Simulation of automatic frequency and power regulators

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Abstract. The motivation of the presented research is based on the need for development of new methods and tools for adequate real time simulation of automation control frequency and power regulators of generator played an important role in the planning, design and operation of electric power system. This paper proposes a Hybrid real time simulator of electric power system for simulation of automation control frequency and power regulators of generator. The obtained results of experimental researches of turbine emergency control of generator demonstrate high accuracy of the simulator and possibility of real-time simulation of all the processes in the electric power system without any decomposition and limitation on their duration, and the effectiveness of the proposed simulator in solving of the design, operational and research tasks of electric power system.

1. Introduction

According to the well-known reasons, the simulation of electric power system (EPS) is the only effective tool for research of processes in EPS as a whole and solving of the design, operational and research tasks, including adequate settings of relay protection and automation system (RPA) of EPS [1, 2]. Therefore, accurate modeling of RPA is one of the conditions for achieving a high adequacy of simulation EPS. At the same time simulation of RPA is quite complex problem that has significant practical value and can to solve a number of tasks. There are most urgent tasks [2, 3]:

- The analysis and optimization of calculated settings of RPA;
- The formation of methods and means of adequate settings of RPA (including automatic voltage regulator (ARV), Automatic frequency and power control (known as automatic generation control (AGC)), and others;
- The development of new emergency control systems of EPS, including multi-agent systems;

In particular, the simulation of AGC of generator is one of the most urgent tasks [4, 5]. Especially important from a researcher's viewpoint is the depth of the simulation, as well as impact of the simulation depth to adequate modeling of the processes in EPS. The main criterion for the solution of this task is ability of realization of the AGC model in the particular simulated EPS with the maximum possibility of simulation depth of AGC model.

Several approaches to solving the task of adequate simulation of AGC model have been implemented during the development of Hybrid real time simulator (HRTSim) of EPS, based on the concept of hybrid simulation and developed in Tomsk Polytechnic University [6, 7]. The first version of AGC model created in 1988 was developed at analog simulation level via operational amplifiers and analog multipliers. In the current version, the AGC model has been realized at digital simulation level via microcontroller, which is a coprocessor of specialized hybrid processor (SHP) of electric machine. As a result the depth of mathematical models and flexibility of parameter controlling have been greatly increased.

According the concept of hybrid simulation [6, 7], the features and properties of the HRTSim can be used for effectively solving a lot of problems, including the real-time simulation of all the processes in the electric power system without any decomposition and limitation on their duration, and testing of AGC under all possible normal, emergency and post-emergency modes of EPS.

The issue of adequate modeling of AGC and turbine emergency control of generating unit are presented are presented in the article.

2. A mathematical model of AGC implemented in HRTSim

The task of synthesis implemented in the microprocessor unit of SHP of HRTSim mathematical model of AGC was the creation a library of universal mathematical model of AGC, which can be adapted by setting the parameters of the transfer functions (coefficients of differential equations) for adequate modeling of currently used in Russian EPS of various hydraulic-mechanical and electro-hydraulic model of AGC.

The mathematical model of AGC was created by analyzing of well-known mathematical units and structures of existing AGC [8, 9]. The developed model of AGC allow us to provide fully and accuracy modeling of AGC operation at primary and secondary regulation, as well as emergency control of generating unit by centralized emergency control system (CECS) of EPS, including automatic pulse unloading of turbine (APU) and post-emergency unloading of turbine (PEU).

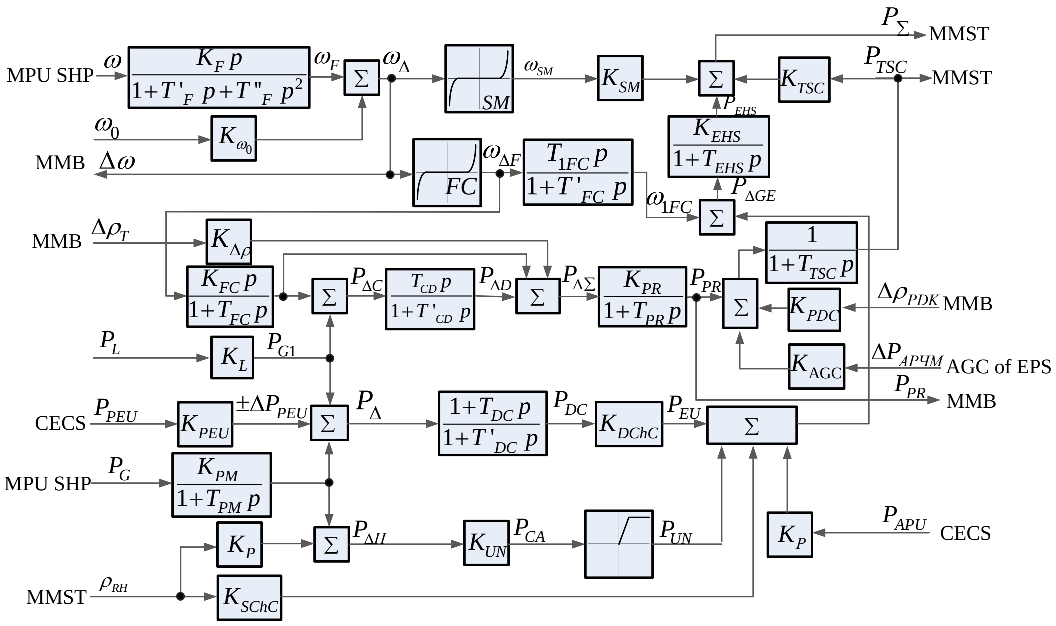


Figure 1. Structural diagram a mathematical model of AGC.

According to Figure 1:

- K_L – programing factor of generator unit load (P_L), determining in AGC active power of generator unit (P_{G1}), which in functional changes of the K_L can display a required load curve;
- K_{PEU} – programing factor of post-emergency unloading (additional loading) of generator unit $\pm\Delta P_{PEU}$;
- Differential equation of generator power meter

$$\frac{dP_{GE}}{dt} = \frac{1}{T_{PM}}(K_{PM}P_G - P_{GE});$$

- Differential equation of frequency corrector of slow-speed circuit of AGC

$$\frac{d\omega_{FC}}{dt} = \frac{1}{T_{FC}}(K_{FC}\omega_{\Delta F} - \omega_{FC});$$

- Equations system of the dynamic correction of the slow-speed circuit of AGC

$$P_{\Delta D} = \frac{1}{T'_{DC}}(T_{DC}P_{\Delta C} - Z_{\Delta C}), \frac{dZ_{\Delta C}}{dt} = P_{\Delta C};$$

- $K_{\Delta\rho}$ – programing factor of the frequency corrector of the slow-speed circuit of AGC at change of pressure of live steam $\Delta\rho_T$ (from MMB – mathematical model of boiler);
- Differential equations of general slow-speed circuit of AGC

$$\frac{dP_{PR}}{dt} = \frac{1}{T_{PR}}\left(K_{PR}P_{\Delta\Sigma} - P_{PR}\right);$$

- K_{PDC} – programing factor of common channel of power control for condensing turbine in sliding movement modes and regulating the steam pressure regulation, including stand-by mode, as well as power control with backpressure, turbines with industrial and cogeneration steam extraction;
- K_{AGC} – multifunctional programing factor, which can be used for modeling of external control actions of AGC from EPS;
- K_{TSC} – transfer ratio of turbine speed changer (TSC);
- Differential equation of TSC

$$\frac{dP_{TSC}}{dt} = \frac{1}{T_{TSC}}(P_{\Delta M} - P_{TSC});$$

- K_P и K_{UN} – programing factor of the corrector of the high-speed circuit of AGC, which, together with the current value of power of generator unit (P_G) from microprocessor unit of specialized hybrid processor (MPU SHP) of electric machine and the steam pressure of reheater (ρ_{RH}) from the universal mathematical model of steam turbines (MMST), forms a corrective action (P_{CA}) according to the equation

$$P_{CA} = (P_{GE} - K_P\rho_{RH})K_{UN}$$

- K_{SChC} – programing factor of the static correction channel of unevenness of the high-speed circuit of AGC;
- Differential equation of the dynamic correction channel of unevenness of the high-speed circuit of AGC

$$P_{DC} = \frac{1}{T'_{DC}}(T_{DC}P_{\Delta} - Z_{D\Delta}), \frac{dZ_{D\Delta}}{dt} = P_{DC} - P_{\Delta},$$

- K_{DChC} – transfer ratio of the dynamic correction channel of the high-speed circuit of AGC;
- K_{EU} – programing factor of the unloading channel of the high-speed circuit of AGC, including channel of the APU, and forms the ΔP_{APU} by shown in figure 2 graphics:

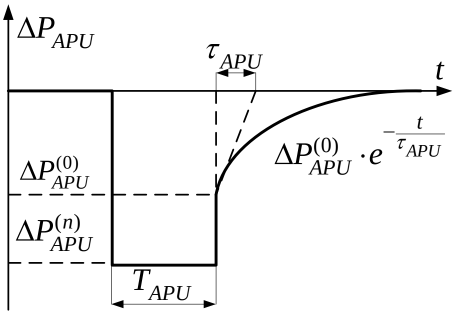


Figure 2. Control actions of the turbine emergency control of generating unit, where $\Delta P_{APU}^{(n)} = var$ – depth of the APU, $n = var$ – index of the depth; $T_{APU} = var$ – duration of the APU; $\Delta P_{APU}^{(0)} = var$ – part of ΔP_{APU}, exponential removing $\Delta P_{APU}^{(0)} \cdot e^{-\frac{t}{\tau_{APU}}}$, $\tau_{APU} = var$.

- Differential equation of speed turbine meter

$$\frac{d^2\omega_F}{dt^2} = \frac{1}{T''_F}\left(-T'_F\frac{d\omega_F}{dt} - \omega_F + K_F\omega\right);$$

- Differential equation of the dynamic frequency correction of the high-speed circuit of AGC

$$\omega_{1FC} = \frac{1}{T'_{1FC}}(T_{1FC}\omega_{\Delta F} - Z_{1\Delta F}), \frac{dZ_{1\Delta F}}{dt} = \omega_{1FC} - \omega_{\Delta F};$$

- Differential equation of the common channel of the high-speed circuit of AGC

$$\frac{dP_{EHS}}{dt} = \frac{1}{T_{EHS}}(K_{EHS}P_{\Delta GE} - P_{EHS});$$

- $K_{SM} = \frac{1}{\sigma}$ – transfer ratio of the turbine governor, where $\sigma = var$ – drop of the turbine governor;
- K_{ω_0} – coefficient of setting of the turbine rotor speed (ω_0).

The developed mathematical model of AGC and mathematical model of the generator unit are implemented via SHP, which is the basic element of HRTSim [7].

3. Experimental research of the AGC model

Experimental researches of the AGC model have based on the simulation of the APU and PEU of the generator unit.

The part of the created intelligent scheme of power cluster "Elgaugol" implemented in the HRTSim has been used for modeling and analysis of AGC model based on the generation unit G-1. (figure 3).

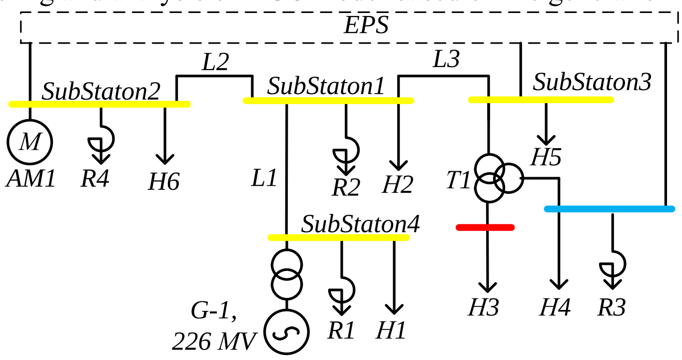


Figure 3. Part of analysis scheme of power cluster "Elgaugol".

The control of APU and PEU is carried out by its preset, which includes:

- Determination and parameter setting of the APU;
- Formation of signal in central system emergency control (CSEC) for PEU as a values of surplus power (P_{SP}), used for deterring a value of generator unit power after PEU (P_{EU}) according to the following equation:

$$(P_{EU} = P_T - P_{SP}),$$

where P_T – current value of load of the steam turbine.

There are parameters of the APU and PEU model, whose value can be changed both stationary and interactively:

- A_P – the value unloading pulse of turbine;
- P_{EU} the value of the unloading pulse of turbine set between A_P to 0, in according to an algorithm of emergency control of generating unit;
- A_0 – the value of the residual control action of the unloading pulse of turbine значение;
- t_P – time duration of the applied pulse;
- T_{EU} – time constant of exponential removal of the unloading pulse A_0 ;
- P_{EU} – the value of generator unit power after PEU;
- K_{EU} –gain factor of the channel of the PEU.

Interactive changing of parameters is carried out using the corresponding table "Prime mover" in the dynamic monitoring and control panel (DMCP) of generator unit. In automatic mode, it is possible to carry out with the specially prepared scenarios that run from the Client software "Script of APU and PEU" from DMCP.

Analysis of APU and PEU model operation in the HRTSim includes the following steps:

1. The performing the dynamics scenario simulated the occurrence of emergency mode and the corresponding operation of the RPA.
2. The modeling the CSEC and exporting the unloading pulse of turbine to the model.
3. The operation of APU and PEU model, taking into account data from CSEC:
   a. Assigning P_{EU} to A_P during the time t_P ;
   b. Changing P_{EU} to A_0 after t_P and removing of the residual control action $P_{EU} = A_0$ with the time constant $T_{EИ}$;
   c. Assigning the PEU settings: P_{EU}, according to the equation (1), and $K_{EU} = (1 - 10)$, (particular value is determined as a result of research);
   d. Zeroing K_{EU} after control time.

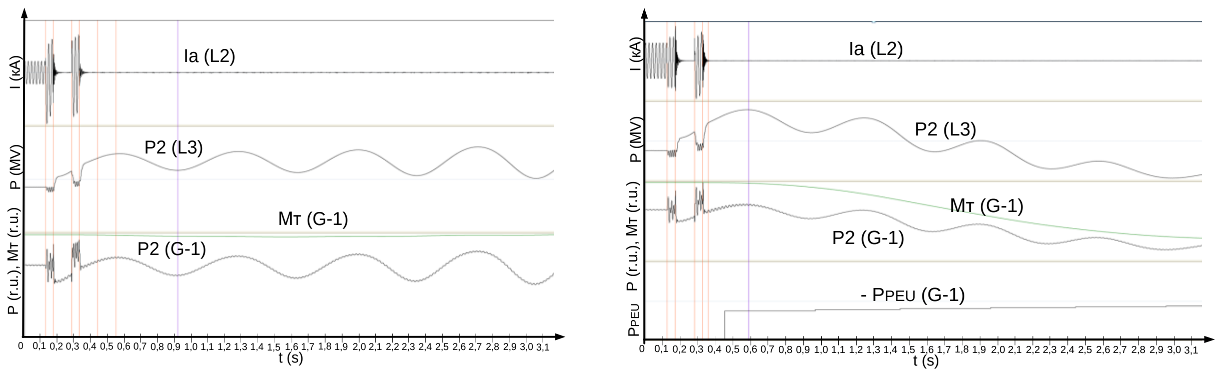
The following research results for determining the effective settings of automatic emergency power control of generator unit by means of a thermal power station of APU and PEU are presented below and modeled at the original operating mode of the simulated EPS:

- Generation unit G-1 produce around 226 MV;
- Overhead line (L1) performs communication G-1 with EPS model and transmit the 136 MV of active power;
- This transmitted active power distribute through two overhead lines (L2 transmit the 105 MV and L3 transmit the 31 MV).

According mentioned scenario:

1. The single-phase short circuit is simulate on a L2;
2. The action of RPA, non-successful reclosing and repeated action of RPA with acceleration simulated.

The consequence of these actions is the weakening of the link G-1 and EPS (L2 tripping and increasing power flow via L3). As a result, CSEC sends action and data to perform turbine emergency control of the G-1. In figure 4a the waveform illustrating the significant power oscillations that lead to the destruction of the stability of EPS, in the operation of relay protection without the use of turbine emergency control is shown. In figure 4b the waveform corresponding to operation of APU without smooth removing of the residual control action is shown. There are some overshoot and long power oscillations in a simulated EPS.



(a) (b)

Figure 4. Waveform in the operation of relay protection without the use of turbine emergency control (a) and with the use of APU and PEU of G-1 ($A_P = 4$ u. un., $A_0 = 1$ u. un., $t_P = 0.1$ s, $T_{EU} = 3{,}5$ s) (b).

The waveform of processes, when APU and PEU are configured, is shown in figure 5 and 6. As can be seen, the power oscillations rapidly damped and EPS stability is saved for the given setting of APU and PEU. It should be noted that the when pulse is equal of 2,5 u. un. (unit of unevenness) the dynamic impact on the turbine valves system is less than pulse is equal of 4 u. un.

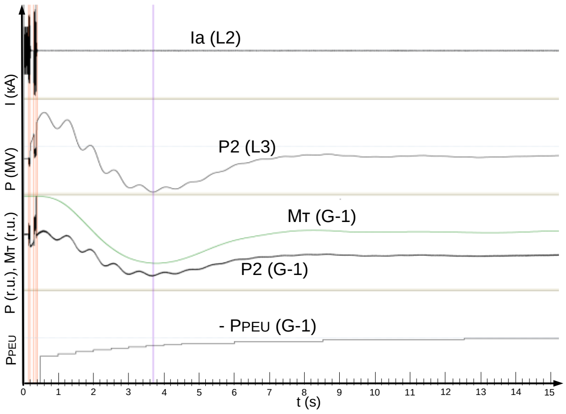


Figure 5. Waveform in the operation of relay protection with the use of APU and PEU of G-1 ($A_P = 2,5$ u. un., $A_0 = 1$ u. un., $t_P = 0.1$ s, $T_{EU} = 3,5$ s).

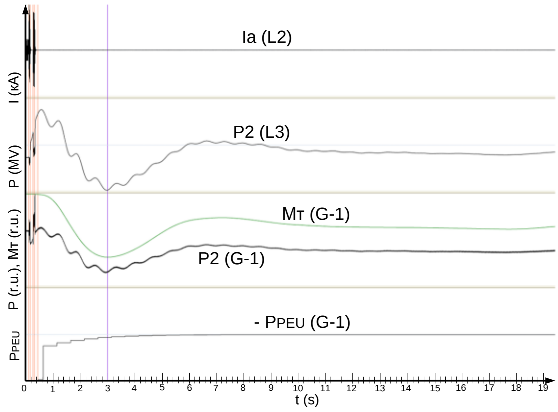


Figure 6. Waveform in the operation of relay protection with the use of APU and PEU of G-1 ($A_P = 4$ u. un., $A_0 = 1$ u. un., $t_P = 0.1$ s, $T_{EU} = 1,5$ s).

As a result of the analysis the following results have been obtained:

- The adequate simulation of developed APU and PEU model in real time is confirmed;
- The optimal settings of developed APU and PEU model for simulated EPS are determined.

4. Conclusion

- The simulation of RPA is an essential part in the simulation of EPS, to achieve the adequate modeling a processes in equipment and EPS as a whole;
- The developed model of AGC implemented in the HRTSim, taking into account the depth of mathematical models sufficient for adequate modeling a processes in EPS;
- The experimental results presented in this paper confirm the adequacy of obtained information, as well as the possibility of using the developed model for analysis and effective settings of AGS to provide a dynamic and static stability of EPS.

Acknowledgements
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