DEVELOPMENT OF PNEUMATIC TECHNOLOGY FOR AUTOMATION AND CONTROL OF SMALL HYDROPOWER PLANTS

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ABSTRACT

Small hydropower plants have been seen as a more sustainable source of energy in comparison with large hydropower plants due to the smaller required flooding area. However, every source of energy production has, inevitably, an impact on the environment. Aiming to reduce the usage of fossil-based products, such as hydraulic oil, a joint effort has been made between the Laboratory of Hydraulic and Pneumatic systems and the companies Reivax Automation and Control and China Three Gorges, in order to introduce the pneumatic technology to the hydrogeneration sector. Characteristics such as easy installation and maintenance, low acquisition costs, and mainly, low environmental impact, make the pneumatic technology an excellent candidate to replace the hydraulic servo actuators that have been traditionally used for automation and control in hydropower plants, which use large quantities of hydraulic oil and provide a high risk of a river bed contamination due to possible leakages or incorrect disposal of hydraulic oil. This paper presents two cycles of development of a pneumatic solution to automate and control the generating unit of small hydropower plants. It includes the first proposed solutions, proof of concepts and drawbacks that were faced, as well as the new challenges and achievements that rose during the design process. The paper also presents the most up-to-date results from a pilot project where a fully pneumatic solution was applied for a generating unit with 438 kVA of generating capacity and a model of development that was identified based on common activities performed during the first two cycles of development.
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Keywords: *Small hydropower plants, sustainability, pneumatic technology, pneumatic servo-actuators*

INTRODUCTION

Electricity generation by hydropower plants has been known as one of the major contributors to renewable energy sources around the globe. In Brazil, for instance, hydro generation corresponds to about 59% of the total energy production [1] and considering the total installed capacity, Brazil is in the third position in the ranking for renewable energy generation [2]. However, every source of energy inevitably results in an environmental impact, either if it is renewable or not renewable. In the case of hydroelectricity generation, the main impacts are related to the flooding caused by the water reservoir, which produces carbon dioxide and methane that results from biomass decomposition in the flooded area and also the destruction of animal life [3].

Therefore, the development of power plants with small capacities has been discussed as an alternative to reduce the environmental impacts of hydro generation [3, 4], since they require a small or even no reservoir, such as the run-of-river power plants [3, 5]. Based on this, many environmental activists and ecologists do not consider large-scale hydro generation as renewable and clean energy [6], such as the International Rivers Network, which released a declaration to exclude hydropower bigger than 10 MVA from the list of renewable energy options [7]. Therefore, small hydropower plants (SHPs) have become a possible substitute for large hydropower, and it has been encouraging the development of SHP in many countries around the world [8]. The classification of generating capacity of hydropower plants varies according to each country, in Brazil, there are three major groups of hydropower plants, the Hydropower Generating Plants (HGPs), with capacities up to 5 MW, Small Hydropower Plants (SHPs), with capacities between 5 MW and 30 MW and Hydroelectric Power Plant with capacities greater than 30 MW [9].

In this context, the Laboratory of Hydraulic and Pneumatic Systems (LASHIP) from the Federal University of Santa Catarina and the company Reivax Automation and Control have been working together to develop a solution to automate and control the generating unit of SHPs by using pneumatic technology, which

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is known for its low environmental impact, excellent cost-benefit ratio and easy maintenance. The application of pneumatic technology in hydropower plants reduces the usage of fossil-based fluids in addition to the reduction of the acquisition and installation costs, being a viable alternative for the standard hydraulic servosystems traditionally applied for these applications.

Therefore, this paper presents an overview of the development process of pneumatic technology for SHPs, including the milestones and drawbacks faced during two cycles of development, making it possible to identify a development model that was successfully applied in order to introduce a new technology on the market.

FIRST CYCLE – IS IT A MARKET OPPORTUNITY?

The first step in the development process was the identification of the requirements of the application. In this sense, several tasks need to be performed to control and automate the hydraulic generating unit. The main task consists of speed regulation of the generator unit to set the desired frequency of the produced energy, which is performed by the speed governor of the hydraulic turbine (Figure 1-a), controlling the inflow of water according to the demanded power. The speed governor must follow a reference velocity and the main operations performed are as follows:

- Turbine start-up: Opening of the distributor vanes, starting the rotation of the generating unit until it reaches nominal rotational speed;
- Synchronism: Adjust the frequency of the generated energy to match the grid's frequency;
- Load taking: Connection of the generator with the grid;
- Load rejection: Disconnections of the generator with the grid;
- Emergency shutdown: The system must be able to close in case of emergency at a pre-determined rate and independent of external power or control sources.

Beyond the speed regulation, the automation of the generating unit consists of a braking system (Figure 1-a), the opening and closing of the admission valve (Figure 1-b), and, in some cases, the actuation of a bypass valve (Figure 1-b) to equalize the upstream and downstream pressure of the admission valve prior its opening. Black-start capability is also desired, that means, being able to start-up the generating unit without electrical energy from the grid.

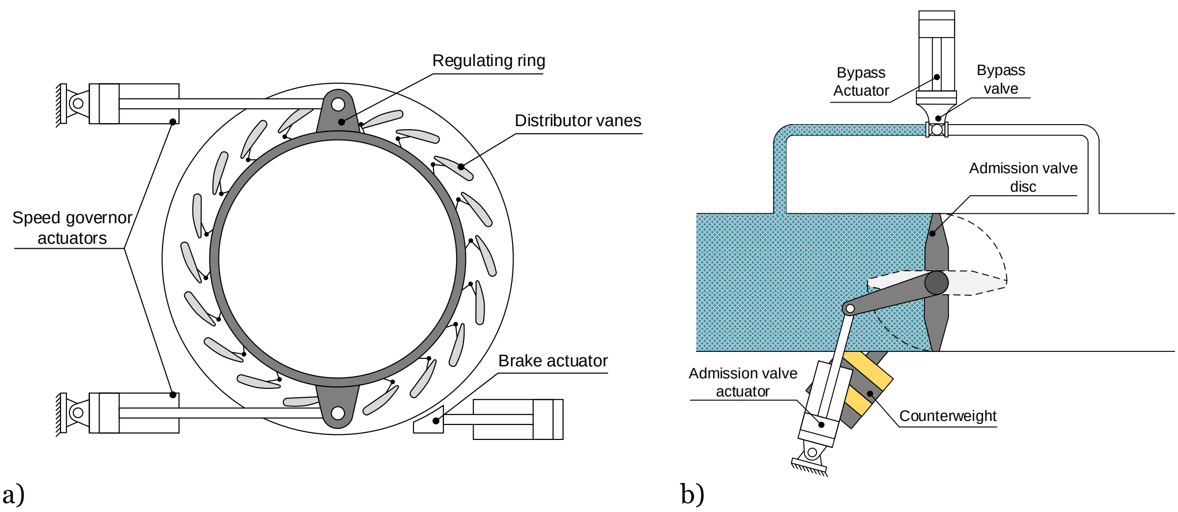


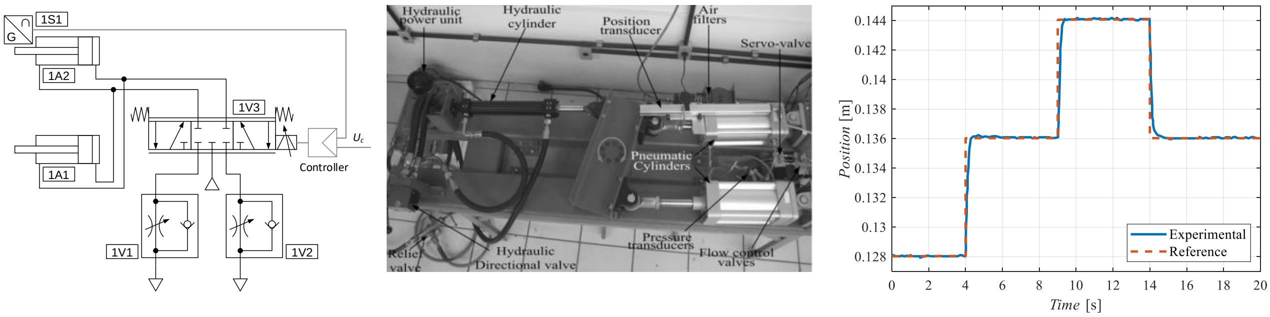
Figure 1 - Actuation systems of a hydraulic generating unit; a) Speed governor, b) Admission valve.

The automation and control of hydropower plants have been done traditionally by servo-hydraulic actuators. Robust and reliable, the hydraulic technology is a consolidated solution for applications that demand closed loop control with strict positioning requirements, such as control surfaces of aircraft, pitch angle control of wind turbines, and speed governor of hydro turbines. However, with the advances in pneumatic positioning systems, [10] identified the possibility to apply the pneumatic technology to control the speed governor of hydropower plants, offering an opportunity to reduce the usage of mineral oil, an easier installation and maintenance, and a lower acquisition cost.

Tasks such as load rejection, synchronism, turbine startup, load taking and emergency shutdown, defined the main requirements in terms of dynamic response and steady-state error [11, 12]. Requirements for the load force were defined by the required maximum mechanical work, which revealed an operating range for the pneumatic technology for machines up to 1 MVA of generating capacity [4].

A classical concept of a servopneumatic system (Figure 2-a), composed of a proportional servovalve (1V3), linear actuators (1A1 and 1A2), and flow control valves (1V1 and 1V2) was considered by [10]. A dynamic simulation model was developed in order to assess the capability of the servopneumatic system to withstand the operating conditions and meet the design requirements. The model included non-linearities inherent in servopneumatic systems, such as the dead zone of proportional valves and friction of the cylinder. The closed loop control was made by a PID controller and a dead-zone compensator was used to minimize the effects of the proportional valve's dead zone.

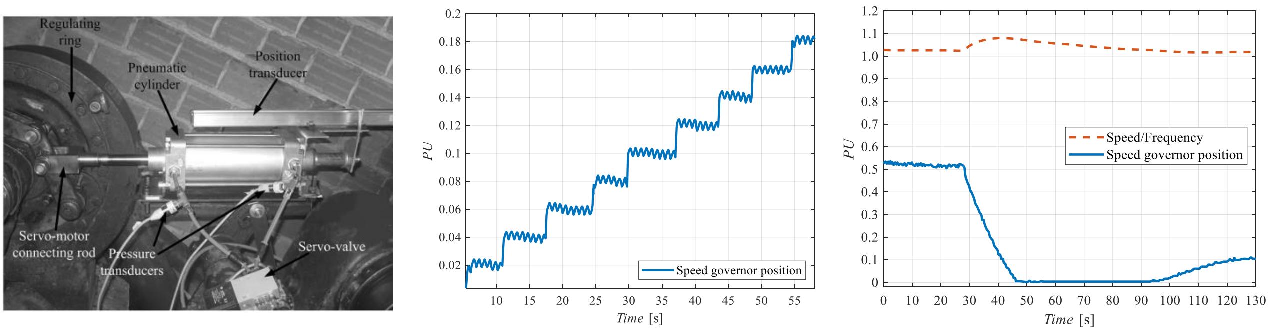
The preliminary results obtained by simulation evidenced that the pneumatic solution was able to meet the design requirements. On the sequence, a test rig was developed (Figure 2-b) in order to validate de developed model and perform further investigation of the proposed solution. The expected most critical conditions were applied on the test rig through a hydraulic actuator, which generated the load for the servopneumatic system. The results showed the validity of the dynamic model, moreover, it indicated settling times of about 0.56 seconds and 0.24 mm of steady-state errors (Figure 2-c). Tasks equivalent to turbine start-up, emergency shut down, synchronization, and steady-state control could be successfully achieved by the proposed solution.



a) b) c)

Figure 2 – First proposed solution (adapted from [10]); a) Pneumatic diagram, b) Test rig, c) Experimental step response

The next step consisted of a small-scale prototype running in a speed governor of a Francis-type turbine with 35 kVA of installed capacity. A servopneumatic system was installed to control the distributor of the turbine (Figure 3-a) and the controller consisted of a PID with a dead zone compensator. Tests were carried out to evaluate the settling time, automatic start-up, and load rejection.

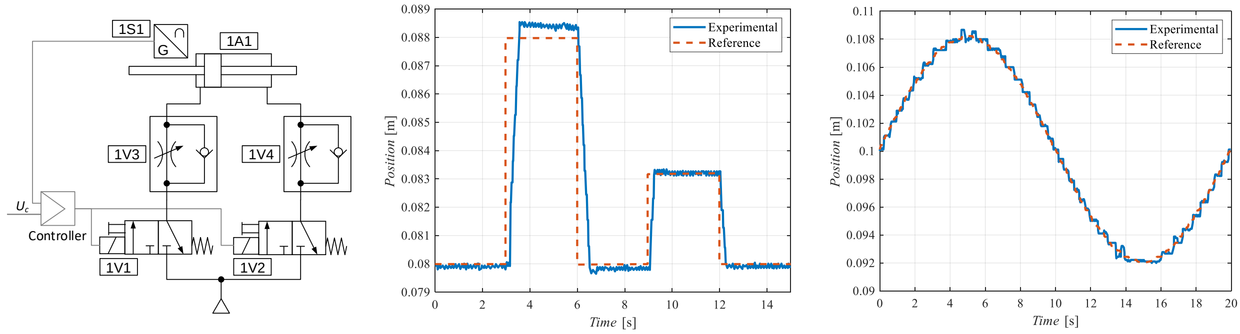


a) b) c)

Figure 3 - Small-scale prototype (adapted from [4]); a) On site installation, b) In load step response, c) Load rejection test

The on-site results showed a settling time of less than 0.25 seconds (Figure 3-b). At steady-state, an oscillation of less than 1 mm was observed, which was caused by the vibration of the machine (The unit PU stands for a relative value compared to the maximum nominal value of the variable). An overshoot of 8% occurred for load rejection tasks (Figure 3-c), which is acceptable since a reference value for overspeed in load rejection is up to 30%. Even with adverse operating conditions of the generating unit, due to clearances in the turbine mechanisms, the servopneumatic system was able to work within the recommended values of settling time and speed overshoot, which were 1.25 seconds and +30%, respectively, for this application [12, 13].

One limitation of the standard servopneumatic system was the high cost associated with the servovalve, which reduced the economic appeal of the proposed solution. Therefore, in [14] it was designed a servopneumatic system actuated by fast switching on/off valves (1V1 and 1V2 of Figure 4). The control strategy was composed of a PID, a compensator for the saturation zone of the valve, and a Pulse Width Modulation (PWM) technique, with frequencies between 10 and 75 Hz.

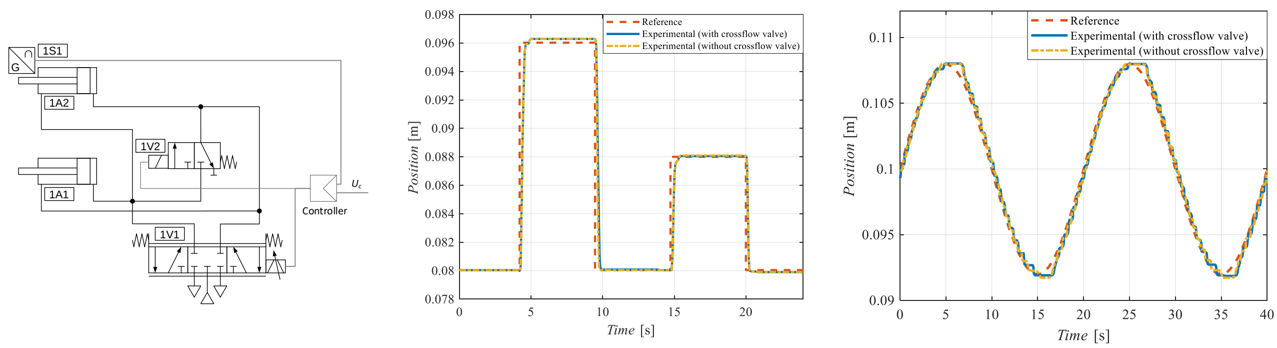


a) b) c)

Figure 4 - Solution based on fast-switching on-off valves (adapted from [14]); a) Pneumatic diagram, b) Experimental step response, c) Experimental trajectory following.

Results for unloaded tests showed an accuracy of +/- 0.5 mm, either for step response (Figure 4-b) and trajectory following (Figure 4-c). The promising results would make it possible to significantly reduce the acquisition costs of the actuation system for speed governors. However, the switching frequency applied on the directional valves reduced its life span, making it difficult to be used for applications that run continuously, such as speed governors.

Aiming the increase the energy efficiency of servopneumatic systems, [15] proposed a solution to reuse the expansion energy of the compressed air when the cylinder is moving in the same direction of the load. The solution is presented in Figure 5-a), which is composed of a standard servopneumatic system with a proportional servovalve (1V1) and a fast-switching 3/2 crossflow valve (1V2) connecting chambers A and B of the actuators (1A1 and 1A2). The control strategy consisted of a PI controller and dead zone compensator for the servovalve and a PI controller with a set of rules and PWM technique for the crossflow valve.



a) b) c)

Figure 5 - Solution focused on energy efficiency (adapted from [15]); a) Pneumatic diagram, b) Experimental step response, c) Experimental trajectory following

Tests performed with 5 kN of load, with and without the crossflow valve, showed no significant difference between both solutions in terms of dynamic response and positioning accuracy, with errors no bigger than +/- 1 mm (Figure 5-b, c). However, the crossflow valve resulted in an average saving of 54% of compressed air, resulting in a payback of about 2 years for a hypothetical application in a speed governor, compensating for the extra costs related to the acquisition of the fast-switching valve and a differential pressure sensor. Moreover, the limitations of the life span of the cross-flow valve are mitigated, since this valve will be used just for displacements that occur in the same direction of the load, such as the closing movements of the distributor, which occurs less frequently.

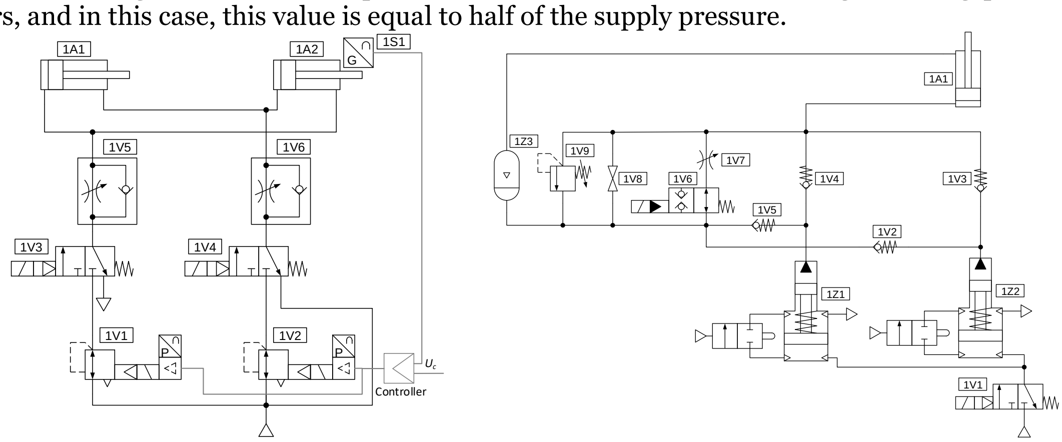
The first cycle of development of the pneumatic technology was capable to demonstrate the technical viability of the proposed solution, with robust data gathered through dynamic simulation models, experimental test rigs, and a small-scale application with a Francis turbine. At the end of the first cycle, the main challenges that needed to be overcome were the acquisition cost of the servopneumatic valves and the actuation of the admission valve of the generating unit, where high actuation forces are commonly needed and a standard linear actuator would not be capable to attend the design conditions.

SECOND CYCLE – ADDING NEW REQUIREMENTS

After the first cycle of development to test the technical viability of using pneumatic technology for automation and control of SHPs, a new cycle of development started with The Brazilian National Electric Energy Agency (Aneel) R&D project number PD-00387-0117/2017. The new goals included the reduction of acquisition costs, the development of a solution to actuate the admission valve based on pneumatic power, and the implementation of a pilot project in a 438 kVA Francis turbine, being the first system to permanently operate the turbine with pneumatic technology.

Again, the design process started by understanding the requirements of the application. Beyond the dynamic response and steady-state error of the speed governor, emergency closing and black-start were added to the list of requirements. For the turbine admission valve, a high actuation force is necessary due to the counterweight and water column over the valve's disc. It also required an automatic closing, without the need for electric energy. Several conceptions and technologies were evaluated as possible solutions to actuate the speed governor and the admission valve, the main basis for the decision-making was the meeting of the design requirements as well as the economic viability of the solution. Discussions about possible solutions are given in [16, 17].

Figure 6-a) presents the proposed architecture for position control, where two proportional pressure regulator valves with discrete actuation (1V1 and 1V2) have proved to be more suitable since this model of valves is capable to align characteristics of proportional operation with high flow capacity, moderate acquisition costs, and a large number of manufacturers. Emergency valves (1V3 and 1V4) were installed between the proportional valves and the pneumatic actuators, in such a way that in an eventual emergency condition or loss of power, the distributor will be automatically set to its closed position. Moreover, flow-control valves (1V5 and 1V6) are used to adjust the maximum opening and closing velocities. Black-start operations can be performed with the pneumatic energy stored in the compressed air reservoir. The control strategy consisted in a PID controller that converts the position error into a pressure reference for the pressure regulator valves. An anti-windup technique is applied to the integrator controller to avoid the unbounded growing of the integral error. Also, a pressure offset is used to set the average working pressure of both chambers, and in this case, this value is equal to half of the supply pressure.



a) b)

Figure 6 - Proposed solution to automate and control the generating unit; a) Actuation system for the speed governor; b) Actuation system for the admission valve

For the actuation of the admission valve, a hydropneumatic jack was designed in partnership with the company Bovenau, where new functionalities were implemented in order to attend to the design requirements. Figure 6-b) presents the hydro-pneumatic diagram of the developed solution. A set of two pneumatic pumps (1Z1 and 1Z2) is being used to increase the opening velocity of the valve. The jack's actuator is 1A1. A 2/2-way normally open hydraulic valve (1V6) grants an automatically closing of the admission valve in the case of loss of power. The closing velocity is regulated by a flow-control valve (1V7) and, the manual valve (1V8) can be used as a redundancy for the retracting movement of the hydropneumatic jack. The equipment is remotely operated by switching the feeding valve (1V1) and the hydraulic return valve (1V6).

The proposed solutions were evaluated through dynamic simulations, which results corroborate with the capacity to attend the design requirements of the application [16, 18]. A test rig named Platform of Dynamic Loading (Figure 7) was developed aiming to perform experimental tests and further investigate the proposed solutions. The main characteristic of the test rig is its capacity to generate forces up to 260 kN, providing means for the actuation systems of the distributor and the admission valve to be tested in full-scale conditions.

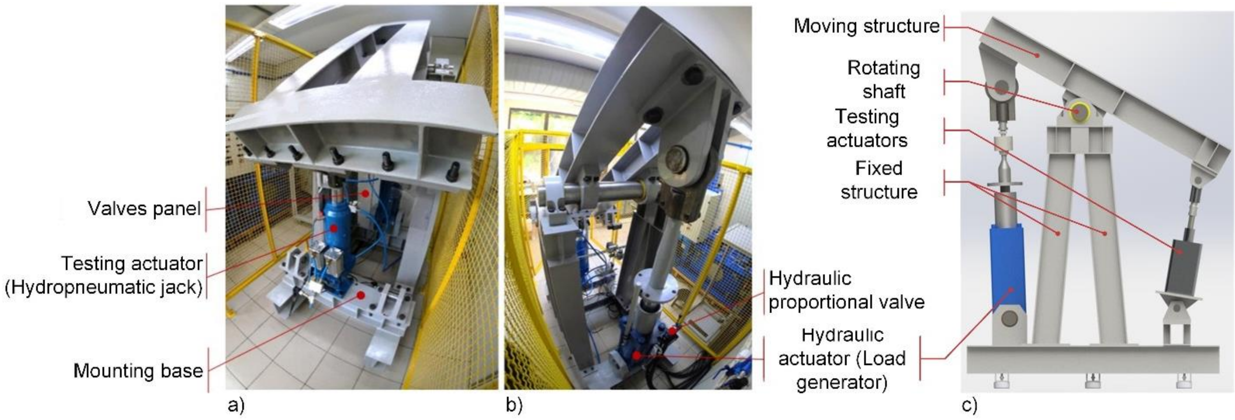


Figure 7 - Platform of Dynamic Loading (adapted from [19]); a) Front View, b) Rear view, c) Side view

In order to simulate the real and most adverse conditions of the distributor, the applied force over the pneumatic actuators was set to 26 kN, corresponding to the maximum force expected on the pilot project application [16]. Equivalent tests for the opening of the distributor, synchronism of the generator with the electrical grid, and load rejections were carried out and presented in Figure 8.

As can be seen in Figure 8, the position control system was able to follow the reference values with excellent dynamic response and low positioning error. At steady state, the biggest error observed during the testing was 0.64 mm. Moreover, the response time for the load rejection (closing of the distributor) was 7.2 seconds, which is within the specification for this application according to the turbine manufacturer.

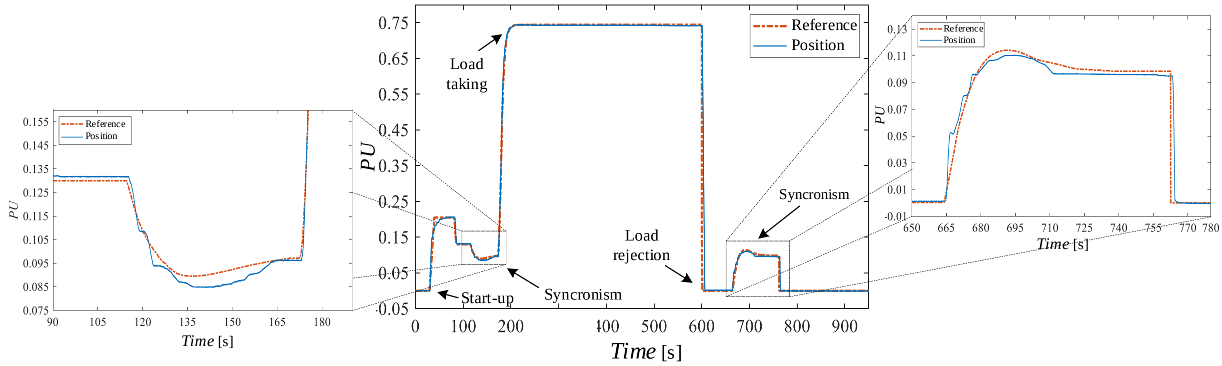


Figure 8 - Test rig results for position control using pressure regulator valves (adapted from [19])

The hydropneumatic jack was also tested at the test rig with a load force of 153 kN, which is the maximum force expected for the pilot project application according to the admission valve manufacturer. It presented a constant and regular behavior during the opening, in such a way that the opening time was completed in 150 seconds. The capacity of the hydropneumatic jack to maintain the extended position for a long period of time was also tested and the nominal load (153 kN) was kept for a period of 8 hours with the pneumatic supply pressure completely ceased during this period. At the end of the experiment, the retracting was just 0.35 mm, showing excellent stability.

Based on the results obtained through simulation and test rig experiments, the development of the pilot project began. The goal was to install a pneumatic system for the complete automation and control of the auxiliary generating unit from the hydropower plant located in Salto Grande-SP, Brazil, which is under the concession of the company China Three Gorges Brasil. The generating unit is composed of a horizontal Francis turbine and a synchronous generator. With an average water head of 18.5 m, the generating unit has a total of 438 kVA of installed capacity.

The selection of the actuators and valves for the distributor was made based on the operating point method [20, 21]. A hydropneumatic jack with a maximum capacity of 294 kN was designed in partnership with the company BOVENAU. The spatial distribution of the pneumatic components at the operation site is presented in Figure 9–a), as well as a few images of the generating unit after the installation of the components (Figure 9–b, c, d).

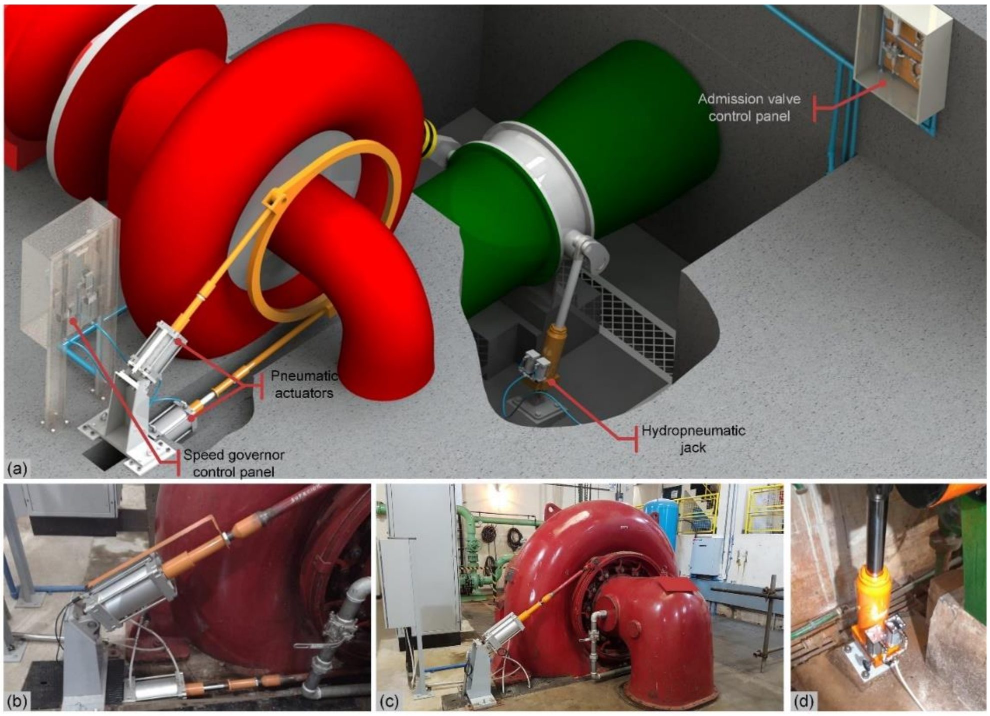


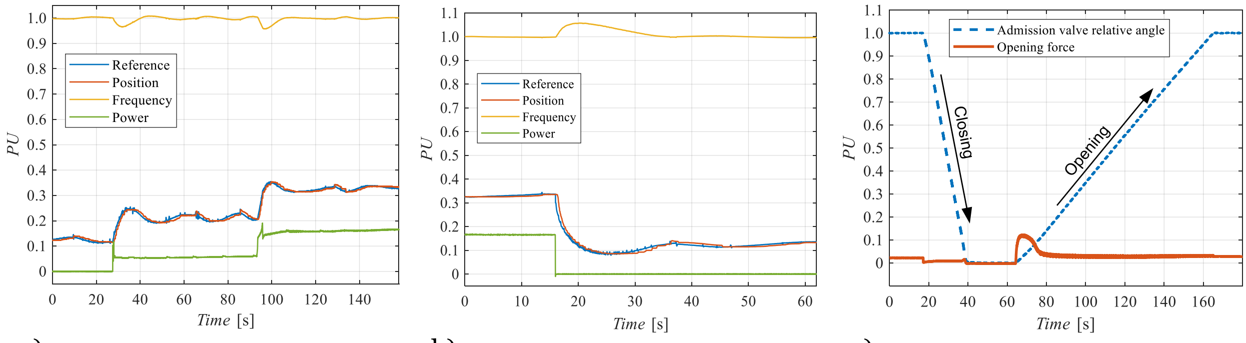
Figure 9 - Pilot project installation site (adapted from [22]); a) General view of the pneumatic solution, b) Pneumatic actuators of the distributor, c) Front view of the Francis turbine, d) Hydropneumatic jack.

Figure 10-a it is presented the data for the generating unit operating in load and isolated from the grid. The electrical load was created by a resistor bench, where different nominal loads were adjusted, starting with 22 kW (0.05 PU) and following with 70 kW (0.16 PU). The servopneumatic system was capable to follow the reference trajectory with an excellent dynamic response. This behavior is reflected in the generator frequency, which presented an oscillation between 0.9953 to 1.005 PU (59.72 to 60.3 Hz) at steady-state, which is within the limit of +/- 0.5 Hz established by the Electric System National Operator. During the transition from 22 kW to 70 kW, a frequency oscillation of 0.0347 PU (2.082 Hz) occurred and the time to reach nominal frequency was approximately 18 seconds. For these cases, the Electric System National Operator recommends a maximum time of 45 seconds for operation at frequencies between 57.5 and 58.5 Hz, demonstrating that the dynamic response of the servopneumatic system meets the requirements.

It is also important to note that the fluctuations in the rotational speed are also caused by the operational mode of the generator unit, which is isolated operation (The most difficult operational mode to control). Due to the low inertia of the turbine-generator set, the speed tends to fluctuate more when compared with bigger turbines or even when compared with the same machine operating synchronized with the national grid.

The dynamics of the system were also evaluated by a load rejection task (Figure 10-b), which was performed from a power of 72 kW (0.1662 PU). As it can be seen, the servopneumatic system was capable of properly respond to this perturbation, reducing the opening of the distributor from 0.33 PU to 0.12 PU, which is the opening to keep the nominal frequency without load. Moreover, the overspeed was 5.8%, which is within the recommendation of the turbine manufacturer, where an overspeed limit of 30% is used to trip the generating unit.

Figure 10-c) presents the data for the opening and closing of the turbine admission valve, which is made by the hydropneumatic jack. The task was performed with the generating unit in operation. The closing and opening times were 23.35 and 101.67 seconds, respectively. According to the manufacturer of the admission valve, the opening time must be between 80 and 160 seconds. The desired closing time was not specified, but the main rule is that the water hammer effect must be avoided. Since this phenomenon was not observed during the testing, it was assumed that the obtained closing time was acceptable.



a) b) c)

Figure 10 - Pilot project results (adapted from [22]); a) In load speed regulation, b) load rejection test, c) Closing and opening of the admission valve

The tests performed with the pilot project proved the capacity of the pneumatic technology to automate and control the generating unit of small hydropower plants, being capable of successfully performing tasks of opening, closing, load taking, and load rejection of the speed governor, as well as opening and closing of the admission valve. Moreover, the pneumatic solution has been found to be economically viable, with acquisition costs 45% lower than an equivalent hydraulic solution [22].

IDENTIFICATION OF A DEVELOPING MODEL

After two complete cycles of development of the pneumatic technology for SHPs, it is possible to identify a set of 5 common activities performed in both cycles, which can be organized into a development model, providing a path to be followed during the development of new technologies related to hydropower generation. This model is depicted in Figure 11, in which the blue spiral line indicates the first cycle and the green spiral line indicates the second cycle.

The set of activities that compose the development cycle results in a progressive understanding of the application's needs and the feasibility of a proposed solution to meet the requirements. It also reduces the risks inherent in every development process, because the solutions are progressively tested in different environments and conditions, and just when one activity is successfully completed, the next one will start. As the spiral grows, the maturity of the technology increases. Nonetheless, the costs and risks involved also increase, justifying the necessity to start the development process with a good understanding of the problem, testing possible solutions through simulations and test rigs, and applying it to small-scale prototypes.

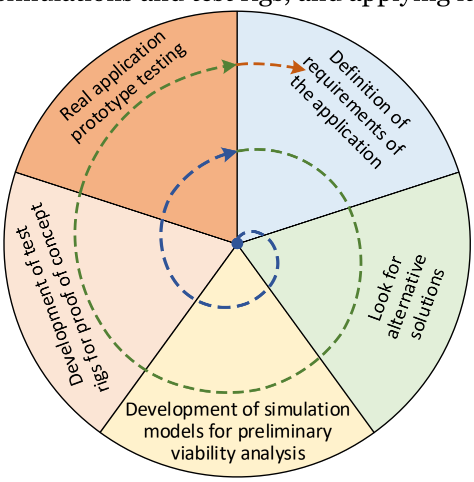


Figure 12 – Spiral development model

The red spiral line in Figure 12 indicates the beginning of the third cycle of development, which has already started for the development of the pneumatic technology for SHPs. Right now, new perspectives and challenges are being discussed. Among them, is the application of pneumatic systems to control the pitch angle of Kaplan turbines, where challenges are raised due to the transmission of pneumatic power into the turbine's rotor as well as the delay caused by the long transmission line.

CONCLUSION

This paper presented the development process of a fully pneumatic solution for the automation and control of small hydropower plants. The development occurred through two cycles of development, where the proposed solutions were progressively tested and evaluated and the rise of new requirements were addressed.

The actual solution consists of linear actuators and two proportional pressure regulators to control the speed governor. The admission valve is actuated by a hydropneumatic jack, developed specifically for this application. Both solutions have built-in capacities for emergency closing (fail safe) to operate in case of electrical power loss. They also make it possible to perform black-start tasks, allowing a full startup of the hydropower plant without energy from the grid.

After two complete cycles of development, it was demonstrated the capacity of the pneumatic technology to automate and control the generating unit of small hydropower plants. The pneumatic solution offers the advantage of having an easier installation and maintenance process, with an acquisition cost roughly 45% lower than an equivalent hydraulic solution, which has been traditionally applied for these applications. Recent analysis made by Reivax pneumatics team has shown that with commercial components it is possible to reach turbines with power up to 30 MW.

Beyond the economic viability, the presented technology promotes the reduction of fossil-based fluids and reduces the risks of river bed contamination, contributing to the constant demand from society for cleaner energy production in accordance with the current development trend of small hydropower plants as an alternative to reduce environmental impacts.

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