Challenges during the Control System retrofit in a 900 MW HPP with Double Pelton Turbine that operates as a Synchronous Condenser

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In high head hydroelectric projects, most of units are Pelton turbines. In some cases, two runners are used on the same shaft with one generator rotor in-between, a system known as Double Pelton turbine. As the Pelton turbine does not operate under water, the unit can easily be used as a synchronous condenser, just by closing the water flow through the nozzles. The operation of hydro generators as synchronous condensers is becoming even more important due to the increasing wind and solar generation. When necessary, the machine must return to generator mode and dispatch its maximum power in the shortest time, assisting the electrical system, even avoiding a blackout. Modern control systems containing embedded testing tools are desirable, facilitating commissioning tests and maintenance work. Modern mechanical systems with high pressure and less oil make an environmental appeal in the control of the generating unit.

1. INTRODUCTION

A Pelton turbine normally operates in power plants with a head from 300 to 2000 meters, and can generate from a few MW to over 200MW each machine, depending on the available water flow. In installations where the turbine-generator set has an horizontal shaft, in some cases there are two rotors on the same shaft, known as Double Pelton turbine, allowing operation with only one of the runners. As a Pelton does not operate drowned, its operation in synchronous condenser mode is possible, allowing it to return quickly to the generator mode, something interesting due to the accelerated increment of solar and wind power generation.

This work presents the challenges faced during the modernization of the speed control and automation systems in three generating units with Double Pelton Turbine in a 900 MW power plant. This modernization involved the replacement of three old independent (fully mechanical) speed governors with a digital system, which incorporated the control of both turbines (sides A and B) as well as the automation system of the generating units. In addition, the modernization included interventions in the mechanical part of the governor, changing the hydraulic pressure from 12 to 120 bar, in the motors command center, and in the supervision and control system – SCADA, including special logics for loading ramp from 0 to almost 900MW in less than one minute.

The chapter 2 will present the historical context of the power plant. In chapter 3 the modernization processes will be detailed, focusing on the relevant parts. In chapter 4 the commissioning tests results will be presented and discussed. Finally the conclusions and references will be presented.

2. CONTEXTUALIZATION

2.1 Power Plant History

The Henry Borden Power Plant was the main work of the so-called "Projeto da Serra", a gigantic investment in the production of electric energy undertaken by the Canadian company The São Paulo Tramway, Light and Power Company Limited, between the 1920s and 1960s. The project had great economic, social and environmental impact and included the construction of the hydroelectric power plant in Cubatão - a world pioneer for the time - and of reservoirs and dams in Serra do Mar, in addition to inversions and channeling of rivers.

To start the undertaking, the American engineer Asa White Kenney Billings came to Brazil to do a study on the best area for implantation of the plant. The Cubatão region was chosen because it was located between the two largest and most important cities in the state: the capital São Paulo and Santos. The power plant was also close to the São Paulo Railway (Santos - Jundiaí), which would be useful in transporting heavy material for the construction of the contract. In addition, due to the 720 meters difference between the top of the mountain and the sea level, the waters gained strength and, in a fall in the water mains, would move the plant's turbines. Thus, the works began in the early 1920s, with around six thousand workers working from where the Rio das Pedras reservoir would be to the plant site, at the foot of the mountain [1].

Both the materials and the extremely specialized labor for the construction of the plant came from outside Brazil. The construction site, at the time, was a completely unpopulated region, causing various diseases in workers, including malaria.

The idea of building the pipe going down the mountain range of the sea was to achieve a vertiginous fall, used by large plants. Currently, in Brazil, there are only two plants that use large turbines for high falls: Henry Borden and Parigot de Souza (in the state of Paraná).

With the growing demand for electricity, the plant needed to be expanded. The other tubes of the set came in a big engineering work that included the change of the course of a river and the formation of the Billings dam, which increased Henry Borden's production.

The idea led by an American engineer was to get water to feed Henry Borden by pumping water from the Tietê River. A natural affluent, the Pinheiros River, had its course changed, and became a channel, where two pumping stations (Pedreira and Traição) in São Paulo city started to pump and extract water from this river. Adding the two pumping stations, the Billings reservoir was formed. With 14 generating units, Henry Borden maintained the title of largest plant in Latin America, until the construction of the Furnas Plant. If it acted in isolation, the plant would have the capacity to serve an area with two million of residents [2].

The Henry Borden complex is composed of two high-fall powerhouses (720 meters), called External and Underground, with a total of 14 generator sets driven by Pelton turbines, making an installed capacity of almost 900MW, with a nominal flow of 157 m^3/s.

Since October 1992, the operation of this system has been complying with the conditions established in the by Resolution SMA-SSE-02, of 02/19/2010, which only allows pumping the waters of the Pinheiros River to the Billings Reservoir for flood control, reducing the energy produced at Henry Borden by approximately 75% [1]. However, in the event of a major disturbance in the electrical system, the plant will be able to inject almost 900MW into the system after about one minute.

2.1.1 External Powerhouse

The oldest of the powerhouses has eight external penstocks and a conventional powerhouse. The first unit was inaugurated in 1926, and the others installed until 1950, in a total of eight generator sets, with an installed capacity of 469MW.

Each generator is powered by two Pelton-type turbines, driven by the waters from Rio das Pedras ("Rocks River") reservoir, which reach the Valve House where, after passing through two butterfly valves, they descend the mountain through the penstocks, reaching their respective turbines, covering a distance of approximately 1,500 meters [3]. In the Figure 1 the External Powerhouse photos are presented.


a) External View


b) Internal View


c) Penstocks

Figure 1 – External Powerhouse

2.1.2 Underground Powerhouse

The expansion of Henry Borden Power Plant took place until 1950. The option for underground construction was to avoid placing more tubes along the hill. Anchoring this piping securely to the hillside was very complex and expensive. In the 1950s, there was already a technology that made construction cheaper, which was the drilling of a tunnel along the interior of the mountain. An adductor tunnel with three meters of diameter and 1,500 meters long was made inside the Serra do Mar ("Sea Mountain") to take the water from the reservoir and lead the water to the underground powerhouse [2].

The underground powerhouse is composed of six generators with vertical axis, installed inside the rock, in a cave with 120 m long, 21 m wide and 39 m high, whose installed capacity is 420 MW.

The first generator starts to operate in 1956. Each generator is powered by a Pelton turbine with vertical axis and four nozzles [3]. Figure 2 shows the Underground Plant photos.

a) Internal View – Generators b) Internal View – Valves

Figure 2 – Underground Powerhouse

2.2 Double Pelton Turbine

The Pelton turbine is used in hydraulic projects with a considerable head, 300 meters or more, and can generate from a few MW to more than 200MW per unit. There are Pelton turbines with vertical axis and horizontal axis, and when the axis is horizontal, two turbines on the same axis can be used, driving a single synchronous machine. This system is often called Double Pelton turbine.

A synchronous machine driven by this type of turbine allows generating with only one of the turbines in operation while the other turbine remains with the nozzles closed. This is interesting for maintenance and availability too. The independent operation of the two turbines must be taken into account by the generating units automation systems, assuming conditions that allow the degraded operation with only one of the turbines, in addition to requirements for independent start and stop processes. For the governor the requirement for independent operation is also relevant, since a fault that generates blockage should affect only the defective side.

In older systems, each of the turbines was controlled by an independent governor, since it was not possible to activate the injectors of the two turbines by the same mechanical governor. In microprocessed digital systems, this is possible through a single governor.

Some generating units equipped with hydraulic turbines operate as a synchronous condenser, providing or absorbing reactive power, which can happen during the night, while during the day the machine produces active power. Generator sets with Pelton turbine have the ability to operate as a synchronous condenser without the need of mechanical interventions in the turbine (air injection in the suction, for example), since this type of turbine does not work drowned. For a synchronous machine driven by a Pelton turbine to operate as synchronous condenser it is sufficient that the injectors are closed with the unit connected to the grid.

Such an operating characteristic must be taken into account by the governor system, since a failure of any electrical or mechanical device associated with one of the turbines should not necessarily stop the unit, as it can operate as a condenser, maintaining the injectors closed. In some cases, some machines are kept operating as a synchronous condenser to save water, but when necessary, they quickly return to operate as generators, dispatching active power to the system.

3. MODERNIZATION

3.1 Speed Governor

3.1.1 Hydraulic Systems

The speed governors originally installed were fully mechanical, based on the fly-ball type control, developed by James Watt in 1788. Such equipment proved to be robust for operating for many years. Some positive points of this system are described below.

- does not need power supply for most components;
- presents physical robustness;
- suffers little wear and tear with the operation, requiring replacement of parts after many hours of operation;
- low obsolescence, considering its operation itself, without considering the functions of the new equipment (oscillography, etc.);

On the other hand, the fully mechanical governor also has negative points:

- need for maintenance and replacement of oil frequently;
- low speed measurement accuracy, since it was based on mechanical belts;
- impossibility to establish exactly the same control for two machines in parallel, since the adjustment was based on the screws tightening;
- limitation to redundancies, both in the control and in the transducers (nozzle position, deflector position, frequency and power measurement, etc);
- does not have communication protocols for remote signals monitoring;
- does not have signals (oscillography) or events (SOE) recorders, facilitating previous diagnoses (predictive maintenance), reports and construction of operation / maintenance histories;
- impossibility of having, in Pelton doubles, a single regulator to control the entire generating unit (two turbines).

In Figure 3 original system photos are presented, from different manufacturers, based on the Watt pendulum, with the control based entirely on mechanical elements.


a) Woodward governor

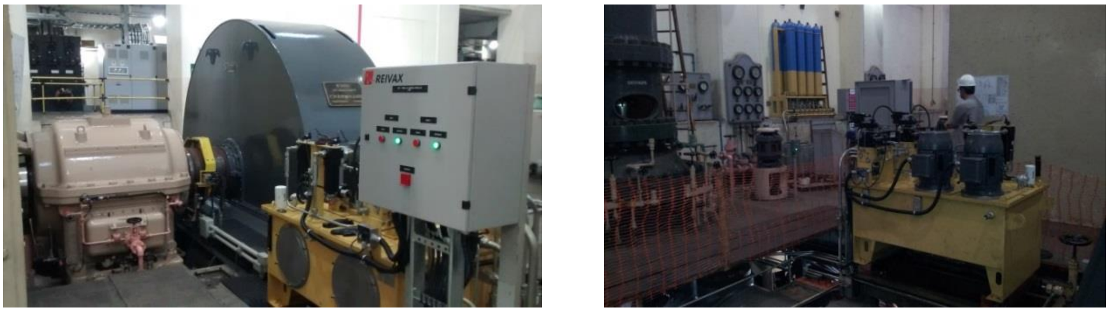

b) Pelton governor

Figure 3 – Original Mechanical Speed Governors

The modernization of mechanical components included changing the operating pressure of the hydraulic system, from 12 bar, with air-oil accumulators, to 120 bar, operating with nitrogen-oil (N_2O) accumulators. With this modification, the size of the components was very small, and the amount of oil needed went from 8,000 liters to 600 liters each generating unit.

The new Hydraulic Power Unit (HPU) has a panel for local controls for maintenance, local instruments for indication, a double filter and two pumps for pressurization. The HPU has a hydraulic circuit for connection to the adjacent machine also through a register (manually operated) to supply the hydraulic system of the other machine, if necessary.

In Figure 4 modernized system photos are presented, including the new Hydraulic Power Unit and the new set of accumulators.

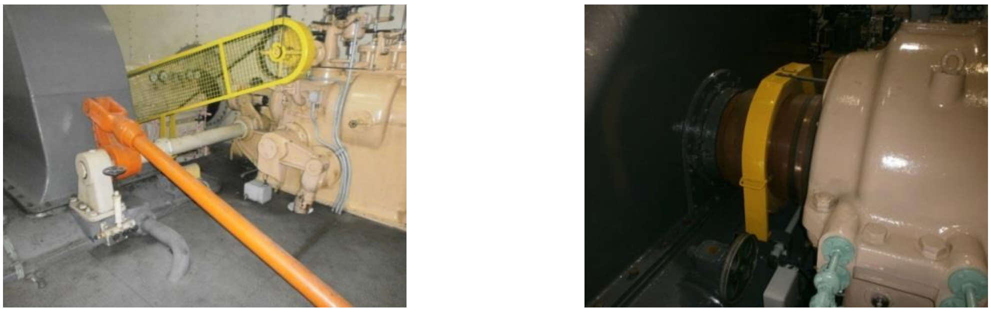


a) Hydraulic Power Unit (HPU) b) HPU and Accumulators

Figure 4 – New Speed Governors – Hydraulic parts

Another relevant mechanical modification was the belts removal, used to measure the shaft rotation. They are replaced by a toothed wheel installed on the machine shaft, which allowed the rotation measurement by inductive sensors, increasing precision and reducing maintenance. The new governor also allows the machine's rotation measurement by measuring the terminal voltage frequency from the Potential Transformers (PTs).

In the Figure 5 are presented photos comparing the original system with the new system.

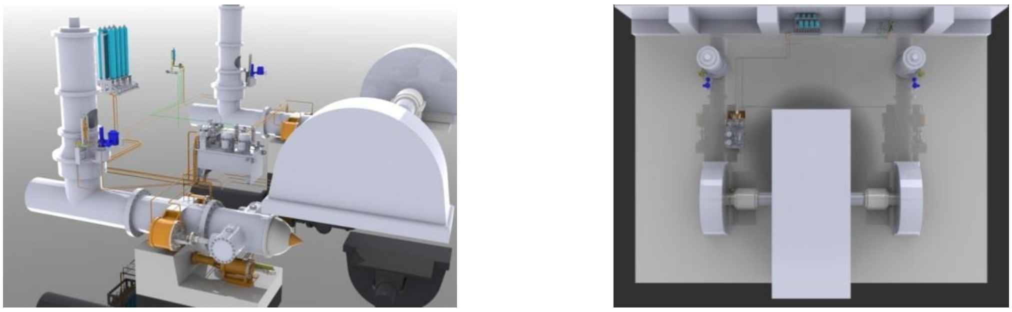


a) Original system: Belts b) New system: Inductive sensor

Figure 5 – Speed measuring – Original and new systems

Another modification was the original nozzles servomotors by standard size cylinders (available on the market), adapted inside the original pistons. The original deflector servomotor was modified receiving an independent actuator driven by mechanical cams as in the original governor. The new digital controller uses a proportional directional valve and reached a closing time of less than one second, good for a Pelton turbine.

The Figure 6 shows modernized system isometric drawings where it is possible to observe the new governor hydraulic structure: nozzle and deflector pistons, accumulators, position transducers, hydraulic power unit, adduction valve and pipes.



a) Perspective view b) Upper view

Figure 6 – Speed Governor – Isometric drawings of the modernized system

3.1.2 Digital Governor

The new digital governor drives the two turbines (side A and side B) with a single control panel, in addition to having advanced control functions (test screen, maintenance support) and supervision tools (oscillography, event logs, etc).

The governors and automation systems modernization brings the following advantages: increased reliability, centralization of information and control of processes, capacity for logical adaptation, easier maintenance. For synchronous machines with a Double Pelton Turbine, which can work as a synchronous condenser, these benefits are even greater due to the specificities of the control system, already presented.

- simulated isolated network test, according to IEC 60308 [5] and IEEE 1207 [6].
- controls the two turbines, side A and B, independently;
- in case of total failure of the system, on one side, it continues to operate on the other side;
- in the event of a total failure of the governor, the machine is not stopped, but the adduction of the two turbines of that machine is closed, keeping the unit operating as condenser (logic specified by the customer).

In Figure 7 the new control panels photos are presented.

a) External View

b) Internal View

Figure 7 – New Digital Governor – Control Cabinet

In the Operation Room, there is a mix between push buttons of the original systems, from the 1920s, contrasting with the modernized systems, with touchscreen HMI and the supervision systems (SDSC). This is very clear in the photos shown in Figure 8.

a) Power plant control panels

b) Governor Remote Control

Figure 8 – Operation Room

3.2 Automation and Subsystems

In addition to changes in the speed governor (digital and hydraulic), automation functions were implemented, which make the process of starting the unit, stopping, increasing / decreasing the generation, generator-condenser conversion completely automatic, by the control room or by the controller's HMI.

A relevant function implemented is the completely automatic start of the unit, from completely stopped to the synchronized machine, activating the excitation system and also the automatic synchronizer. In addition, it is possible to monitor the unit's bearings, where temperature sensors and oil flow sensors were installed. The information is displayed on the local and remote screens.

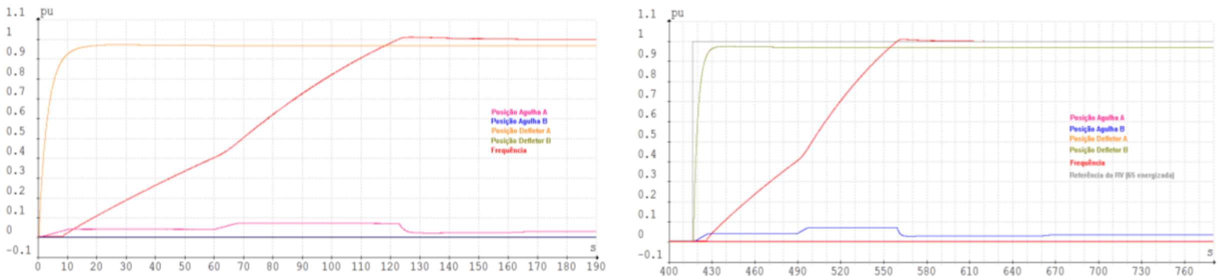
Monitoring of the generator was also included, including the winding temperature and the cooling water flow. Such information is also presented on the governor operation screens. The emergency engine starting systems were modernized, with new control panels, for local or remote activation, through the automation system. In addition, bearing lubrication and water pumps for the generator's cooling were reformed. The oil injection pumps in the bearings and the generator cooling pumps were recovered, which showed strong wear and tear for many years of operation, malfunctioning and low efficiency.

4. COMISSIONING

After the new components installation a set of tests were necessary to guarantee the correct functioning of each element. The commissioning tests are carried out in parts: dry tests (machine stopped), offline tests, and online tests. The results obtained in the main tests will be presented. All the oscillography presented was based on the Commissioning Report [8].

4.1 Automatic Start

The generator unit can be started independently by each turbine: side A or side B. The test was carried out by both sides. The oscillography of the tests are shown in Figure 9.



a) Start with turbine A b) Start with turbine B

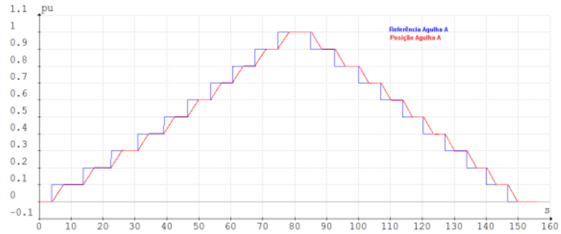
Figure 9 – Starting the Machine

4.2 Tuning the controller in different conditions

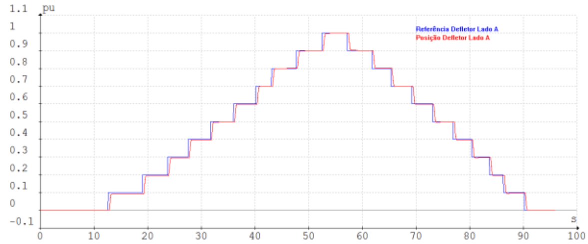
The control loops tuning results during dry tests, offline tests, and online tests are shown in the Figure 10.

An important test for evaluating the performance of power control is the simulated isolated network test, based on the IEC 60308 [5] and IEE 1207 [6] standards. The test considers that the machine is operating isolated, which is the worst condition for a speed regulation. It is considered an increase (or decrease) of load, causing the frequency to drop (or increase), causing the regulator to react and control the frequency.

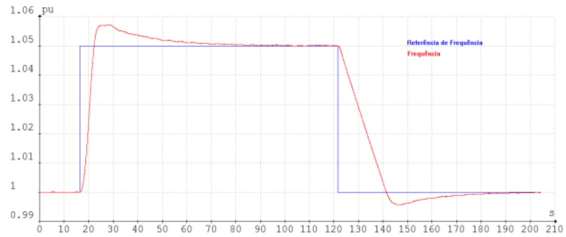
This functionality is available on the governor's HMI, making it easier for the commissioner to use this tool. The Figure 11 presents the results during the comissioning.



a) Nozzle step responses

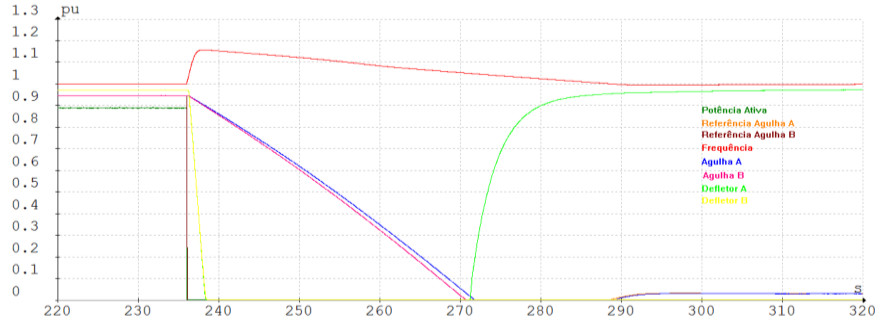


b) Deflector step responses



c) Frequency step response

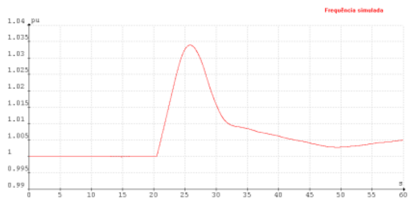
d) Active power step response



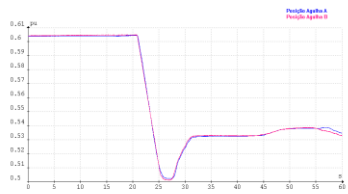
e) Load rejection

Figure 10 – Tuning the control loops

a) Reference and Active Power signals



b) Simulated frequency signal



c) Nozzles signals

Figure 11 – Isolated testing

4.3 Generator – Condenser conversion

Due to the use of water from the plant's reservoir to supply drinking water to the city of São Paulo, the generation of the Henry Borden plant is very low today. Therefore, the plant remains almost all the time operating without generate, but synchronized to the system operating as a synchronous condenser.

Due to the plant's context in the current Brazilian electrical system, the plant generates less energy, operating as a synchronous condenser most of the time, but with the possibility of reversing the operation and providing nominal active power to the system in less than one minute, as it is part of a “recovery corridor”. Such functionality was implemented and tested in the new control system.

5. CONCLUSION

The project to modernize the governors systems at Henry Borden Power Plant included replacing the governor control part and profound changes to the hydraulic systems, in addition to including the unit's automation functions, were concluded. It brought several challenges for both the customer, for causing a profound change in the operation and maintenance mentality, as well as for the equipment manufacturer, due to the requirements raised by the customer, both in the logical and mechanical parts.

The installation of the mechanical parts and the control parts was carried out as foreseen in the schedule, culminating in all the commissioning tests. The final result was excellent, as it brought numerous functionalities that the original system did not have, as well as monitoring and control tools that were not available.

Given the brutal change in the philosophy of operation and maintenance, all plant operators and maintainers were trained to work with the new system. Many of the plant's workers had worked at the plant for more than twenty years, and were completely accustomed to the original system. When the new system came into operation, many workers felt “groundless”, due to the considerable changes in philosophy. This process has been gradual, with employees getting used to the new reality, and little by little, realizing the advantages of the new system.

The retrofit process of the plant took place between 2014 and 2016. Currently, the three generating units are operating commercially, bringing greater security to the operation and maintenance teams, due to the modern tools now available.

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