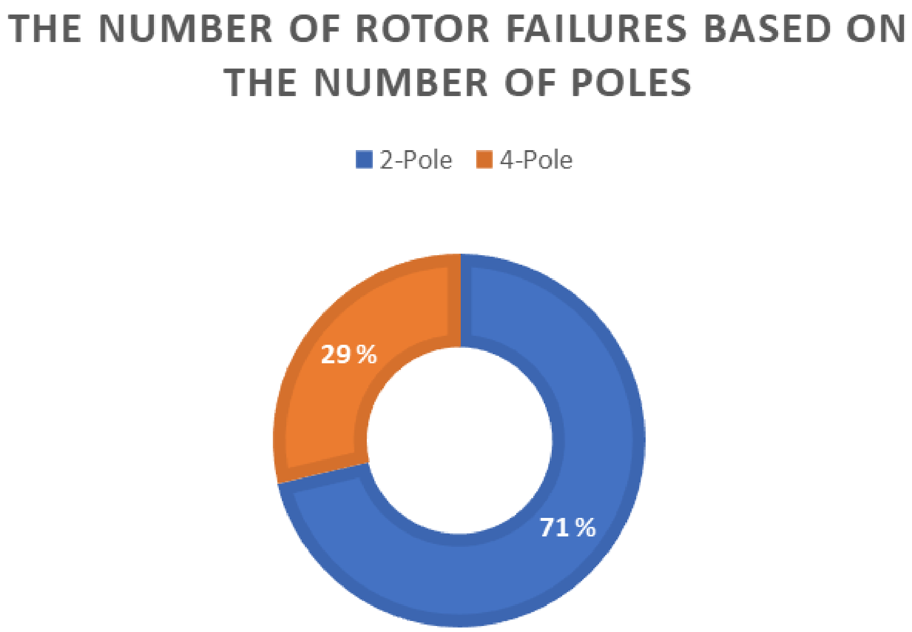


FIGURE 36. The number of rotor failures based on the number of poles

6.5 Year of manufacture

The failure of turbo generators manufacturing over the decades has been relatively steady. Machines manufactured in the 1990s had slightly more defects than machines manufactured in the 1970s and 1980s, indicating a decline in generator manufacturing quality over the past decades. Figure 37 shows the failure of the rotors of turbo generators according to the decade of the generator's manufacture. The results are in proportion to the number of generators inspected.

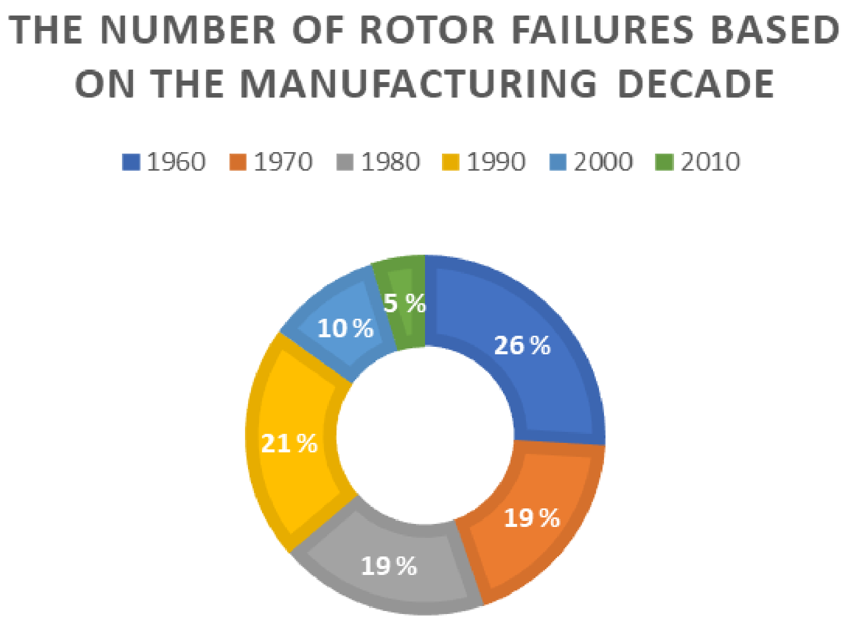


FIGURE 37. The number of rotor failures based on the manufacturing decade

6.6 Method of use

Slightly more than half of the rotor failures occurred in generators whose external power source is a gas turbine. This may be at least partly caused by the way gas turbine power plants are used. In Finland, gas turbine power plants are often used as backup power plants, whereby the generator starts up in a situation where more power is needed to maintain the electricity distribution. Backup power plants are often only running for a short time, when numerous start-ups stress the generator more than the almost constantly rotating machine. When the generator is out of use, moisture can also accumulate in its windings, which weakens the condition of the generator. However, the difference in the number of failures of gas and steam turbines is marginal. Figure 38 shows the number of generator rotor failures based on the type of turbine. The results are in proportion to the number of generators inspected.

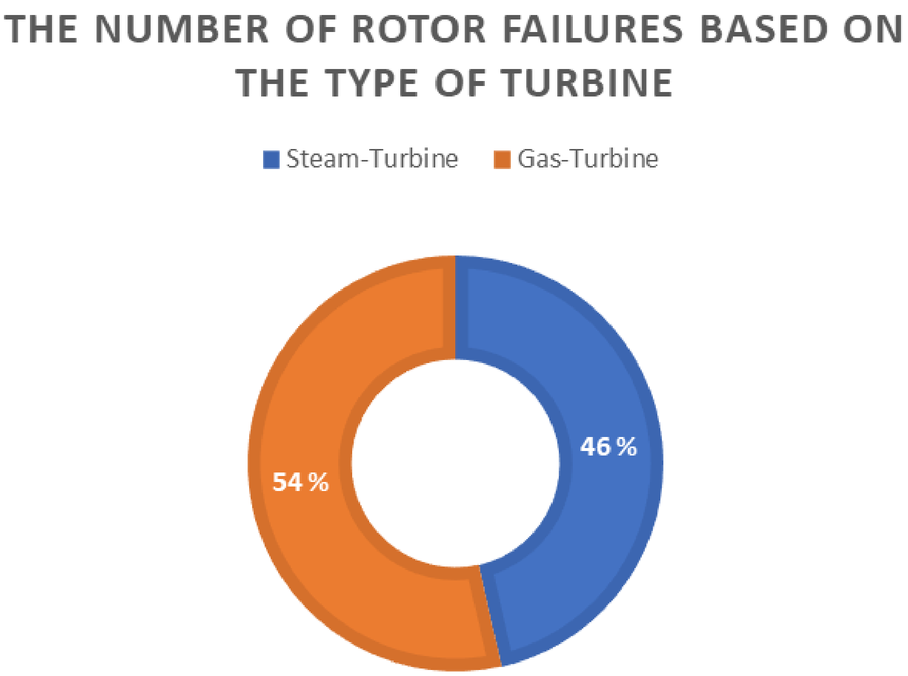


FIGURE 38. The number of rotor failures based on the type of turbine

6.7 Component

Almost a third of rotor failures requiring workshop repair have been caused by damage in the winding head area, such as movement of support blocks, deformation of winding ends or cracking of solders. A significant part of the faults requiring workshop repair are also caused by retaining rings. Figure 39 shows the number of defects that required workshop repair per rotor component.

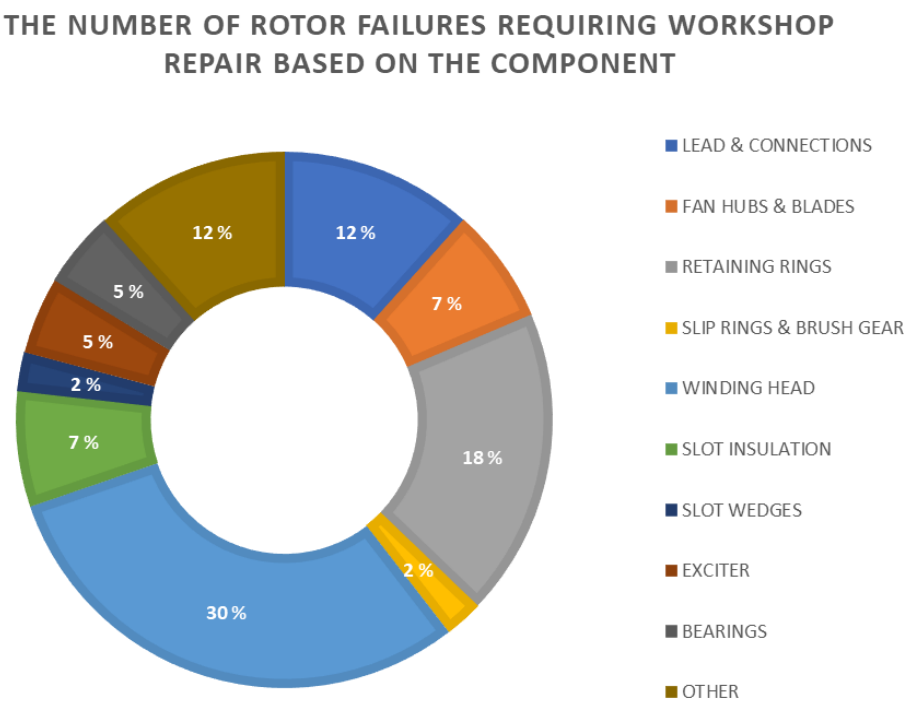


FIGURE 39. The number of rotor failures requiring workshop repair based on the rotor component

7 CASE – CRACKED AND DEFORMED WINDING END REPAIR

In the autumn of 2014 a generator underwent an opening revision according to the maintenance program, where the rotor was pulled out.

7.1 Observations and measurements

In connection with the major overhaul performed on the generator, the rotor was checked with an endoscope, and several fractures in the solder joints and deforming of the winding ends was found. Due to the detected defects, it was decided to send the rotor to the workshop for repair.

In the workshop electrical test (before dismantling of retaining rings) was performed without deviations. Crack detection of the retaining rings, rotor forging, fan ring and fan blades was done without indications.

7.2 Troubleshooting

During the workshop repair, a total of 39 fractures (figure 40) or poorly made solder joints were found in the rotor winding in the winding head area.

FIGURE 40. Fractures in soldered corner connections (19)

Due to the deformation of the winding ends, the distance blocks had also broken and the end winding was slightly deformed (figure 41).

FIGURE 41. Deformed winding head (19)

7.3 Procedures

The rotor was rewinded with new coppers (figure 42) and new soldering joints were made (figure 43). Rewinding always also includes renewing the entire winding insulation and new support blocks. At the same time, the rotor fan blades were also replaced. The problem in winding head is a common type fault in this generator model.

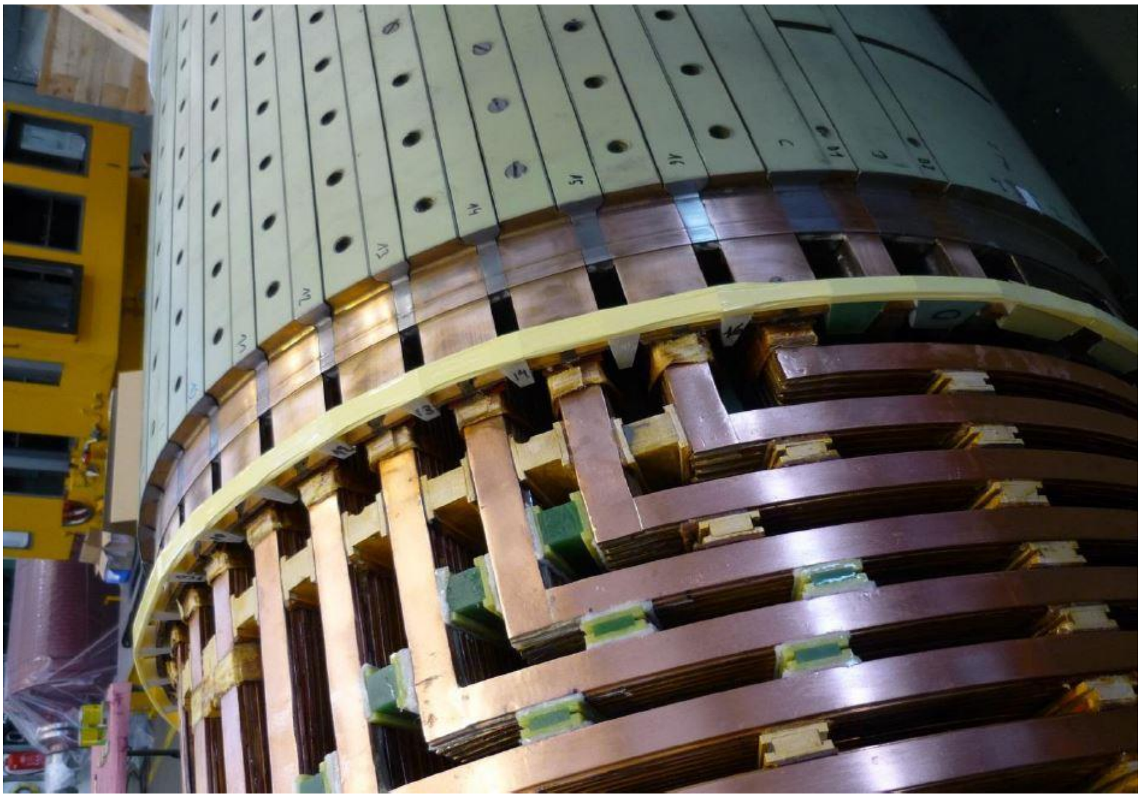


FIGURE 42. Rewinded rotor (19)

FIGURE 43. New soldered corner connections (19)

After corrective action the balancing and overspeed test of the rotor together with electrical tests at standstill and during rotation through RSO was performed without remarks.

7.4 Evaluation of the benefits

By rewinding the rotor, the generator got a lot more operating time and electricity production could continue normally.

8 CASE – ROTOR GROUND FAULT REPAIR

The generator suddenly went offline in the spring of 2019 without planning. The machine was tripped by the earth fault protection relay of the generator rotor circuit. The power plant's own staff located the fault in the rotor circuit, after first removing the magnetizing carbons.

8.1 Observations and measurements

Three days later, when the turbine rotor had been cooled to below 200 °C, the rotor could be stopped briefly for a while. During the shutdowns, the rotor fault could be located near the inner slip ring. Winding resistance measurement, impedance measurement and DC voltage distribution measurement were used as measurement methods. After the measurements, melted copper was found at the base of the radial stud of the inner slip ring.

8.2 Troubleshooting

Six days after the generator shutdown, when the turbine rotor had cooled below 100 °C, the rotor could be stopped for a longer time and the slip ring shaft at the end of the rotor could be dismantled. The rails and studs were removed from the slip ring shaft. The broken connection (figure 44) of the radial stud (figure 45) was an expected finding, but a small surprise was that the lamella of the second power bolt had also gotten so hot that it had slightly changed its colour.

FIGURE 44. Copper in the radial stud hole that caused the ground fault (19)

FIGURE 45. Damaged inner slip rings radial stud (19)

8.3 Procedures

The disassembled copper parts were compared with the spare parts found in the warehouse, after which it was decided to install the spare parts in their places. The radial studs of the axial connection of the copper rails fit perfectly, so the decision was easy.

RSO, impedance and winding resistance measurements were performed on the assembled rotor. The measurement results were normal and the generator could be taken back into production. The generator was synchronized back to the grid 8 days after the ground fault.

8.4 Evaluation of the benefits

With immediate corrective measures, the generator was restored to normal operating condition and its use could be resumed relatively quickly. If the customer had not had the necessary spare parts in stock, the unplanned interruption would have lasted significantly longer.

9 SUMMARY

Regular condition monitoring helps to detect possible failure mechanisms and signs of wear, which reduces the risk of expensive repairs and unexpected interruptions. In addition, regular maintenance can optimize the condition and efficiency of the generator by preventing contamination and overheating through inspections and cleaning.

The results obtained in this study shed light on various factors that affect rotor failure. The research revealed that faults leading to rotor damage are more common in high-speed 2-pole turbo generators, likely due to greater centrifugal force. Most of the cases leading to rotor failure occurred with generators with a voltage of 10.5–11.5 kV and a power of 100-199 MVA. In addition, the research suggests that gas turbine power plants, which are often used as backup power sources in Finland, can contribute to rotor damage due to short periods of operation. The research also found indications that the manufacturing quality of the generators had deteriorated in recent decades. It is also noted that the specific manufacturer of the generator may play a role in the frequency of rotor damage.

The results show that a significant part of the rotor damage that required workshop repair is caused by problems in the winding head area or in the retaining rings. This particularly emphasizes the importance of proper inspection and maintenance of these parts to prevent failure.

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