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# MULTIPARAMETER MONITORING OF THE SPEED ADJUSTMENT SYSTEM OF A 390 MW FRANCIS TURBINE

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### Abstract.

*Hydrogenerators have great importance in the context of the Brazilian energy matrix, where hydroelectricity accounts for more than 65% of power generation. There is an increasing need to monitor the entire generation system, due to the increase of electric power availability index. Thus, this work will present a case study of monitoring of 390 MW Francis turbines by means of real time data acquisition of structural and dynamic components of the speed regulation system, the main control system of hydraulic turbines. This work was motivated due to the high number of shear pin failures of the speed governor distributor mechanism and power limitation of turbine, object of this study, which causes losses in the availability of this hydrogenerator. Therefore, monitoring based on measurements of micro strain using sensors of the strain gages type was used in the distributor mechanism. After the tests, excessive deformation of the adjustment ring and turbine cap can be achieved, causing excessive torque and spurious loads on the drive cranks of the guide vanes. The implemented solution aimed to reduce the coefficient of friction of the bearings to levels lower than those considered in design so as to avoid the overload of torque in the drive. The multi-parameter monitoring system adopted for the diagnosis proved effective and a suitable tool for complex diagnoses in large hydraulic machines.*

**Keywords:** speed governor, hydraulic turbine, strain analysis, monitoring system.

## 1. INTRODUCTION

There is an increasing need to monitor Brazilian hydrogenerators in order to avoid unforeseen failures and unplanned shutdowns due to the high availability rates required by the Brazilian electricity regulator (ANEEL). It is important to highlight in the fact that the Brazilian electric system operates in an interconnected national grid (SIN) that cover all macro-regions of the country, allowing a high flexibility power generation in the energy dispatch, considering the different climatic regimes between north northeast and south-southeast. The different regions can be exporters of energy, sometimes importers, depending on the hydrological regime and local rainfall regime, establishing a high efficiency way of harnessing the available water resources in all Brazilian river basins.

Hydrogenerators have great importance in the Brazilian energy matrix, once hydroelectricity accounts for more than 65% of energy generation (B.E.N, 2018). These systems are well advanced and allow a great flexibility in the electrical distribution network (Li et al., 2019), besides being used in 16% of the planet and representing the most important source of sustainable energy (Eini et al., 2019). Usually these machines are accompanied by a speed control system (rotation) that allows the control of the water inlet flow to the turbine rotor. This system has the function to eliminate divergences of synchronous rotation (rotation error) through a PLC that in turn activates the hydraulic control of

servomotors that move the linkage mechanism of directional vane, to control the flow of water that accesses the turbine and thus keeping the rotation constant (Alves, 2018).

Thus, this work will present a case study of monitoring of 390 MW Francis turbines through real time data acquisition of structural and dynamic components of the speed regulation system, which is the main hydraulic turbine control system.

The motivation of this work was due to the high number of shear pin failures of the speed regulator distributor mechanism and power limitation of turbine due to incapacity of torque of servomotors to correct operate the mechanism of speed governor (speed distributor), in higher heads regime of 2nd powerhouse Tucuruí Power Plant, which causes a loss in the availability of the hydrogenerator. Thus, monitoring based on micro strain measurements using strain gage sensors was used.

## 2. METHODOLOGY

This work use structural and dynamic analysis methods, through the experimental technique of micro strain, to diagnose the operational condition of the velocity distribution system based on the information provided by strain gages sensors, strategically located in the mechanism of the regulator speed (speed governor). The sensors used in this case, had a chart of certified calibration expedited by manufacturer HBM.

### 2.1 Sensor location

The Francis turbine speed control system of unit 13 of Tucuruí Hydroelectric Power Plant has twenty four (24) sets of wicket gates with upper lower connecting rods, cranks, trunnions and guide vanes and four (4) servomotors with a force capacity of 1450 kN, to opening, closing and control operations of the speed governor system. These components are shown in figure 1. The maximum operating pressure of the hydraulic system is 64 Bar.

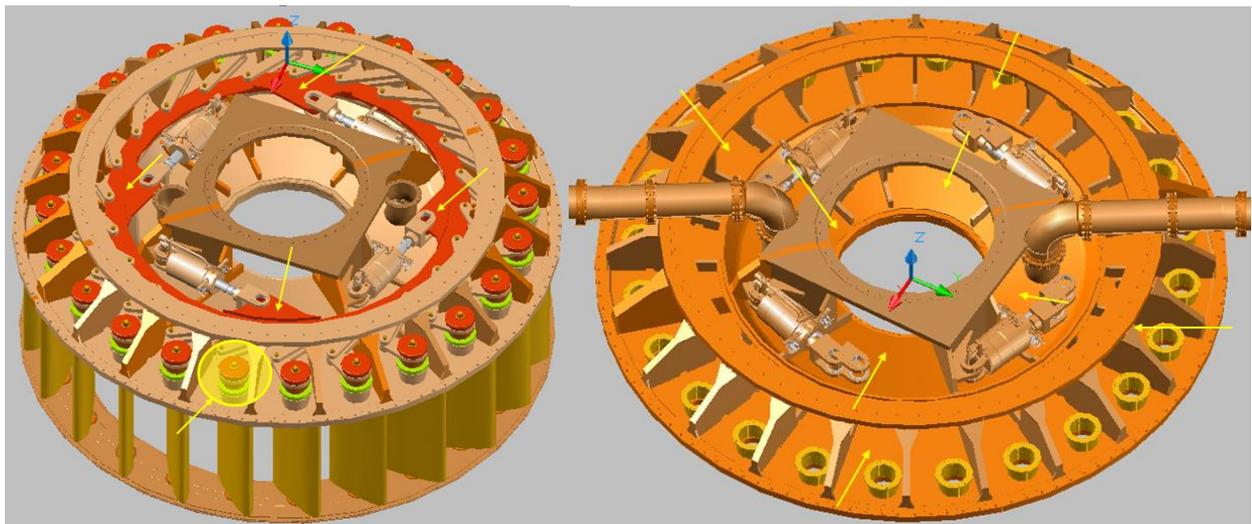


Figure 1. 390 MW hydraulic turbine distributor system and location of the strain gages.

The positioning of strain gages is a critical step in the microstrain data acquisition process. However, only with its correct positioning can the measurement results be analyzed comparatively with a reference data in Project or in FEM (Finite Element Method) and detect the presence of faults and abnormalities. The yellow aims in the figure 1 shows the selected location of the sensors.

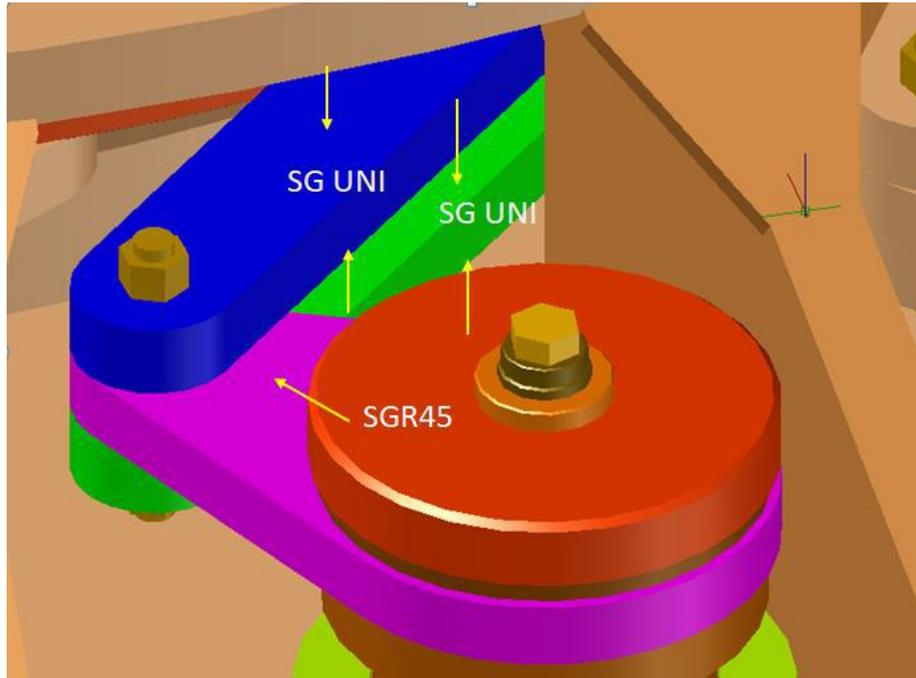


Figure 2. Chosen location of the strain gages in the cranks and trunnions of speed governor mechanism.

## 2.2 Sensor instalation

Before installing the sensors it is important to ensure that the mechanical component to be monitored is free of loads and structural or dynamic forces, in addition to its own weight. Once this condition is achieved, strain gages should be glued onto a previously prepared, sanded, paintless and oily substance directly on the metal surface as shown in Figure 3. Preferably, one-component cyanoacrylate type adhesives should be used. After the bonding of the sensors, a mechanical and chemical protection of the strain gages was mounted using epoxy resin. This protection is essential to ensure the functionality of strain gage in humid environments, immersed in water or contaminated with oil. The connection of the sensor circuit in the wheatstone bridge, the micro strain value obtained under these conditions should be the zero value or reference value.

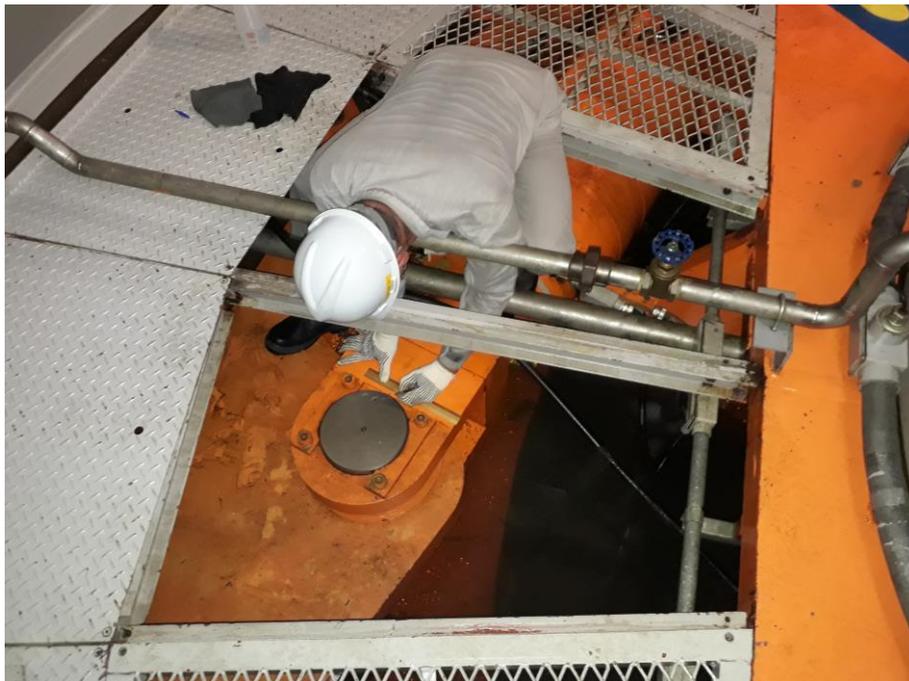


Figure 3. Installation of the strain gage in the fork of linkage of servomotor 1 with synchronism ring

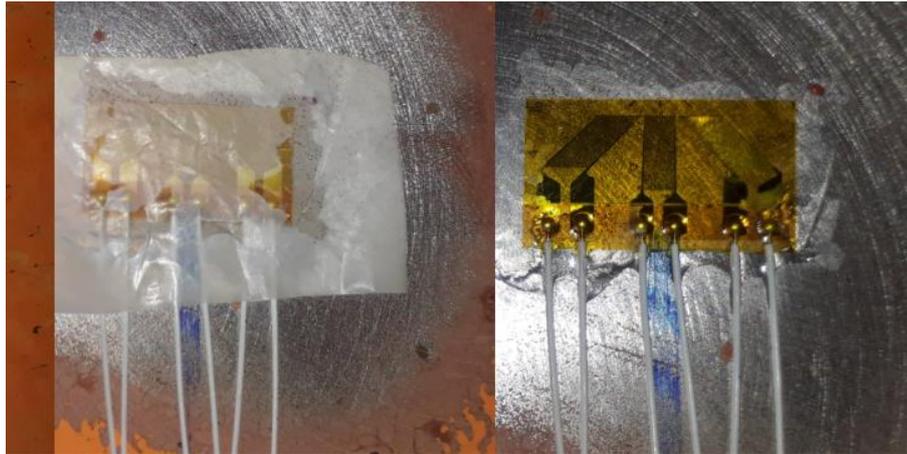


Figure 4. Fitting the 45° rosette type sensors of the distributor mechanism timing ring with Loctite® 496.



Figure 5. Mechanical and chemical protection of strain gauges using epoxy resin

### 2.3 Software e Hardware for data acquisition

The HBM MGC Plus data collector was used, combined with the CATMAN version 3.1.3 software to perform the microdeformations test. The parameters adopted for experimental stress analysis were: modulus of elasticity of 206 GPa and Poisson coefficient of 0.3 of ASTM A36 steel, that is the material of mechanical components of speed governor mechanism.



Figure 6. Operation of the data acquisition system during the multi parameter tests in the 390 MW Francis Turbine 13 of Tucuruí Power Plant.

## 2.4 Operational procedure

In order to guarantee reliability of the results, it is necessary to subject the speed governor to various operational conditions to evaluate the micro strain results of different applied forces in the mechanical components. In this way, the tests of opening and closing of the distributor were carried out with machine without presence of water, opening and closing of the distributor in "dead water", that is, with presence of water at the same level of the downstream raised and closed water outlet. Then the machine was started and turned empty (without load) and finally a load ramp was applied up to 50 % load, steps of 40 MW from 50 % to 100 % of the operational load.

## 3. RESULTS AND ANALYSIS.

To demonstrate the possibilities of the mechanical diagnosis using the proposed multiparameter monitoring system, we'll present the results obtained during the tests of the Francis Turbine 13 of the Tucuruí Power Plant, in the past year (2018).

The graphs of the results of the micro strain and pressure of servomotor 1 test results are shown in figure 6. These results were recorded in "dead water" operations (turbine without water flow) with the HBM MGCplus data acquisition chain. The graphs were taken from Catman software, in order to measure the mean coefficient of friction of the mechanism and pressure distribution of the chambers inside the servomotors.

Some notes about the expected behavior of the components are important to analyze the results. The strain signal expected for the fork of the servomotor (linkage between servomotor and synchronous ring) is compression loads in total opening, once the servomotor is totally extend in this position. In total closure the traction loads is expected in the fork, once the synchronous ring is totally closed before the servomotor reach the total retracted position. It's calling crushing effect of the wicket gates and it's necessary to guarantee the maximum sealing of the speed governor when it's closed.

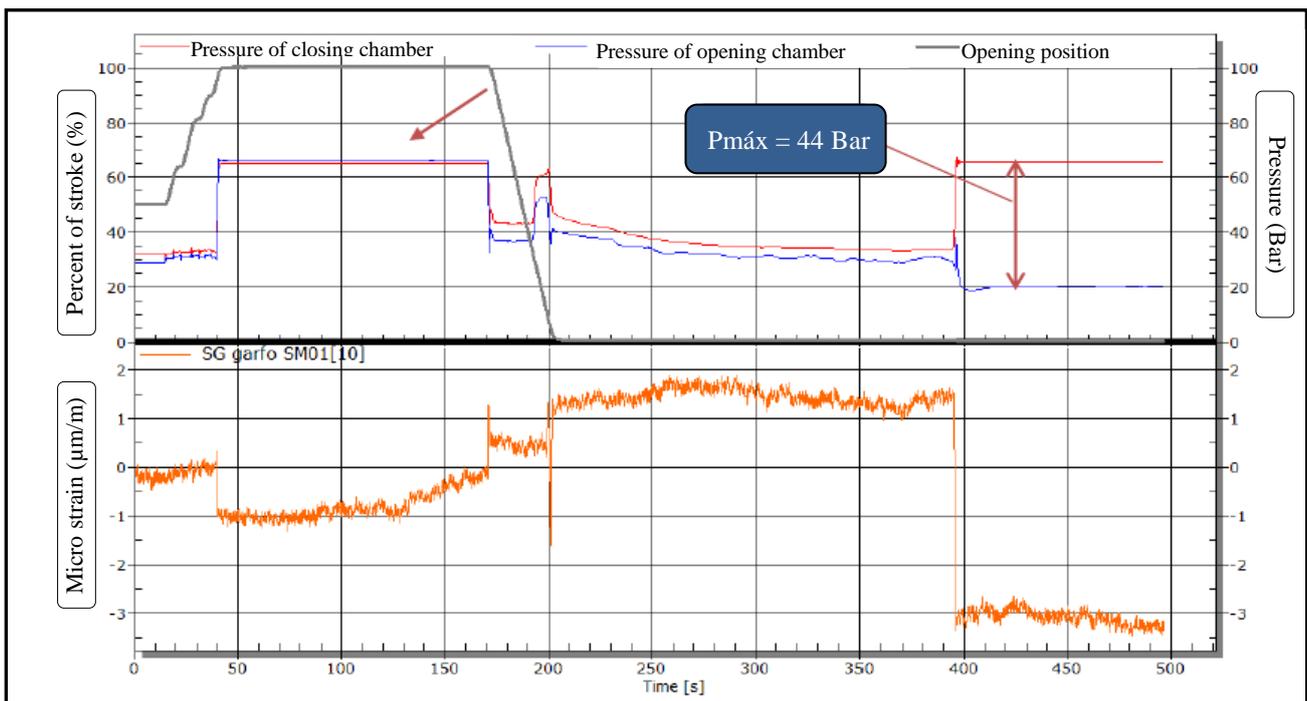


Figure 7. Pressure in the chambers and micro strain of the fork of servomotor 1.

The results in the figure 7, shows that servomotor 1 presented nonconformities in the distribution of pressures in the total closure and in the total opening. The maximum pressure in closing position was 44 Bar (instead 64 Bar), denoting Losses of 20 bar by leakage through the opening chamber, in the fully retracted position. Also, it could be seen equalization of pressures in the fully distended position. In the intermediate positions of the stroke, the servomotor presented regular behavior. In the crushing of the wicket gates, the fork of the servomotor presents compression loads instead of traction, denoting poor position adjustment of the servomotors forks for pre-compression adjustment of the guide vanes.

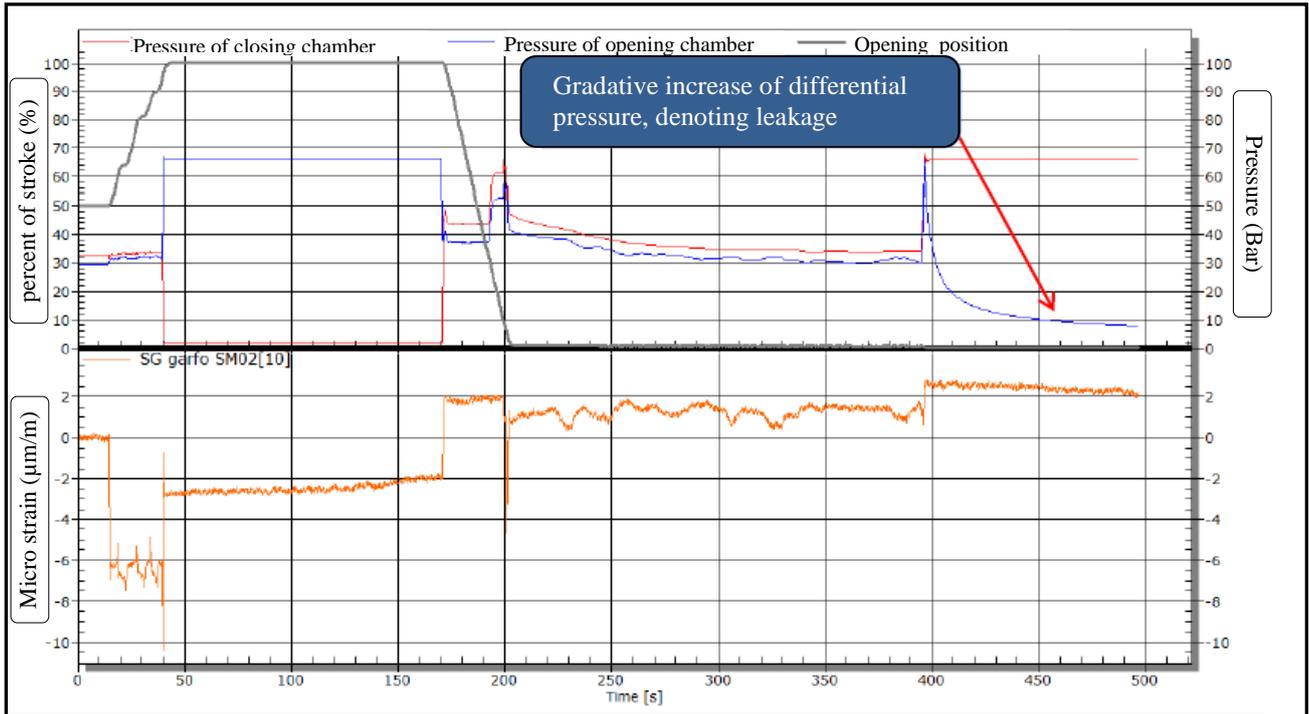


Figure 8. Pressure in the chambers and micro strain of the fork of servomotor 2.

In the figure 8, we can see that servomotor 2 presented regular pressure distribution at the intermediate position of the stroke. In the crushing of the wicket gates (total closure), the fork of servomotor presented traction load of coupling with the adjustment ring, as required in the in the assembly specification. The gradual reduction of the differential pressure in the crushing denotes internal leakage of other servomotors, reinforcing the diagnosis of leakage in the servomotor, in the fully collapsed position.

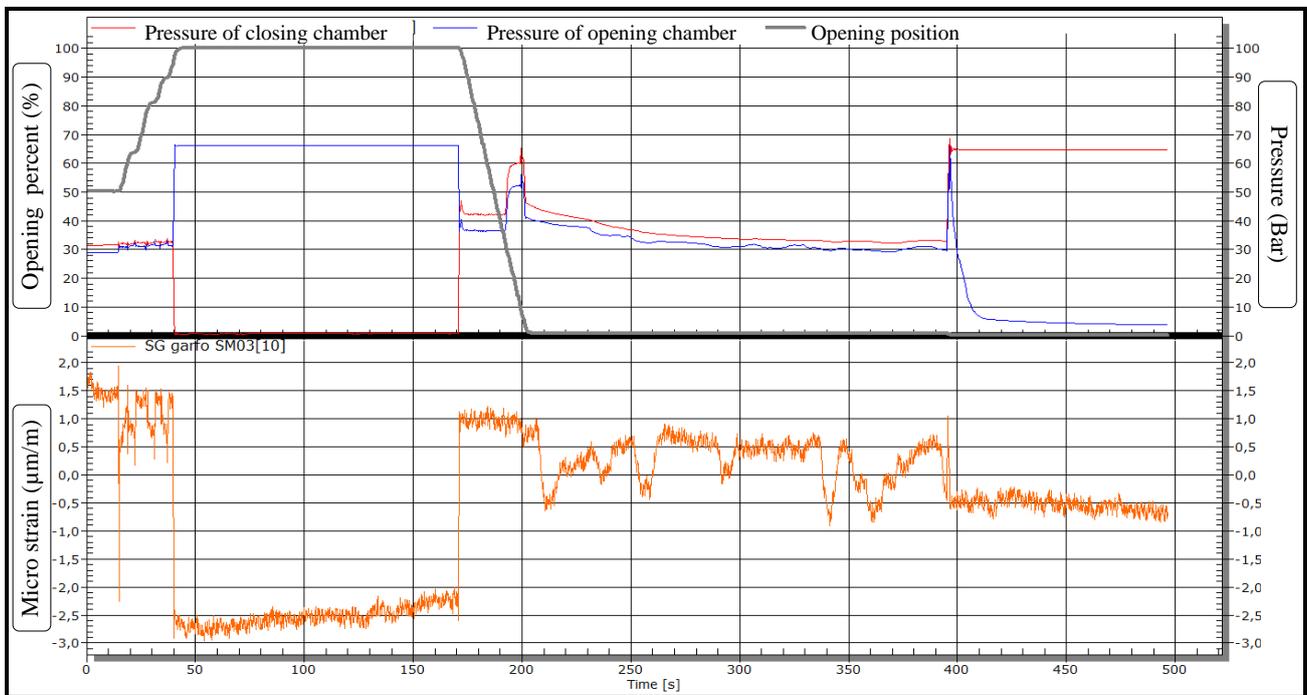


Figure 9. Pressure in the chambers and micro strain of the fork of servomotor 3.

The servomotor 3 presented a standard pressure distribution of the chambers and strain of the fork (linkage between servo and synchronous ring) in the opening, closing and in intermediate stroke. In the crushing of the wicket gates it

presented neutral load in the fork of coupling with the adjustment ring, denoting bad adjustment of position of the fork of coupling of the regulating ring.

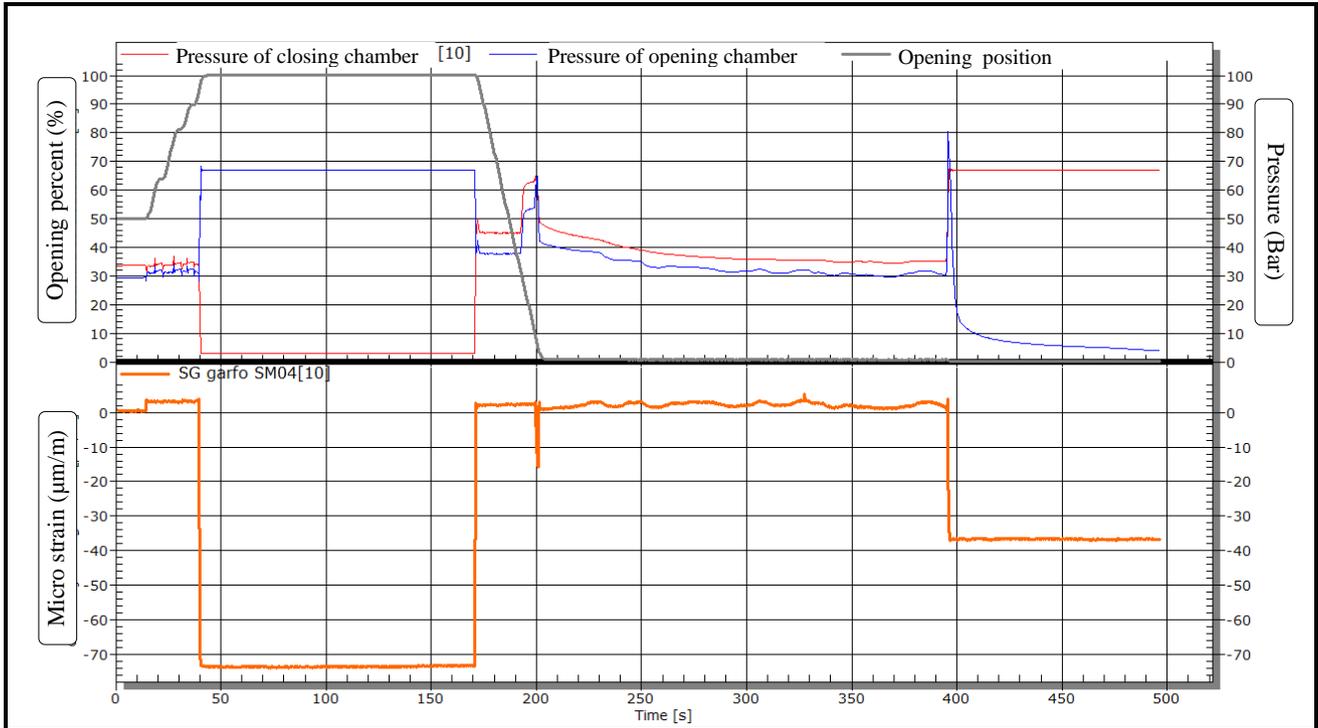


Figure 10. Pressure in the chambers and micro strain of the fork of servomotor 4.

The servomotor 4 presented a regular behavior of the pressure distribution along the stroke. In the crushing, it presented compression load in the fork of coupling with the regulating ring, denoting bad regulation of position of the fork. Pressure differential with gradual pressure reduction of the opening chamber, denotes the internal leakage of the adjacent servomotor, n<sup>o</sup>.1.

The graph below, demonstrate the results of force applied by the servomotors before the five-year maintenance:

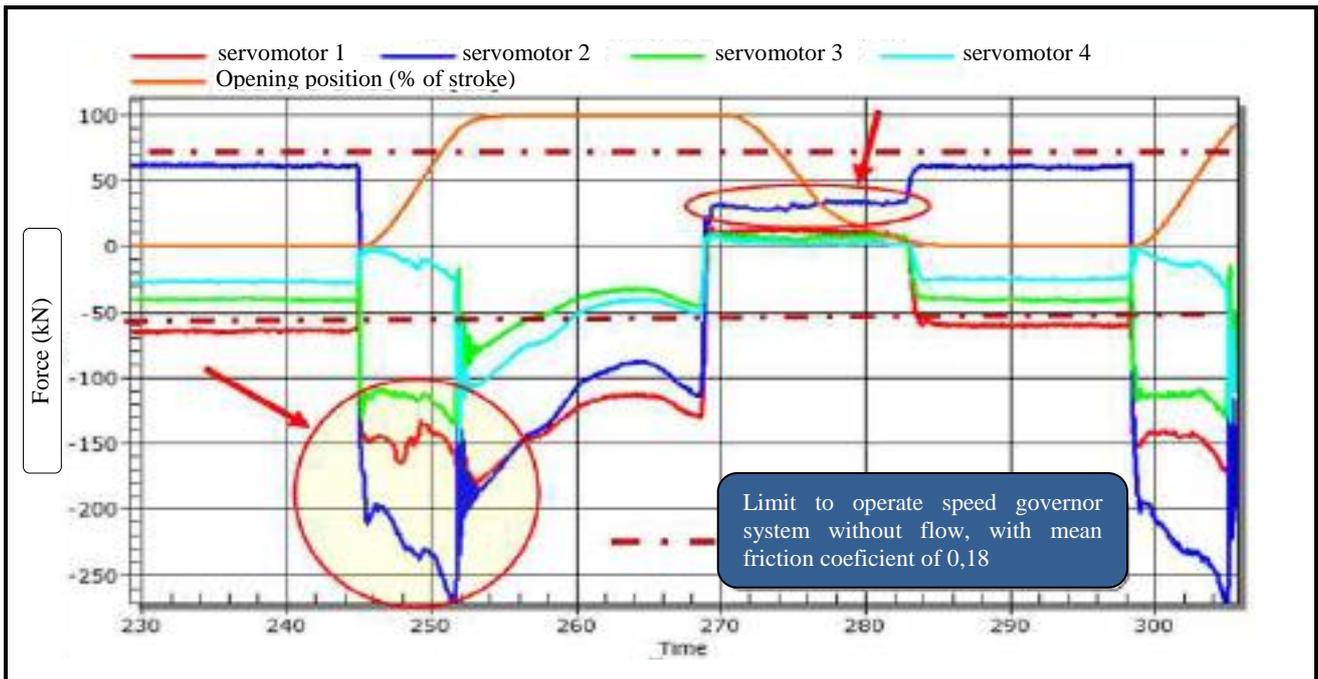


Figure 11. Drive force of the servomotors before change of the material of guide vanes journal bearing by PTFEE. Detail of the load reference value for the maximum coefficient of friction predicted in the design.

The analysis of loads in the speed governor mechanism show a significant overload in opening operation mechanism, without flow of water, that demonstrate a higher degradation of self-lubricate components in the mechanism of speed governor. Another important observation is the difference between the loads of the opening and closing operation and non linear loads in opening operation. In the test of *dead water*, is expected a constant load once there's no torque resistance generate by flow of water. Also in a standard operation this loads must be equal (opening and close). We conclude that there were another elements in mechanism that causes a non-linearity phenomena in the loads of opening. After maintenance, and complete disassembly of the mechanism, becomes clear that screws of the self-lubricate bearings were dropped out by the vibration in the cover of the turbine. This dropped screws, creating an aggressive interface between synchronous ring and steel guide in the cover of turbine (see fig.12). In fact these elements reached a point of fusion along the guides, causes an higher increases of loads in the mechanism. The overall strategy to correct the loads of the mechanism was change the material of self-lubricate components of the mechanism by PTFEE and reduces the friction coefficient.



Figure 12. Degradation of self-lubricate guide of the synchronous ring.

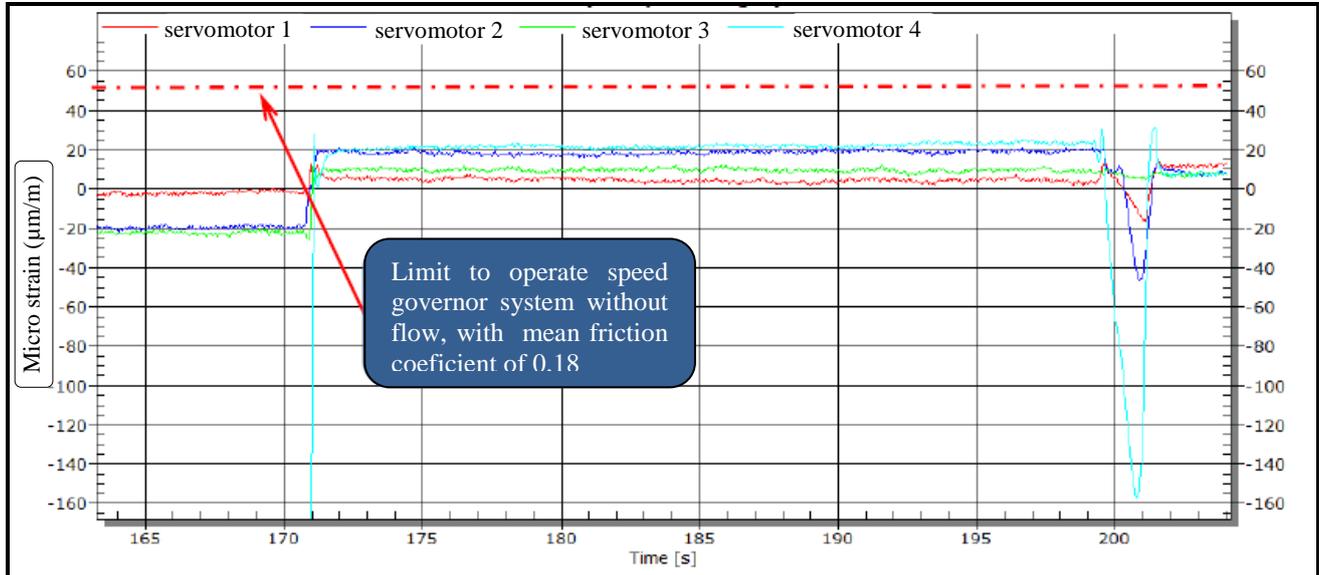


Figure 13. Drive force of the servomotors in opening operation after change of the self-lubricate material of the journal bearings by PTFEE.

As can see in figure 13, after the maintenance, was a significant reduction of the average friction coefficient of the mechanism after the replacement of the bushings with PTFE material (improvement implemented by the maintenance), and improvement of the heel sectors of the vane guidelines with increased contact area. The mean coefficient of friction of the mechanism after maintenance fell from 0.42 to 0.05.

After analyzing the structural and operational parameters of the dead water tests of the distributor system of the UGH-13, the following conclusions can be made:

- Significant reduction of the average friction coefficient of the distributor mechanism. From 0.42 (before maintenance) to 0.05 (after maintenance).

- Position of the coupling forks of the servomotors with the adjustment ring outside the technical specifications of assembly for the condition of pre-tensioning (crushing).
- Servomotor 1 presents non-conformities of the pressure distribution of the opening and closing chambers in the fully collapsed and fully distended position.

The figure 14 below show the micro strain of the turbine cap when subjected to the filling loading of the pipe (forced conduit). The angular position is referred to the pipe direction. 0° is aligned to the entrance of the spiral case.

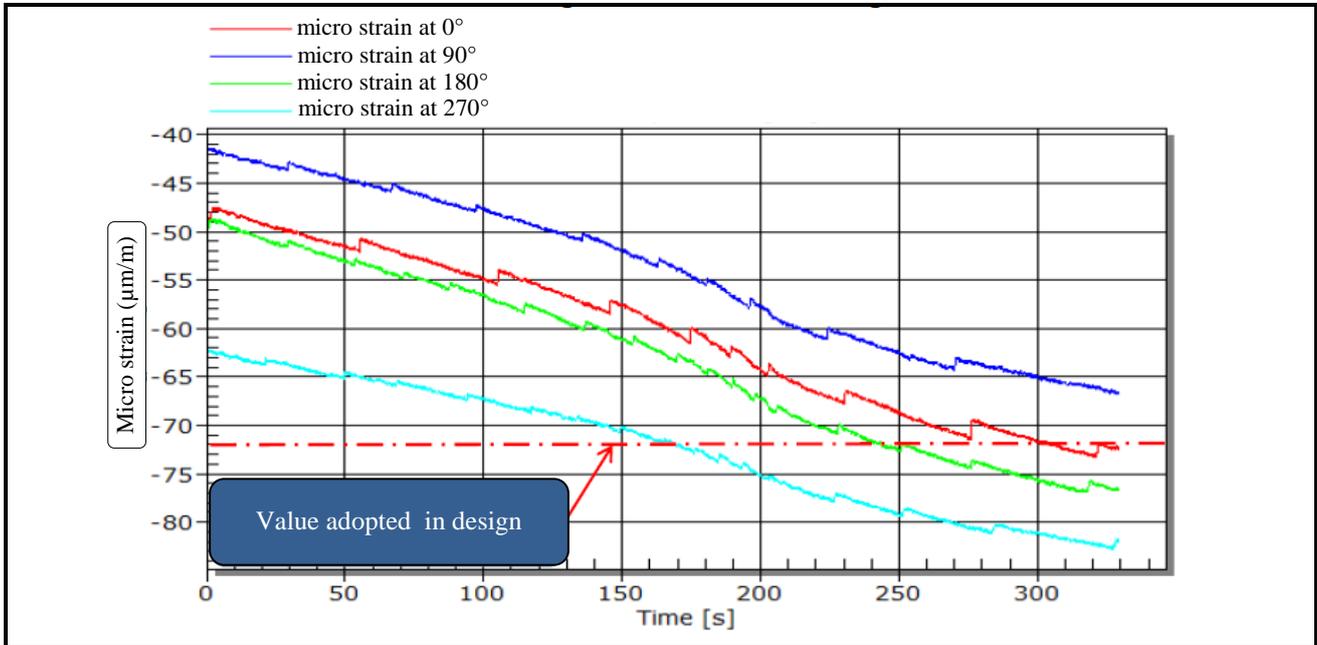


Figure 14. Radial microstrain of the turbine cap (orthogonal arrangement) during the pipe filling. Detail of the limit value, considered in design.

The deformation of the turbine cap during the filling of the penstock, extrapolated the design reference values. The turbine cap exhibited a lower axial stiffness resulting in increased drive torque of the guide vanes due to increased radial load on the journal bearings. These excessive torque values, combined with wear and increased friction of the old bearings, culminated in the recurrence of shear pin failures.

#### 4. CONCLUSIONS

The experience with multiparameter monitoring of the speed governor in 380 MW Francis turbine, could be resumed with the following conclusions:

- The monitoring system built was very useful and is an important tool to make complex diagnosis in dynamic and structural systems of the big Francis Turbines (> 100 MW).
- The most important variable considered in multiparameter system is source of loads (pressure, force or torque) versus strain and temporal position of components. Only with this set, combined with design model is possible to develop a fail diagnosis.
- In the specific case, the results generated by system could make evident the fails like: overload of radial strain in the turbine cap, spurious torque in synchronous ring and leakage in servomotors. These results help the maintenance corps to make a decision to perform a complete disassembly of speed governor and change components for other with better materials and geometry.
- An evolution of this system is recommended with better mechanical and chemical protection of the sensors, including connections of the terminals. Also, the numbers of sensors can be reduced and optimized with methodology like *Taguchi*.

## 5. ACKNOWLEDGEMENTS

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