Development of a Solution for an Overheating Problem and Reactive Power Increase in the Three Generator Units of a Hydroelectric Power Plant

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Abstract— **Analytical calculus and computational models of multiphysics problems were used in order to solve an overheating problem and simultaneosly increasing reactive power in a generator group of a Hydroelectric Power Plant (HPP). All of them present the same geometrical, mechanical and electromagnetic characteristics. A method of iteration using Finite Elements Analysis (FEA) called Simplified Virtual Laboratory (SVL) was used to find a solution from an accurate, reliable and fast process. Models of Electromagnetics, Computational Fluids Flow (CFD), Heat Transfer and Stress Analysis were done. Finite Elements Models were used to evaluate different aspects and to develop the final solution.**

I. Introduction

Since its installation, almost twenty years ago, the generator group, of 71,9 MVA each unit, was disabled to generate the nominal reactive power, established on its original specifications, caused by an overall overheating, but just a few years ago the interest of the generator's operator to solve this problem appeared when the Government announced the pricing of reactive power. This means, the generator's operator would receive money, from this time, for the reactive power generated.

The reason of the overheating was analysed by the Research Group throughout a project previously done where was detemined that overall overheating was caused by a highly increase of temperature at the excitation winding [1].

II. Problem Definition

The overheating occurs due to generator's size. The generator's diameter is smaller than it should be. To compensate this, the manufacturer made the rotor larger, increasing its axial length. To minimize the overheating effect, Fig 1., the manufacturer used a trapezoidal shape for polar core which allowed the complete annulation of centrifugal force tangent component over the polar coils, in order to eliminate the interpolar support providing a major airflow through the machine's interpolar channels. However this design was not enough to extract the heat generated at the appropriate rate. Maximum temperature registered was 146^{o}C at polar coils. One of the goals was to low that temperature between 25 ^{o}C to 30 ^{o}C.

Fig. 1. Overheating effects at the excitation winding. It was burned at rated reactive power excitation.

III. Project's Methodology

Analysis of solution was evaluated since the feasible and cheapest economical option. The method employed for this project is briefly described below:

*Calculus of total losses of the machine based on results from test's data, according to IEC 34.2A.
*Revision of refrigeration's system:
-Calculus of water flow for refrigeration's system.
-Calculus of air flow for refrigeration's system.
- Revision of excitation winding design.
*Evaluation of electromagnetic behavior using analytical and Finite Elements Methods.
*Study of methods for increasing heat transfer through improving ventilation's system:
-Fan's verification, using wind tunnel through CFD models.
-CFD models of Interpolar channels to determine current air's velocities.
-CFD model of axisymmetric section of the entire machine.
-2D Heat transfer model of machine's rotor.
*Solution`s Strategy
-Elaboration of Redesign's proposals of machine's rotor.
-Iterative procedure between analytical results and heat transfer models of new redesign's proposals.
*Mechanical, Electromagnetics and economical evaluations of feasible solution's proposals.
*Conclusions and recommendations.

A. Calculus of total losses of the machine based on results from test's data.

0-7803-8987-5/05/$20.00

Results from test´s data show differences between values of losses defined by manufacturer and the effectively measured. Results from test's data of the machine were used to determine the total losses through this equation:

$$P_{tot} = P_{i^2r} + P_{fe} + P_{exc} + P_{vent} \quad (1)$$

Where:

P_{i^2r} : Ohmic losses at stator winding.

P_{fe} : Iron losses at stator core.

P_{exc} : Ohmic losses at excitation winding.

P_{vent} : Ventilation losses.

From data taken in site:

TABLE I.
VALUES OF THE ELECTRICAL MACHINE LOSSES

Losses in kW				
P_{i^2r}	P_{fe}	P_{exc}	P_{vent}	P_{tot}
270.22	381.18	337.44	171.8	1160.6

Total losses value to make further calculations were 1160,6 kW instead of 1095 kW mentioned as design's value by manufacturer in its original specifications.

B. Revision of refrigeration's system

A new revision of refrigeration system is done, developing calculus of water flow and air flow in order to satisfy heat transfer requirements to avoid overheating.

1) Calculus of water flow for refrigeration system

From total losses result, water flow value necessary to evacuate them was calculated through next equation:

$$Q_w = \frac{P_{tot}}{C_p \cdot \rho \cdot \Delta T_w} \quad (2)$$

Where:

Q_w : is the water flow.

P_{tot} : are total losses of the machine.

C_p : is water's specific heat.

ρ : is water's mass density. Its value is a mean integral value calculated between inlet and outlet water's temperature.

ΔT_w : is temperature difference between inlet and outlet's values at the radiator's system

2) Calculus of air flow for refrigeration system

From total losses result, air flow value necessary to evacuate them was calculated through next equation:

$$Q_{air} = \frac{P_{tot}}{C_p \cdot \rho \cdot \Delta T_{air}} \quad (3)$$

Where:

Q_{air} : is the air flow.

ΔT_{air} : is temperature difference between inlet and outlet's values of air ventilation circuit.

C_p and ρ are values defined for air in equation (3).

With these results a comparison table between manufacturer's data and Research Group's data is developed.

TABLE II.
COMPARISON OF PARAMETERS

PARAMETERS	Measured in site	Manufacturer	Research Group from Universidad del Valle	Units
Total Losses	1160	1095	1160,6 * 1,05	kW
Refrigeration´s water flow	200	200	210	$\frac{m^3}{h}$
Refrigeration´s air flow	40,1	55	60,9	$\frac{m^3}{s}$

From this comparison are noticed differences between manufacturer's values, measured values and calculated data.

An increase of water flow was an option evaluated in site. However it didn't solve overheating problem. A complete redesign of radiator system would be necessary in order to try overheating problem. This proposal could solve in part overheating problem but not the increasing of reactive power problem.

Air flow's increase requires an evaluation of machine's fans and ventilation system. This was the next step in the search for a solution. A huge difference between air flow's calculated value and the measured one is noticed.

3) Revision of excitation winding design

From manufacturer's design about polar coils, depending on number of turns, thickness of each turn and temperature's rising for excitation winding, it was required a heat transfer convective coefficient about 185 W/m^2 ^{o}C which is impossible to get with the current machine's air flow.

Heat transfer coefficient depends on materials, coil's sizing and air velocity around the surface to decrease temperature. Air velocity for a fixed area at Interpolar zone depends of generator's RPM.

According to conventional designs, at the Interpolar channels zone, distance between polar coils is less than the minimum distance allowed what means that polar coils are too close to each other. One of the consequences of this physical disposition of polar coils is less space to air flow at

Interpolar channels. When rotor`s diameter is reduced the polar height is reduced too, so in order to have the adequate number of turns for polar coils, a less turn's thickness was imposed. Additionally, at higher temperature, coil's cupper resistivity is increased and higher excitation voltage is required. Everything described above causes a larger loss density and an excessive temperature rise.

C. Evaluation of electromagnetic behavior using analytical and Finite Elements Methods.

Electromagnetic Analysis of the machine was implemented to describe the current behavior and to compare it with electromagnetic behavior imposed by the solution proposed. Aspects evaluated included: No load Saturation´s curve, Magneto Motive Force (MMF) under load, resultant MMF wave and Armature reaction in steady state behavior, among others. Heat generated by iron and ohmic losses was calculated too through magneto-thermal models and these data were used as input in heat transfer models.

D. Study of methods for increasing heat transfer through improving ventilation system

Refrigeration`s system present a ventilation circuit and a radiator`s system. Radiator`s system was formed by eight heat exchangers.

According to electrical machines design this ventilation's circuit is an axial one, with two axial fans, each one of them, with 85 blades. There are two ventilation's subcircuits, generated by fans, upper and lower respectively.

1) Fan's verification

Analytical verification of the machine's fans was done through fluid flow mechanics of a fan's blade. Fig. 2 shows one of the fan's blades and the geometry used for analysis.

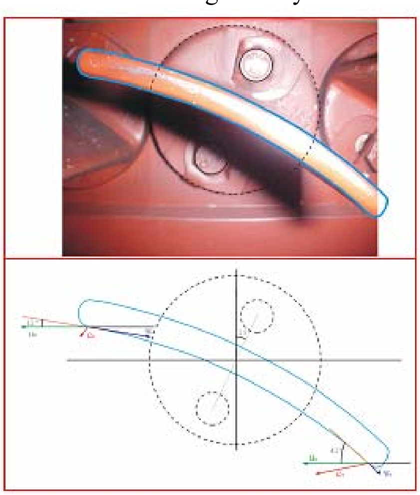

Fig. 2. Wing's detail of the upper axial fan. Wind star at the entrance and exit of the airflow passing through the fan's blade.

Next figures show the wind stars of fan's blades.

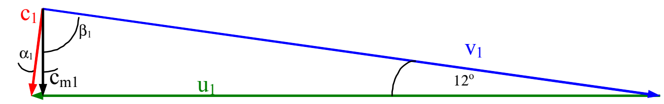

Fig. 3. Wind star at the entrance of a fan's blade.

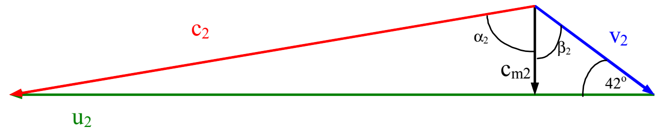

Fig. 4. Wind star at the exit of a fan's blade.

Form figures above next parameters were defined:

c_m: is axial velocity of air.
v: is the value of relative velocity between the air and the fan's blade.
u: is the fan`s blade velocity.
c: is the value of absolute velocity of air.
α: is the angle between absolute velocity`s vector of air and the axial velocity's vector of air.
β: is the angle between relative velocity`s vector of air and the axial velocity's vector of air.
Lower index shows the entrance point of air at the fan`s blade, with number 1 or the exit point of air at the fan`s blade with number 2.

From axial fan's theory [2], axial velocity of air is the same on every point of the axial fan's blade.

Thus,

$$c_{m1} = c_{m2} = c_m \qquad (4)$$

Fan`s verification had the purpose of checking air`s flow generated by the axial fan`s of the machine. To achieve this task, calulations (showed below) were developed.

$$u = \omega \cdot r \qquad (5)$$

where:
ω: is the angle speed of the machine in rad/s.
r: is the mean radius of fan`s rotation

$$\omega = \frac{RPM \cdot 2\pi}{60} \qquad (6)$$

where:

RPM: Is the number of revolutions per minute of the fan. In this case is the same one that the electrical machine.

The radius of fan's blade is calculated as a mean value form data obtained as is shown in the next figure.

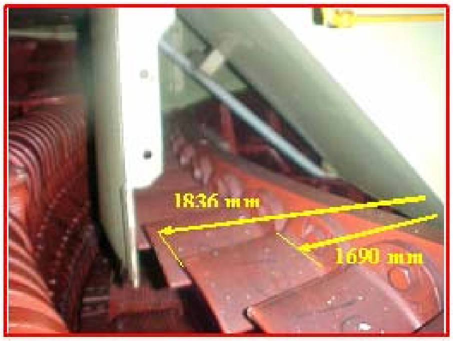

Fig. 5. Inner and outer radius of fan's blades.

$$r = \frac{r_o + r_i}{2} \quad (7)$$

Where

r_o : is the outer rotational radius of a fan`s blade. Equals to 1836 mm

r_i : is the inner rotational radius of a fan`s blade. Equals to 1690 mm.

$$v_1 = u \cdot \cos(\alpha_1) \quad (8)$$

Where α_1 was obtained from Virtual wind tunnel using Computational Fluids Dynamics (CFD) and SVL method. Observe fig. 6. Another way to calculate this angle, analytically, is assuming that there is no separation of boundary layer in this zone so α_1 is equal to the attack`s angle of the fan's blade. However this assumption must be done carefully because is not always true, especially where fluid flow has high velocity and does not present laminar behaviour.

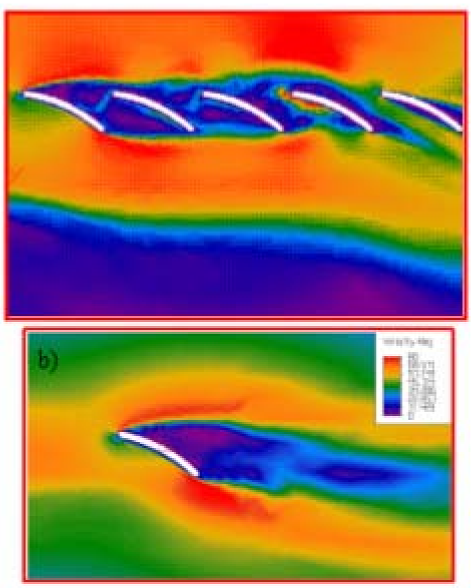

Fig. 6. Evaluation of fan`s blades through a virtual wind tunnel developed by CFD.

$$c_m = v_1 \cdot sen(\alpha_1) \quad (9)$$

$$Q = c_m \cdot A_s \quad (10)$$

where

Q : is the air flow generated by one fan.

A_s : is the air`s outlet area at the axial fan.

From mathematics;

Air flow Q generated by one fan is 21.86 m^3/s, so the air flow generated at the machine is twice the mentioned value, 43.71 m^3/s, because there are two axial fans in the machine. Making a comparison with data from table 2 is show air flow measured in site which is 40,08 m^3/s. So this calculus could be taken into account to further considerations.

Virtual wind tunnel of these fan`s blades allowed search for increasing efficiency, changing the attack`s angle of the blade from 12^o to 15^o with steps of one degree, according to ventilators theory [2], but every different angle to the current one showed excesive turbulence and a decreasing of axial velocity of air. Aditionally, it was necessary 129 man-power hours to make this change in site (which was the fastest option).

2) CFD models of Interpolar channels to determine current air's velocities.

All these models were created starting from assumptions like air was uncompressible and there was just one phase on the fluid flow.

Virtual wind channel had the purpose of determining fan's blades efficiency and to find out axial velocity provided by the fan under rated conditions. These data were necessary in order to develop a model of interpolar channels. Besides, attack's angle of fan's blades was evaluated to confirm the better performance of these pieces. Warning, these blades didn't present NACA profiles and that's why a simulation of its performance was necessary.

Results of wind channel simulation were used as input data for modeling interpolar channels. The main objective of this model was to find the axial velocity of air through these channels in order to calculate, analytically first, convective heat transfer coefficient and then obtain more accurate results with multiphysics models that involved a heat transfer and CFD model of the dominion studied.

Models of Interpolar channels under all considerations and assumptions taken above were done to find out what was the value of axial velocity of air in this zone. A 2D model was done unwounding the cilindrical rotor`s shape.

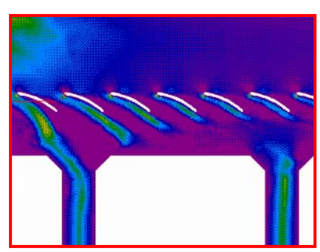
Fig. 7. CFD Model of Interpolar channels. View of the upper axial fan.

Outcomes of these models revealed a value of a mean axial air`s velocity of 25 m/s. Analytical calculus was 24 m/s.

3) CFD model of axisymmetric section of the entire machine

After these models, perhaps the most representative one was done, simulating the air flow of ventilation circuit through a 2D cross-section model. This model had the purpose of providing air velocity data in every part of the machine to support analytically and by FEA models convective coefficients and thus heat transfer models of the generator. Fig 10 and 11 show some graphical results of these models.

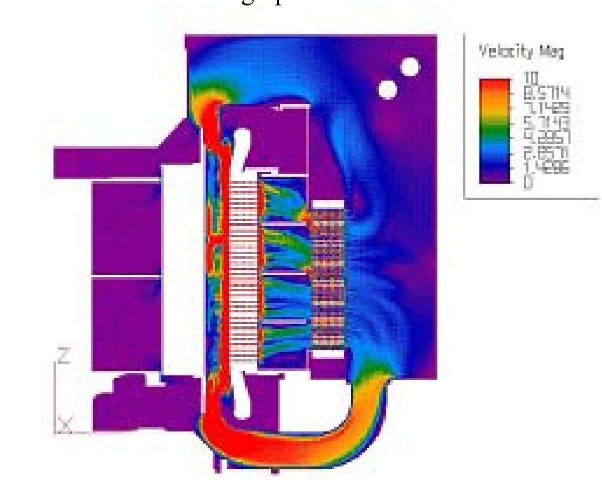

Fig. 8. Axisymmetric cross section of the ventilation circuit system's airflow using CFD.

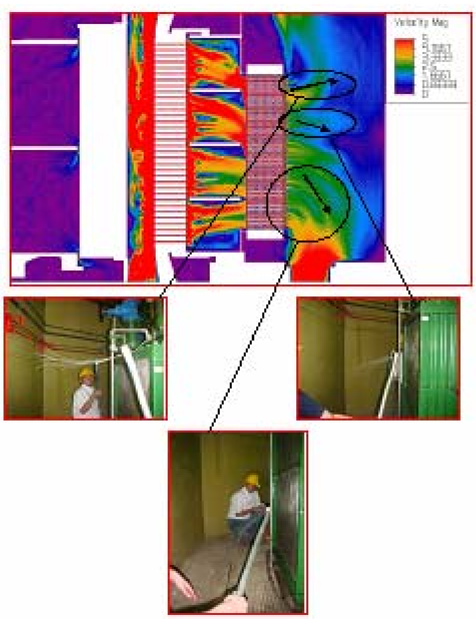

Fig. 9. Validation of the air flow Finite Element Model of the ventilation circuit system.

Air's pressure increase and air's axial velocity, were necessary to represent an axisymmetric cross section of the generator's airflow using Computational Fluids Dynamics (CFD) through Finite Elements Models. With these data and heat transfer theory, calculus of convective coefficient begun.

4) 2D Heat transfer model of machine's rotor.

Analytical calulus were used to find a heat transfer convective coefficient, [3],[4],[5],[6],[7], in order to evaluate and iterates Finite Elements Models with these values.

Fig. 10 shows dominion used to develop heat transfer models. From Measured data, different boundaries were imposed and an unstaedy state rutine employed in order to iterates convective coefficients and to build a more accurate steady state heat transfer model. See Computational Models Section from this paper. Closed zones indicate heat transfer convective coefficient location.

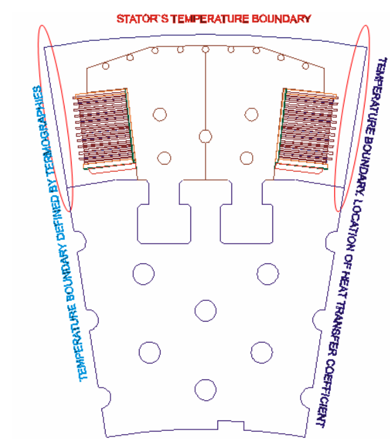

Fig. 10. Dominion used to develop heat transfer models.

Fig. 11 shows one of the termographies which in addition with Rotor's temperature measurements were also used to determine temperature boundaries on heat transfer models.

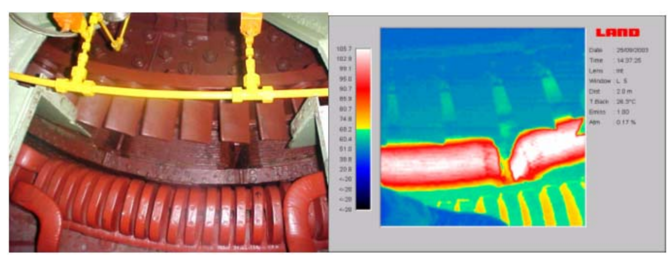

Fig. 11. Termography of polar coils.

Fig. 12 and 13 show results of heat flux and a temperature profile obtained from a generator's heat transfer model. These figures specifically correspond to the polar winding. It is appreciable how almost all the heat generated by Joule Effect in the excitation winding is transferred to the airflow at the interpolar channels through the copper fins.

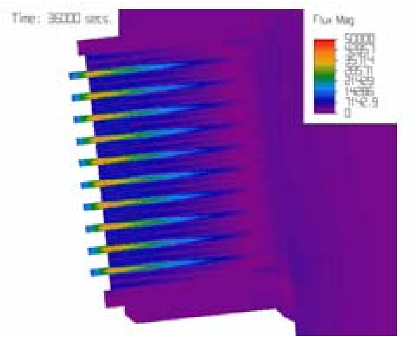

Fig 12. Result of a heat transfer model of the excitation winding. The heat flows from the rotor to the airflow at the interpolar channel through the copper fins of the winding. The data is in J/m^2.

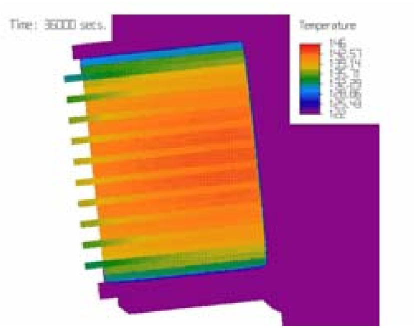

Fig 13. Result of a heat transfer model of the excitation winding. Current temperature profile of the rotor's winding. The data are in ^{o}C degrees.

IV. Solution Strategy

When this thermal effect was recognized, the solution to the problem became clear.

A way to generate less heat and to increase reactive power was reducing the heat density through the increment of the total area of excitation winding. There were two paths to accomplish this goal. One of them is increasing the number of turns of the rotor's winding and the other one is increasing the cross sectional area of every turn reducing isolation's thickness. Isolations proposed was "H" type. Several proposals of cooper fin's shapes were evaluated.

Previously it was established that the number of turns of the rotor's winding shouldn't be changed. The main reason were the undesirable M.M.F. (Magneto Motive Force) variation, besides there wasn't enough space to introduce the necessary additional turns.

The second path to reduce heat density generated (loss density, W/m^3) was increasing the cross sectional area of every turn. This increment was done through the thickness of each winding turn. The area was not increased through its width because it could cause a reduction of the interpolar channel space, changing the current airflow of the ventilation circuit. This was the way how to generate the less heat as possible. Now just one goal was remaining; how to extract the major quantity of heat that was possible!

A new proposal of fin shape was done, Fig. 14, (after developing several more) and evaluated by thermal and mechanical models. What the Research Group did was to increase as much as the mechanical resistance would allow it, the cantilever length of the cooper fin.

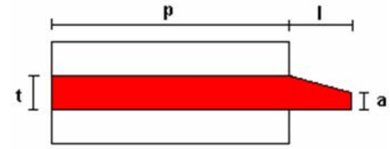

Fig. 14. Graphic specification of the new copper fin shape proposed for the excitation winding.

Where p is the coil's width, l is the coil's cantilever length, t is the coil's cupper thickness and a is the final coil's cupper thickness at the end of the cantilever coil.

The mechanical restriction was the overspeed state. [7],[8]. Once the proposal of a fin shape satisfied the thermal and mechanical requirements, a final electromagnetic verification of the new geometrical and mechanical configuration of the excitation winding was done. It is shown in Fig. 15.

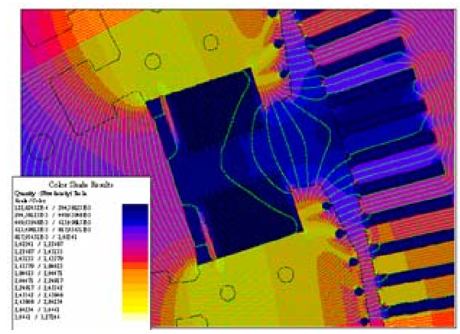

Fig. 15. Electromagnetic Finite Element Model of the new mechanical configuration.

FEA models of this multiphysics phenomenon were used and the result was a fine modification in the geometry of the excitation winding. A 0.5 mm increment of the thickness of each winding turn and five mm length's increment at the cantilever cooper fin with a new trapezoidal shape instead the old rectangular one. Final temperature obtained at polar coils through FEA was 112^{o}C.

Currently the generator's owner is preparing the construction of the new rotor's windings under the Research Group's specifications.

The key for the success of the project was the optimisation developed by 2D FEA models linked with the equations which govern the physical phenomena.

V. Computational Models

In order to simulate actual characteristics of this electrical machine it was necessary to build up different models of electromagnetism, fluid flow, heat transfer and mechanical analysis. Each one of the computational models was done in a 2D dominion using specific assumptions to simulate, in the right way, the respective physical phenomenon.

A modeling procedure through different FEA models was done and used for simulation of the current physical states and the proposed one to evaluate overall machine's response to any change in order to find a reliable solution. This procedure that includes analytical formulation to support and bring additional data, is based on a new technical concept (but already used for several years), the Simplified Virtual Laboratory (SVL), which key goal is to get fast, accurate and reliable results for complex multiphysics problems, not for a research environment but for an industrial one that demands results in terms of days or weeks, tops.

In SVL, the main rule is FEA models are used to simulate conditions, not to make a perfect representation of the real behavior of the studied device, but to generate outcomes that let to researchers finding reliable data to achieve a right solution in order to save computational resources, time and thus money. 3D models are avoided as much as theory makes it possible.

Some equations solved by FEA modeling were:
From Heat Transfer:

$$\rho \cdot C_p \cdot \left(\frac{dT}{dt} + \{\vec{V}\}^T + \vec{\nabla} T \right) + \nabla \bullet \{\vec{q}\} = q_v \qquad (11)$$

Where:

ρ : is the mass density. For most mechanical and electrical components in the machine, this value was constant, but for CFD models were used air, this value could change depending on temperature range.

C_p : is the specific heat. A Constant Value for most components of the machine but not for air in the calculus of convective heat transfer coefficient.

T: Temperature. Is a scalar space-time field T(x, y, z, t).

t: Time.

$\{\vec{V}\} = \begin{Bmatrix} V_x \\ V_y \\ V_z \end{Bmatrix}$: is the velocity vector for mass transport of heat.

$\{\vec{q}\}$: is the heat flux vector.

q_v : Heat generation rate per unit volume.

Assumptions made for CFD models:

- There´s only one phase.
- The Fluid is incompressible.

From Fluids Flow the Incompressible Energy Equation:

$$\frac{\partial(\rho C_p T)}{\partial t} + \frac{\partial(\rho V_x C_p T)}{\partial t} + \frac{\partial(\rho V_y C_p T)}{\partial t} + \frac{\partial(\rho V_z C_p T)}{\partial t} =$$

$$= \frac{\partial}{\partial x}\left(K \frac{\partial T}{\partial x}\right) + \frac{\partial}{\partial y}\left(K \frac{\partial T}{\partial y}\right) + \frac{\partial}{\partial z}\left(K \frac{\partial T}{\partial z}\right) + q_v \qquad (12)$$

V_x, V_y, V_z : Components of the velocity vector.

K : Thermal Conductivity.

In FEA even when the real state of a physical model corresponds to a steady state one, due to computational algorithms in most cases, steady states processors used to simulate these phenomenons are not reliable because there are not enough data to input so it is necessary to use non-steady state processors to model steady state phenomena. Steady State processors use an iterative algorithm to calculate one value having the rest, but if there's lack of some of this information (which in real world is not always feasible to get), outcomes of this steady state model could be wrong. This is another SVL´s recommendation which lets save time and to bring maximum accuracy even if processor used is not the cheapest one, when there's not enough information.

VI. CONCLUSIONS

- Calculus determined a D.C. current for the rotor's winding of 1098A to generate the original specified reactive power. However this value is 120A larger than the nominal D.C. current established at the specifications of the machine.
- The manufacturer determined the design airflow of the machine in 55 m^3/s. From analytical formulation and field measurements it was established by CONVERGIA that the necessary airflow to evacuate all the heat generated was 61m^3/s. However the airflow metered in situ was 41 m^3/s.
- From simulations and field measurement it was established the asymmetry and non-specified differences of the upper and lower ventilation circuit of the airflow. The air pressure's drop is higher at the upper circuit and the major airflow goes through the lower ventilation circuit, which is completely the opposite of the construction and operation specifications of the machine.
- To increase the airflow, the attack angle of the fan's blade was evaluated. However, CFD simulations showed that an increase of the current attack angle would decrease the axial air velocity due to appearance of turbulence and an effect of separation of boundary layer.
- Without attack angle's modification of the fan's wings, an increase of the airflow value for the ventilation circuit system can be obtained using outer forced ventilation with ventilators located above the current upper machine's fan. However, a turbulence effect must be taken into account and a complex variation of the airflow can occurred.
- The major heat transfer from rotor occurs through the cooper fins of the rotor's winding due to forced convection by air flowing at a determined velocity in the interpolar channels.
- The higher temperatures at the rotor's winding are at the inner side of the winding, where the heat transfer is low. The asbest and electrical isolation layers between the rotor's winding and the polar core work as a thermal isolation reducing heat transfer by conduction to the polar core.
- The final solution, located at the rotor's winding, is to make a 0.5 mm increment of the thickness of each winding's

conductor turn and five mm length's increment at the cantilever cooper fin with a new trapezoidal shape instead the old rectangular one.

- SVL probed to be an industrial and reliable tool in order to solve complex problems that require work teams with interdisciplinary knowledges.

VII. Acknowledgement

The authors gratefully acknowledge the contributions of Professor Oscar Román Tudela Specialist on Electrical Machines, Switzerland 1984, responsible for our Electrical Machines School and permanent guide.

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IX. Biographies

José L. Oslinger G. Born on January 13th 1969 in Colombia. Undergraduate studies in Austria at University of Technology Graz in 1991. Electrical Engineer from Universidad del Valle 1996. Professor of Electrical Machines of Universidad del Valle. Candidate to Doctor in Engineering from Universidad del Valle. He has been guest professor to ETSII from Universidad Politécnica de Madrid.(2.000 and 2003). His working area is the theory, design, diagnosis in site, maintenance and modeling of rotational and linear electrical machines.

Harold J. Díaz M. Born on April 4th 1972 in Colombia. Electrical Engineer from Universidad del Valle 2002. Honored thesis: "Investigación sobre el calentamiento en el núcleo ferromagnético de las unidades generadoras de la Central Hidroeléctrica de Playas". Professor of Electrical Machines Laboratory of Universidad del Valle, 2004. Currently he is student of Master in Engineering from Universidad del Valle. His working area is the theory, design, diagnosis and modeling of rotational electrical machines.

Jairo A. Palacios P. Born on November 6th 1955 in Colombia. Electrical Engineer from Universidad del Valle, 1982. Specialist on Design of Small Hydroelectric Power Plants, Switzerland 1991. Specialist on Eolic Energy from ETSII of Universidad Politécnica de Madrid, Spain, 1996. He is Doctor in Industrial Engineering from ETSII of Universidad Politécnica de Madrid, Spain, 1998. Currently he is Director of the Research Group in Energy Conversion. His workings Areas are Electrical Machines, Alternative Energy Resources and design of Power Plants.

Guillermo A. Jaramillo P- Born on February 4th 1977 in Colombia. Mechanical Engineer from Universidad del Valle, 2001. Specialist on Theory and Practical Use of Finite Element Method from UNED, Spain.2003. Currently he is student of Master in Engineering from Universidad del Valle. He's been working on Finite Element Analysis (FEA) since 1998. His working area is Computer Aided Engineering (CAE) through FEA in multiphysics problems. Builder of SVL concept.