Dynamic Model of Hydro Power Plant “Djerdap I” in Serbia

Dipl.-Ing. Axel Holst, Dipl.-Ing. Miloš Golubović, Prof. Dr.-Ing. Harald Weber

Abstract. The paper presents the procedure for modelling and identification of parameters of the model for hydro power plants (HPP) in general and one practical application of the method on hydro power plant “Djerdap I” on river Danube in Serbia. According to the measurements conducted on site, the model was implemented in the software package Matlab/Simulink and verified by number of simulations which are as well presented in this paper. The Project “Modelling and Simulation of Hydro Power Plants” is a part of cooperation between University of Rostock, University of Belgrade and University of Skopje and is supported by German Academic Exchange Service (DAAD).

Keywords

Hydro Power Plant, Matlab/Simulink, Turbine Controller, Voltage Regulator, Parameter Identification, Dynamic Simulation

1. Introduction

The investigations presented in this paper are a part of DYSIMAC Project, which results in academic cooperation between University of Rostock (Germany) and Universities of Belgrade (Serbia), Skopje (Macedonia) and Tirana (Albania). The Project is a program of Stability Pact for South-eastern Europe and is financially supported by German Academic Exchange Service (DAAD).

The creation of dynamic models of power plants is necessary tool on the way to creating complete model of the electrical power system. This dynamic net model enables to perform simulations of some possible dynamic scenarios in electric power generation and distribution systems, such as blackout start, island mode operation or power system restoration after blackout. In light of the recent changes in electrical market and structural organisation of power companies, the use of such analyses, which should improve the quality/reliability of the grid, increases.

With the data from the measurements of HPP “Djerdap I”, a dynamic model of the power plant is designed, as a future sub-model of the complete grid representation. Additional measurements in other significant power plants are necessary to complete the whole model.

2. Measurement of the Hydro Power Plant

The hydro power plant “Djerdap I”, one of the largest hydro power plants in Europe, consists of two parts on Serbian and Romanian side of river Danube, with common barrage and boat lock on each side. The installed nominal power of each of twelve (six units on each side) Kaplan turbines is 190 MW.

The measurements were conducted by engineers from the University of Rostock on December 15th-17th 2003 with assistance of the engineers from HPP “Djerdap I”, Electric Power Company of Serbia (EPS) and University of Belgrade.

The measurement equipment consists of a Laptop with DAQ (16 channels, 12 bit) running LabView programmable measurement software. Some of the measured signals are presented in Figure 1 as encircled input and output signals.

All the experiments were performed with Unit 2 in interconnected operation. There was no possibility to run the investigated unit in load island operation.

For identification of the dynamic behaviour of the unit, the set points for active power (Turbine regulator affected, i.e. power generation control loop) and generator voltage (Voltage Regulator affected) were changed manually in separated experiments by giving input commands from command board for increasing/decreasing power or voltage.

Dipl.-Ing Axel Holst, teaching assistant and PhD. student at the Institute of Electrical Power Engineering at the University of Rostock, Germany (phone: +49 381 4987104 e-mail: axel.holst@uni-rostock.de)

Dipl.-Ing Miloš Golubović, design engineer in Elem & Elgo Ltd. Belgrade, Serbia and PhD. Student at the University of Rostock, Germany (phone: +49 381 4987104, e-mail: milos.golubovic@uni-rostock.de)

Prof. Dr.-Ing Harald Weber, Professor and Head of the Institute of Electrical Power Engineering at the University of Rostock, Germany (phone: +49 381 4987101, e-mail: harald.weber@uni-rostock.de)

Exact values for set points of generator voltage and active power were not available because of the analog electronic/mechanical controllers. The recorded command signals -1/0/1 were used to register the time of the change, but set points required from the model had to be identified and appropriate signals constructed.

3. Model of the Power Plant

The model of the power plant was made in Simulink and consists of the following dynamic sub-models:

- Hydraulic and mechanical system (incl. turbine and mechanical losses)
- Turbine regulator (electrical and hydro-mechanical part)
- Voltage regulator and excitation system
- Generator electrical and mechanical part, electrical losses

The block-scheme of the complete model with its sub-models is presented in Figure 1.

This is a per unit model, i.e. every signal is given in per units (p.u.). This simplifies the interface between the parts and makes the algorithm for modelling and identification, as well as evaluation and comparison of the results, easier.

The modelling and subsequent identification were conducted in phases, for each sub-model. Where possible, the parameters (time constants, amplifications, characteristics) were identified separately. The single models were connected in two decoupled main regulation paths:

- Power geneation system – Hydro-mechanical part, turbine regulator, generator
- Voltage regulation path – Voltage regulator, excitation system, generator (electrical part)

In third stage, the whole model was connected from its sub-parts and identified parameters were verified.

The model of the generator is a general model, whose parameters are normally taken from the power plant documentation and additionally identified after connection of the complete power plant model.

The starting parameters for identification have to be chosen from the available power plant documentation, to be calculated or selected from experience.

4. Identification Algorithm

The identification process for the hydro power plant model is divided in a few steps. The measurement points play a very important role in dividing the general model in sub models which can be identified separately. The base of all work is a table with stationary state values in many different steady-operation-points. This table enables to define not time-dependent connections and to detect offsets.

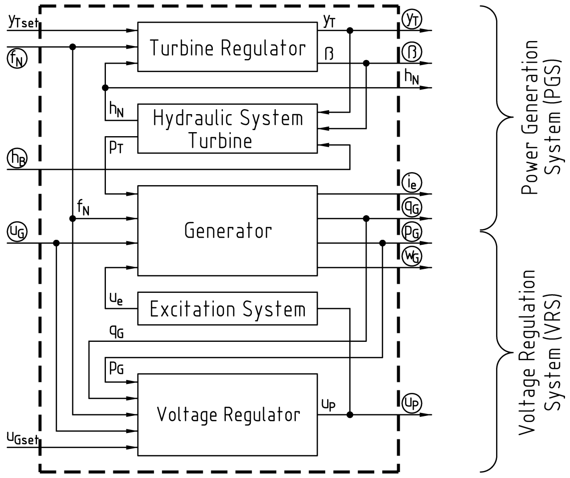

Figure 1: General representation of sub-models of the power plant "Djerdap I"

The identification is executed in the following order:

- Approximation of the function turbine cross-section vs. blade angle and turbine opening
- Approximation of the hydraulic and mechanical losses characteristic
- Approximation of the optimal „shell curve“ characteristic of the Kaplan turbine
- Identification of hydraulic part
- Approximation of the function blade angle vs. turbine opening and net height – “Combinator” function
- Identification of active power set point regime and turbine regulator
- Identification of dynamic losses due to difference of reaction speed of changing turbine opening and blade angle position
- Identification of generator voltage set point regime
- Identification of synchronous generator and voltage regulator with excitation system

For identification the least square error method is used. The square error between measurement and simulation should be minimized by variation of the model parameters. At the end the optimal parameters are found. This procedure was programmed in Matlab.

The time interval for calculating the least square error is variable. When identifying more then one parameter at a time the weight of the parameters can be changed.

5. Power Generation System

A. Hydraulic Part of the Hydro Power Plant

Power plant “Djerdap I” is a low pressure run-of-river hydro power plant where usually no water tunnel and surge chamber exist, so only the penstock into the turbine should be modelled. In fact, there is also not a real penstock but only a grid in front of the turbine inflow, from where two inlets lead in to the turbine circuit. The main flow is actually cut by the wall behind the grid forming two inlet channels. The measurement points are located in front of the grid and on both inlets into the turbine. The water level in front of the grid is taken for upper water level, while two other points are taken to be on the turbine inlet.

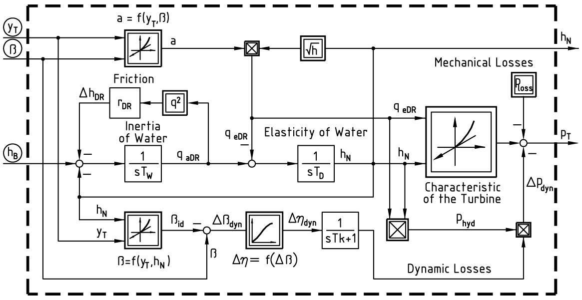

Figure 2: Hydraulic part sub-model

The penstock model is able to simulate the inertia of the water (Figure 2). The inertia time constant T_W was identified by comparing the dynamic behaviour of the model and the simulation. The elasticity of the water is simplified modelled by one time constant (T_D).

Both of the constants had to be identified, as no data were available. Because of very short inflow and therefore very weak influence of elasticity effect, time constant T_D could not be identified very accurately. The factor for the friction losses R_{DR} is calculated from stationary values of net and gross height and water flow, in respect to quadratic relation between height losses and water flow:

$$\Delta h = h_B - h_N = r_{DR} \cdot q^2 (p.u.) \qquad (1)$$

Average value from all stationary values was used for the model. The identified values are shown in TABLE I.

Additional blocks shown in the Figure 2, representing the hydraulic sub-model, are "combinator" function $\beta = f(y_T, h_N)$, Kaplan turbine "shell curve" and cross-section characteristic of the turbine actuators $a = f(y_T, \beta)$.

The first two functions model the Kaplan turbine behaviour and control. Cross-section *(a)* is on the other side just an auxiliary signal for the sub-model and physically represents the equivalent cross-section of the inflow of the water into the turbine working circuit. In the model, it is the interface between hydraulics (pressure and water flow) and mechanics of the turbine controller (turbine opening and blade angle). The Torricelli equation $q = a \cdot \sqrt{h_N}\ (p.u.)$ is the basis for the identification of the function parameters:

Stationary values from the measurements were used for identification. Values for cross-section were calculated from stationary values in the following way:

$$q = f(h_B, p_G) \qquad (2)$$

, iteration process form the turbine characteristic

$$h_N = h_B - r_{DR} \cdot q^2 \qquad (3)$$

$$a = \frac{q}{\sqrt{2 \cdot g \cdot h_N}} \qquad (4)$$

, where the following symbols are used:

h_N – net height

h_B – gross height

q – water flow through the turbine

r_{DR} – friction coefficient of the hydraulic system

With calculated stationary values, the desired 3-dimensional characteristic was defined and included in the model.

B. Kaplan Turbine Model

The Kaplan turbine is double controlled by turbine opening (y_T) and blade angle (β). Positions of turbine gate and blades are defined by corresponding servo motors which are provided by the turbine controller.

As described in the previous chapter, these two values define the inflow cross-section and at the same time the pressure (net height) and the water flow into the turbine.

Net height and water flow are the inputs for the "shell curve" of the turbine, for which the data were provided by the manufacturer. For each stationary q (water flow) and h_N (net height) information about the values for net power of the turbine (p_T), efficiency of the turbine (η_T), turbine opening (y_T) and blade angle (β) for nominal speed can be read. In our model, we use the option to get power of the turbine.

This characteristic is a part of available power plant documentation and is result of earlier conducted experiments on the turbine. It was digitalized, adjusted to conducted measurements in order to meet possible changes of characteristics during the operation time and additionally smoothed (spline method). The function is included in the model as a 3D “Lookup-Function” block (Figure 3).

This "shell curve" is optimal, i.e. for some steady state of net height and turbine opening, the blade angle is exactly defined by the "combinator" function $\beta = f(y_T, h_N)$, in order to get the highest efficiency possible. In transition processes the turbine's working point falls below this maximal efficiency.

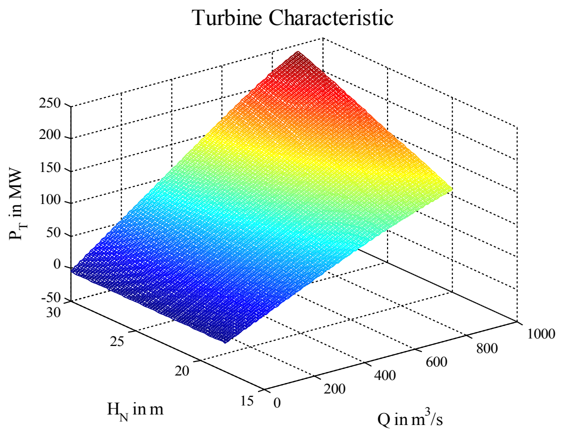

Figure 3: Characteristic of the turbine, derived from the "shell curve"

The combinator is actually a special mechanical system in the turbine controller. The function was calculated/identified from the given set of curves $\beta = f(y_T)$, for different net heights. The characteristics were digitalized and a 3D function was modelled. It is shown as mesh plot in Figure 4. The function is given in the model as 3D "Lookup-Function" block.

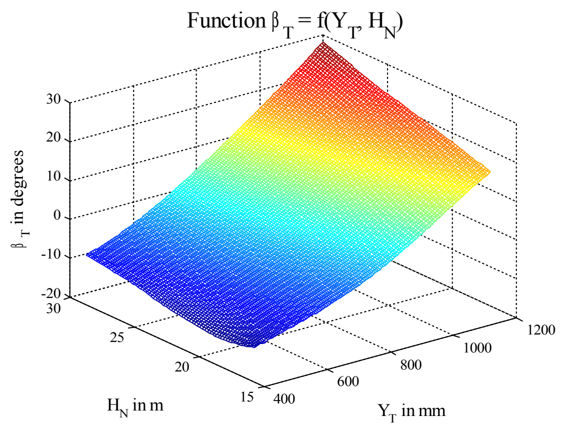

Figure 4: "Combinator" – function $\beta = f(H_N, Y_T)$

C. Turbine Controller Model

Turbine controller in the power plant is of an old Russian type and consists of analogue electrical and mechanical part.

In the electrical part the input signals are compared, amplified to certain level and transformed to the mechanical movement which excites the mechanical controller of "I" type. The controller defines the opening position of turbine gates. This required position is achieved via system of auxiliary and main servos and also defines via "combinator" block the angle position of turbine blades. Again, via separated system of servos the blades move to the required position.

As mentioned, the set point of the turbine regulator does not exist as a signal that could be measured. The signals "up" and "down" could theoretically be used as input and the principle they are based on can be modelled (by integrating the signals), but the signals are not completely exact as there is always some measurement sampling error possible and practically we have analogue command to the turbine controller. This could cause simulation error and therefore equivalent set point was identified and input in the model as normal set point signal.

The value for set points during the measurements was determined from the primary regulation equation from stationary values, as power plant "Djerdap I" takes part in the primary regulation.

$$\Delta f + \sigma_p \cdot \Delta p = (f_{set} - f) + \sigma_p \cdot (p_{set} - p) = 0 \qquad (5)$$

In this case, signals for turbine opening are compared, instead of power, but the effect is the same, if approximately $p \sim y_T$.

$$\Delta f + \sigma_p \cdot \Delta y_T = (f_{set} - f) + \sigma_p \cdot (y_{T,set} - y_T) = 0 \quad (6)$$

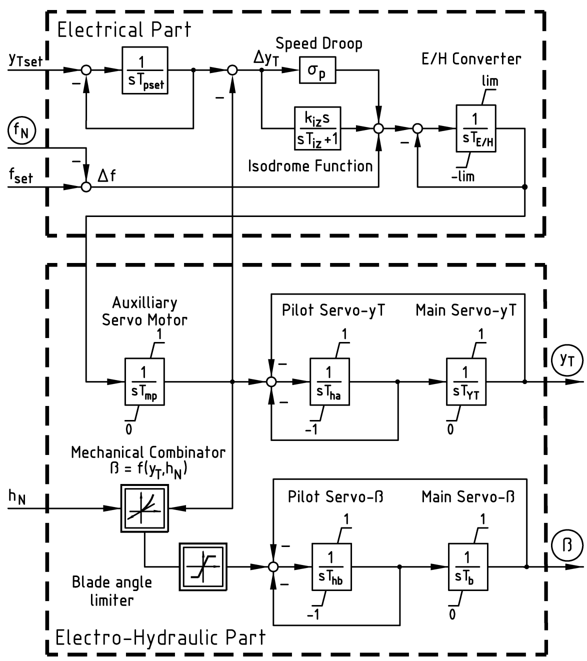

Figure 5: Turbine Regulator sub model

D. Identification of the Parameters

For identification of the parameters of the the model, according to the described algorithm, we used those measurements, where the commands for changes of active power were given.

The set of determined parameters enabled to conduct the final simulations and present them together with the measurement plots.

In the final model, some limiter values couldn't be exactly determined because these limits were not reached during the measurements. Some of the values may be supposed.

The list of the identified parameters for power generation part of the model is shown in the tables below (TABLE I and TABLE II).

TABLE I
IDENTIFIED PARAMETERS OF HYDRAULIC PART

Parameter	T_W	T_D	r_{DR}
Identified Value	0.2 s	0.04 s	0.01

TABLE II
IDENTIFIED PARAMETERS OF TURBINE REGULATOR MODEL

Parameter	T_{pset}	σ_p	k_{iz}	T_{iz}	$T_{E/H}$	T_{mp}
Identified Value	0.2 s	0.04	3.5	10.0 s	1 s	0.039 s
Parameter	lim	T_{ha}	T_{Yt}	T_{hb}	T_b	
Identified Value	0.14	0.111 s	0.599 s	0.85 s	2.36 s	

6. Generator Model

The model of the generator is based on the non-linear fifth order model [1]. This model has been chosen as the most appropriate for the operational mode in which the aggregate is working (interconnected operation) at the time of measurements' conduction. Model inputs are excitation voltage, generator voltage and turbine (mechanical) power. Model outputs are active and reactive power and excitation current. Excitation voltage signal is provided by the excitation system while the generator voltage is in this mode dependent on the network.

The mechanical losses in the bearings of the shaft are already included by the power of the turbine and the generator losses depending also on speed. These losses are calculated from the table of losses and subtracted afterwards. Electrical losses are included in the generator model via stator resistance. Other losses (in the brushes etc.) may be neglected. Both mechanical and electrical part of the generator is included in this model.

7. Voltage Regulation Path

A. Voltage Regulator

Automatic voltage regulator performs a regulation by voltage deviation *dU*, voltage derivative *U'*, frequency deviation *df*, frequency derivative *f'*, excitation voltage U_p, excitation voltage derivative U_p' and excitation current derivative I_p'. The structure of the sub-model is presented in Figure 6.

The central part of the regulator is a 3-step amplifier on whose input the weighted regulation signals are collected and summarized. The main regulation characteristic is a "P" type.

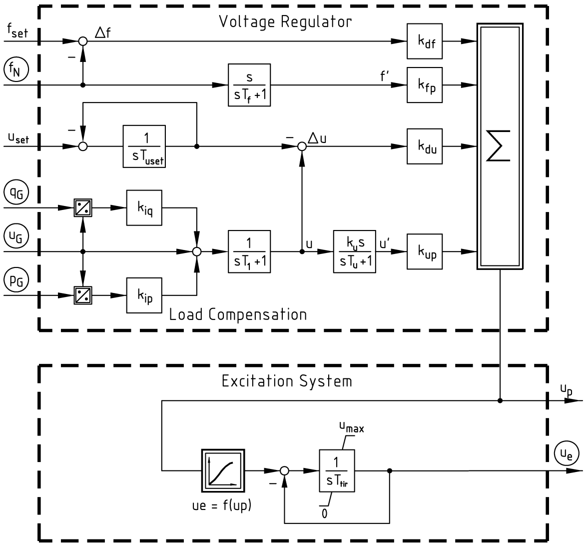

Figure 6: Voltage Regulator sub model

In a current compoundation block of the regulator generator voltage signal is combined with generator current signal in order to perform compensation of reactive impedance of block transformer and achieve necessary static of the characteristic of the generator with regulator on high voltage buses of the power plant.

The procedure for determining generator voltage set point is the same as for the changes of active power, for the turbine regulator. The changes of generator and reactive power are made by giving increase/decrease commands represented by signals q_{up} and q_{down}.

Signal of the voltage set point in the model is determined by stationary values of measured signals, knowing the structure of the controller, while moments of changes are determined according to measured signals for q_{up}/q_{down}. Thus, the signal of generator voltage set point is generated.

$$(f_N - f_{set}) \cdot k_{df} + (u - u_{set}) \cdot k_{du} = u_p$$
$$\Rightarrow u_{set} = u - \frac{u_p - (f_N - f_{set}) \cdot k_{df}}{k_{du}} \tag{7}$$

, where voltage u is measured generator voltage with static correction.

$$u = u_G + k_{iq} \cdot \left(\frac{q_G}{u_G}\right) + k_{ip} \cdot \left(\frac{p_G}{u_G}\right) \tag{8}$$

The signals q_{up}/q_{down} should not bring any confusion because the "up" command increases the excitation and by this the reactive power is increased. Generally, the voltage of the generator working on stiff network is changed in very narrow interval. At nearly constant active power delivered to the network, where no command is given to the turbine controller, change of excitation influences reactive power of the generator and so the voltage, too. We may observe command for changing excitation as command for changing voltage or reactive power. This command can be generally given by inputting exact value for reactive power or voltage or by giving command up/down, which is the case here.

B. Generator Excitation System

The output of the controller defines via thyristor control blocks the firing angle of the thyristors in fully controlled thyristor bridges. It is important to notice here that the signal "excitation voltage" is measured at the output of the controller and not directly on excitation circuit. The current is on the other side measured directly.

The structure of the excitation is very simply modelled by static function between measured output of the regulator and excitation voltage and delay of 1st order, caused by thyristor group and blocks for adjustment of the signal.

It is also important to note that measured voltage u_p is not really excitation voltage, but control signal from the regulator, which determines the excitation voltage. That is why stationary function between measured signal from the regulator u_p and measured excitation current i_e was determined. As the reference system was chosen so that in p.u. units is $u_e=i_e$, this function can easily be transformed into p.u. system as $u_e=f(u_p)$.

C. Identification of the Parameters

The voltage regulator with excitation system were identified together. The signals, used as criteria for comparison, were reactive power (q_G), excitation voltage (u_e) and excitation current (i_e). The Generator voltage input is a measured signal, because the network characteristic couldn't be determined due to the parallel operation of several units during the measurement.

Models of the generator and voltage regulator were first roughly identified separately. In this manner, generator was identified with measured value of excitation voltage as input instead of simulated value from the regulator. Afterwards such model of the generator was attached to voltage regulator model and the closed loop was identified accurately.

Parameters of the regulator were difficult to determine because there is certain interdependence between them and identification algorithm was not able to find unique solution independent on starting points. That is why identification was done partly per hand and in steps, where some of parameters were fixed for identification and other free to be changed.

Finally, identified values for generator and voltage regulator are presented in tables below.

TABLE III

IDENTIFIED PARAMETERS OF GENERATOR MODEL

Parameter	xd	xd'	xd''	xq	xq''
Identified Value	1.85	0.48	0.24	0.94	0.25
Parameter	Td'	Td''	Tq''	TA	
Identified Value	1.555 s	0.08 s	0.085 s	6.45 s	

TABLE IV

IDENTIFIED PARAMETERS OF VOLTAGE REGULATOR

Parameter	T_{uset}	k_{iq}	k_{ip}	T_1	T_u	k_u
Identified Value	0.198 s	-0.03	0.07	0.5 s	0.093 s	0.9
Parameter	T_f	k_{fp}	k_{df}	k_{du}	k_{up}	T_{tir}
Identified Value	0.1 s	1.44	8.23	6.5	35	0.052 s

8. Simulations

The model made in described manner was verified after connection of the sub-models in one complete power plant model. After fine tuning of the parameters some additional simulations can be made.

Here, some comparisons of the simulations and measured signals are presented.

In one of such measurement (the command is given in sense of increasing active power of the unit in small steps – 10-20 MW. The figures below (Figure 7, Figure 8; Figure 9 and Figure 10) show the comparison between simulated (red) and measured signals (blue), for turbine opening, blade angle, active power and net height.

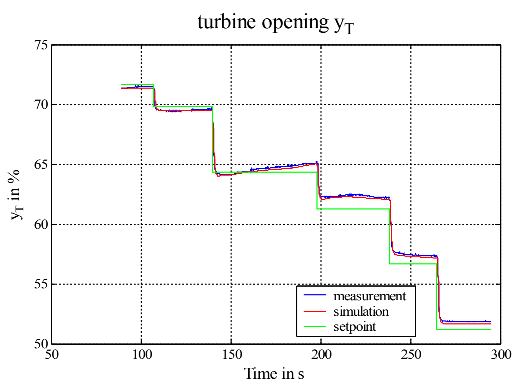

Figure 7: Turbine opening for Experiment 1

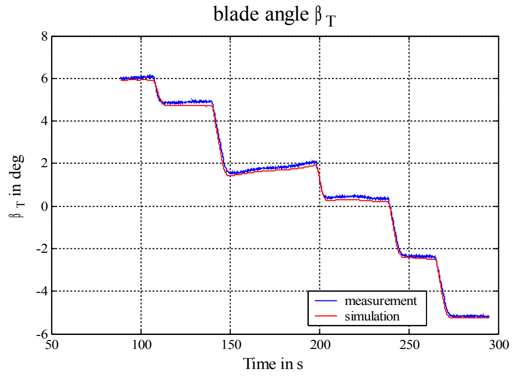

Figure 8: Turbine blade angle for Experiment 1

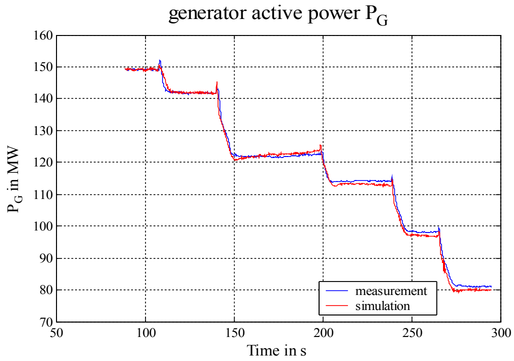

Figure 9: Generator active power for Experiment 1

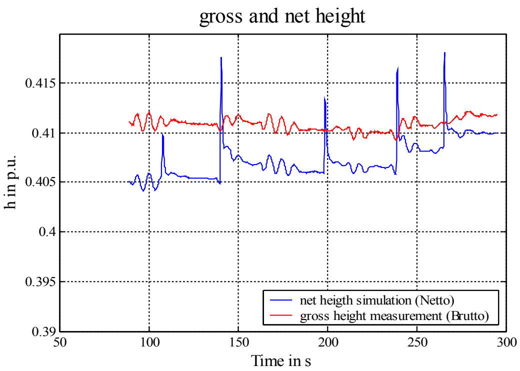

Figure 10: Gross and net height (pressure) for Experiment 1

Besides measured and simulated signals for turbine opening also set point signal $y_{T,set}$ is presented (green). A little bit higher deviation of the simulated (and measured as well) signal of turbine opening from the set point can be explained by existing frequency drop and "isodrome" function. This function improves dynamic response to deviation of set point of active power.

Net height signal doesn't fit the measured signal correctly because static pressure is measured and dynamic pressure simulated. The static pressure signal was not measured directly but generated by measured signals of height in front of the turbine and lower water height.

The plots in Figure 11, Figure 12 and Figure 13 derive from experiment where a change of power set point from nearly 80 MW to 140 MW in step form was made. After reaching the stationary state, the power was decreased in smaller steps.

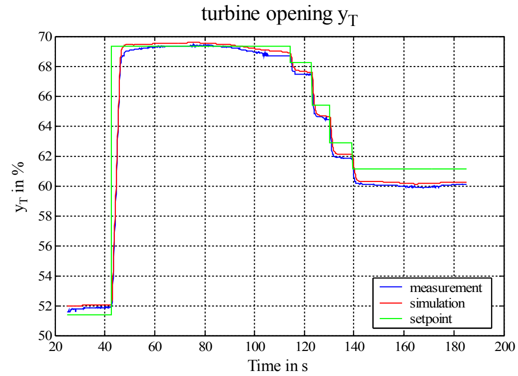

Figure 11: Turbine opening for Experiment 2

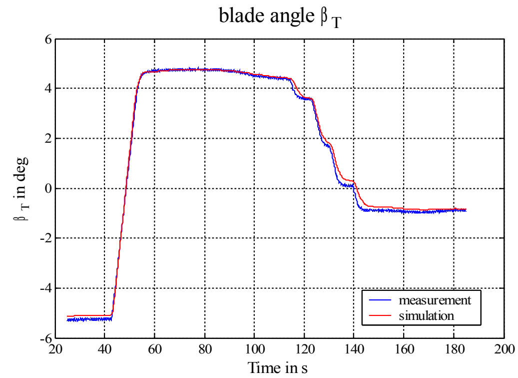

Figure 12: Turbine blade angle for Experiment 2

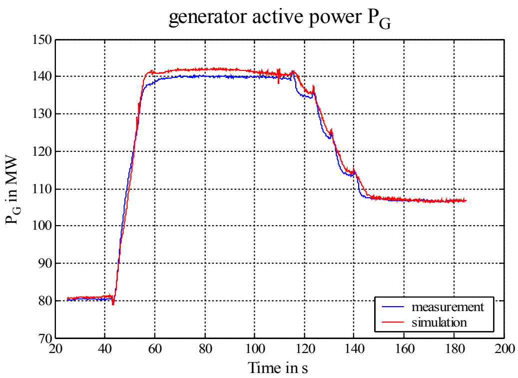

Figure 13: Generator active power for Experiment 2

In Figure 14, Figure 15 and Figure 16 results of one of the simulations, demonstrating the reaction of voltage regulation path, are shown. In this experiment the q_{up} signal was given in order to change the corresponding signals for excitation voltage and current, reactive power and generator voltage in steps. As for power generation part, the simulated and measured signals are compared.

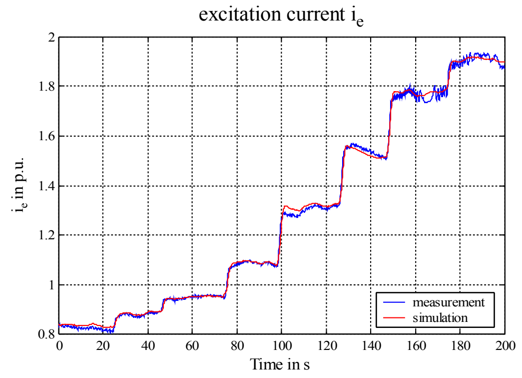

Figure 14: Excitation current for Experiment 3

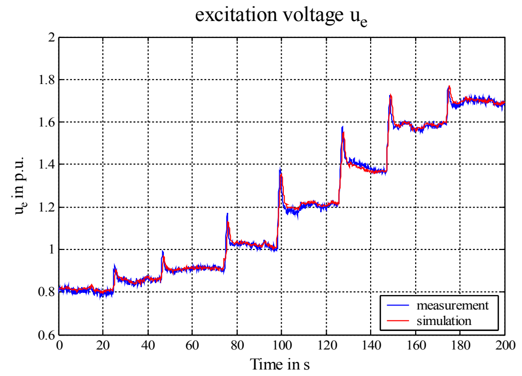

Figure 15: Excitation voltage for Experiment 3

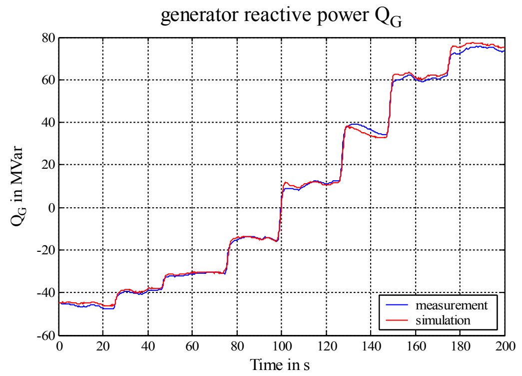

Figure 16: Generator reactive power for Experiment 3

It can be seen that good fitting of the measurements was achieved for all the relevant signals. (excitation voltage, excitation current and reactive power). Generator voltage was measured and as such used as input signal. It is also presented for comparison purpose only.

9. Conclusion

The comparison of the simulations with the created model and the measurements from the power plant proved the model to be correct for interconnected operation mode.

Some restrictions still have to be considered. It could not be verified whether the island operation can be simulated and number of security options couldn't be modelled. Further improvements of the model in this sense, with additional measurements after latest refurbishment works on the power plant, is possible.

The model can be used for further development of the dynamic net model as well as for internal analyses in the power plant.

Based on the measurements in the hydro power plant “Djerdap I” and on provided power plant documentation, a dynamic model of the power plant was designed and identified. The report shows in detail the modelling and identification steps. Unfortunately, the measurements included certain restrictions. Island operation and small load operation in interconnected mode of the examined unit could not be tested. Also, due to old analogue regulators, no internal signals could be measured which made identification rather difficult.

Documentation, received in the power plant was extensive but very few parameters were explicitly given and therefore it was not possible to adopt and fix some values during the identification. Stationary characteristics were of good quality and seem to suite the reality although some of them are rather old.

This model of HPP “Djerdap I” can be used for experiments concerning the power plant. It can also be implemented in the Serbian dynamic grid model for investigations concerning power supply problems.

Because of the individual properties of each power plant and for validation purposes measurements are strongly recommended to support the modelling and identification process of the dynamic power plant models.

In addition, the load characteristics of the grid nodes have to be modelled together with the transmission lines, transformers and security equipment.

With a network simulation tool like DIgSILENT the dynamic behaviour of the grid can be simulated. University of Rostock has experience in this field as well as in transferring models from Matlab/SIMULINK to DIgSILENT.

References

[1] Harald Weber: Dynamische Netzreduktion zur Modalanalyse von Frequenz- und Leistungspendelungen in ausgedehnten elektrischen Energieübertragungsnetzen, Dissertation, Stuttgart (Germany), 1990

[2] Axel Holst, Miloš Golubović, Measurement, Modelling, Identification of Hydro Power Plant „Djerdap I“ - Final Report, Rostock, 2005