Hydroelectric Power Unit Simulator for Turbine Governor Testing

V. Bakarić, I. Mišković, K. Horvat

Brodarski Institute, Av. V. Holjevca 20, Zagreb, Croatia
vedran.bakaric@hrbi.hr, ivan.miskovic@hrbi.hr, kruno@hrbi.hr

Abstract - **Computer-based simulator of water turbine and its environment has been developed for the purpose of turbine governor analysis, design and testing. During the final governor testing in the factory, the finished governor cubicle is linked with the hardware-in-the-loop turbine simulator using the signals which will later link it with the real hydroelectric power unit and other systems at the plant. During the earlier development phases, the governor is implemented as a part of the simulator. Besides helping in the governor design and subsequent improvements, the simulator significantly quickens commissioning of the governor system and thus both improves its quality and reduces costs.**

I. INTRODUCTION

The research effort reported in this paper was initiated with the goal to develop a computer-based simulator for the purpose of development and testing of turbine governors for hydroelectric power plants. Initially, the main objective was to perform hardware-in-the-loop (HIL) testing of completed turbine governors as the central part of Factory Acceptance Testing (FAT) for the governors. In such tests the new hardware unit which has to be tested is connected with the simulator of the plant in order to check its behavior over the wide range of operating conditions before it will be installed in the real plant. Therefore, a HIL simulator has to run in real time and be pretty versatile. However, the most important part of the simulator is appropriate plant model.

Modeling of water turbines is very complex task. The turbine itself is highly nonlinear and the model also has to encompass influences of both water intake and electric power unit [1]. The most accurate turbine models are non-analytical, described by several three-dimensional hill diagrams. Various simplified analytical non-linear models have been also developed [2], [3], [4]; these models can be further linearized and used for both governor design and simulation analysis. All these models in most cases describe only nominal operating conditions of the turbine, while HIL simulation requires seamless circling through all important operating modes, including start-up, stop and reaction to large disturbances. This problem has to be dealt with in a satisfactory way, as well as the other big modeling challenge, determination of the model parameters, since they are often not known precisely.

After short introductions into HIL simulations and modeling of water turbines, this paper presents the HIL simulator which has been used in turbine governor FAT testing for several hydro power plants [5]. Several important observations on lessons learned during the simulator development are highlighted in the paper.

II. HARDWARE-IN-THE-LOOP SIMULATORS

During a HIL simulation the controller which is being tested is not a part of the simulator – instead, it is implemented using the same hardware and software as in the real world and connected with the simulator of the plant and its environment. The signal interface between the controller and the simulated plant is set as it will be with the real plant. The simulation runs in real time.

Depending on the intended testing program and the system to be tested, complexity of a HIL simulator can vary widely, as well as its fidelity to the real plant. The simplest form of a HIL simulator is the simulation board with arrays of lights and manually operated switches and knobs, quite enough for check of input and output signal logic, reaction to alarm states and even some simple control loops. The modern HIL simulator is, nevertheless, much more powerful and flexible because it has in its core a real-time digital processor running mathematical model of the plant. The required complexity and fidelity of a HIL simulator has been rising steadily because of ever more complex control systems and algorithms, as well as ever higher demands on the desired control performance. HIL simulators of the most critical applications (e.g. aircraft engines) are very complex and highly specialized emulators of the real plant. They are extraordinary expensive, but, nevertheless, much less so than the plant prototype. However, if not such stringent fidelity is required, a pretty good HIL simulator can be accomplished with quite affordable costs, based on a commercially available general-purpose real-time hardware platform and its associated software. The most demanding task during the development of such simulator is development and subsequent tuning of the simulation model. In any case, when the HIL simulator customized for one controller exists, it can be rather easily modified to perform tests of a different controller intended for the same control task at similar plant.

HIL simulations excel with very complex, sensitive and expensive plants and their equally complex and sensitive controllers. They have been traditionally associated with aircraft and ships and their subsystems as well as with various military systems, but today they are commercially most widespread in the automotive industry.
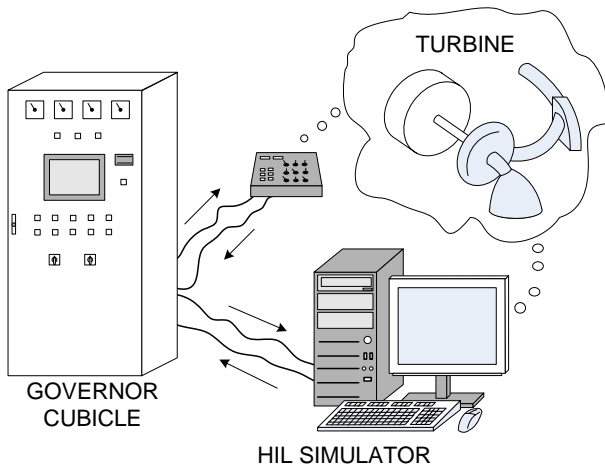
Figure 1. Hardware-in-the-loop simulation for turbine governor testing

They are also widely used in other areas, including robotics and power systems.

As an example, HIL simulation setup for turbine governor testing is shown in Fig. 1. The governor is implemented on the PLC (Programmable Logic Controller) platform built into the governor cubicle, which contains also the local operator station and various elements for equipment protection, power supply, signal distribution and conversion. The simulator emulates the governed turbine and its environment, as well as other plant subsystems and some parts of the turbine governing system not available for HIL testing. The real-time application runs on the PC workstation with either dedicated real-time controller board or specialized real-time operating system. It makes the main part of the simulator. Additional simulation board with buttons, switches and knobs is a convenient method to emulate numerous signals used by the turbine governor but not needed by the real-time water turbine model at the workstation; it can be made either as a hardware unit (as in Fig. 1) or as an independent software application.

Basic purpose of a HIL simulation is to test a complete, manufactured control system or some part of it without making real experiments at the controlled plant. On the other hand, testing of the control unit mounted and installed at the real plant is performed during commissioning and after these tests the new unit is officially proclaimed completed if it performed satisfactory. Although HIL testing cannot altogether substitute commissioning testing, the number and the duration of tests during that latter phase can be substantially reduced (according to some reports, up to 95% of the testing can be performed without experiments on the real plant). Even when commissioning testing is mandatory, many faults and possible improvements can be noticed during HIL testing and subsequently dealt with in this earlier phase, which is much simpler and less expensive at this time. In particular, the operator interface can be thoroughly checked, finely tuned and adapted to customer suggestions through HIL simulations.

HIL testing is invaluable when difficult-to-achieve, undesired or potentially dangerous operating modes and situations are to be tested without dangers, possible damage or great expenses unavoidable if such experiments were to be performed on a real plant. In addition, HIL testing of the control system can be performed simultaneously with the development and construction of the plant itself, before it is completed and ready for mounting of its controller. In such way the development cycle can be substantially quicker, which is of paramount financial importance for larger projects with tight development schedules.

III. TURBINE GOVERNING SYSTEM MODELING

General layout of turbine governing model for a water turbine is shown in Fig. 2. The model consists of three main parts: the governor, the turbine with water intake and the electric power unit with electric grid influences. In the case of HIL simulation, the governor is not a part of the simulator. However, the off-line simulator variant with the governor included in the model has been also developed for the purpose of governor analysis and design.

The simulation model has to be versatile, covering wide range of plant operating modes and events. Modeling accuracy which can be achieved is often limited by imprecisely known parameters. Fortunately, HIL tests in this case do not require extraordinary accuracy.

A. Turbine Governor

The turbine governor controls water flow through the turbine, and therefore its rotational speed and mechanical power output (load) [3]. The control signal is the opening of some flow control mechanism, in most cases wicket gates at the turbine stator. Modern turbine governor consists of the electronic part with control algorithm
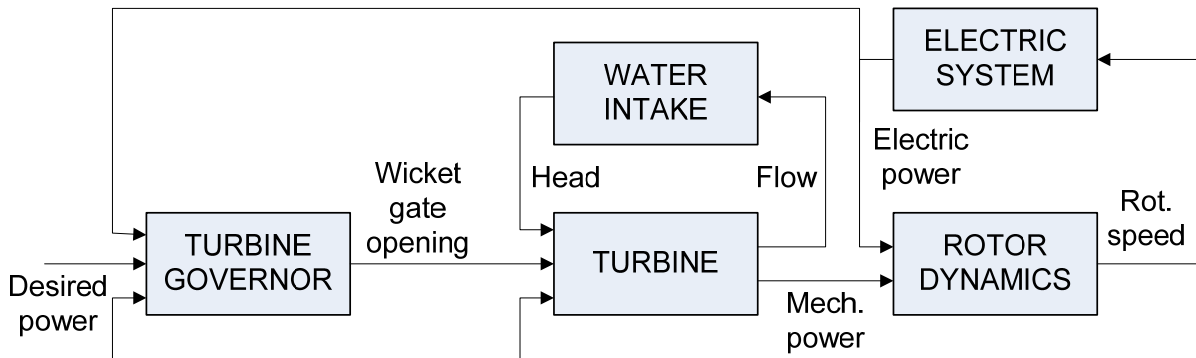

Figure 2. Simplified block-diagram of turbine governing system

running on a digital processor and the hydraulic part which acts as the control signal amplifier and operates the opening mechanism via hydraulic servomotor.

Basic control algorithm of the turbine governor contains three basic controllers acting in a two-step cascade, with the speed controller or the load controller as the first step and the opening controller as the second step. Selection of the controller for the first cascade step depends on the power unit operating mode. All three controllers are typically implemented as some variant of PID (Proportional-Integral-Derivative) algorithm. The algorithm also contains parameter gain scheduling, signal filtering, magnitude limiters and rate limiters, speed regulation characteristics function which enables load control to be obtained through speed controller and vice versa, start and stop sequences, manual and remote control modes and, if desired, additional control loops. Most of these additional functions can be omitted if the governor is included in the simulator.

Hydraulic servo unit is pretty complex non-linear system, but it can be substantially simplified if it has to be included in the model. Basic model consists of a first-order lag and integrator with limited input and output.

B. Turbine and Water Intake

Water turbine is mathematically described with two non-linear characteristics: the flow characteristics and the load or torque characteristics. For the case of the Francis turbine, they can be written as

$$q_T = f_q(y_P, h_T, w_N)$$
$$P_m = f_P(y_P, h_T, w_N)$$
(1)

where q_T is flow through the turbine, P_m turbine mechanical power output (load), y_P wicket gate opening, h_T water head (difference of headwater and tailwater level given as height value with dynamic losses included), and w_N turbine speed. Similar equations are valid for other water turbine types as well. For example, characteristics of a double regulated turbine (Kaplan, bulb) have the same form as (1), but with additional input y_R, which is the pitch angle of the runner vanes. For the sake of convenience, the opening y_P (as well as y_R) is given as linear position of its hydraulic servomotor piston.

The most accurate representation of relation (1) is given by hill diagrams obtained during model tests with the unit turbine model performed by its manufacturer. These non-analytical diagrams are, however, pretty cumbersome to use. In the case of three or more independent inputs they become totally impractical. Workarounds and simplifications are possible, but they limit hill diagrams towards nominal steady-state turbine operation. In particular, large deviations from nominal speed are not within their scope.

Less accurate analytical non-linear models are approximations of a hill diagram. One of them is the IEEE model [2], which for normalized variables takes the form:

$$q_T = y_P \sqrt{h_T}$$
$$P_m = A_T h_T (q_T - q_{NL} w_N) - D_a (w_N - w_B).$$
(2)

Adjustable model parameters are turbine gain A_T, turbine flow at which the generator has null load q_{NL} and turbine throttle coefficient D_a, while w_B is nominal turbine speed. This model is also not valid for turbine starting and stopping sequences, but it can be extended to include them as well with introduction of additional terms or variable model parameters.

Mathematically, water intake is tightly coupled with the turbine. It has to be modeled with differential equations. The most accurate representation uses partial differential equations, but the following simplification is good enough in most cases:

$$\dot{h}_T = \kappa (q_D - q_T)$$
$$\dot{q}_D = (h_S - h_T - h_L)/T_w.$$
(3)

This model uses an additional variable, water flow at the penstock inlet q_D. The model parameters, dependent on penstock dimensions and materials, are pressure wave expansion parameter κ and water acceleration time constant T_w. Static head h_S depends on the water level in the reservoir and is considered to be constant. Head loss of the water intake is represented by the term h_L. Basic head loss is proportional to the flow squared with the loss coefficient k_L, as $h_L = k_L q_T |q_T|$. Additional oscillation-throttling term is needed for small flow values.

For short water intakes, water can be modeled as a non-pressurable fluid ($q_T = q_D$), which simplifies (3) to

$$\dot{q}_T = (h_S - h_T - h_L)/T_w.$$
(4)

C. Power Unit and Electric Grid

When modeling equations of the turbine and power unit speed w_N, two cases are possible. If the unit is connected to a large electric grid, then it can be supposed that any influence of the unit on the grid frequency is negligible (infinite electric grid hypothesis). In that case, the unit speed is determined by the grid frequency f_N (converted into the equivalent unit speed), $w_N = f_N$. Electric power of the unit is then calculated as equal to the mechanical one with subtracted conversion losses.

On the other hand, if the unit is the only power producer at the grid, then the following equation holds:

$$\dot{w}_N = \frac{1}{T_m} \frac{P_m - P_e}{w_N}$$
(5)

where P_m is mechanical and P_e electrical power of the unit. Mechanical time constant T_m is determined by unit's moment of inertia. For the range of small unit speeds the denominator of (5) has to be limited with some $w_\varepsilon > 0$ in order to avoid division with zero. Electric power of the isolated unit is modeled as determined by the external load P_L as:

$$P_e = P_L + D_p (w_N - f_N)$$
(6)

with grid throttling coefficient D_p as a model parameter.

With the substitution $P_e = 0$, equation (5) is valid for the case when the unit is not connected to the grid; braking is then achieved with negative values of P_m.
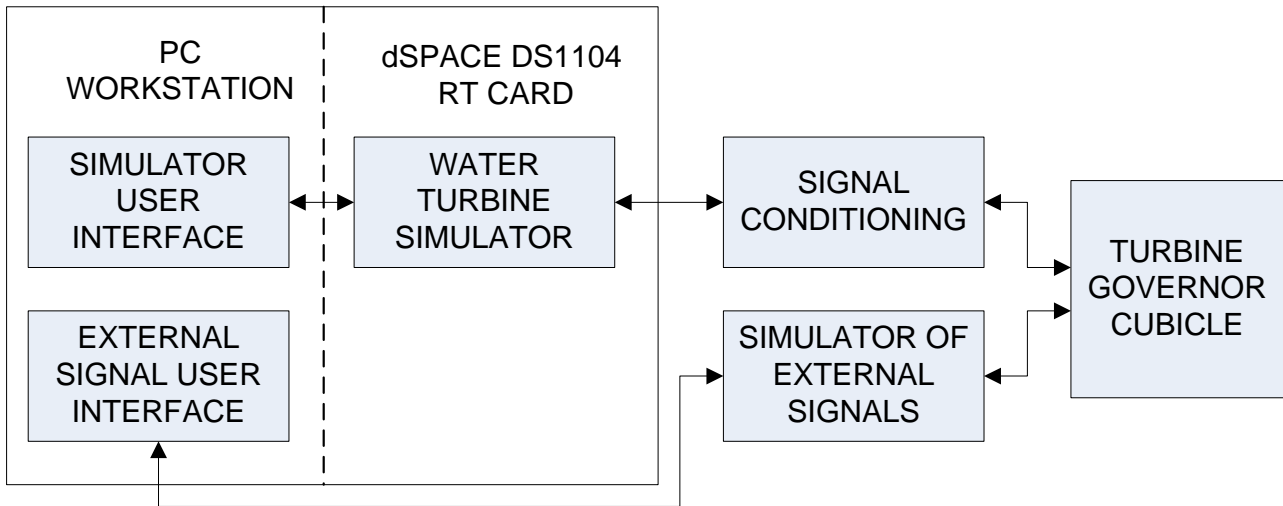
Figure 3.   Block diagram of hardware-in-the-loop turbine simulator

IV.   WATER TURBINE SIMULATOR

Simulator of the turbine governing system has been prepared in the *Matlab-Simulink* programming and simulating environment (*The MathWorks, Inc.*) following the principles outlined in the previous section. The off-line variant runs on the PC workstation within *Simulink*, while the HIL variant (Fig. 3) has to be compiled to real-time code before downloading to the DC 1104 R&D controller board (*dSPACE GmbH*) with a dedicated real-time processor. The real-time controller board is embedded in the PC workstation and uses its customized connector board (also provided by *dSPACE* – Fig. 4) for easier connecting to the process signals, in this case turbine

governor cubicle (Fig. 5). Signal conversion between the two units is needed, since the real-time board uses exclusively analog voltage signals of ±10 V and binary logic signals of 0-5 V, while the turbine governor typically operates with analog current signals of 4-20 mA and binary signals of 0-24 V. Simulator of external signals deals with signals needed by the governor, but not included in the turbine model. In this case (Fig. 3) it was implemented with a CompactRIO Real Time Controller hardware platform (*National Instruments*) with user interface as a *LabView* application on the PC workstation. Signals simulated in this way include alarms originating from turbine wheel and turbine bearing, alarms indicating various malfunctions in the turbine governing system

Figure 4.   PC workstation with embedded dSPACE real-time controller board and its connector board

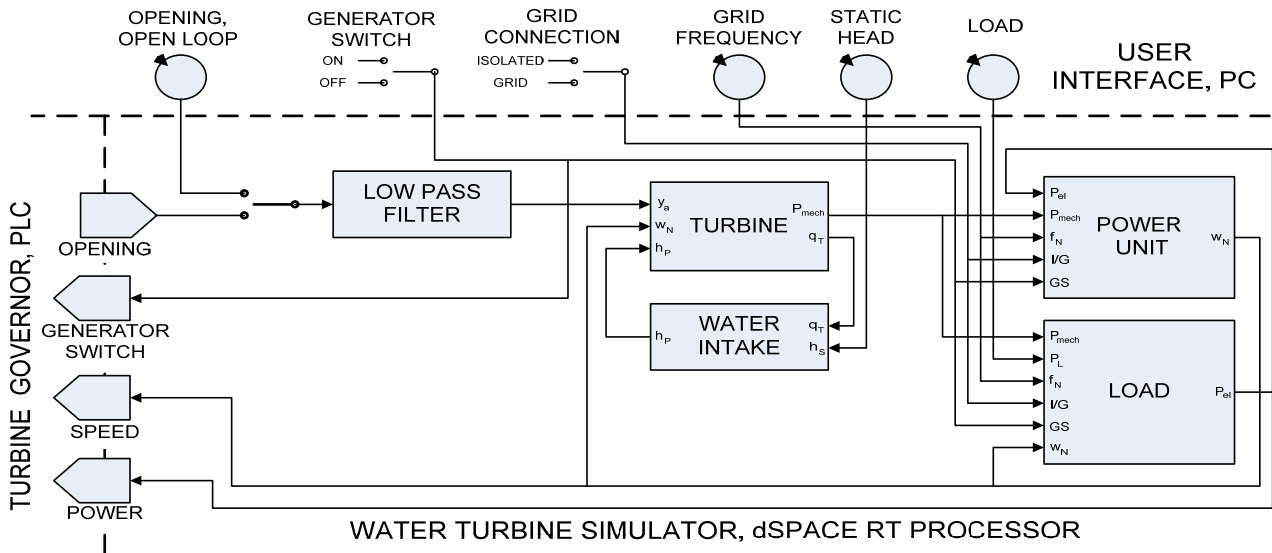Figure 5.   Turbine governor cubicles of HPP Lešće prepared for HIL testing

Figure 6. Real-time application of HIL simulator and its interfaces

itself (hydraulic system, sensors, power supply loss), signals indicating fulfillment of additional conditions required for turbine start, commands from remote operator stations, additional indications of turbine runaway, additional emergency stop requests, and the like.

Fig. 6 depicts signal flow within the HIL simulator and between it and its interfaces for the case of a Francis turbine. The governor provides the opening signal which is filtered and given to the turbine model coupled with the water intake model; the turbine model calculates mechanical power which is then sent to the power unit block and the load block, which calculate speed and electric power, respectively; these two signals are thereafter returned to the governor, together with the generator switch position set at the simulator user interface. The user interface is implemented within *ControlDesk* (*dSPACE*) at the workstation running the simulation (Fig. 7); it provides representation of the most important simulator signals and also enables setting of several Boolean and numeric simulation parameters via virtual switches and knobs or direct numerical input, as preferred. Besides the generator switch position, electric grid type (isolated or infinite), grid frequency, load and static head are set in this way. All these parameters can be changed manually during the HIL simulation. The user interface also enables open-loop turbine control using manually set opening for the purpose of checking the operation of the simulator itself.

During a HIL simulation, most important signals of the simulated turbine are being recorded at the turbine governor with data acquisition system PersonalDAQ 3000 (*IOTech/MCC*) and associated software ServiceLab (*ServiceLab/NI*). The same equipment for data acquisition is used during tests performed on real turbines (Fig. 8).

HIL testing of a turbine governor performed within FAT testing encompasses all governor functions and elements, starting with the basic functionality and going towards more complex functions: start and stop sequences, reaction to alarm signals, opening control, speed control, power control, switching between several control modes, sudden loss of load, testing of additional systems and equipment. Initial governor parameters are set before the HIL testing with the help of the off-line turbine governing model. The parameters, as well as control sequences, are then being tuned and modified in two steps: during HIL simulations and during commissioning.

V. PERFORMED TESTS

The simulator has been used to develop and test turbine governors of several hydro power plants. Turbine governing system of all three units of HPP Lešće was subject to HIL tests before delivery to the plant. In this case governor cubicles were tested together with hydraulic power units and auxiliary drives. Hydraulic servo was not tested, but appropriate hydraulic circuit with servo valve and cylinder was set on a hydraulic test stand. In contrast, HIL testing for the main units of HPP Čakovec involved only governor cubicles. In this case hydraulic system of the turbine governor was included in the real-time model. Further differences from the previous case were caused by different turbine type: HPP Čakovec has double regulated bulb turbines and short water intake, while HPP Lešće has Francis turbines. And finally, work performed for the main units of HPP Senj included only off-line simulations.
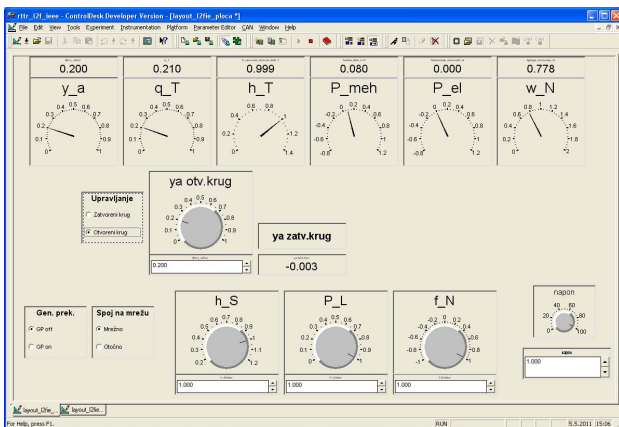

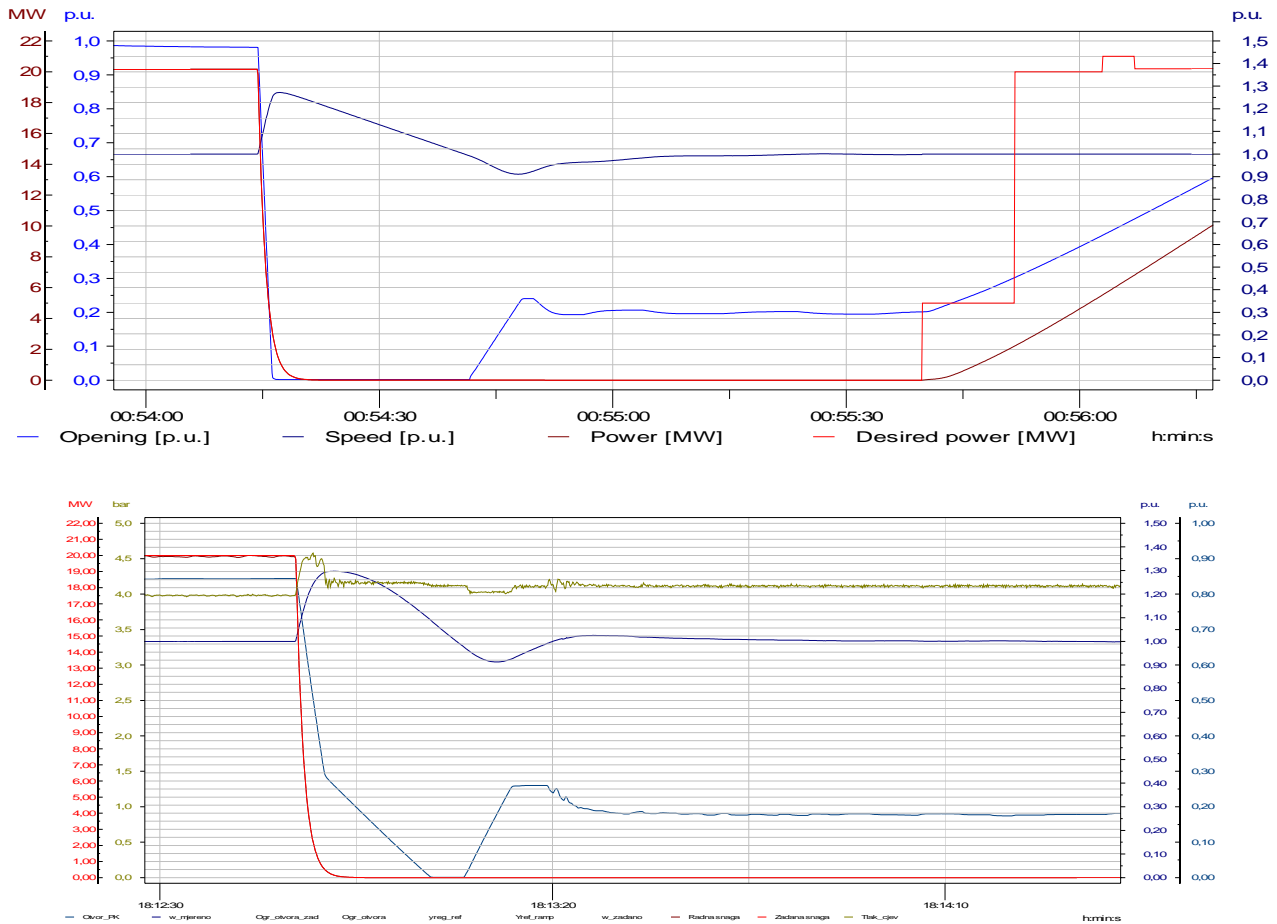Figure 7. User interface screen of HIL simulator (ControlDesk)

Figure 8. Comparison of response to loss of load at 20 [MW] power of the HIL simulator (top) and the real plant (bottom), unit B of HPP Lešće. Opening and speed given in relative units [p.u.], and active power in [MW].

This power plant also uses Francis turbines, but with much longer penstock than HPP Lešće, which is moreover at Senj shared by all power units.

All HIL tests were performed in the presence of representatives of the customer. As expected, no major faults with the tested equipment were encountered. Suggestions and additional requests of customers were discussed and, if agreed, subsequently implemented. These were mostly some minor modifications of the operator interfaces of tested cubicles, but several dealt with improvements of governing sequences.

Fidelity of the turbine model to the real plant achieved for HIL simulations has been quite satisfactory, in spite of rather simple shape of the selected model. As an example, comparison of responses to loss of load of the model and the real plant is shown in Fig. 8. Similarity of the speed response is good enough for the purpose of HIL simulations. Much of the observed difference can be ascribed to different closing sequence, with some influence of imprecisely set parameters and neglected secondary effects. In fact, pretty high degree of fidelity can be achieved if the model is finely tuned after the recorded plant responses, but this was not possible in this case since the plant was in the process of construction during HIL tests. It can be concluded that a more complex turbine model is not required for this application.

VI. CONLUSION

HIL simulator described in this paper has significantly improved the quality of FAT tests for turbine governors. In this way governor software and hardware can be pretty thoroughly checked and modified according to customer's suggestions prior to mounting at a real plant, which significantly helps in the latter commissioning phase.

REFERENCES

[1] P. M. Anderson and A. A. Fouad, "Power system control and stability", IEEE Press, 1994.

[2] IEEE Working Group on Prime Mover and Energy Supply Models for System Dynamic Performance Studies, "Hydraulic turbine and turbine control models for system dynamic studies", IEEE Trans. on Power Systems, vol. 7, no. 1, pp.167-179, Feb. 1992

[3] K. Horvat, "Fault tolerant turbine governing system for hydroelectric power unit," Ph. D. thesis, Faculty of Electrical Engineering and Computing, Zagreb, 2006, in Croatian

[4] M. Brezovec, "Nonlinear digital simulation model of hydropower unit with double regulated turbine", M. Sc. thesis, Faculty of Electrical Engineering and Computing, Zagreb, 2002, in Croatian

[5] V. Bakarić, I. Mišković, K. Horvat, D. Bojić, D. Šikić and M. Stojsavljević, "HIL testings of turbine governing system of HPP Lešće," Proc. 10th HRO CIGRÉ Session, Cavtat, Croatia, USB-key, Nov. 2011, in Croatian