The Study of Synchronous Generators' Voltage and Frequency Group Prognostic Controllers of a Small-scale HPP

Yuri N. Bulatov[1], Andrey V. Kryukov[2, 3], and Konstantin V. Suslov[3]
[1] Bratsk State University, Bratsk, Russia
[2] Irkutsk State Transport University, Irkutsk, Russia
[3] Irkutsk National Research Technical University, Irkutsk, Russia
Email: bulatovyura@yandex.ru; and_kryukov@mail.ru; souslov@istu.edu

***Abstract*—The application of a large number of distributed generation plants, built on the basis of synchronous generators in Electric Energy System (EES), requires solving the problem of their centralized control, adjustment of voltage and frequency local controllers, which entails taking into account a large number of interrelated system parameters. These problems can be solved using prognostic control algorithms. The purpose of the study was to determine the effect of the proposed group prognostic voltage and frequency controllers for small-scale Hydroelectric Power Plant (HPP) on various operating modes of the EES. The studies were conducted in the MATLAB environment using the Simulink and SimPowerSystems simulation packages. The results of computer simulation indicate that the use of group prognostic controllers significantly reduces overshoot, oscillability index, transient time and voltage dips, and frequency in the normal and emergency conditions. The proposed methods of the group prognostic controller formation and tuning allow to improve quality indices of small-scale HPP voltage and frequency control, while retaining the former settings of synchronous generators controllers.**

***Index Terms*—Distributed generation plants, small-scale HPP, synchronous generators, automatic speed controller, automatic voltage controller, group regulation, prognostic control algorithms, simulation**

I. Introduction

The application of Distributed Generation (DG) plants [1]-[6] in Power Supply Systems (PSS) located near power consumers makes it possible to reduce the load of the supply network, reduce transmission losses, and improve the reliability of power supply and power quality [7], [8]. In this case, DG plants on renewable energy sources contribute to reduction in harmful impact on the environment.

When using a large number of DG plants in Electrical Energy System (EES), a problem of their AC frequency centralized regulation and stabilization can emerge. Different DG plant types have their own local controllers which shall be tuned properly for different EES operating modes. Thus, quite a difficult task emerges in order to optimize the settings of a large number of local controllers with respect to their mutual influence. Automatic Voltage Controllers (AVC) and Automatic Speed Controllers (ASC) of rotor rotation [9]-[11] are considered as interrelated controllers for DG plants operating based on synchronous generators.

In addition, when using several synchronous hydroelectric generators of the same type in the DG plant of a small-scale Hydroelectric Power Plant (HPP), the problems of optimization of their loading and group regulation shall be solved. This requires creation complex models of EES, PSS with DG plants and their controllers, and time-consuming calculations, taking into account a large number of the system interrelated parameters. There is another approach associated with the use of prognostic control algorithms [12], that ensure operation of the controller based on the computed control error forecast $\varepsilon\,(t+\Delta t)$. Prognostic control algorithms are used in power electronics [13], [14], as well as in electric motor control [15], [16]. These works use complex predictive models with a finite set of controls. At the same time, it is easy enough to implement predicting with a linear model. The comparison of various prognostic control algorithms given in [12] shows that linear prognostic algorithms are able to compete with the best nonlinear ones. In [17] a universal search-free method for tuning linear prognostic proportional-integral-differential (PID) controllers is given. The article [18] shows that linear prognostic PID controllers can be effectively used in a single-loop boiler superheater control system. Work [19] shows the advantages of a control system with a predicting module and gives recommendations for selecting the optimal predicting time to regulate the thermal process. Numerous studies based on computer models of EES with DG plants [17], [20], [21] indicate, that the application of linear prognostic link in AVC and ASC allows to improve the control quality indices.

Below is the description of the methods used to control the voltage and frequency of a group of low power synchronous hydrogenerators, the description of computer models of DG plants and the proposed group controllers of prognostic type, as well as the simulation results for the modes of disconnecting communication with EES and short-time three-phase fault. The research was conducted in MATLAB environment. The purpose of the study was to

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Corresponding author: Konstantin V. Suslov (email: souslov@istu.edu).

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determine the effect of the proposed group prognostic voltage and frequency controllers of a small-scale HPP hydrogenerators on various operating modes of the EES.

II. The Method of Voltage and Frequency Group Regulation Using Prognostic AVC and ASC

The AC frequency is the most important parameter of the EES operating mode, which is subject to quite stringent requirements in terms of deviation from the nominal value. The application of linear prognostic models, which allow to improve classical ASC of synchronous generators, makes it possible to more effectively stabilize frequency avoiding changes in the controller settings [21]. When regulating the EES voltage, it is also possible to effectively use the prognostic AVC of generators [20].

The linear prognostic link (LPL), which can be used in the above controllers, is described by the following transfer function [17]:

$$W_p(s) = T_p s + 1 \tag{1}$$

where T_p is the time constant of prognostic link; s is the Laplasian operator.

To determine the time constants of the AVC and ASC prognostic link of each unit in different operating modes, it is proposed to use natural oscillations frequency of the generator rotor f_p [22]:

$$f_p = \frac{\sqrt{P_s\left(\omega_0 / T_{\text{je}}\right)}}{2\pi}, \quad P_s = \frac{E_q U_g}{X_d}\cos\delta \tag{2}$$

where P_s is the synchronizing generator power, p.u.; U_g is the rated voltage, p.u.; δ is the angle between voltage and EMF E_q, elec. deg.; X_d is the inductive resistance along longitudinal axis, p.u.; ω_0 is the rated angular frequency, rad/s; T_{je} is the equivalent constant of mechanical inertia of the unit, s.

The time constant of LPL in this case will be determined by the value inversely proportional to the natural oscillations frequency of the generator rotor as T_p=1/f_p. The structural diagram of the proposed system of voltage and frequency control by means of prognostic AVC and ASC for a separate synchronous generator is shown in Fig. 1. In accordance with (2), the frequency f_p, and hence, the time constant of the prognostic link T_p depend on the load angle of the δ synchronous generator. When the operating mode changes, the proposed control system in Fig. 1 automatically computes the forecasting time and reconfigures the prognostic links for AVC and ASC.

In Fig. 1 the following transfer functions correspond to individual units: W_{ASC} is the transfer function of ASC; W_{AVC} is the transfer function of AVC; W_G is the transfer function of the generator; W_E is the transfer function of the exciter; W_T is the transfer function of the turbine; W_p is the transfer function of LPL (1).

For group control of synchronous generators running in parallel, one of them can be assumed as a master and determine the time constants of LPL by the load angle of δ this generator. Using the master generator method makes it possible to build a group prognostic automatic speed regulator (GPASR) and a group prognostic automatic voltage regulator (GPAVR). As an example, Fig. 2 shows the structural diagram of GPASR. The structural diagram of GPAVR looks similar, but the generator voltage is the regulated parameter in it. It should be noted that there is only one unit in the considered GPASR and GPAVR, which computes the time constant T_p for all LPL in AVC and ASC.

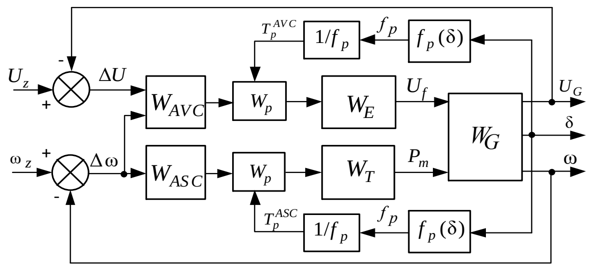


Fig. 1. Voltage and frequency control system that uses LPL in AVC and ASC: U_z – generator voltage set value; U_f – generator excitation winding voltage; ω_z – generator rotor set speed value; P_m – mechanical power on turbine shaft.

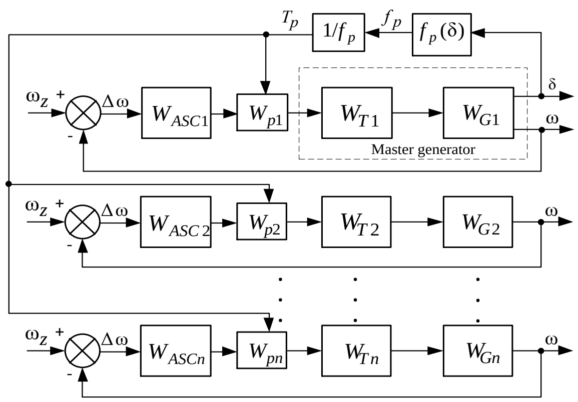


Fig. 2. The structural scheme of GPASR when using the master generator method: n is the number of units in the group with their prognostic ASCs.

III. Description of the Study Simulation Model and Proposed Group Controllers

The research was conducted in MATLAB environment using the simulation model of a small-scale HPP developed using Simulink and SimPowerSystems packages, the schematic diagram of which is shown in Fig. 3.

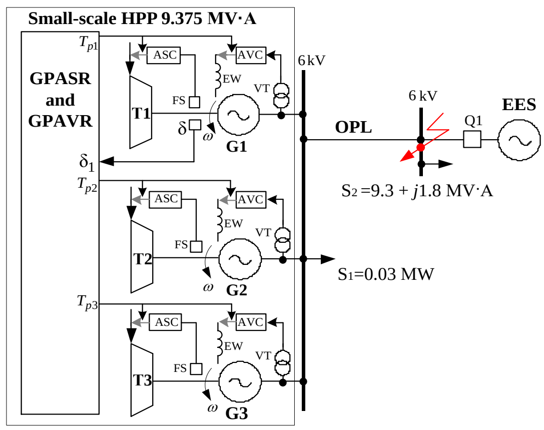


Fig. 3. Schematic diagram of a small-scale HPP with local and group prognostic AVC and ASC: FS – frequency sensor; EW – excitation winding; VT – voltage transformer; T – turbine; G – generator.

The small-scale HPP under study consists of three hydrogenerators with capacity of 3.125 MV·A each and voltage of 6 kV. Normal and emergency operating modes of a small-scale HPP, which is connected to the EES through a 5 km long 6 kV overhead power line (OPL) with a load of 9.3+j1.8 MV·A at its receiving end, were simulated (Fig. 3).

Normal steady-state mode with 50% loading of each hydrogenerator was taken as the initial one. The rest of the electrical energy to power the consumers at the end of the OPL was supplied from the EES. The diagram of the simulation model developed in MATLAB system is provided in Fig. 4. The presented model provides for possibility to introduce the following disturbances (Fig. 4): disconnection of communication with the EES using the Breaker unit; short-term three-phase fault using the Three-Phase Fault unit.

The description of the AVC prognostic models used is provided in [21]. In this work, a modified model of the prognostic AVC is used, which allows to automatically compute the time constants of LPL depending on the load angle of the δ master generator and to change them for various operating modes. At the same time, it is proposed to set LPL in the AVC separately in the voltage control channel and separately – in the frequency control channel. The diagram of the proposed Simulink-model of prognostic AVC is provided in Fig. 5 (when simulating, for practical reasons were assumed as follows AVC tuning factors: k_{0u} =100, k_{1u} = 50, $k_{1\text{If}}$ = 1, k_{0w} = 1.28, k_{1w} = 0.73).

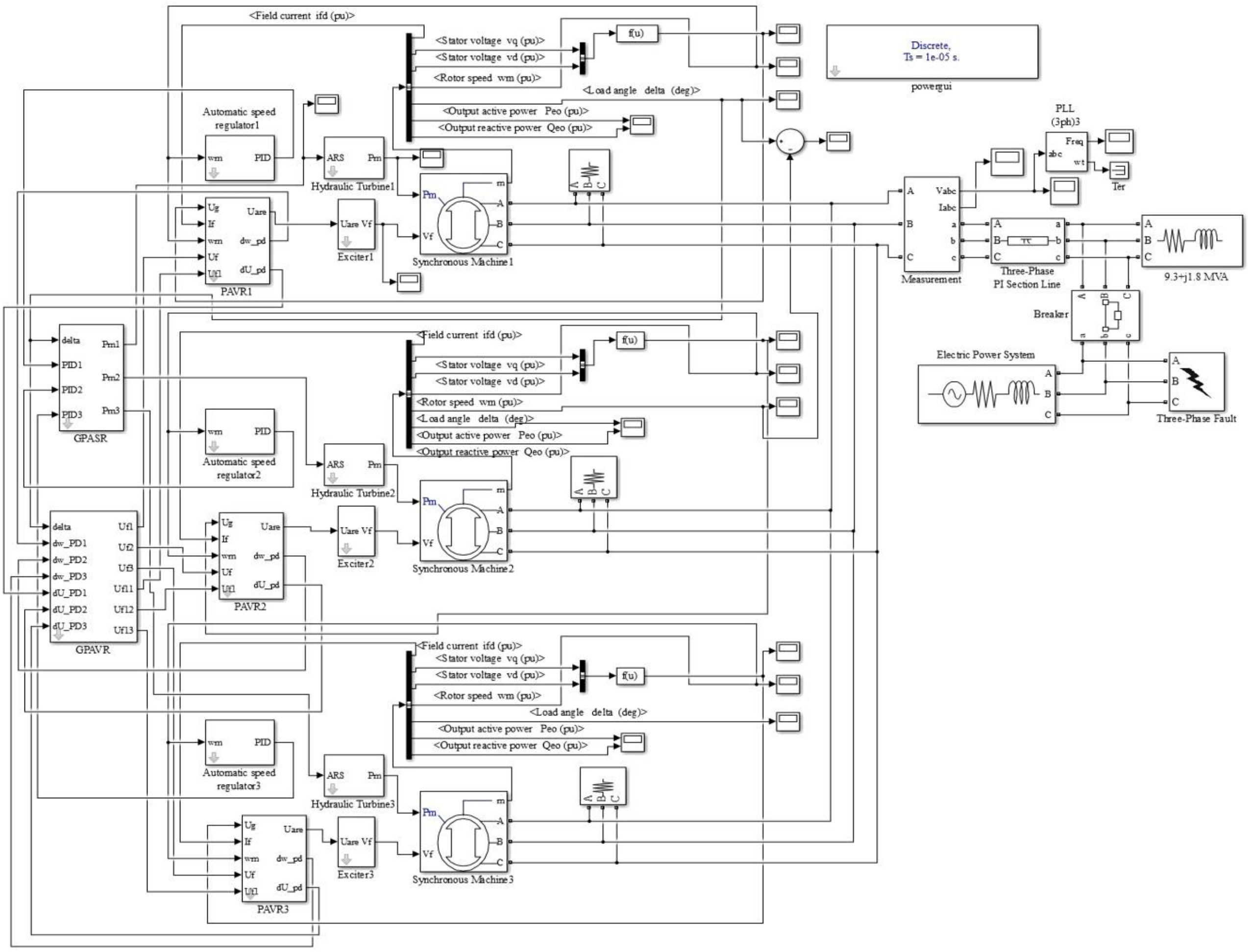


Fig. 4. The circuitry of the small-scale HPP simulation model in MATLAB.

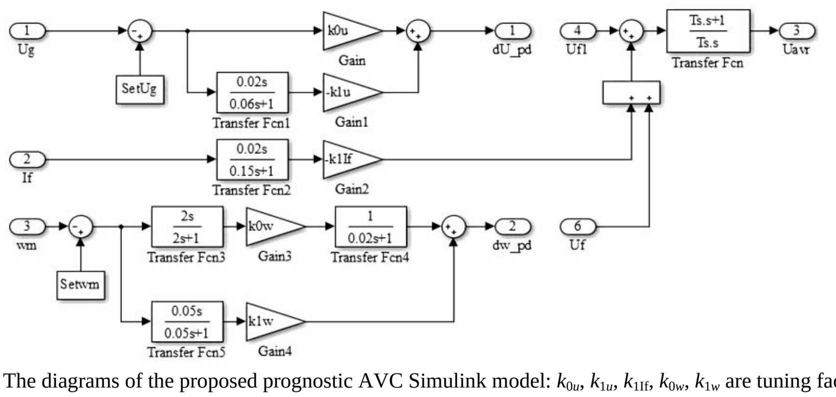


Fig. 5. The diagrams of the proposed prognostic AVC Simulink model: k_{0u}, k_{1u}, $k_{1\text{If}}$, k_{0w}, k_{1w} are tuning factors.

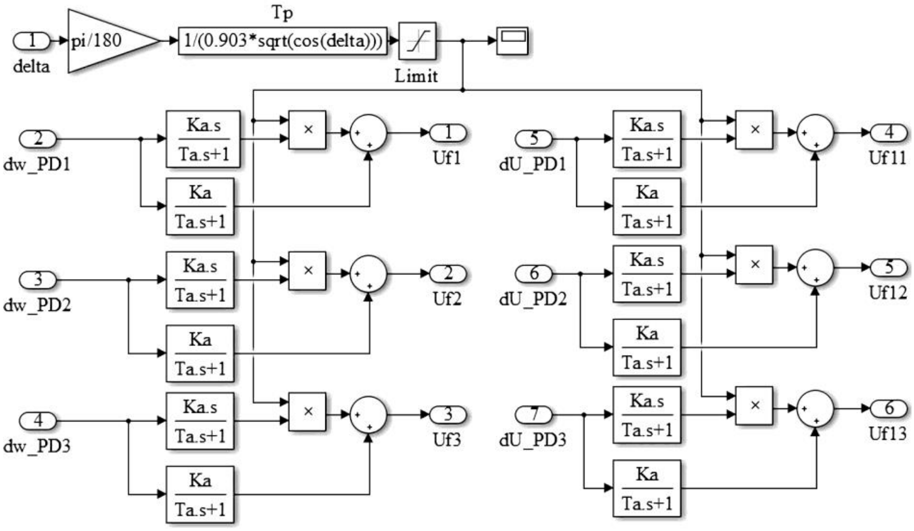


Fig. 6. Diagrams of GPAVR simulink-model.

The generators local ASC were simulated with controllers with PID control algorithms, described by the following transfer function:

$$K_p + K_i \frac{1}{0.1s} + K_d \frac{1}{s+1} \quad (3)$$

where K_p, K_i, and K_d are ASC tuning factors (when simulating, for practical reasons were assumed as follows: $K_p = 7.55$, $K_i = 2$ and $K_d = 0.75$); s is the Laplasian operator.

The prognostic links in the GPASR and GPAVR were considered separately for each generator, and the forecast time determining units had a common linkage by the load angle δ of the master generator. The diagrams of Simulink-models of the proposed GPASR and GPAVR are shown in Fig. 6 and Fig. 7.

The following hydrogenerator parameter values were used for simulation: $X_d = 2.84$ p.u., $E_q = 1.1$ p.u., $U_g = 1$ p.u., $T_{je} = 3.779$ s.

The structural diagram of the hydraulic turbine model used with the main servomotor (Hydraulic Turbine units in Fig. 4) is provided in Fig. 8 [22].

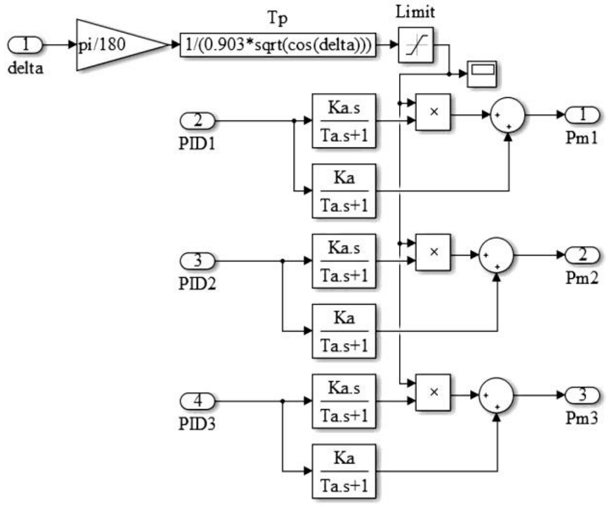


Fig. 7. Diagrams of GPASR simulink-model.

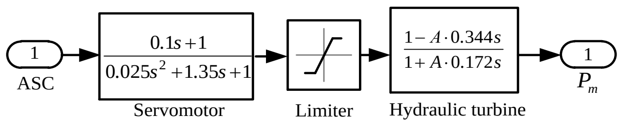


Fig. 8. The structural diagram of the hydraulic turbine model with the main servomotor: A – the opening position of a wicket gate.

IV. Simulation Results and Main Conclusions

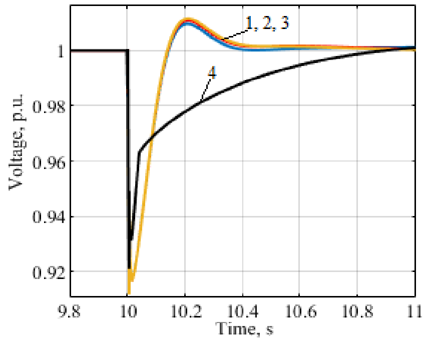
Using the described simulation model the following modes were studied:

1) Transition of the small-scale HPP operating mode to the allocated load when the communication with the EES is disconnected on the receiving end of the OPL by the switch Q1 (Fig. 3);

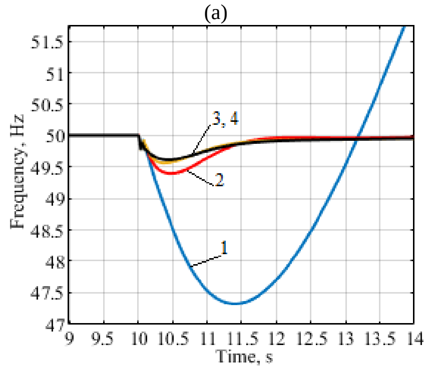
2) Short-term three-phase fault at the receiving end of the OPL (Fig. 3).

Based on modeling results of the specified modes, the following regulation indicators of EES mode parameters were compared: generators load angle δ, voltage on the busbars of small-scale HPP and AC frequency in the network when using conventional AVC and ASC without the prognostic link with a typical setting, prognostic AVC and ASC, as well as GPASR and GPAVR tuned to the resonance frequency of natural oscillations of the master generator rotor of the small-scale HPP (Fig. 6 and Fig. 7). It should be noted that generators AVC and ASC tuning was not changed in all the modes and control modes under consideration.

Fig. 9 and Fig. 10 show the temporal dependencies of the above regime parameters when communication of the small-scale HPP and EES is disconnected. The results of comparison of parameters of the above regime indicate that the use of voltage and frequency group prognostic controllers positively influences the indicators of control quality in comparison with the local control of conventional or prognostic AVC and ASC: voltage and frequency dip in the mains (Fig. 9) is reduced; transient time for frequency in the mains is reduced (Fig. 9, (b)); there is no voltage overshoot on the buses of small-scale HPP (Fig. 9, (a)).



(a)



(b)

Fig. 9. Temporal dependencies of PSS operating parameters when communication with EES is disconnected: (a) – the generator voltage; (b) – the mains frequency; 1 – conventional AVC and ASC without LPL used with typical tuning; 2 – the local regulation of prognostic AVC and ASC; 3 – the use of GPASR and conventional AVC without LPL; 4 – the use of GPASR and GPAVR.

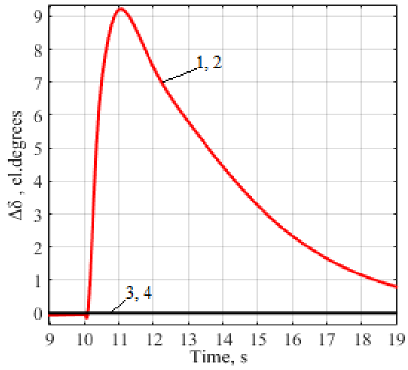


Fig. 10. Temporal dependencies of the mutual angle of the generators rotors $\Delta\delta=\delta_1-\delta_2$ when the communication with the EES is disconnected: designations 1, 2, 3 and 4 correspond to Fig. 9.

At the same time the use of GPASR and GPAVR allows to virtually eliminating possible fluctuations of mutual angle of two generators rotors of the small-scale HPP, which positively affects the intragroup movements at the station, while increasing the stability of parallel operation of synchronous generators (Fig. 10).

Then, a three-phase short circuit was simulated at the end of the overhead power line, which was turned off using relay protection. Fig. 11 and Fig. 12 show the time dependences of the parameters of the EES mode at a three-phase fault of 0.3 s duration. The use of GPASR and GPAVR in the short-time short-circuit mode also allows to exclude possible oscillations of the mutual angle of the two generators rotors of the small-scale HPP, which positively affects the uniformity of loading of units and intragroup movements at the station (Fig. 11).

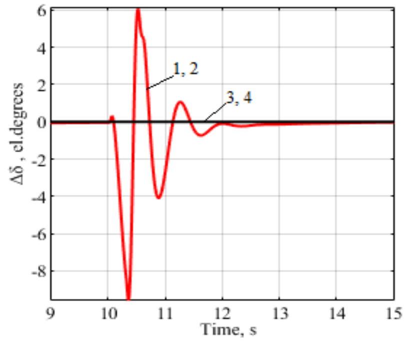
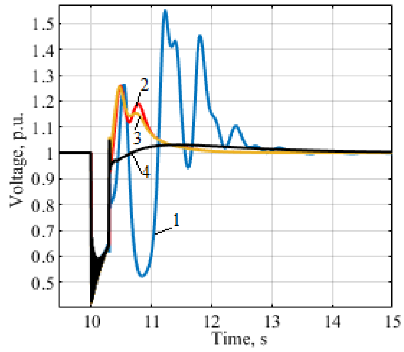
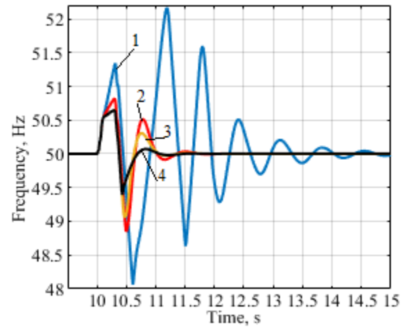


Fig. 11. Temporal dependencies of the mutual angle of the generators rotors $\Delta\delta=\delta_1-\delta_2$ for short-time three-phase fault: designations 1, 2, 3 and 4 correspond to Fig. 9.



(a)



(b)

Fig. 12. Time dependences of the parameters of the EES under study for a short-time three-phase fault: (a) – the generator voltage; (b) – the mains frequency; designations 1, 2, 3 and 4 correspond to Fig. 9.

The simulation results show that the use of GPASR and GPAVR improves the control quality in comparison with the local control of conventional or prognostic AVC and ASC: the transition process time and the overshooting value for voltage on the busbars of small-scale HPP (Fig. 12, (a)); the oscillability of voltage after short-circuit failure is significantly reduced (Fig. 12, (a)); the transition process time and the value of overshooting for frequency in the mains is significantly reduced (Fig. 12, (b)); the oscillability of frequency in the mains is reduced (Fig. 12, (b)).

V. Conclusion

The computer modeling results allow us to make the following conclusions:

1) The use of LPL in AVC and ASC of hydro generators compared with conventional controllers with typical setting improves damping properties, while

significantly reducing overshoot, oscillability and transient time for voltage and frequency in the mains in case of disconnection of communication with the EES and especially during short-term three-phase fault.

2) The use of voltage and frequency group prognostic controllers has a positive effect on quality control indicators in comparison with local control of conventional or prognostic AVC and ASC. Disconnecting the communication with the EES reduces the voltage and frequency sag in the mains, significantly reduces the transient time for the frequency in the mains, and also eliminates voltage overshoot on the buses of the small-scale HPP.

3) The use of the proposed group prognostic controllers of voltage and frequency for short-term three-phase faults also improves the control quality in comparison with the local regulation of conventional or prognostic AVC and ASC: transient time and overshoot for station bus voltage are significantly reduced; voltage oscillation after short-circuit outage is significantly reduced; transient time and overshoot for mains frequency are significantly reduced; and frequency oscillability in the mains is reduced.

4) The use of GPASR and GPAVR allows to exclude possible fluctuations in mutual angle of two generators rotors of the small-scale HPP for all considered modes. It positively affects the uniformity of units loading, intragroup movements at the station, while increasing the stability of synchronous generators parallel operation.

5) Methods of formation and adjustment of voltage and frequency group prognostic controllers based on determination of oscillations resonance frequency of the master generator rotor are proposed. The proposed approach makes it possible to obtain the best quality indices of voltage and frequency control in the EES while retaining the previous settings of synchronous generators AVC and ASC.

Conflict of Interest

The authors declare no conflict of interest.

Author Contributions

Conceptualization, Y.B., A.K. and K.S.; methodology, Y.B. and A.K.; software, Y.B.; validation, Y.B., A.K. and K.S.; formal analysis, Y.B. and A.K.; investigation, Y.B., A.K. and K.S.; resources, K.S.; data curation, A.K.; writing—original draft preparation, Y.B.; writing—review and editing, Y.B., A.K. and K.S.; visualization, Y.B.; supervision, K.S.; project administration, Y.B. and A.K.; funding acquisition, K.S. All authors had approved the final version.

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Yuri N. Bulatov is the Head of Energy Department at Bratsk State University, Russia. He graduated from Bratsk State University in 2007. Yuri Bulatov received his degree of Candidate of Technical Sciences at the Irkutsk State Transport University in 2012. His research interests include: modeling of power and control systems, modeling and control of electric power system operating conditions; power grids; smart grids.

Andrey V. Kryukov is professor of Transport Electric Engineering Department at Irkutsk State Transport University, professor of Power Supply and Electrical Equipment Department at Irkutsk National Research Technical University, Russia. He graduated from East Siberian Technological Institute in 1974. Andrey Kryukov received his degrees of Candidate of Technical Sciences from Leningrad Polytechnic Institute in 1982 and Doctor of Technical Sciences from Energy Systems Institute of the Russian Academy of Science in 1997. His research interests are: modeling and control of electric power systems and power supply systems of the railroads; smart grids.

Konstantin V. Suslov is head of Department of Power Supply and Electrical Engineering at Irkutsk National Research Technical University, Russia. IEEE senior member. He graduated from Irkutsk State Technical University with specialty "electric drive and industrial automations". He has doctor of science degree in technics. Research interests related to the computer engineering and automation, reliability of power systems, power quality, and modeling of power and control systems, modeling and control of electric power system intelligent power systems.