DEVELOPMENT OF AN ANALOG AND DIDACTICAL SIMULATOR FOR HYDROELECTRIC POWER PLANTS

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Abstract —The aim of this paper is the development of a new tool for teaching, training and experimentations of hydropower plants. This educational tool, designed in collaboration with Hydro-Québec of the region of Abitibi Temiscamingue (Québec), will absolutely be useful in practical teaching and training of production’s staff and future production engineering students in hydroelectric power stations. The paper presents the simulator’s digital and analog aspects. In each case, the process of implementation and of use is exposed. Some results of the model of the generator demonstrate the ability of the latter to be useful for almost all simulations.

Keywords: simulator, hydroelectric power plant, Staff and students of hydroelectric, training tool, analog/digital, Matlab/Simulink.

1. INTRODUCTION

Hydropower is the third source of electrical energy production in the world. It is an important renewable energy resource which converts energy flowing water into electricity. This production means achieves a symbiosis between quantity, quality and respect of the environment in energy generation. It represents the first in the province of Quebec, making it a Canadian model in the control of greenhouse gases emissions [15]. However, the effective cost of production and adequacy between energy needs and consumption remain a challenge for the company. In fact, in 2005, a record electricity consumption led Hydro-Québec to increase the cost of energy [4]. In addition, the government provision for energy consumption is 22% between 2001 and 2016 [4]. Consequently, the government’s policy has been reshaped to include hydropower development, innovation and efficient use of energy [10]. The optimization of existing power plants and the training of their stakeholders is a key step in solving the above-mentioned challenges. However, such training and optimization requires adequate tools for teaching and experimentation.

In fact, numerous references suggest that students learn best when they take an active role in learning through discussion, practice, and application of concept and ideas [9]-[11]. Many other means such as Project Based Learning (PLB) [8] are implemented to facilitate compatibility between theoretical and practical teaching. Unfortunately the field of hydropower faces a problem of educational tools for practice. It would be unprofitable and illusory to stop an operating plant for training purposes. In addition, the plant’s impressive size makes it unrealistic to be used for on-site teaching. Finally, the high level of security coupled with the environmental concerns has restricted the plants’ visits to bare minimum.

Strategies to tackle those challenges have been developed through a partnership between Hydro-Québec and the University of Abitibi-Temiscamingue since 2003. This is achieved by building a hydropower plant simulator, which is the case study of the work presented in this paper. Both the digital and analog aspects have been presented.

The digital aspect is based on mathematical models which describe the operation of the plant’s parts which include the water tunnel, penstock, surge tank, hydraulic turbine, governor and electrical network [3] [5] [7] [12]. These mathematical models, leading to simulation programs are increasingly used in education and training. The achievement of operational goals requires not only a theoretical lesson presentation and simulations, but also practical activities both in the laboratory and on the field. Such practical activities require the analog aspect of the simulator.

The present paper is divided into three main parts. The first part focuses on the presentation and description of the analog simulator [1]-[2]-[7], while highlighting the similarities with conventional hydropower plants. The second part focuses on the digital simulator, while emphasizing on the methodology used for it design. Both
parts also include their operating procedures. The last part presents some results of the model of the generator for the digital simulator.

2. THE ANALOG SIMULATOR

The analog simulator is depicted in Fig. 1. Apart from the frame, the simulator can be split into three main subsets as shown in Fig. 2. They are the hydraulic, the electrical, and the control parts. These three subsets are generally used to design the numerical models, and to explain the operation of hydropower plants. There are also electrical and thermal safety devices not shown in Fig. 1, but which are essential for plant operation. Such safety issues are also essential for the training of plant operators.

![Fig. 1. Analog simulator](image)

The water tanks: In a real hydro power plant, the upper and lower reservoirs play respectively the role of the dam and the downstream watercourses. The upper water tank’s capacity is 4,262 m$^3$. The remaining water kinetic energy is recovered by the draft tube prior to the downstream reservoir. Water is successively pumped from the lower to the intermediate, and finally to the upper tank. The simulator does not need debris grid in the top tank, as it operates in a safe environment.

The penstock: Just as in a real hydro power plant, it brings water to the runner. It has a 0.254m diameter in the simulator, and was designed for a flow rate of 0.0646m$^3$/s. It also contains a return pipe and motor pump used either to refill the upstream tank, or for the recirculation of water in the circuit. The return pipe is found in the simulator, not in a real hydropower plant.

The surge tank: It contributes to eliminate water hammer and cavitation in the circuit. It is not useful for the simulator; however the system is equipped with a breather which control mechanism helps preventing air bubbles in the circuit.

The spiral case: It is the water entering gate to the turbine; designed to keep its tangential velocity constant along the consecutive sections and to distribute it peripherally to the distributor. It is equipped with a mobile guide vane which controls the discharge into the runner and adapts the angles of the flow inlet to those of the runner blades. These blades rotate around their axes by connecting rods attached to a large ring which synchronizes the movement of the gate mechanism. In emergency situations, they can be used for shutting down the flow to the turbine although their use does not preclude the installation of a butterfly valve at the entrance to the turbine. The spiral case is found only in hydropower with Francis turbine type. A typical spiral case with its gate mechanism is presented in Fig. 3.

The runner and draft tube: The energy conversion from the hydraulic to the mechanical form is done by runner as water is axially driven to the draft tube. The diameter of the runner was fixed at 0.206m. The draft tube of a reaction turbine aims to recover the kinetic energy still remaining in the water getting out from the runner. Another draft tube objective is the reduction of the turbine outlet velocity due to the proportionality between the water’s kinetic energy and its velocity.

2.2. The electrical subset

The generator: The energy conversion from the mechanical into the electrical form is achieved by the generator. Such function is maintained in a real hydropower plant; therefore it is a sufficient student reference. They do have a more impressive size in

Fig. 2. The three subsets and link between different parts
hydropower plants as compared to the simulator. It is fixed vertically as indicated in Fig. 3, and has a 3.7KVA estimated power.

The transformer: It helps in reducing losses by Joule effect in the transport of energy over long distances. In a simulator, the transformer is mainly useful for educational purposes.

The load: Many different loads are used in electrical networks. They can be identified by their powers (active \( P \), reactive \( Q \)) and their voltage \( V \). From Equation (1), the equivalent model parameters \((r_x, x_x)\) of a \((P, V, Q)\) load can be obtained for a steady state generator ratings. As specified in [13], this model is practically appropriate for small gas, wind, hybrid, and hydroelectric stations with a single generator. Other configuration of a single generator connected to a load are well explained in reference [3].

\[
\begin{align*}
    r_x &= \frac{P}{V^2} = \frac{z_x}{V^2} \\
    x_x &= \frac{Q}{V^2} = \frac{z_x}{V^2}
\end{align*}
\]

Where \( P, Q, V, \) and \( i \) are respectively per unit active power, reactive power, terminal voltage and current of the generator. \( z_x = r_x + jx_x \) is the per unit load-equivalent impedance.

![Fig. 3. A vertical axis generator and its winnowing system.](image)

2.3. The control parts

The control part is made up of the excitation system, the speed controller, and mechanical control devices. The excitation system helps in maintaining the output voltage at a nominal value, while the speed regulator controls the both the equality between the power input and output, and the nominal value of the turbine speed. The simulator of this work had a 720rpm runner speed, and an output voltage of 600V. Fig 4 shows how the exciter and the controller are put together. The mechanical control devices are used for temperature, oil level, oil injection in the rotating part, braking, over speed, and vibration regulation.

![Fig 4. Speed regulator and exciter put together.](image)

The excitation system: The exciter determines the reactive power of the network by controlling the excitation current. An operational diagram for the excitation system of an isolated power plant is presented in Fig. 5 [7]. Nowadays, direct current excitation systems are almost all replaced by static or alternative current (AC) excitation system[3]-[7]. The simulator of this work uses an AC excitation system type. The exciter is directly mounted on the generator shaft. It is equipped with rotating rectifier diodes. Still as shown on Fig. 5, the stator of the exciter is fed by a controlled rectifier through a regulator that ensures an accurate voltage.

![Fig. 5. Functioning diagram of an excitation system](image)

The speed controller: The speed controller maintains the runner speed at 720 rpm. It is associated to the servomechanism system. An operational diagram of a speed controller for an isolated power plant is presented in Fig. 6. The accelerometric regulators found in power plants can be easily converted into PID controller [7]-[12]. As presented in Fig. 6, the speed is controlled via the fluid, thus the inertia of the generator and the water starting time are considered in design.

Mechanical control devices: There exist many mechanical control devices; however, some examples are the system made by the oleo pneumatic tank and its pump, and the injection pump.
The simulator of Fig. 1 has thus been designed by putting together the different described parts. For teaching purposes, it will be important to apply Francis turbine, in the description of a hydropower plant parts while indicating their method of operation, and performing relevant experiments.

2.4. Operation and utilization.

2.4.1. Operation

The analog simulator consists of a water tank of about 4,262 m³ that can run the Francis turbine for one minute. The supply of the turbine is made via a penstock of 0.254m diameter with a flow rate of 0.06m³/s. The synchronous generator of 3.7VA receives an estimated 2937W power and transforms it into electric power. The draft tube helps in damping the water power before it enters the downstream pool. The speed controller associated with the valve control mechanism keeps the speed of the generator to a nominal value of 720 rpm. The excitation system helps to maintain the voltage constant at 600V. The breather and its system keep the penstock free of air bubbles. The upstream tank is refilled with water by a feedback circuit using a motor pump. During operation, the operator can normally choose between closed circuit and the use of the upstream tank.

2.4.2. Utilization

As initially stated, this tool is mainly for training and experiment purposes. Such training activities include a presentation and explanation support for the various parts of a hydroelectric plant; the use for the starting and the shutting down of a power plant; the use for load rejection and load acceptance, short-circuit, over-speed tests; the use for optimization tests as well as validation of the numerical results.

Additionally, it can be used for an extra safety system by reducing non-necessary visits. In fact, the analog simulator will be used for the explanation of the hydropower plants operation to tourists.

2.5. Design procedure.

The design procedure is based on the principle of power homology. It simply implies a perfect similarity between the model and the prototype [6]. The design procedure of the simulator includes the selection of the key parameters such as the height of the fall, the flow rate, the power of the turbine, and its rotation speed. Such selection was subsequently followed by the choice of turbine wheel diameter. Finally, the key parameters were calculated using the similitude laws of equation (2) applied to the existing power plant. The best result was the closest to the key parameters.

\[
\frac{H_1}{H_2} = \left( \frac{D_1}{D_2} \right)^2 \left( \frac{N_1}{N_2} \right)^5 \end{equation}
\[
N_{11} = \frac{D_1}{D_2} \left( \frac{N_1}{N_2} \right)^{\frac{1}{2}} \end{equation}
\[
O_{11} = \frac{Q_1}{D_1^2} \end{equation}
\[
Q_2 = \frac{D_2^2}{D_2^2} \end{equation}

3. THE DIGITAL SIMULATOR

3.1. The implementation

The implementation of the digital simulator is done in Matlab/Simulink. The models derived from the physical subsystems equations and the existing links between them. These equations describe the hydropower’s hydraulic, mechanical, and electrical performance. The implementation of the digital simulator is guided by two key objectives. The first objective of the digital simulator is producing repetitive and accurate results which fully agree with existing references. The second objective is its ability to be used for educational purposes. This can be achieved by proper choice of models and curves to be observed. Fig. 7 shows the implementation procedure of each element, while Fig. 8 summarizes the desired objectives. The final digital simulator implemented in MATLAB/Simulink is shown in Fig. 9.
Fig. 8. Implementation of the numerical simulator

Fig. 9. Digital simulator

3.2. Operation and Utilization.

The process consists in successively executing the parameter files (.M), and the simulink files (. Mdl). It must be repeated following each parameter change. Just as in a real life hydropower plant, all tests are conducted by acting on the load. For instance, in the absence of a load, \( z_j \gg 1000\text{pu} \), while \( z_j = 0 \) for short circuit.

Apart from the starting, the shutting down and the presentation that are only performed with the analog simulator, all other tests can be performed on the digital simulator. Additionally, prediction and optimization will be done with the digital simulator. The flexibility that allows this part gives a large possibility to learners to carry out a great number of experiments and to make considerations that are not possible with the analog simulator.

The model of the synchronous machine allows performing tests by simple load variations; however good initial conditions are constantly needed.

4. SOME RESULTS

The results presented here are those of the model realized for the synchronous generator. Given the educational purpose of the article, equations are not developed. They are developed in a scientific paper in progress. The generator is designed for a local load although it is possible to use an infinite bar [3] or other configuration. The model permits switching on, load rejection and short circuit. Additionally, it takes into account the saturation of the magnetic circuit. The machine data and initial conditions used for the simulation are presented in the reference[14]. During one minute, four operating states are successively carried out with the model of the generator. A no-load operation, after 0.25s, a switching on is realized on a load \( z_j = 0.324 + j0.324 \). A load rejection occurs at 0.5s and it becomes \( z_j = 0.1 + j0.1 \). Finally a short circuit occurs at 0.75s. The chosen outputs are armature and field currents, and armature voltage. The Zooms 1, 2 and 3 of the current, are presented in Fig. 11 and 13.

Fig. 10. abc Armature currents and voltages of the generator.

Fig. 11. Current after a line switching (Zoom 1: left) and current after a Load shedding (Zoom 2: right).

Fig. 12. Current after a short circuit (zoom 3: left), and field current (right).

These results are consistent with the literature[14].

The designed will help teaching by its visualization power. Moreover, as presented in Fig. 9 the results have a more generalized view. Although the results presented mostly focus on the electrical results, its originality is the generalized possibility it offers to fully appreciate the whole behavior of the hydropower plant following every
change. Appreeciable results can thus be obtained for the mechanical and the hydraulic systems.

Some electrical concepts which can be properly taught using the designed simulator include the maximum current in short circuit, and nil in no load as indicated in (Fig. 10, to 12); and inversely for the voltage. It can also clearly show the reaction of the dampers which return the current to an acceptable value during a short circuit. Fig. 10 shows that the load causes a voltage drop, thus the design excitation system would contribute in bringing the voltage to its nominal value. Finally, it can be shown that the field current undergoes disruptions to any variation in the armature circuit, mainly during the short circuit (Fig. 12).

In addition, the analog simulator exhibits simply and clearly the operation of hydraulic power plants in general, and particularly those using Francis turbine.

5. CONCLUSION

The simulator is presented in its digital and analog aspects. The technique used to achieve each of these aspects is also presented. The operating procedure, the different cases of use of each aspect in teaching are also presented. Subsequently, some results of the model of the generator are presented. It demonstrates the ability of the latter to carry out all the simulations by a simple variation of the load. Some teaching lessons from the results obtained are given. As this paper focuses on a teaching tool, very few mathematical equations have been used. This will be done in an article in progress.

References


