Development of a reality oriented simulation model of the hydro power plant Bajina Bašta

H. W. Weber, I. Skokljev, N. Obradovic, G. Jankovic, M. Golubovic

Abstract—**The most important aim of the work done by the Stability Pact for South Eastern Europe of the European Community is the improvement of research and education capabilities in the universities and institutes involved. Especially the students of Power Electrical Engineering need a more practice oriented education as requested by the local companies. Therefore in the here presented cooperation between the University of Belgrade, Serbia and the University of Rostock, Germany the measurement, modeling, identification and simulation of existing hydro and thermal power plants in Serbia form the main content of students work needed for creating diploma theses accepted at both universities. For this reason, after agreements with the Electric Power Company EPS, the 368-MW-HPP-Bajina Bašta at the river Drina was selected to perform measurements necessary for constructing a dynamic simulation model of the plant as part of diploma theses for two students of the University of Belgrade.**

Index Terms—**Hydro Power Plant Bajina Bašta, Improvement of Research and Education, Stability Pact.**

I. INTRODUCTION

ONE of the most important aims of the European Community in the Stability Pact of South Eastern Europe concerning the Balkan Countries after the war is to stabilize the research and education capabilities of the universities. In this context the exchange of knowledge and peoples is of main importance. Therefore the Institute of Power Electrical Engineering of the University of Rostock established research and education contacts to the University of Skopje, Macedonia and the University of Belgrade, Serbia and at the same time to the ESM company in Skopje and the ESP company in Belgrade respectively. With these contacts it was possible with assistance of professors, assistants and students of the respective faculties and with engineers and specialists from the companies to construct dynamic simulation models of hydro power plants necessary for overall simulation models of the whole power systems of the involved countries. This overall simulation models then later will be used for investigations like:

- Black Start Capabilities after Black Out
- Behavior in isolated operation
- Primary and secondary power reserve capabilities
- Reduction of losses in the plants
- Overall dynamic behavior of the whole system including stability investigations

II. THE HYDRO POWER PLANT BAJINA BAŠTA

The hydro power plant Bajina Bašta (Fig.1) is situated on the river Drina, near the borderline between Serbia and Bosnia & Herzegovina. The hydro power plant was built in 1966 and is one of three HPPs that constitute the Public Company ‘Drinske Hidroelektrane’.

Fig. 1. Layout of the power plant Bajina Bašta on the river Drina

III. MEASUREMENTS

In Fig. 2 a scheme of the hydro power plant Bajina Bašta is shown. The circled signals are the measured ones directly in the power plant. But also signals of the different controllers are measured, overall signal list see Table II.

The measurements are conducted at only one generator-turbine system. The other systems are treated as similar. All experiments were executed in interconnected operation. There was no possibility to run the investigated unit in island operation.

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TABLE I

MAIN TECHNICAL CHARACTERISTICS OF THE HPP BAJINA BAŠTA

Catchment’s area	14.797 km²
Mean discharge	352 m³/s
Turbine installed discharge	644 m³/s
Total capacity of a storage reservoir	340 hm³
Designed net head	65.1 m
Height of hollow gravity concrete dam	90 m
Length of the dam crest	461 m
Number of vertical aggregates	4
Rated speed	136.4 rpm
Installed capacity	368 MW

For the identification of the dynamic behavior of the unit set points of active power, reactive power and generator voltage were changed stepwise manually in separate experiments.

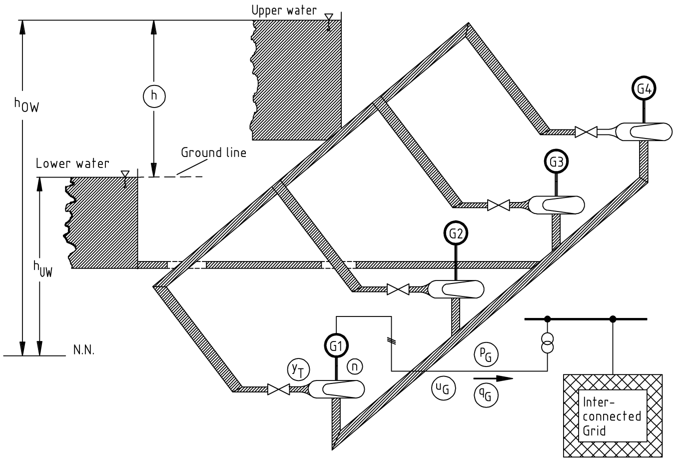

Fig. 2. Scheme of the hydro power plant Bajina

In Table II all the measured signals are listed. The measurements were conducted with a 16 channel, 16 bit measuring equipment using the Labview software.

IV. MODELING AND IDENTIFICATION

Before the identification of the parameters can be conducted, a reality oriented model of the hydro power plant has to be constructed. For this reason all the available documentation was investigated including also commissioning documents. After this investigation an overall dynamic model of the plant could be developed. For overview of the different model elements see Fig. 3.

The identification process for the hydro power plant model is divided in a few steps. The measurement points play a very important role for dividing the general model in sub models which can than be identified separately. The base of all work is a table with stationary state values in different steady-operation-points. This table makes it possible to define the time-independent connections and to detect offsets.

The identification is conducted in the following steps:

- Approximation of the function between gate opening and Gate Vane position
- Identification of active power set point (where necessary) and turbine regulator
- Approximation of the ‘shell curve’ characteristic of the Francis turbine
- Approximation of the losses characteristic
- Approximation of the functional dependence between cross-section and gate opening
- Identification of hydraulic part
- Identification of generator and voltage regulator with excitation system

TABLE II

MEASURED SIGNALS

Channel no.	Signals
1	Water pressure
2	Valve position
3	Speed
4	Active power
5	Reactive power
6	Generator voltage
7	Excitation voltage
8	Excitation current
9	Frequency
10	Set point active power
11	Generator frequency
12	Net height
13	Signal of governor
14	Breaker

The used identification method is the least-square-error-algorithm of the Matlab Software, which was comparing the measured and the simulated signals for all measured discrete signal points, procedure see Fig. 4.

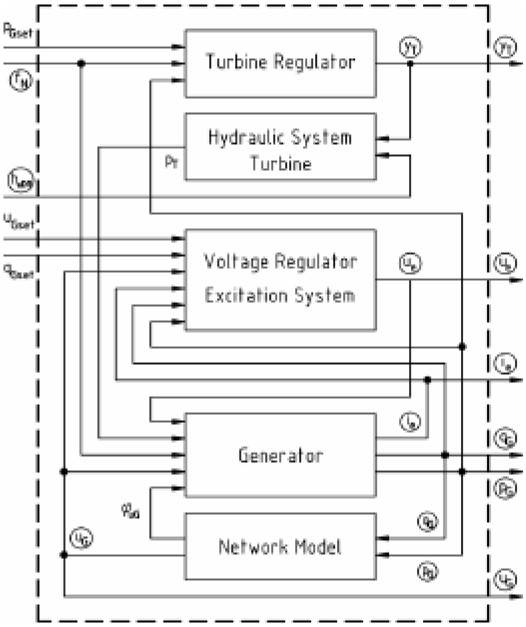

Fig. 3. Block diagram of hydro power plant “Bajina Bašta”

The hydro power plant model is nonlinear. It consists of the following sub models:

- Hydraulic and mechanical (turbine and mechanical losses) part
- Turbine regulator
- Voltage regulator with excitation system
- Generator electrical and mechanical part, electrical losses
- Network model

All physical data are in per unit system. Input values of the model (in interconnected mode) are set points for active and reactive power, set point for generator voltage, the network frequency and the upper water level. Outputs are active and reactive power on the contacts of the generator and generator voltage.

The model is valid only for interconnected mode because the measurements were conducted in this mode only. That is the reason why frequency is being used as input. This value depends from network conditions.

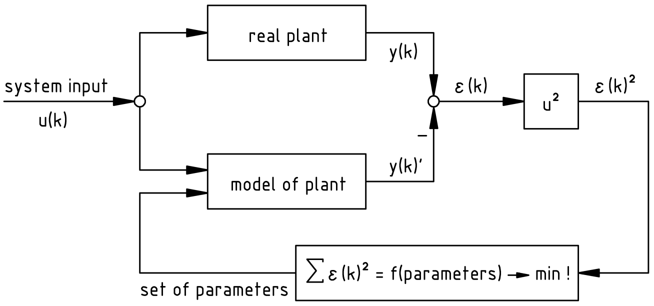

Fig. 4. Least Square identification method

In addition, other states of the model can be monitored, such as excitation current and voltage, guide vane position, pressure, flow etc.

A. Modeling of hydraulic part

The model for a high pressure hydro power plant generally consists of the following elements: water tunnel, surge chamber and penstock.

In our case water tunnel and water chamber don't exist, which is common for the run-of-river plants like Bajina Bašta, so there is no need to model them. The penstock is relatively short (inflow length approx. 80m) but it is still convenient to take the elasticity of water and the sides of the penstock into consideration. The penstock model is able to simulate the inertia of the water, see Fig. 5. The inertia time constant T_W had already been calculated ($T_W = 1.4714$s) for nominal conditions and this parameter was included in the model. The elasticity of the water and the penstock is also modeled by one time constant (T_D). This parameter has been identified.

B. Francis turbine model

The Francis turbine is controlled by gate opening (y_T). This value is put into relation with cross-section, approximated and applied to the model via the Torricelli equation: $q = a \cdot \sqrt{h_{eDR}}$ [p.u.], where h_{eDR} is net head, i.e. energy height and q - flow of the water. The value for the net head is the output of the hydraulic part. Net head and water flow, calculated in this way, are the inputs for the so called 'shell curve' of the turbine, provided by the manufacturer. The used equation is $p_T = q \cdot h_{eDR} \cdot h_T$ [p.u.]. The output of this curve can be either efficiency ?$_T$ or power of the turbine p_T. In our case we use power of the turbine.

C. Turbine controller model

In HPP Bajina Bašta the turbine regulator type HPC 642 from Alstom is in operation (Electrical part). Gate opening (y_T) is determined by this turbine regulator, consisting of two parts, electrical and electro-hydraulic part, see Fig. 6.

The heart of GV controller is a PID controller, whose inputs are both, power deviation and frequency deviation. The equation that defines the input of the PID is

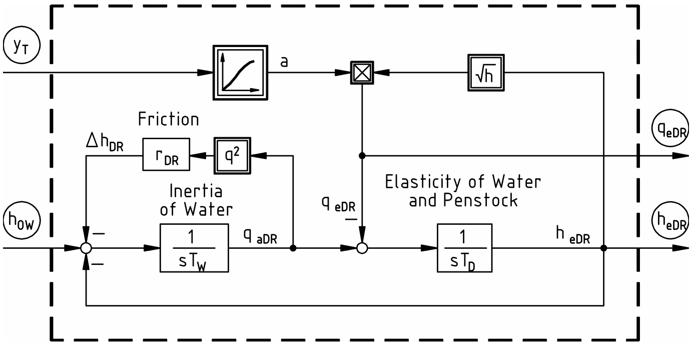

Fig. 5. Hydraulic part model

$err = \Delta p \cdot s_p + \Delta f$, where sp is speed droop (in smooth operation 4 %).

Depending from the mode in which the system is, the parameters of the PID and the value for speed droop are changing. Four modes of operation are possible: no load operation, smooth operation, disturbed operation and isolated grid operation. In our case only smooth mode is active, so D part is not active. Both active power and GV position can be used for feedback. In our case active power feedback is being used and, knowing that the output of the controller is GV reference, function $y_{GV} = f(p_G)$ is required.

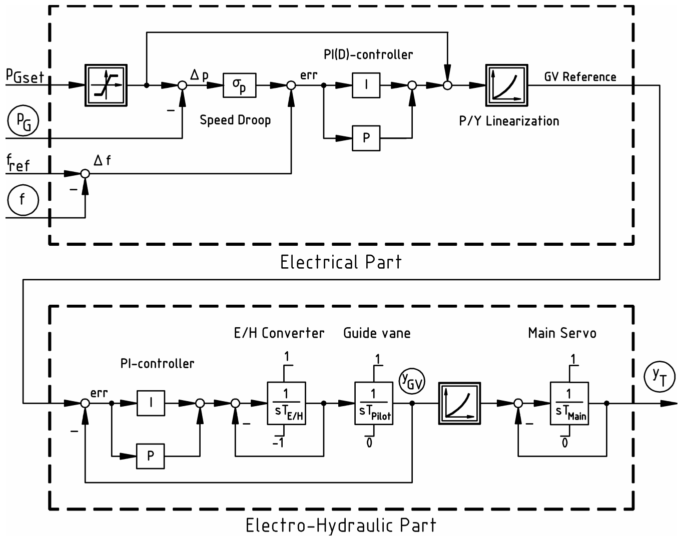

Fig. 6. Turbine Regulator model

That is P/Y Linearization function. It is applied in the model.

The output of the electrical part is guide vane (GV) actuator position reference signal (y_{GV}), which is the input of the actuator, via one control coil, where this signal is being compared with actual GV actuator position. The error influences via the PI controller the electro hydraulic (E/H) converter, which deflects and causes, via the pumping set (oil hydraulic), the GV servomotor to move in the opening or closing direction. The speed of this GV servomotor is proportional to the deflection of E/H converter. The position of the GV servomotor is GV actuator position. The main servomotor, influenced by the GV, moves the blades (gate opening y_T). The function between GV actuator position and gate opening is identified and applied in the model.

D. Generator Model

The model of the generator is based on the well known nonlinear fifth order model. 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, frequency, 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 dependable from the network.

The mechanical losses in the bearings of the shaft are included in the mechanical model. These losses are calculated from the table of losses and subtracted afterwards. Electrical losses are included in the generator model via stator resistance. Both mechanical and electrical parts of the generator are included in this model. All the parameters are provided by the existing documentation.

E. Voltage regulator and excitation system model

In Bajina Bašta the voltage regulator and gate control unit type GMR3 by ELIN is in operation. It is connected to the static excitation system, in shunt connection. All the parts of this unit are described in the documentation, supplied by the manufacturer.

This unit comprises a complete voltage regulator, the firing circuitry for single-phase or three-phase operation and the control logic that is necessary for proper operation of the excitation system. Two different modes of control are possible:

- Voltage regulation (automatic operating mode) and
- Field-current regulation (manual operating mode).

Only the first mode was active during the measurements. In this mode either generator voltage or reactive power set points can be set by the operator. Both possibilities were applied in the measurements.

In the main (master) control loop (automatic operating mode) the generator voltage reference (defined by both set points) is compared with actual value and the deviation influences via a PI(D) controller (D - component is set to zero by the regulator software) the excitation current setpoint, see Fig. 7.

In the slave control loop (manual operating mode) field-current reference (defined by PI(D) output in our case) is compared with actual value and the deviation influences via a P(I) controller (I - component is set to zero by the regulator software) the excitation voltage. The output of this controller defines the firing angle for the thyristors, being part of the rectifier, which generates the excitation voltage. The safety limits and security equipment are not modeled because the complexity of the model would significantly increase. Load compensation, on the other hand, had to be modeled as operating in the power plant. It supplies an additional set value for generator voltage. When reactive power regulator (AQR) is active, its output also influences generator voltage set point and these two influences exclude each other. While AQR is active load compensation is turned off.

Inputs of the model are mentioned set points, excitation current (field-current), generator voltage and active and reactive power. The only output is excitation voltage.

F. Network model

This model is necessary to simulate generator voltage (u_G) and generator voltage angle (f_{uG}), depending from the injected active and reactive power. These signals are used as inputs of the generator model. The idea is to define network voltage as a constant ('strong grid') and to define the parameters of the network (r_n and x_n) as constants too. These values are treated as model's predefined values. The inputs of the network model are generator active and reactive power flowing in the network direction.

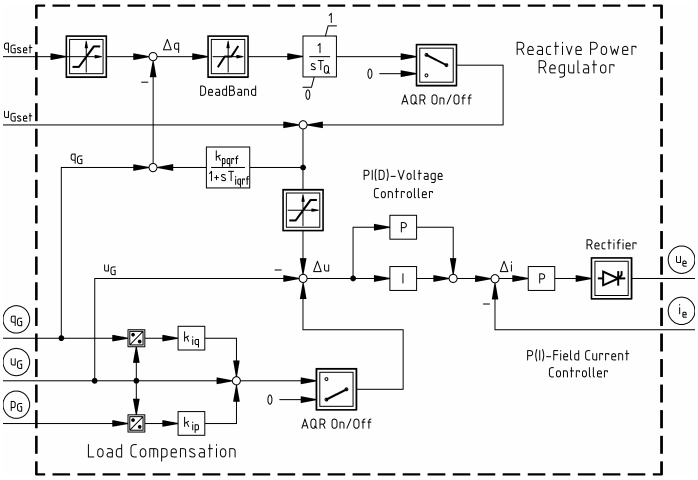

Fig. 7. Voltage regulator and excitation system model

V. IDENTIFICATION RESULTS

After applying the least square identification method to the power plant model, the main parameters shown in table III could be identified. These parameters could not be calculated directly from the documentation and so they are only a result of the identification process. Actually measured values and the values produced by simulation are shown, and could easily be compared, in Fig. 8, 9 and Fig 10. Simulation was based on measured input signals and parameters defined through identification process.

In Fig. 8 there are shown the results of the simulation using a stepwise change of the active power setpoint. As can be seen the quality of the simulation is very good, except for the water pressure where there is an offset. Here the

TABLE III
CALCULATED AND IDENTIFIED PARAMETERS

Hydraulic part			
T_W	T_D	r_{DR}	
1.4714 s	**0.12 s**	**0.00806**	
Turbine regulator			
T_{PI}	k_{PI}	T_{Pilot}	T_{Main}
1 s	**3 s**	**1 s**	**0.25 s**
Generator			
x_d	x_d'	x_d"	x_q
1.1	**0.4**	**0.2**	**0.45**
x_q"	r_S	T_d'	T_d"
0.22	**0.013**	**1.8 s**	**0.038 s**
T_q"	T_A	? $_{Sätt}$	$k_{Sätt}$
0.055 s	**8.2 s**	**0.88**	**0.25**
Voltage regulator			
v_{PU}	k_{iq}	k_{pqrf}	k_{St}
6	**-0.04**	**15.99**	**3**
T_Q	T_{iqrf}	T_{Spl}	T_{SpD}
80 s	**0.02 s**	**0.7 s**	**0.006 s**

measuring equipment seems to have a systematic error.

In Fig. 9 the results are shown for step changes in the reactive power setpoint. Also in this case the quality of the model is very high. The excitation voltage and current are fitting the measurements very well, as stands for the generator terminal voltage, too.

In Fig. 10 the results are shown for step changes in the generator voltage setpoint. It can be clearly seen that in this case the voltage controller of the plant is reacting much faster than in the case with reactive power setpoint changes.

These results show clearly that high quality models of the power plants can be achieved and further used for all types of investigations concerning the operation of the system.

VI. CONCLUSION

Within the Stability Pact South Eastern Europe investigations in hydro power plants are conducted to enable students from the involved universities in the Balkan Countries to make practice oriented diploma theses. In this paper a practical approach to modeling and identification of parameters for the HPP Bajina Basta in Serbia at the river Drina is presented. For the measuring campaign and the production of the theses the students needed altogether six months. A four month visit to the University of Rostock was included in that period.

The results of the work are really impressive. The students can develop a model of the power plant that could further be used for various purposes. Furthermore, the results are very useful for the Serbian Electric Energy Company (EPS). The results will be used for investigations concerning:

- Black Start Capabilities after Black Out
- Behavior in isolated operation
- Primary and secondary power reserve capabilities
- Reduction of losses in the plants

Overall dynamic behavior of the whole system including stability investigations

VII. REFERENCES

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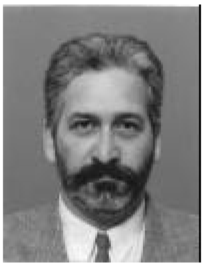
VIII. BIOGRAPHIES

Harald Weber was born 1954 in Heidenheim, Germany. He obtained his Ph.D. degree from University of Stuttgart in 1990. He has worked in EGL Elektrizitats Gesellschaft Laufenburg AG and currently he is professor at the University of Rostock, Department of Electrical and Electronic Engineering. He is also IFAC Vice Chairman of TC on "Power Plants and Power Systems

Ivan [kokljev (1953, Yugoslavia) received the B.S., M.S. and Ph.D. degrees (1977, 1984, 1990, respectively) all from the the Electrical Engineering Faculty, University of Belgrade. Currently, he is a full-time professor at the Electrical Engineering Faculty, Belgrade, Power Systems Department. He is teaching and researching in Power Systems Planning and Operation.



Goran Jankovic, born 1959 in Belgrade, received his B.Sc.El.Eng. Diploma at the Electronics Faculty, at the University of Belgrade, Yugoslavia (1985). Presently, he is employed in EPS (Electric Power Industry of Serbia) as a software engineer. His main professional interest is software development, especially for hard real-time systems. He was part of a development team for implementing of local regulators for LFC (Load Frequency Control) on hydro power plants Djerdap 1 and Bistrica during 2000, 2001 and 2002.

Nikola Obradovic, born 1963 in Belgrade, received his B.Sc.El.Eng. Diploma in Power Engineering (1989) and his M.Sc.El.Eng. title (1999) at the Electrical Engineering Faculty, University of Belgrade, Yugoslavia. He is employed as power engineer in EPS with main interests in power system control, especially primary, secondary and tertiary control of active power. He developed the algoritm for new AGC system in EPS and was part of an implementation team for development of local LFC regulators on hydro power plants Djerdap 1 and Bistrica He is member of UCTE ad-hoc group "Geographical Distribution of Reserves".

Miloš Golubovic was born 1979 in Belgrade. He graduated from University of Belgrade, Faculty of Electrical Engineering, in 2003. He participated in DAAD project “Modeling and Simulation of Hydro Power Plants” at the University of Rostock, Department of Electrical and Electronic Engineering. He is currently employed in Elem & Elgo Co. Ltd. – Belgrade, Serbia and Montenegro and is engaged as a design engineer in projects of overhead transmission and distribution lines and public lighting.

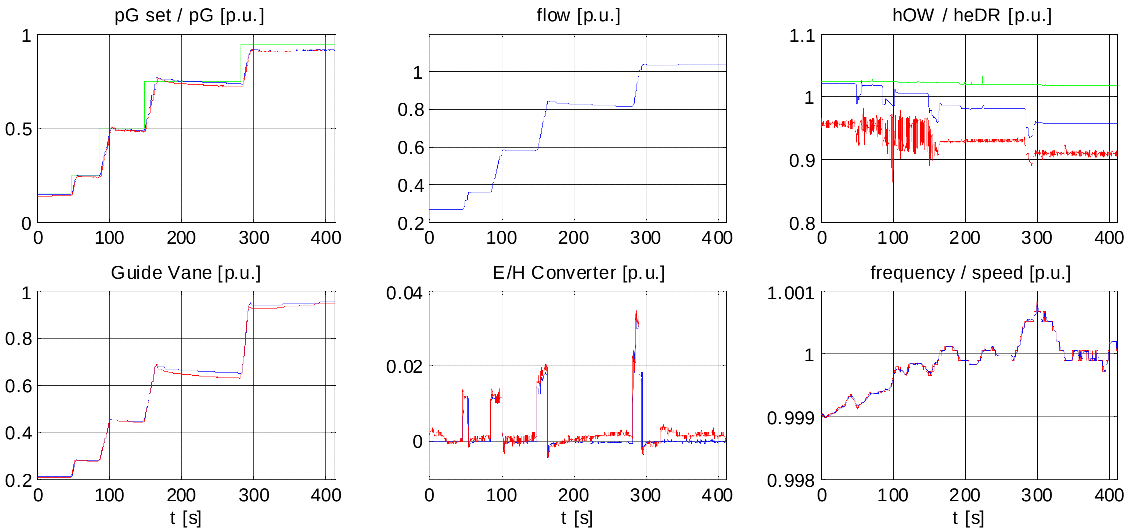


Fig. 8. Simulation results after stepwise change of active power setpoint (signals: green-inputs, red-measured, blue-simulated)

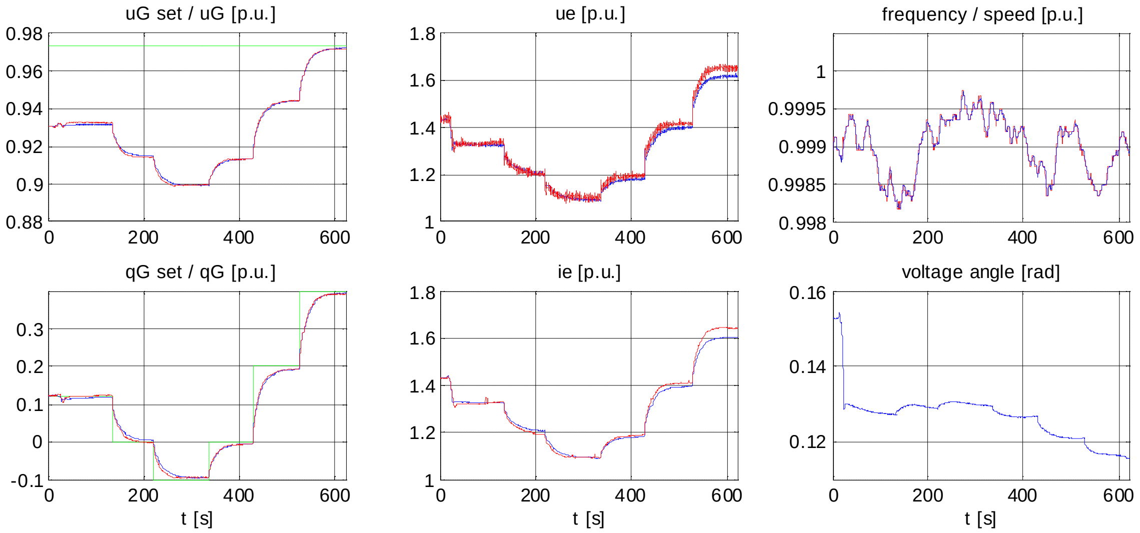


Fig. 9. Simulation results after stepwise change of reactive power (signals: green-inputs, red-measured, blue-simulated)

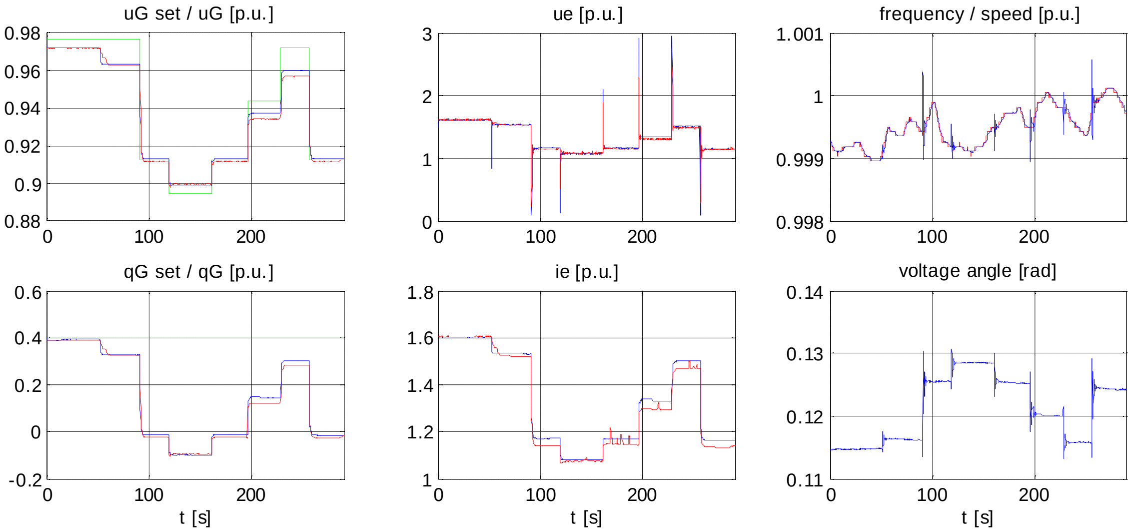


Fig. 10. Simulation results after stepwise change of voltage setpoint (signals: green-inputs, red-measured, blue-simulated)