

Thermal Design of a Hermetically Sealed Turbo-Generator Operating in a Small-Power CHP Plant

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Abstract: - The thermal design of a steam cooled, hermetically sealed turbo-generator operating in a small-power combined heat and power (CHP) plant is presented. The generator is a high-speed solid-rotor induction generator with a slitted solid steel rotor the nominal power of which is 1 MW and the rated speed 14000 min^{-1} . The structure of the generator as well as the flow path of the cooling steam is discussed in detail. A thermal resistance network based thermal analysis is performed in order to evaluate the temperature distribution inside the generator.

Key-Words: - Solid rotor, induction motor, thermal analysis, steam cooling, high-speed turbo-generator

1 Introduction

A vast portion of the electricity of the world is produced by turbo-generators. The most common way to produce electricity is by boiling water, superheating it and then extracting energy by letting the steam expand in a steam turbine. Since the rotation speed of steam turbines is usually quite high, about $10\,000 \text{ min}^{-1}$ or more, a turbo-generator is used in converting the energy of the rotating motion into electricity.

There are several types of turbo-generators available on the market. In conventional turbo-generator constructions a mechanical power transmission (a step down gear) is used between the turbine and the generator to set the rotating speed of the generator as desired. In this case the generator can be of any electrical machine type but synchronous machines are typically used. In sophisticated new high-speed designs the turbine and the generator as well as the main feeding pump are mounted on the same shaft. The losses by the mechanical gearbox are avoided and full speed control is achieved. If the process steam is not allowed to get in touch with the electrical machine, an axle seal is needed to separate the turbine and the generator from each other. In high-speed designs the electrical machine is generally a medium-speed machine type, for example a solid-rotor induction machine or a permanent magnet synchronous machine [1]. Besides the mechanical structure, generators can also be differentiated by the cooling medium used. They are [2]:

- Air-cooled generators, where heat is removed from the machine by air that is circulated through the machine. The air may be continually replaced by cool air from outside the machine (open ventilation) or it may be cooled by an intermediate heat exchanger and re-circulated around the machine (totally enclosed ventilation). Maximum achievable power of the air-cooled generators is about 600 MVA [3].
- Hydrogen-cooled units, in which air is replaced by hydrogen as a cooling medium. Such machines operate with a sealed gas environment, and the heat is removed from the hydrogen using a water-to-hydrogen heat exchanger. Maximum achievable power of the hydrogen-cooled generators (stator winding indirectly cooled) is about 650 MVA [3].
- Liquid-cooled generators, where the heat generated in the stator windings is removed by water flowing directly through the winding. Any other heat generated in these machines is removed by hydrogen gas. Maximum achievable power of the hydrogen/water cooling is about 2200 MVA [4].
- Steam-cooled, hermetically sealed generators, in which the cool process stream is used to remove heat from the generator. In these designs special attention must be paid on the insulation materials, because steam is a substance, which cannot be tolerated by traditional insulating materials [5]. Furthermore, auxiliary water cooling units are needed to ensure the performance of the cooling system. Steam-

cooling can be used in small power plants up to a few MVA.

Nowadays special interest in the energy production has been paid on the environmental aspects such as reduction of the greenhouse gas emissions. Practical energy efficient solutions can be categorized into a concept called combined heat and power (CHP) cogeneration. This concept is widely used in industrial energy production schemes. Industries that use thermal energy, such as high pressure steam, have found economical solutions for the production of steam and electricity using fuel sources as near of the thermal load as possible.

In this paper a cooling system and the thermal analysis of a hermetically sealed high-speed turbo-generator used in a small CHP plant are presented. The turbine and the generator as well as the main feeding pump are mounted on the very same shaft and the cool low-pressure process steam flowing out from the low pressure turbine is used as a main cooling medium of the generator. There is no mechanical axle seal between the turbine and the generator. A labyrinth seal is used, however. The main advantages of the hermetic structure are the modular structure, and, because of the lack of water leaks no additional water purifying supply unit is needed. The generator type analyzed is a solid-rotor induction generator with a slitted solid rotor structure. The details of the steam resistant insulation system of the generator are presented in [5].

2 Overview of the Generator

The analyzed generator is a three-phase, 1 MW, 233 Hz, two-pole, solid-rotor, high-speed induction machine designed at Lappeenranta University of Technology. The solid rotor was axially slitted and the number of the rotor slits was selected in such a way that the rotor structure is strong enough to withstand the mechanical stresses due to the momentary peripheral speed of 334 m/s. According to the analysis presented in [6] the number of the rotor slits was selected to be 40. The depth of a slit was 40 mm and due to the practical manufacturing reasons, the width of the slit was selected to be 2.5 mm. The rotor core material was structural steel (S355J0 / EN 10025) and the outer diameter of the rotor was 270 mm. Due to the excessive centrifugal forces no copper end-rings were used in the rotor, i.e. the rotor ends are of the same material as the rotor core. The length of the rotor ends were selected to be 20 mm. The length of the air-gap is 3 mm. The stator stack length is 276 mm and the

number of the stator slots is 60, respectively. The nominal slip of the generator is 1 %. A two-layer, 5/6-short pitch winding is used in the stator to reduce the effect of the 5th and 7th winding harmonics on the rotor surface losses. The cross-sectional geometry and the flux plot of the generator studied are illustrated in Fig. 1.

In order to design the cooling system of the generator the generator losses and their distribution have to be known as accurately as possible. The electromagnetic generator losses, that is, copper losses in the stator windings, iron losses in the stator and in the rotor were evaluated using two-dimensional finite-element analysis [7] as well as analytical equations found e.g. in [8]. The losses due to the cooling gas friction are calculated using analytical equations found in [9].

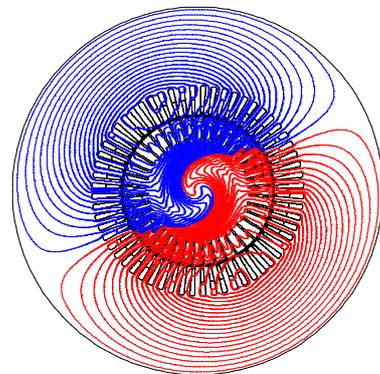


Fig. 1. The cross-sectional geometry and the flux plot of the studied solid-rotor induction generator with 40 rotor slits at a slip of 1 per cent.

3 Cooling Design

The cooling system of the analyzed turbo-generator differs significantly from the conventional cooling solutions because the process steam from the low-pressure turbine is used as a main cooling medium. Furthermore, the conventional machine structure used to minimize gas friction losses in high-speed applications where the stator stack is divided into two parts and the space between the stator sections is used as a radial cooling duct cannot be used due to the excessive temperature rise at the stator end-windings. The performance of the cooling system is boosted by using auxiliary glycol/water cooling channels in the stator frame. Also the phase change of the cooling fluid is used to improve the overall cooling of the generator. In this chapter the cooling fluid flow path inside the generator is discussed in detail.

3.1 Flow path of the cooling fluid

The turbo-generator is mounted at an upright position. A radial blower, which is placed at the upper part of the generator, is used to aspirate the inlet steam from the bottom of the generator through the air-gap to the upper part of the generator. The temperature of the inlet steam from the low-pressure turbine is 74 °C and the steam is at the saturated state. In the preliminary design stage the energy balance based analysis was used to evaluate the state of the cooling steam at different parts of the generator. It was noticed that if the steam penetrating the air-gap is dry or saturated, the steam will superheat while absorbing heat from the generator and the temperature rises rapidly especially in the lower end-windings. In order to intensify the cooling of the lower end-windings and to keep the end-winding temperature moderate, the dry inlet steam is humidified by injecting water into the steam. In this case the cooling steam absorbs heat effectively from the outer surface of the lower end-windings as a result of the vaporization of the water drops. Furthermore, when the mass amount of the water in steam is sufficient, the steam will stay moist and the temperature of it will not increase when it flows through the air-gap. To ensure that the steam leaving the air-gap is not superheated but moist near by the saturated state, the temperature of the steam leaving the air-gap is measured and the amount of the water injection is controlled to fulfill the conditions mentioned above. In the design point of the generator the amount of water is 3.6 per cent of the total mass flow rate of the inlet steam.

In the air-gap the moist steam absorbs heat from the stator and the rotor and after having passed the air-gap in the machine axial direction the steam temperature is 70 °C. It is seen that the temperature of the steam is lower at the end of the air-gap than before entering it. This is due to the pressure drop and steam drying in the air-gap flow. Furthermore, the mass flow rate dependent losses due to the power needed to accelerate the cooling fluid into tangential movement turn into heat after the cooling steam has left the air-gap, i.e. in the upper end-winding space. Therefore, the temperature of the steam rises to 82 °C before entering the radial blower.

The steam heats up in the blower and it leaves the stator of the radial blower at the temperature of 120 °C. After the radial blower the steam flows to the upper end-winding space where the water leakages from the bearings and the main feeding pump are mixed with steam and the steam is condensed. This result that the upper end-windings are almost totally

immersed with a saturated water-steam mixture the temperature of which is 74 °C. Due to the water immersion the convective cooling of the upper end-windings is extremely efficient. There is a plastic sleeve between the upper end-winding space and the air-gap to prevent the water to flow into the air-gap. The cooling fluid leaves the upper end-winding space through the holes in the frame, and, it enters the inlet of the low-pressure condenser. The flow path of the cooling steam in the interior parts of the hermetically sealed generator is illustrated in Fig. 2.

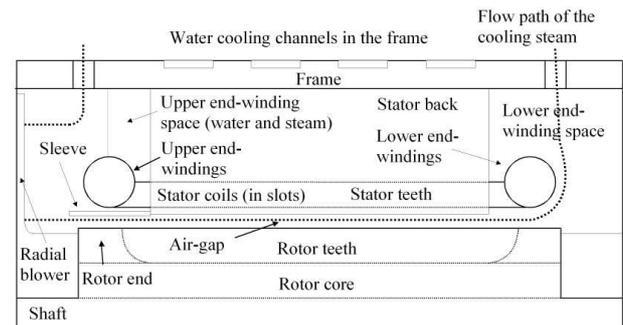


Fig. 2. The axial structure of the hermetically sealed generator and the flow path of the cooling steam.

4 Thermal Analysis

In order to evaluate the performance of the cooling system and to ensure that the temperatures at different parts of the generator do not exceed the temperature limit of 115 °C set by the insulation system, a thermal resistance network based thermal analysis was performed. In the thermal network model, the axial length of the generator was divided into two parts in order to solve the axial temperature distribution of the generator. The thermal resistance network model used contains 27 nodes and one half of its structure is shown in Fig. 3. The convection coefficients were calculated using analytical equations found in [7] and [10]. The main equations as well as the basic structure of the thermal model used are presented in detail in [7]. A special cooling matrix was utilized to model the heating of the cooling steam [11].

The use of the cooling matrix requires that the volume rates of the cooling steam at different parts of the cooling steam flow path are exactly known. In the slitted rotor structure the most critical flow path is the air-gap. This is due to the fact that the air-gap flow is actually divided into two parts, the one flowing through the actual air-gap and the other flowing through the slits of the rotor. The volume flow rates of steam flowing through each flow path are calculated by setting the pressure drop equal in

both the flow paths. The pressure drop Δp of the cooling steam flow is

$$\Delta p = \xi \frac{L}{D} \frac{\rho v^2}{2}, \quad (1)$$

where ξ is a friction factor, L is the length of the flow path, D is the hydraulic diameter of the flow path, ρ is the mass density of the cooling fluid and v is the speed of the cooling fluid. The friction factor is calculated iteratively using the Colebrook-White equation

$$\frac{1}{\sqrt{\xi}} = -2 \log_{10} \left[\frac{2.51}{Re \sqrt{\xi}} + \frac{K}{3.71D} \right], \quad (2)$$

where K is the surface roughness of the flow path. The Reynolds number Re is defined as

$$Re = \frac{\rho v D}{\mu}, \quad (3)$$

where μ is the dynamic viscosity of the cooling fluid.

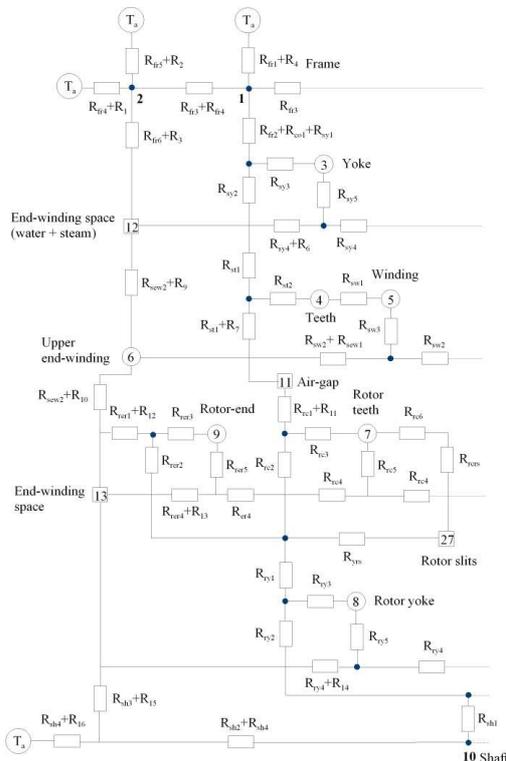


Fig. 3. One half of the thermal resistance network model used in the thermal analysis. The whole model includes two similar networks in parallel.

The thermal analysis was performed at the nominal operation point of the generator, i.e. the rotational speed of the rotor was 14 000 min^{-1} . The calculated electromagnetic losses at the nominal point were 22.15 kW and the corresponding gas friction losses were 5.44 kW. The temperature of the process steam entering the generator was 74 °C and the mass flow rate of the steam was 0.1786 kg/s.

4.1 Analysis of the thermal results

The calculation results revealed that the maximum temperature of the generator is 116.2 °C and it occurs in the coils in stator slots at the lower part of the generator. Because the maximum temperature occurs at the centre point of the coil the temperature at the surface of the coil is somewhat lower, it can be concluded that the temperature limit set by the insulation system is not exceeded in the nominal point operation. In the lower end-windings the velocity of the humid cooling steam flow is 83 m/s and the convection coefficient between the cooling fluid and the surface of the lower end-windings is 99 $\text{W/m}^2\text{K}$. Therefore, due to the enhanced convective heat transfer from the lower end-windings to the humid steam the temperature of the lower end-windings is a bit lower, i.e. 111.6 °C. Because of the immersion cooling, the cooling of the upper end-windings is found very efficient. The convection coefficient between the upper end-windings and the water is between 600 – 800 $\text{W/m}^2\text{K}$ and the temperature of the upper end-windings is 85.9 °C.

The temperature of the solid rotor remains quite stable, that is 100 °C, along the axial length. The corresponding convection coefficients were 440 $\text{W/m}^2\text{K}$ between the rotor surface and the air-gap flow and 215 $\text{W/m}^2\text{K}$ between the rotor slits and the steam flow in the slits. The maximum temperature in the stator, that is 110 °C, occurs in the stator teeth in the lower part of the generator. However, the temperature of the stator remains at the level of 105 °C along the axial length of the generator. The temperatures at the most important parts of the generator are given in Table 1.

In order to ensure that the temperatures inside the generator do not exceed the temperature limit set by the insulation system as well as to be able to overload the generator, an auxiliary water-glycol-cooling was designed in the frame of the generator. The purpose of the auxiliary cooling system is to absorb as much losses from the stator of the generator as possible thus minimizing the amount of the heat from the stator that is removed from the machine by the air-gap flow. The auxiliary cooling system was designed in such a way that the mass

flow rate of the water-glycol mixture is 0.7 kg/s and the inlet temperature of the fluid is 38.3 °C. According to the analysis performed at LUT, the temperature of the frame will drop to the value of 52 °C when the auxiliary water cooled stator frame is used. Furthermore, the use of the auxiliary frame cooling will decrease the temperatures presented in Table 1 by 15 – 25 °C.

Table 1.
The calculated temperatures of the generator analyzed.

Part of the generator	Temperature (°C)
Stator back (upper)	103.8
Stator teeth (upper)	107.6
Coils in stator slots (upper)	112.4
Upper end-windings	85.9
Stator back (lower)	105.3
Stator teeth (lower)	110.7
Coils in stator slots (lower)	116.2
Lower end-windings	111.6
Rotor teeth (upper)	94.8
Rotor end (upper)	99.4
Rotor teeth (lower)	97.5
Rotor end (lower)	103.8
Frame (average)	76.6

5 Conclusions

The cooling design and thermal analysis of a hermetically sealed turbo-generator operating in a small-power CHP-plant is presented. The process steam is used as a main cooling fluid and the electrical machine used as a generator is a high-speed solid-rotor induction motor.

According to the thermal analysis based on the thermal resistance networks, the maximum temperature, that is 116.2 °C, occurs in the lower coils in stator slots. In order to boost the performance of the cooling system, an auxiliary water cooling jacket is used in the stator frame. By using the auxiliary water cooling the temperature distribution of the generator can be kept at a moderate level. The future work is concentrated in the manufacturing and testing of a full scale prototype.

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