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PERFORMANCE ANALYSIS OF AN AERATION VALVE AND ITS PROTECTIONS OF A GENERATING UNIT IN ITAIPU HYDROELECTRIC POWER PLANT

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Abstract. *With the growing energetic need present in the world, it is increasingly necessary the development of researches and facilities seeking a better use of renewable natural resources. This paper is applied in the study of turbines present in Itaipu Hydroelectric Power Plant. In such turbines, which have a Francis type rotor, a vortex is formed inside the draft tube that, besides generating cavitation, can pulse in such frequency resonating with these machines' structures, producing vibrations that may cause structural failures in the turbines, generators and the power plant foundations. These damaging effects can be reduced using aeration systems. A performance analysis will be done using maintenance records and disorders analysis reports (RAP), allowing verification of the operating conditions of the turbine and fatality of water inlet in air pipes. In addition, a simulation of a dynamic model using the MATLAB software allows the detection and behaviour analysis of the vortex from the valve actuation and verification of the valve's protection settings. Through the improvements detected, it is possible to reduce machine stoppages by tripping, thus increasing the availability of the turbines.*
Keywords: *hydraulic, performance, analysis*

1. INTRODUCTION

The energetic capacity throughout the world is increasingly growing. In the year of 2010, the United States led the ranking with 1039 gigawatt of installed capacity, followed by China with 998 gigawatt and Japan with 287 gigawatt. Holding the ninth place, Brazil had a installed capacity of 114 gigawatt, which main energetic sources were hydroelectric, thermal, biomass, nuclear and wind power.

The predominant energy source in Brazil is the hydroelectric, with a installed capacity of 81 gigawatt, a number that put the country in second at the world rank, losing only for China with 219 gigawatt of installed capacity (EIA, 20–). A comparison among countries and its energetic sources is shown in Fig. 1.

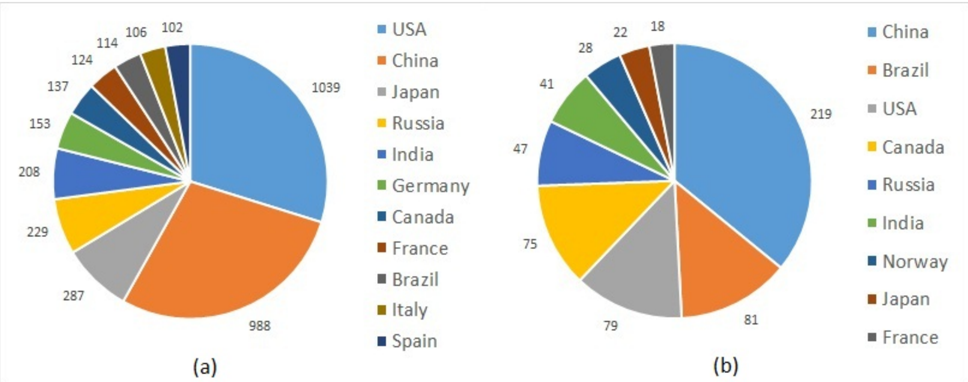

Figure 1. Total (a) and Hydroelectric (b) energetic installed capacity in 2010

With the growing energetic need in the world comes the necessity to research developments seeking a better use of renewable natural resources. Brazil is the holder of one of the biggest existing hydrous potential and, therefore, it is indispensable the good operation of the country's hydroelectric power plants.

The most important hydroelectric power plant in Brazil is the Itaipu Binacional, with 20 generating units, providing 14000 megawatt and assuring the rank of biggest hydroelectric power plant in clean and renewable energy production of the world.

Each generating unit consists in all equipment, mechanical or electrical, necessary for production of electricity. In a hydroelectric power plant the generating unit is composed by a generator, a turbine and their auxiliary equipment.

Hydraulic machines are used since antiquity to convert water's kinetic and potential energy into other forms of energy,

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like waterwheels, used since ancient Greece. Unlike pumps, which provide energy to the fluid, turbines extract the fluid's energy through a component called rotor, wheel or runner via a set of vanes, blades or buckets mounted on the wheel (Pritchard, 2011).

Although, factors that reduce the efficiency, cause structural damage or even failure of the turbines are frequent and, most of time, impossible to eliminate. One example is the vortex generated in the draft tube that may cause severe damage to the turbine's structure and foundations. Therefore, methods must be proposed and studied to minimize these effects and increase to maximum the turbine's operative availability.

2. PROBLEM DESCRIPTION AND THE USE OF AERATION SYSTEMS

2.1 Helical Vortex

In hydraulic turbines with a Francis rotor, the same used in Itaipu power plant, occurs a phenomenon called helical vortex or vortex rope. This vortex consists in an air vortex with a helical shape originated in the draft tube cone, as shown in Fig 2.

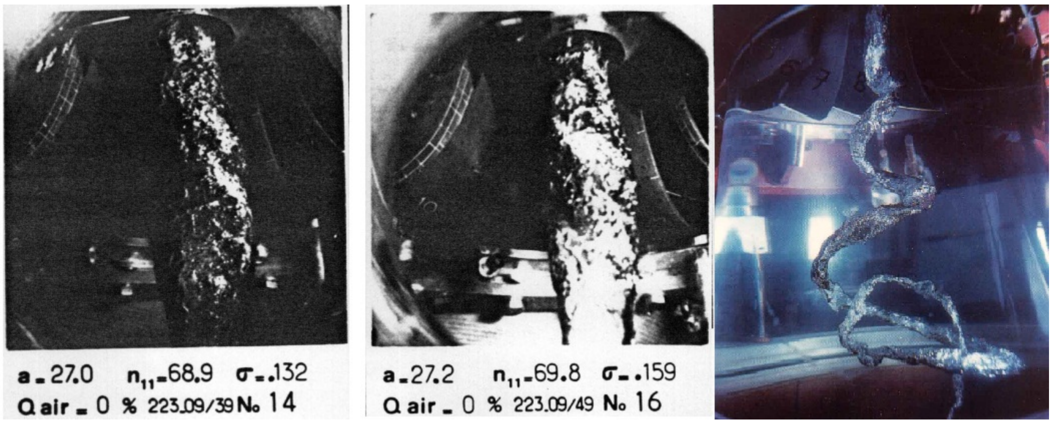

Figure 2. Vortex rope formed in the draft tube

When analyzing the velocity triangle in the turbine's blade, it is possible to easily understand how this swirling is formed. Francis turbines working at optimal project conditions have a purely axial exit water flow, as shown in Fig. 3, however, when working at partial or full load, i.e. not optimal conditions, the fluid exiting the spiral casing starts to have a tangential velocity component V_t creating a tendency in the fluid to swirl.

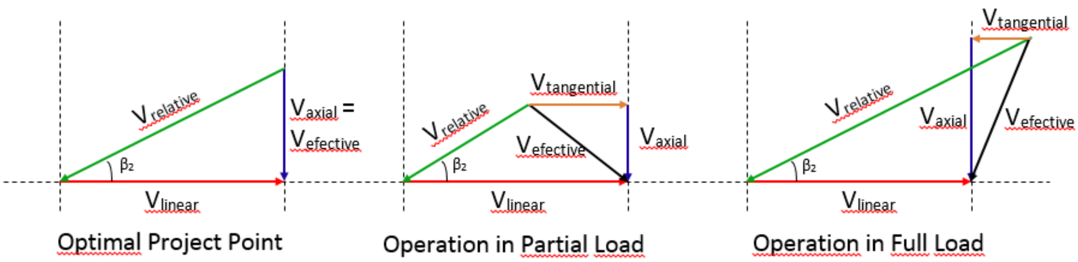

Figure 3. Velocity Triangle at Runner's Blades

The effects of partial and full load in velocity and vortex formation can be easily understood by analysing the velocity triangle in the turbine's blade end, shown in Fig. 3.

At partial load the relative velocity is reduced thus decreasing the axial and effective velocities. A tangential velocity appears in the same direction the turbine rotates and a helical vortex is created rotating the same way the water.

However, when working at full load, the relative, axial and effective velocities increase. The tangential velocity component has a opposite direction than the linear velocity and the created vortex tends to rotate in the opposite direction of the water and acquire a bulb-like shape.

A low pressure region is created when the turbine is working in partial and full load. This region, summed with the vortex pulsation, produces cavitation that may cause severe damage to the turbine's structure and shorten its life.

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2.2 Helical Vortex Effects in Itaipu Power Plant

Itaipu's turbine's optimal operation points are when the wicket gate is 78% opened, with a head turbine $118.4m$ and a turbine power of $715MW$ (Marra, 1996). Therefore, when operating above or beyond that point, instabilities start to appear.

When the wicket gate opening (Wo) is under 30%, unorganized vortexes are present. For a range of $30\% < Wo < 60\%$, partial load vortexes occur. When working in a range next to the optimal project point, i.e. $60\% < Wo < 92\%$, there are no disturbances in the turbine. Full load vortexes appear when the wicket gate opening is above 92% (Itaipu Binacional, 1993).

Partial load vortexes have a frequency next to $0.35Hz$. It is cavitating and creates a lateral imbalance of forces that amplifies the axis oscillations.

In Itaipu power plant, the cavitation problem was solved through the combination of 4 factors:

- Appropriate Thoma Coefficient: the Thoma coefficient is a parameter that allows the verification of occurrence of cavitation in a particular turbine, depending only on its project and installation. In other words, the elevation where the turbine is installed modifies the Thoma number and the cavitation can be theoretically eliminated;
- Optimization of the Hydraulic Profile: even though the project of the turbine is such the Thoma number indicates no cavitation, in practice it is not true. Therefore, through a study of the hydraulic profile and reduced scale models, it is possible to reduce even more the effects of cavitation;
- Turbine Operating Range: the turbine operating range is almost always in the normal range for Francis turbines.
- Injection of Compressed Air: in the turbines of units U01, U02 and U03 there is a compressed air injection system that, when in low load (operating range where cavitation occurs) the effects of cavitation are reduced.

However, the biggest problem is when the machines are working at full load. In those cases, the vortex has a frequency of $1.2Hz$ and, besides being cavitating, it pulsates near the natural frequency of the water inside the penstock. This phenomenon causes an excitation of the water and high pressure oscillation thus causing accelerated detrition in involved equipments and structure and may even lead to a breakage of the structure where the water flows (Itaipu Binacional, 1993).

To attenuate the vortex effects, atmospheric air can be introduced into the turbine through an aeration system. This would increase the pressure inside vortex and, consequently, reduce its pulsation amplitude. However, it's important to determinate the quantity of air because of its efficiency loss effects. These losses can, in a great amount of operation points, reach a value of 1% to 3% (Straatmann *et al.*, 2013).

Furthermore, the aeration system can reduce the cavitation noise and smooth the operation.

2.3 Itaipu's Aeration System

Itaipu's aeration system consists in two aeration ducts, one drainage duct, an aeration valve and its labyrinth and a main duct, linking the valve and the turbine wheel, as shown in Fig. 4.

The aeration ducts capture atmospheric air in EL. 89 (89 meters above sea level) and conduce it until the aeration valve. At the end of each aeration duct, a motorized butterfly valve operates usually opened, being automatically closed when the unit is stopped. By having a pre-load applied, the valve's activation is based in the low pressure inside the spiral casing. In other words, the valve will only activate when the pressure inside the spiral casing is so low that wins the pre-load applied in the valve.

The connection between the stationary part and the rotating part of the aeration box is through fix and moving labyrinths, theoretically dimensioned to be tight until a downstream level of 138 meters (Marra, 2007).

Although theoretically speaking, everything is perfect, in practice the tightness of the labyrinths can be won. The water that manages to pass the labyrinths must be conduced out of the aeration box, which is done through the drainage duct.

The air passing through the valve is conduced to the spiral casing through the main duct, located inside the hollow shaft of the generator and the turbine.

It's important to notice that the downstream elevation can be above the valve's and, in case of a valve failure, water can enter the aeration system and leak to the unit's electrical and mechanical equipment. When that happens, the valve's electrical protections stop the turbine by tripping.

3. AERATION VALVE OF ITAIPU

Acting as the core of the aeration system, the aeration valve is a device that allows or interrupts air supply to the spiral casing. Its shaft has 3 self-lubricating bearings and its axial movements are damped by oil dashpots.

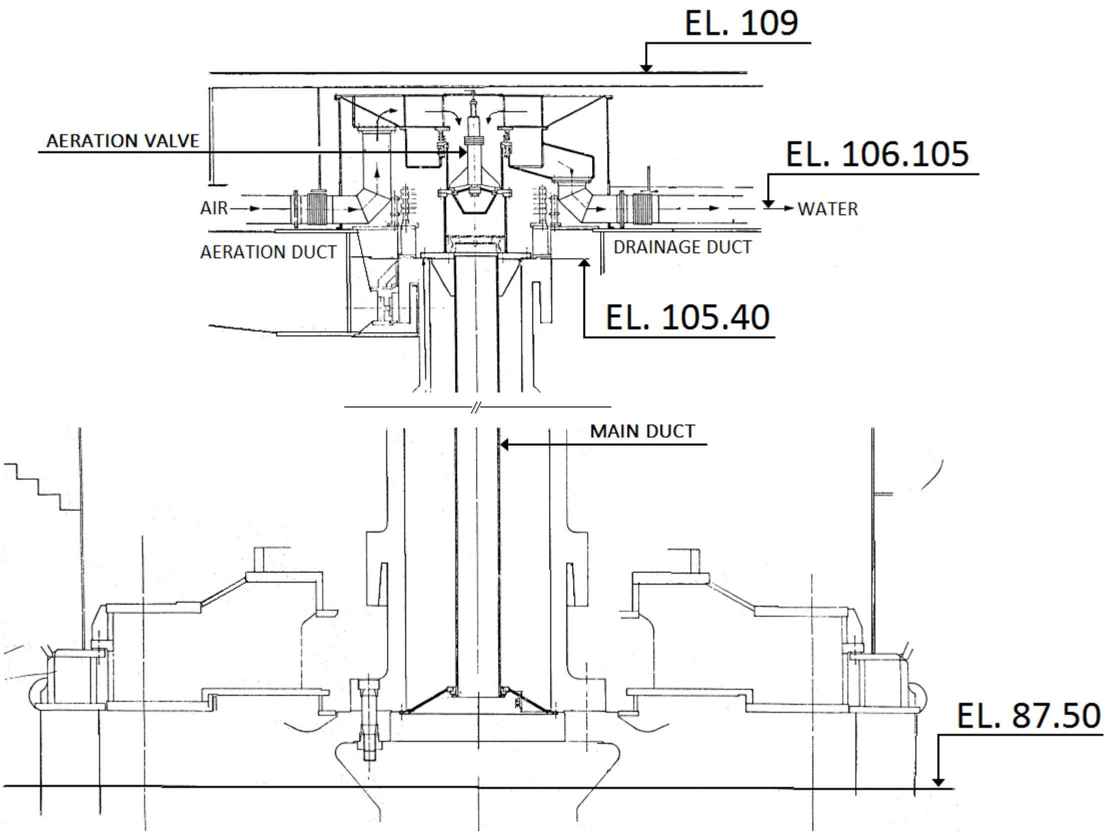

Figure 4. Aeration System Scheme in Itaipu Binacional

To prevent efficiency loss, the air flow through the valve is limited to a maximum of 2% (at atmospheric pressure) of the water flow in the turbine. A more detailed view of the valve can be seen in Fig. 5.

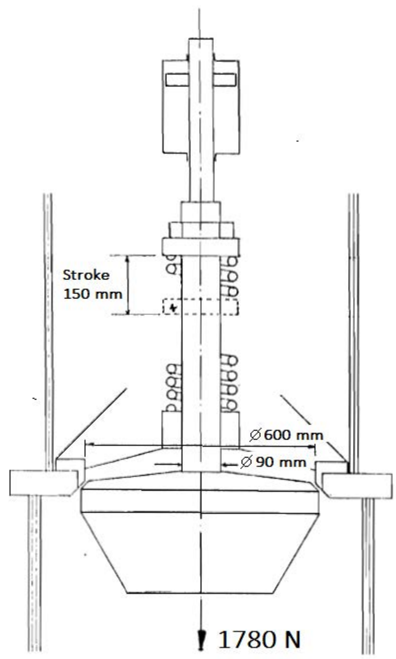

Figure 5. Aeration Valve

Installed on top of the generator shaft (EL. 106.35), the valve was projected to start opening under a vacuum of $4903N/m^2$ and be fully opened under $15690N/m^2$. Using the area shown if Fig. 5 it is possible to calculate the forces corresponding to the mentioned pressures. Therefore, for an area $A = 0.276m^2$ the forces found were:

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$$\begin{pmatrix} F_0 \\ F_{fo} \end{pmatrix} = \begin{pmatrix} 1343N \\ 4330N \end{pmatrix} \tag{1}$$

Where F_0 is the necessary force to open the valve and F_{fo} is the minimum force acting on the valve to keep it fully opened.

In full load, operation region studied in this paper, the valve should open in a range from $102m$ to $126.7m$. To lower net heads, the valve does not open, however the vortex in the spiral casing is drastically reduced or non-existent (Marra, 1996).

4. PROTECTIONS AND ALARMS OF THE AERATION VALVE

The aeration system can be very useful by reducing the turbine instabilities, however, if operation and maintenance conditions are adverse, catastrophic failures can happen.

The aeration valve's main purpose, as already said, is to allow atmospheric air into the turbine. But, in some conditions of downstream level and distributor opening, water from the turbine can rise until the valve's level and even go thought it.

One of the characteristics of this valve is sealing the pipe in which it is installed. If this sealing is compromised or the valve fails letting water go through it, there is a high chance of occurring leakage to the turbine's components (e.g. slip ring).

To prevent this leakage from occurring, sensors were installed in the aeration and drainage pipes as shown in Fig. 6. Those sensors are level sensors, detecting the presence of water and, after a certain value, send a signal to a relay that shuts down the turbine (trip).

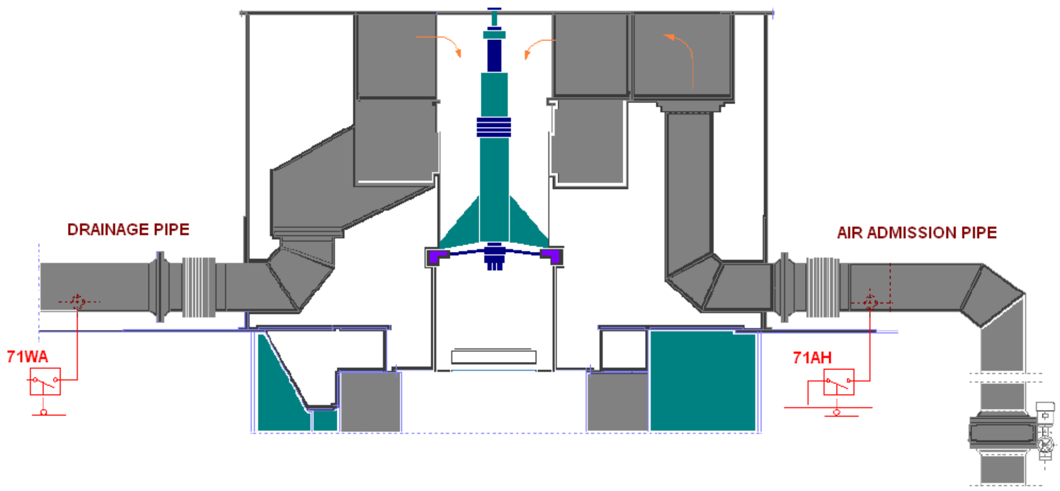

Figure 6. Water detecting sensors in the drainage and air pipes

The sensor in the drainage pipe is named 75WA and the sensor in the air admission pipe is named 75AH. These, when actuated, send a trip signal to relays 86N and 86E, respectively. Relays number 86 are lockout relays, this means that, during a fault condition, it locks out the breakers to prevent re-energizing the system and, after that, they can only be reset manually.

5. CASE STUDY OF AERATION VALVE FAILURE

To exemplify the damage a failure in the aeration valve can cause, a study was made considering the generating unit fully stopped.

If the valve was working normally, it would be closed, preventing water to enter the aeration box and leak to the turbine's components. However, if it is failed, water would pass through it and reach the aeration and drainage ducts. With the unit stopped, the labyrinth tightness is non-existent and a flow of water is generated in these ducts.

To find the water flow in each duct, Bernoulli's equation was used considering two sections: one at the downstream river level and the other at the end of each duct.

$$z_1 + \frac{{v_1}^2}{2g} + \frac{P_1}{\gamma} = z_2 + \frac{{v_2}^2}{2g} + \frac{P_2}{\gamma} + H_l \tag{2}$$

Where z_i is the elevation (m), v_i is the fluid velocity (m/s) and P_i is the pressure (Pa) of each section (for $i = 1, 2$), g is the gravitational acceleration (m/s^2), γ is the specific weigh of the fluid (N/m^3) and H_l is the head loss (m) considered through sections 1 and 2 and calculated using Eq. 3.

$$H_l = H_{ma} + \sum H_{mi} \tag{3}$$

Where H_{mi} are the minor head losses, calculated using Eq. 4 and H_{ma} is the major head loss, calculated using Darcy-Weisbach's equation (Eq. 5).

$$H_{mi} = K * \frac{v^2}{2g} \tag{4}$$

$$H_{ma} = f * \frac{L}{D} * \frac{v^2}{2g} \tag{5}$$

Where K is the loss coefficient, f is the Darcy friction factor approximated using the Moody diagram, L the tube length (m) and D the tube diameter (m).

Minor head losses were considered for the rotor, aeration valve, labyrinth, entrances and elbows of drainage and aeration ducts and the butterfly valve in the end of the aeration ducts.

From the downstream river level until the entrance of the main duct in the spiral casing, head loss was not considered for it is approximately zero. Specific weight used is from water at $20°C$, therefore $\gamma = 9789N/m^3$, for a gravitational acceleration of $g = 9.81m/s^2$.

The relation between the area of each minor loss and the water flow is given by Eq. 6.

$$Q = v.A \tag{6}$$

Where Q is the flow (m^3/s) and A is the area (m^2).

Using the equations shown it was possible to calculate the flow, where three cases were studied:

- Case 1: Both Aeration Ducts Closed

  $Q_1 = 1.67m^3/s$

- Case 2: One Aeration Duct Closed and One Opened

  $Q_2 = 2.33m^3/s$

- Case 3: Both Aeration Ducts Opened

  $Q_3 = 2.55m^3/s$

6. PERFORMANCE ANALYSIS

To analyse the behaviour of the aeration valve and its protections Disturbance Analysis Reports (RAPs) since 1990 were used. These reports are made by the Divisão de Estudos Elétricos e Normas (OPSE.DT) of Itaipu and analyse all disturbances that causes machine stoppage.

Figure 7 shows the number of disturbances that lead to a machine stoppage by actuation of the aeration system's protections.

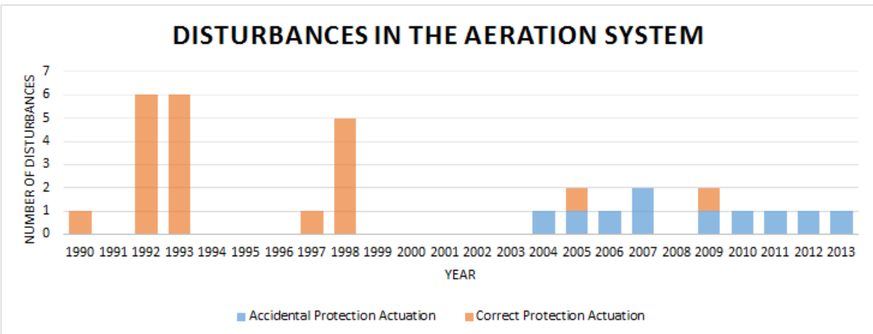

Figure 7. Disturbances in the aeration system since 1990

One can notice a high number of disturbances in the first four years. In this period (1990-1994), there was no adequate comprehension of the importance of the aeration valve in the generating units operation, therefore there was no control procedures during the maintenances of the valve. This led to many failures due to a transitory reflux (i.e. small quantities

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of water passing through the valve because of a high downstream level) and valve failures. These last, in most cases, because of an oil loss in the valve's damper (Marra, 2007).

There was a high incidence of disturbances in the year of 1998. These were most due to failure in the obturator tightness combined with rises of the Paraná river.

The faults from 2004 onwards were basically due to failure or accidental actuation of the protections 75WA and 75AH. In a few cases, the electronic module of these protections were replaced. Preventively, the sensors were raised $50mm$ of their original elevation, as a trial for preventing actuation due to little and irrelevant amount of water reaching these protections.

The worst disturbance happened in 1997. In such, the aeration valve's string was broken preventing its closure during a load reduction. With a high downstream elevation (above the valve's elevation), water went through the valve and, as the drainage duct was semi-obstructed, water leaked to the slip ring and upper guide and combined bearings. That made the unit stay shut for approximately 38 days.

In short, the total number of disturbances in the aeration system since 1990 is 31 where, in 21 of them, the turbine stopped because of a correct protection actuation, while in the other 10, there was an accidental protection actuation. A linear tendency line is also shown in Fig. 8, indicating that is decreasing as the years pass.

The median number of failures per year is 1.35. Figure 8 shows the median number of failures per year in groups of 4 years each.

Figure 9 shows a comparison between the disturbances in the aeration system with disturbances from other locations, such as schemes of emergency control, bearings, excitation system, speed governor, pure water system, transformers and others.

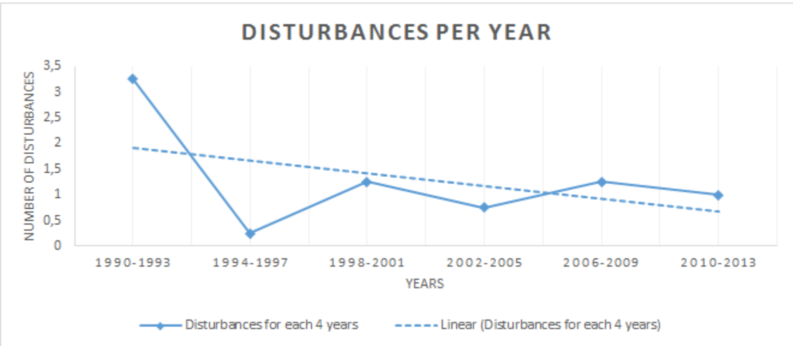

Figure 8. Median of Disturbances per Year since 1990

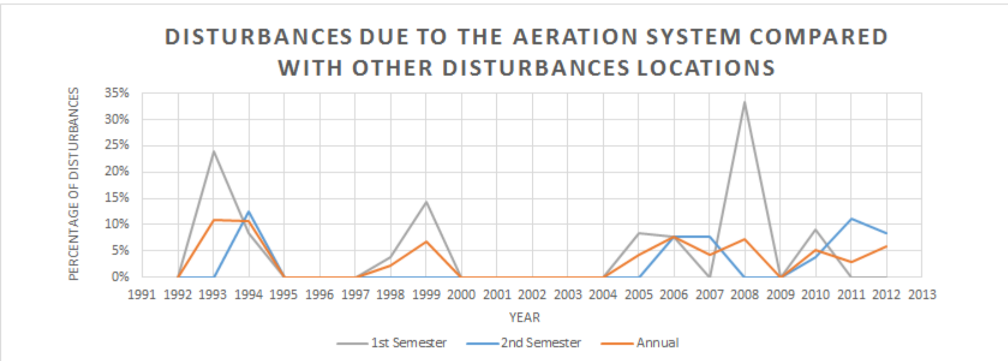

Figure 9. Machine stoppage due to disturbances in the aeration system compared to other disturbances locations

7. CONCLUSION

The aeration valve, as well as the aeration system, are of great importance for an optimal operation of all generating units in Itaipu. Reduction of several factors that can contribute to a catastrophic failure are greatly reduced when proper using the aeration system.

As could be seen in chapter 5, if the aeration system fails the consequences are severe, therefore, good methods and procedures of maintenance are essential for constant improvement and consequent decreasing of the number of machine stoppage due to the aeration system.

Machine tripping occurred in the analysed period can be due a lot of factors, such as the damp loss of the aeration valve, tightness loss of the obturator, total or partial loss of the valve's string pre-load and accidental actuation from

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protections 75WA and 75AH. Thus, it is of extreme importance to fully understand the damage each amount of water causes in each case so more deep studies can be directed to the most critical components.

To better understand the functioning of the valve, a MATLAB model of the aeration valve and the helical vortex is being developed. This would allow the detection and behaviour analysis of the vortex from the valve actuation and the verification of protection setting of the valves.

These settings, once unsuccessful attempted to be changed, could reduce machine stoppages by tripping when the quantity of water passing through the valve is allowable. The model created to simulate the vortex would allow great knowledge of its behaviour and allow studies for different methods and its efficiencies to reduced the effects caused in the turbines.

When comparing the disturbances in the aeration system with disturbances from other locations, it is possible to see a small, although considerable, presence of the aeration system, being responsible for 3.64% of machine stoppage from years 1991 to 2012.

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