THERMAL EVALUATION OF GENERATOR COOLING SYSTEM OF PARAIBUNA HPP

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Abstract. *This study presents an evaluation of the thermal cooling system of generators of a hydroelectric power plant located in Paraibuna, belonging to CESP. In the pursuit of energy efficiency and being the generator one of the main equipment of the plant, a study of its thermal conditions of cooling addressing was carried out, following the subsequent actions: measuring the flow of air in the heat exchangers; experimental measurements of thermal performance by varying the water flow in the cooling circuit; and thermal computational modeling of the generator. Applying the original design data, that was aimed to identify the cooling conditions, its limits, operational optimization of the generator and its cooling system. Through the results of modeling, it is possible to identify the distribution of calculated losses. In the search for greater energy efficiency, it is proposed and carried out actions that can generate energy savings, which mainly aim at: cooling water savings; reducing downtime for cleaning of heat exchangers; possible increase in power. The study by modeling confirms that the generator ventilation has 20% higher efficiency than the projected value. It is concluded that the methodology proposed in this study is feasible and applicable in hydroelectric power plants of small, medium and large sizes.*

Keywords: *cooling, generator, hydroelectric power plant.*

1. INTRODUCTION

The generation of electricity is crucial to keep the activities of industrial and human life in the modern world and the need for electricity is increasing continuously. To generate electricity, there are several methods to drive a generator, such as gas turbine, steam turbine, and hydraulic turbines. Due to energy losses in the generator, components are subjected to excessive heating during operation. Therefore, effective cooling is required to maintain the internal temperature of the generator within acceptable values.

Some works in this direction have been made. Tong (2008) lead a numerical analysis of the flow field in the last region of the generator winding. An investigation into the fluid flow around the end of the large hydroelectric generators winding was conducted by Klomberg et al. (2014). Xiong and Gu (2008) studied on the stator temperature distribution comparisons between the evaporative cooling air mode and cooling mode. Hribernik et al. (2011) performed a research on malfunction of the air cooling system of a 10 MW hydro- generator. Mayle et al. (1998) studied the rotational flow in an air leak. Han et al. (2012) conducted studies on numerical characteristics of the air flow in the air gap of a stator of a large turbogenerator air cooled.

The distribution of the mass flow in the rotor ventilation duct was studied by Lu et al. (2008). Considering the same geometric configuration of the rotor, the change of the characteristic in the parameters was analyzed under two conditions, when the shaft is rotating and when it is stopped. Fechheimer (2009) lead an analytical and experimental study on the ventilation of the turbine generator rotor. The experiment considers the effects of axial flow of air in the air gap , the air stream that is incident from the stator ventilation openings and combinations thereof.

All these studies used computational tools to solve the equations. Called Computational Fluid Dynamics (CFD) , this tool produces analyzes that effectively predict temperatures in electrical machines by heat transfer modeling by conduction and convection between the machine and the flow of air (Jamshidi et al.,2015) .

Due to the heat generated by electrical losses, the cooling system is very important to design the generator. The rotor design drawing ventilation is more important that other components, because the characteristics of the airflow in the ventilation duct system are complex. Thus, a study of the flow characteristics and heat transfer in the rotor ventilation duct is conducted to obtain an effective cooling.

2. METHODOLOGY APPLIED

In a power plant, the power generator associated with the turbine is the most complex equipment in its operation due to numerous requests suffered by mechanical, electrical and thermal effects. This work consists in demand of modeling tests that enable the testing of achievements in the main generator, in order to assess its cooling system in full operating condition of power.

2.1 Generator nominal basic data

Power: 42500 W; Voltage: 13.8 kV;
Stator current: 2092 A; Excitation voltage: 125V
Excitation current: 913 A; nº of units installed in this plant: 02; power factor: 0.85

2.2 Cooling generator test

In pursuit of service to the concept of energy efficiency and the generator being one of the main equipment of the plant, the study was conducted of the generator in its thermal conditions of cooling. The main addressed actions performed on the generator (generating unit 2 - UG2) were:

- Air Flow Measurement in a closed circuit;
- Experimental measurements of the thermal performance by applying variations in water flow in the cooling circuit. These tests have not been completed with conclusive results due to the low amount water level (atypical seasonal condition) and therefore with the limitations of water discharge, having only been used an active power of approximately 23 MW, in addition to the lack of cleanliness of the exchangers heat due to fouling of iron bacteria of waste from the gross of the dam water in circulation elements of water from heat exchangers;
- Due to the unusual condition of the amount of water volume, and added to the existing of the sedimentation condition in the exchangers cooling elements, it was developed with the support of a major hydro manufacturer, a thermal computer modeling of the generator, using the original design data, thus seeking information that would lead to a proper evaluation, for the cooling conditions, possible limits, optimizations (efficiency) in operating the generator and its cooling system.

For measuring the air flow from radiators in order to study variations in temperature, an anemometer Tec - Probes Testo was used. Air flow measurements were performed in the six air-water radiators generating unit 2. A wood device was developed, dividing the measurement areas of each exchanger 18 quadrants, as illustrated in Fig.1 (a). For each quadrant, five measurements were performed using the anemometer, one in each corner and one in the center as shown in Fig.1 (b). Totalizing 90 measurements. From the measurement of air velocity versus area of the quadrant the flow values were calculated. During the measurement it was observed that some radiators are mounted without the appropriate seals for their movement.

(a)

(b)

Figure 1 - (a) Detail of wooden quarters built for the measurement
(b) Measuring point to the center of the quadrant

For measurements made it appears that the generating unit 2 has about 20 % excess air flow in relation to the calculated value: Manufacturer drawing reports a total flow of 401 m³/min, while the sum of the measured values reached 488 m³/min. The Paraibuna generating units have 2 types of radiators: the type with finned tubes (tubes with circular fins) and type "compact cooler."

For the measurements, it does not detect significant differences between the two types. If there is need to deepen this subject, the more sensitive measurements of pressure drop (static pressure) between incoming and outgoing air would have to be made, although, as already mentioned above, the measured flow values show higher than expected. Moreover, it was observed that many of the radiators do not have the side trimmings or side seals that allow prevent “leakage" of hot air. In other words, a portion of the air is not being cooled, thereby losing a part of the heat exchange efficiency. It is recommended to perform a detailed inspection and carry out the necessary corrections.

Regarding to experimental measurements of thermal performance, this study indicates recommendations that must be met to achieve reliable results. The minimum requirements to run a heating test are:

- Cleaning of all previous air-water heat exchangers and the ideal is always with the use of water without problems of contamination and Iron Bacteria. Deaeration after re-installed and before releasing for operation;
- Prior calibration of temperature readings systems RTDs (Resistance Temperature Detector);
- Previous measurement of ohmic resistance to cold rotor winding;
- Ideal location determination for measuring Uexc and Iexc (voltage and excitation current respectively), for the measurement of the hot resistance of the rotor winding;
- Have sufficient amount of water quota to load with full capacity as well as a schedule that allows enough time for the different stages of testing, with appropriate varieties in the temperature stabilization;
- Have simultaneous measurement of water flow. Ideal to be in the inlet of the pipe water. Any tests with reduced water flow, which is ideal for valve in the pipe water outlet.

3. COMPUTATIONAL MODELING

The theoretical modeling of the generator, with a view to the conditions of thermal equilibrium, was prepared based on the same design data, drawings and technical manual of operation and maintenance of the manufacturer.

The computational fluid dynamic modeling (CFD) can be used to predict the heat transfer and flow into complex geometry regions. Accurate results CFD can be used to improve the thermal performance of a system without the need for costly experiments. In this work, the computational modeling (CFD) used models of turbulent flow in order to solve the Navier-Stokes equations in their average ways of package called RANS (Reynolds Averaged Navier-Sokes). The software used was the ANSYS, all presented simulations were performed using a k-ε model. The iterative process used to solve the resulting matrix was based on the Euler equations on your first order. The maximum residual amount of 10^{-4} was considered small enough to provide good results of the specified mesh equations according to the given boundary conditions.

The boundary conditions include parameters at the inflow cooling fan, pressure boundary conditions on the flow exiting the rotor rotation speed, and anti-slip condition on all surfaces of the stationary components

Also for modeling, applied to normalized calculation and hydro operation, one being the standard cold air temperature, i.e. 40°C. This is the basic temperature reference for the rest of the machine parts. It means that temperature gradients (Δt) calculated for any part of the generator will always be added to the air temperature "cold" or air outlet of the heat exchanger and entering the machine. If for some reason the temperature of the cold air up to 42°C, the absolute temperature of any part of the machine will be as calculation, that part Δt + 42°C. In other words, the temperature rises linearly increased from baseline. For this concept it is important to remember that the various parties concerned of the machine (stator copper, iron and copper stator rotor) are operating in accordance with the assumptions of calculation and design without operational defects that may violate laws that supported the same project.

The Figure 2, illustrates the results of modeling the generator with a view to the ventilation system. Air speeds in the various parts of the generator were found; taking into account the real dimensions of the parties, the two channels in the rotor ring to provide a portion of the radial ventilation, and together with the axial ventilation promoted by top fans and lower establishes the complete ventilation system generator. The flow of air through the six heat exchangers, found by modeling was 47.2 m^3/s. Compared to the value provided by the original manufacturer of the project 401.2 m^3/min x 1/60 x 6 (exchangers) = 40.12 m^3/s, or about 15% of the value found in the model. Compared with the measured value in the generator 2 of 488 m^3/min x 6 x 1/60 (exchangers) = 48.8 m^3/s, it appears that the total measured air flow and patterned are very close.

Figure 3 illustrates the result of the calculated distribution losses, which are:

- Electromagnetic losses generated in the stator core,
- Losses by Joule effect generated in the copper windings of the stator and rotor,
- Additional losses due to leakage fields,
- Losses due to ventilation friction generated by the cooling air itself which circulates in a closed circuit passing through the rotor ring channels, the heads of the winding, the air gap and the stator ventilation ducts, and finally, the heat exchangers, to be cooled again.

The diagrams of Fig. 2 and Fig. 3 are intimately interconnected, they consider the generator as an adiabatic process (when not taking into account the exchange of heat by convection and by irradiation through the walls of the generator to the external environment), where all the heat generated internally undergoes cooling by circulating air, which ultimately transfers the thermal energy losses to the water which circulates through air-water heat exchangers.

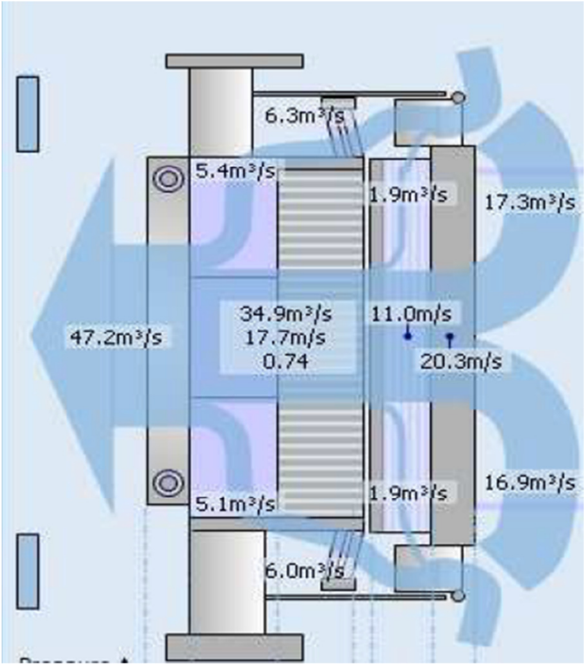

Figure 2 - Ventilation Profile Generator Unit 2 HPP Paraibuna

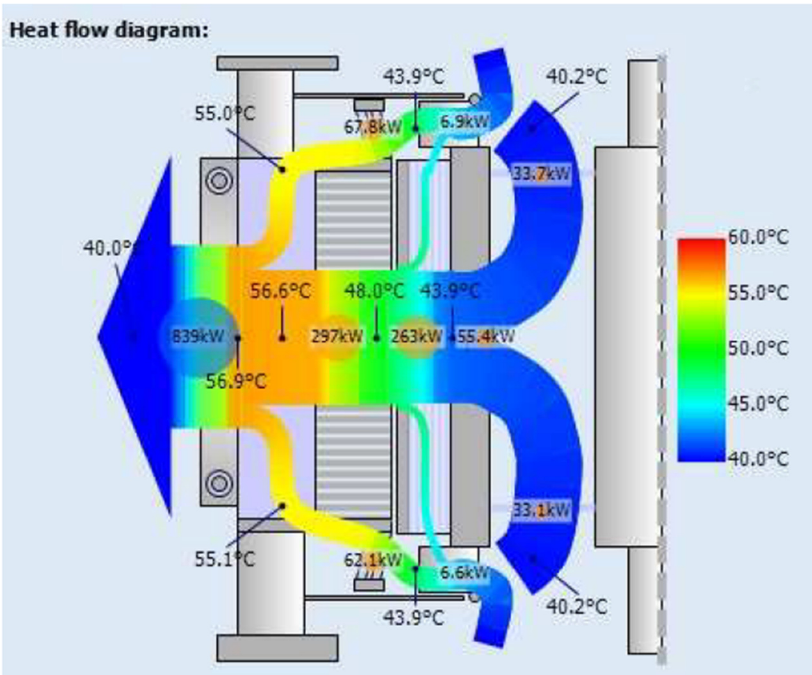

Figure 3 - loss profile and heat flow and generator cooling air to the full rated load

It is also observed that for modeling of losses beyond the logical basic assumptions adopted (air-water heat exchangers operating as if it were new, that is, with full capacity of thermal exchange as designed, with its clean elements, both side water as the air side), some parameters were adopted as "typical parameters" for this size generators that are located in Paraibuna plant, due to unknowledge the actual values of the project, such as electrical conductivity of coppers of the stator and the rotor, and the hysteresis and Foucault losses on the magnetic sheets of the stator core .

At the end, the results of thermal modeling of the generator are given in Tab.1, which shows the value of the stabilized temperature of the interest parts of the generator, considering the nominal operating conditions and temperature of the cooling water inlet 28°C.

In the first column are observed absolute temperature values and the second column the Δt values of the parties of interest, above 40°C.

The thermal reference of the machine is always the temperature of the cold air, set by regulations at 40°C. If for some reason the temperature of the cold air goes "x" degrees, the parts of interest also raise these "x" degrees, i.e., Δt values of these parts are contained.

Table 1 – Stabilized temperatures of generator parts of interest

	Temp.°C	Temp.K
Slot core	97	57
Maximum temperature of the copper in the slot	110	70
Maximum temperature in the winding heads	108	68
Temperature measurement in the rotor winding of copper	84	44
Maximum temperature in the rotor cover .	94	54
Maximum temperature in the stator core	69	29

It is important to note that this theoretical simulation carried out, has the real stator copper temperature (110°C) when the reading slot RTD is only 97°C and the reading of the stator iron RTD is only found 69°C . The 13°C of Δt between the temperature of copper (internally in the bar or coil) and the temperature read in the slot RTD are of special interest and attention when seeking a reduction of lifetime losses of insulating materials.

4. ANALYSIS OF RESULTS

The measurements and computational modeling performed served for a preliminary assessment of the performance of the generator cooling system. However, to obtain data that lead to actions relating to the system, it had to be done the following consideration:

Considering the generator spinning in nominal and excited spin at rated load voltage, the losses caused by ventilation losses iron in the stator core and a small loss Joule - IR2 by excitation current in empty generate, is almost 50 % of total losses generator (not including bearings, of which we are not dealing in this study). The other 50 % will only be generated when the generator is synchronized and loaded, ie the losses Joule IR2 in the stator windings and rotor, and the additional losses, also resulting from the currents that circulate in the stator winding. In summary, there are two almost equal portions of losses: 50 % empty and 50 % at full load.

It should be remembered that the three losses generated during operation with load: IR2 stator, rotor and additional IR2, vary in quadratic function of the current. Thus, in approximate values when the generator is approximately 70 % of the rated current, the additional losses generated will be 50% (0.7 x 0.7 x I2) of the total due to loading.

Stresses also due to the thermal inertia of the parts of the generator, its stabilization temperatures cause certain time to be achieved.

The above consideration leads us to a first conclusion: it is not necessary that the generator receives full cooling immediately on his departure. It can be concluded that up to the full cooling operation from the beginning is harmful and causes mechanical fatigue, especially in elements containing materials with different thermal expansion coefficients, as with the stator winding .

Based on the above and given the main objective of this project, the search for greater energy efficiency, it is proposed to establish a program review of the pumps from the mine closed water loop system (not contaminated with iron bacteria), relative to the cooling system of the generator with the use of the cooling loop rather than the open system. This action is aimed at cooling water savings and reducing downtime for cleaning of heat exchangers.

The above considerations lead to the following savings:

A – Energy Savings:

Conditions or assumptions:
• 2 generating units, generating a total of 84 MW for the contract market;
• Estimated rate in contracted market: 140 R$/MWh;
• Estimated rate on the free market: 280 R$/MWh;
• Using water without the iron bacteria effect (mine water);
• Only one (1) stop per year against four (4) stops in average today to exchange the set of air-water radiators, another set with radiators that have undergone internal and external cleaning;

Direct result, revenues: (4-1) stops x 8 hours x 84MW x R $ 140 / MWh = R$ 282,000;
• Consequence of no need to buy the same not generated energy from the free market:
R$ 282,000 x 280 x 1/140 = R$ 564,000.

Direct revenue or savings: R$ 282,000 R$ 564,000 + = R$ 846,000 per year;

This calculation shows that only by not obligatory stop for replacing radiators contaminated with iron bacteria by other clean, the annual gain can reach R$ 864,000. This is pure revenue, not counting the costs of maintenance work hand and administrative costs of coordination of the stops for maintenance.

B - Turbinable water savings (raw water from the dam):

Currently the raw water from the dam is used for cooling the generators. Therefore, the alternative use of mine water, Iron Bacteria free will also contribute to a dam of water economy, in other words, it could be fueled:

Q nominal water for radiators: 3.6 m^3/ min

Annual consumption = 3.6 m^3/ min x 365 days x 24 hours x 60 min = 1,892,160 m^3 turbinable water.

Annual savings = approximately 2.0 million m^3 of water turbinable.

5. CONCLUSION

Further studies could confirm a possible gain power generated, depending on the turbine characteristics and other components involved. The flow measurements of air through the radiators as well as the study by modeling confirmed that the generator has a ventilation efficiency 20% higher than the projected value. In other words, the generator is able to work more cold or generate more power. Moreover, as already mentioned above, heat transfer calculations of active parts show relative clearance on the absolute temperature. As the generator has the stator winding insulation class F and as known that lowering the temperature will not bring any real significant benefit in terms of increased life expectancy, the most plausible would be leaving for a study of possible power increase.

6. REFERENCES

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7. RESPONSIBILITY NOTICE

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