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Enhancing the dynamic stability of electric power systems through the coordinated tuning of generator predictive controllers

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ABSTRACT

The paper presents a method for the coordinated tuning of automatic voltage regulation (AVR) and automatic speed control (ASC) systems for a group of generators operating in parallel at a power plant. The method also involves solving the optimization problem using a genetic algorithm. The possibilities of using lead-lag elements in AVR and ASC, which impart predictive properties and improve damping characteristics of the controllers, are also considered. A model of a power plant operating in parallel with an electric power system is presented. This model demonstrates effective damping of oscillations under large disturbances when the proposed method is used to adjust the AVR and ASC control coefficients, along with a self-tuning lead-lag element. In this case, voltage oscillations and frequency overshoot disappear, and there is a significant reduction in the maximum deviations of these parameters. In the illustrative case study, the coordinated tuning of the controllers provides a 6% increase in the transmitted power limit and, as a consequence, the enhancement of the stability margin of the electric power system.

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1. INTRODUCTION

Modern electric power systems (EPSs) are characterized by a large length and a large number of electricity consumers. The EPS loads normally change randomly, which can lead to deviations in frequency, which is regulated by primary controllers at the power units of electric power plants using the turbine automatic speed control (ASC) by changing the energy carrier input and, accordingly, the active power output. This, however, causes variations in the voltage at the generator terminals. This parameter is controlled using the automatic voltage regulation (AVR), which changes the field current and the generated reactive power. Thus, the processes of frequency, power, and voltage control are inextricably linked.

The development of AVR tuning methods required devising the algorithms for calculating dynamic stability. To this end, frequency methods implementing the procedure for D-partition in the plane of two AVR tuning coefficients were employed [1]-[6]. These algorithms, implemented in computer programs, were used to solve the control problem at one EPS node. The research in this case involved analyzing the influence of the EPS operating conditions and tuning parameters on the dynamic stability region. The next step suggested designing algorithms for AVR tuning to jointly optimize the parameters of controllers for several power plants. The degree of system stability was utilized as a criterion for the efficiency assessment.

The novelty of the proposed method for coordinated adjustment of the AVR and SAR of generators lies in a two-stage determination of the regulator settings: First, the AVR settings of all generators are determined comprehensively. Then, the AVR and SAR settings of these generators are determined comprehensively, taking into account the SAR settings determined in the first stage.

2. STATE-OF-ART OF RESEARCH

The use of the D-partition method to identify AVR settings in complex multi-machine EPSs is limited [7]. Therefore, the D-partition-based algorithms were improved through the optimization of settings. Further development of frequency methods led to the development of adaptive tuning algorithms based on experimental data [8]. The sequential tuning method created by A. A. Yurganov and V. A. Kozhevnikov has gained significant popularity in practical applications. It suggests replacing the external network of the power plant under study with an equivalent circuit "line – infinite buses" [9]. Gerasimov *et al.* [10] proposed a sequential tuning method based on the integral criterion of total energy.

The multi-parameter optimization methods for searching for AVR settings are considered in [11]. The study involves comparing various optimization algorithms (simplex, genetic, and others), as well as objective functions based on root and frequency criteria for assessing the control process. In [12], a microcontroller utilizing an algorithm relying on the generalized predictive control strategy is proposed for the AVR problem. In a preview study [13], the Elman artificial neural network is used to calculate the AVR tuning parameters, which allows creating an adaptive regulator. In [13], a neural regulator is constructed for the excitation system of a synchronous generator based on the imitating neural control method. This significantly improved the quality of the voltage transient process in the "synchronous generator - static load" system and enabled automation of the AVR synthesis and tuning processes using neural network technologies. The AVR based on fuzzy logic (FL AVR) is developed within the study. Tests on physical [14] and mathematical [15] models show better damping of oscillations in EPS using FL AVR. A method for designing a self-organizing excitation system with fuzzy logic, which combines the functions of AVR and a system stabilizer, is proposed in [16]. A new online learning algorithm that modifies the fuzzy rule base is developed. A method for optimizing an EPS stabilizer based on robust control technology is proposed in [15]. The comparison of a typical power system stabilizer and the proposed robust stabilizer is presented. The simulation results show the efficiency of the latter due to improved performance and reliability. Adaptive excitation regulators are proposed in [17]-[22]. The studies on their application demonstrated their high efficiency when the EPS operating conditions change.

Robust control methods are used to tune automatic speed control [23]. This study considers only the channel of action on the turbine. However, the use of combined frequency and excitation control improves the dynamic properties of the EPS. The use of the H method for optimal control aimed at boosting the performance of synchronous turbogenerators is proposed in [24]. The approach involves using a controller in addition to the AVR and ASC systems, which are installed as standard equipment at the majority of turbogenerator units. Additional control of a decentralized robust governor is proposed in [25]. It is based on the robust control theory. The simulation test results show that the stability is improved by limiting the interference. A distributed model predictive controller for a turbogenerator is proposed in [26]. Its parameters are determined using the models identified in real time. The findings of the research reveal that the proposed approach facilitates damping frequency and voltage oscillations with satisfactory quality compared to a typical control structure with PID controllers. An indirect speed control method based on a microprocessor system is proposed in [27] for a turbogenerator connected to the electrical grid through a direct current link (DC link) using a diode rectifier. This resulted in a non-sinusoidal shape of the three-phase voltage at the generator terminals and led to a significant error in the speed estimate with respect to voltage. Therefore, the study [28] proposed an indirect method for controlling this parameter, in addition to the general tuning of the automatic speed control system. This approach relies on the digital phase-locked loop method with a state observer to detect the positive-sequence voltage. The development of methods for tuning and implementing the automatic speed control has paved the way to the development of neuro-fuzzy systems [29]-[32]. In [29], an adaptive neuro-fuzzy inference system (ANFIS) is proposed to implement a neuro-fuzzy ASC. The authors note that the dynamic model obtained using ANFIS correctly describes the behavior of the turbine to stabilize its operating point under any disturbances. A turbogenerator controller based on fuzzy logic is presented in [30]. It helps the voltage and frequency quickly and accurately reach the desired values. To improve the regulatory capability of turbogenerator units under various operating conditions, a strategy for controlling the unit's operating conditions based on a fuzzy PID controller using a particle swarm optimization algorithm is proposed in [31] to improve the dynamic response. The PID parameters can be adapted in real time. The study [32] proposes a self-tuning fuzzy PI controller to regulate the frequency under large load fluctuations of an islanded synchronous generator of a micro-hydroelectric power plant.

Thus, the examination of the AVR and ASC tuning methods and technologies has revealed that the use of intelligent technologies and adaptive algorithms for regulating voltage and frequency in synchronous generators holds significant promise. This approach will facilitate implementing self-adjusting AVR and ASC. Furthermore, the need to use coordinated control of voltage and frequency becomes especially evident under peak and emergency conditions. Therefore, the method of coordinated tuning of AVR and ASC systems is described below, considering their mutual influence [33]. A technique for coordinated tuning of AVR and ASC of a group of parallel-operating generators of a power plant is given, along with solving the optimization problem using a genetic algorithm. Predictive algorithms are used to improve and regulate the dynamic stability indicators [33].

3. METHODOLOGY FOR COORDINATED TUNING OF THE AUTOMATIC VOLTAGE REGULATION AND AUTOMATIC SPEED CONTROL SYSTEMS OF A GROUP OF PARALLEL-OPERATING SYNCHRONOUS GENERATORS

The interaction between the speed and voltage control subsystems of the generator is manifested in the fact that an EPS has a composite structure and integrates several subsystems interconnected with each other. It becomes essential to take into account the mutual influence of processes in power units to provide the coordinated control of a group of generators at power plants. Technological processes running in individual generators are interrelated through a common load both within a separate power plant, and within the EPS as a whole. Separate consideration of processes in individual parts of power units can lead to a noticeable deterioration in their operation and even instability. Therefore, it becomes necessary to consider these processes within a single dynamic system.

We propose conducting the coordinated tuning of the AVR and ASC of a group of parallel-operating generators of a power plant in two stages. The frequency relations between generators and various parts of the EPS are obvious; therefore, the ASC settings of the group of generators should be determined considering them at the first stage. When identifying frequency control channels for parallel-operating generators, the system should be represented so as to take into account the relations among units operating for a common load. It is important to note that if consideration is given to a group of units operating for common buses, they are usually of the same type, i.e., identical in design and, therefore, are characterized by close dynamic properties. This circumstance allows us utilize an equivalent system, which significantly reduces the order of the characteristic equation.

In the event there are several bus systems at a power plant, several groups of parallel-operating units can be identified. To identify such a system at the first stage, it must be represented as a multivariable system, for example, as shown in Figure 1. The transfer functions of the generator W_G and turbine W_T are found experimentally in the form of complex transfer factors. After the characteristic polynomial of the equivalent system is identified and obtained, the ASC of all units can be tuned. This is achieved by solving an optimization problem to minimize the difference between the coefficients of the characteristic polynomial and those of the corresponding Butterworth polynomial. The AVR settings for the generators are determined by a genetic algorithm [33], where the sought-after controller coefficients are encoded as genes. Then we can switch to the second stage and determine the optimal settings of the AVR and the ASC, given their interplay. To this end, it is necessary to identify individual "turbine-generator" subsystems with the ASC settings obtained at the first stage.

To search for optimal AVR stabilization coefficients given the influence of the ASC, the "turbine-generator" system should be represented as a separate block. This system operates as a doubly-connected system that has two input actions coming from the controllers, and, in the general case, two controlled values - the rotor speed $\boldsymbol{\omega}_G$ and the generator voltage U_G, while the multi-connected (common) controller will have a diagonal connection along the AVR frequency control channel, as illustrated in Figure 2.

Thus, the matrix transfer function of the "common controller," reflecting the relationship between the AVR and ASC systems over the frequency channel, can be represented as (1).

$$W_p = \begin{vmatrix} W_{ASC} & W_{AVR}^{\omega} \\ 0 & W_{AVR}^{U} \end{vmatrix} \tag{1}$$

Where W_{ASC} is the complex transfer function of ASC; W_{AVR}^{ω} is the complex transfer function of the AVR frequency channel; $W_{AVR}^{U}$is the complex transfer function of the AVR voltage channel.

After the identification procedure, the obtained W_p is used to generate the characteristic polynomial of the turbine-generator system with the sought coefficients of the controller settings. Then the optimization problem is solved to reduce the difference between the corresponding coefficients of the desired polynomial, which has the required properties, and similar parameters of the system being tuned. A genetic algorithm is proposed to solve it [33]. It is also worth noting that it is advisable to perform the identification and coordinated tuning of the AVR and ASC of generators according to the described method for various operating conditions of the EPS (for example, for both minimum and maximum load levels), obtaining a set of optimal settings accordingly.

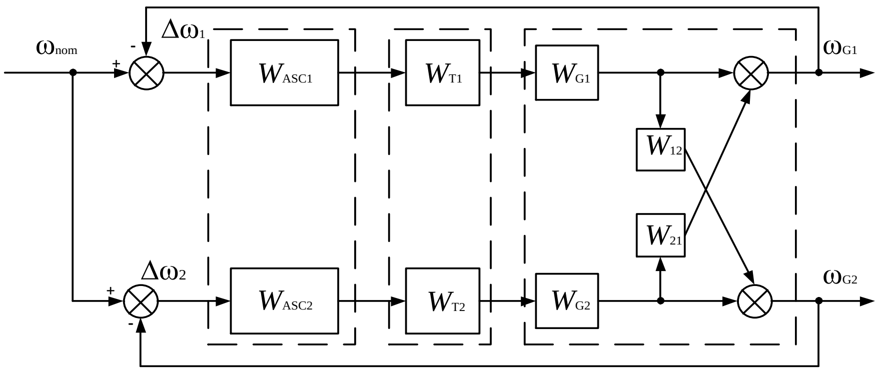


Figure 1. Structural representation of two connected speed control systems

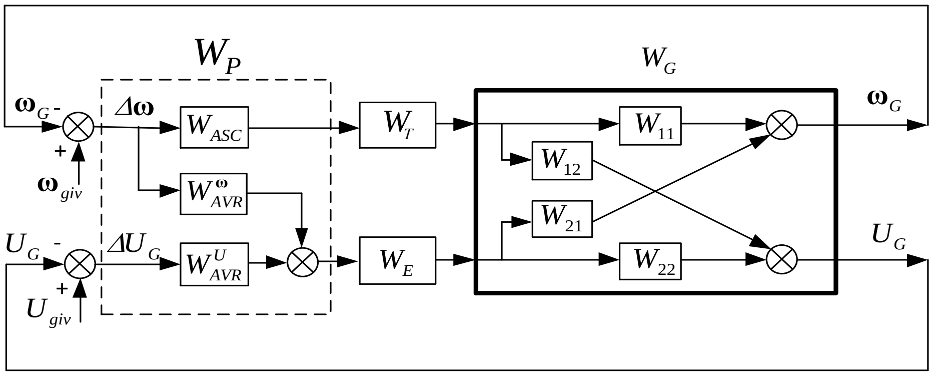


Figure 2. Structural representation of the controlled "turbine-generator" system

4. RESULTS OF APPLYING THE COORDINATED TUNING OF THE PREDICTIVE AVR AND ASC FOR A GROUP OF POWER PLANT GENERATORS

A model of a hydroelectric power plant operating in parallel with the system was developed using the SimPowerSystems and Simulink packages to investigate the proposed AVR and ASC tuning method. The diagram of the EPS model with a hydroelectric power plant is shown in Figure 3. The power plant has two voltage levels: 220 kV and 500 kV. Seven equivalent power units of a hydrogenator-transformer with a capacity of 2,059 MVA and three power units with a capacity of 882 MVA are connected to the 220 kV buses. Two equivalent power units with a capacity of 588 MVA and six power units with a capacity of 1,765 MVA are connected to the 500 kV buses. The generators are equipped with thyristor excitation systems, as well as microprocessor-based AVR and ASC. The model of the turbine with ASC was developed in MATLAB using the Simulink package. In this case, the ASC is modeled by an electrohydraulic controller that employs a PID control algorithm.

Each bus system has connections in the form of an active-inductive load. The lines connecting the 500 kV buses with the system form a ring together (Figure 3). The model allows for the introduction of disturbances such as disconnection or connection of loads on the 220 kV buses and at the receiving end of the 500 kV line. The load powers are shown in Figure 3. The algorithm described above is used to determine the optimal settings for the AVR and ASC. The simulation model schematic of the studied power system, developed in the MATLAB environment, is shown in Figure 4. The models for the generators, transformers, transmission lines, loads, and other auxiliary power system components were implemented using standard blocks from the SimPowerSystems and Simulink libraries. The description of the models used in the simulation model of Figure 4 namely the excitation system, AVR, and hydro-turbine with speed governor, is provided below in the form of their transfer functions.

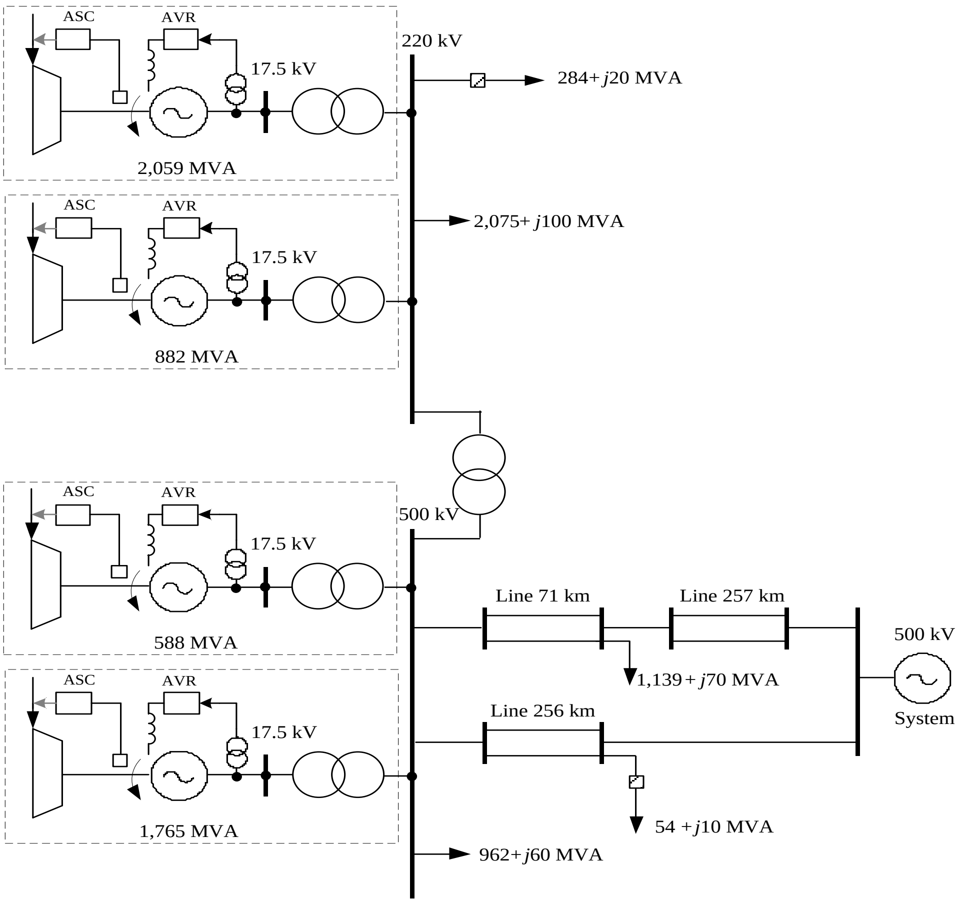


Figure 3. Diagram of EPS under study

The studies described below are aimed at analyzing the impact of the developed method for the coordinated tuning of the AVR and ASC on the EPS stability, focusing on the intra-group movement of generators at the power plant. For this purpose, equivalent units operating on different buses were represented as a doubly-connected system (Figure 1), for which a complex transfer function of the frequency control channel of the generator was obtained. Then, a characteristic polynomial $D^{m}(j\omega)$ and the corresponding Butterworth polynomial $D^{giv}(j\omega)$ with the required degree of stability were constructed:

$$D^{m}(j\omega) = -0.000025\omega^5 + (-j0.00005 \cdot W_G k_p + j0.003325 - j0.005 \cdot W_G k_d)\omega^4 +$$
$$+(0.08905 - 0.0046 \cdot W_G k_p - 0.0005 \cdot W_G k_i + 0.04 \cdot W_G k_d)\omega^3 + (-j0.656 +$$
$$+j0.046 \cdot W_G k_i - j0.041 \cdot W_G k_p)\omega^2 + (-0.1 - 0.1 \cdot W_G k_p - 0.41 \cdot W_G k_i)\omega + jW_G k_i;$$
$$D^{\text{giv}}(j\omega) = j\omega^5 + 3.2361\omega^4 - j5.2361\omega^3 - 5.2361\omega^2 + j3.2361\omega + 1$$

The genetic algorithm determined the following ASC settings: k_p = 932.66, k_i = 30.52, k_d = 31.24. On this basis, the 500 kV busbar turbine-generator system was identified, and a characteristic polynomial for the system presented in Figure 2 was designed:

$$D(j\omega) = W_{11} \cdot W_{ASC} \cdot W_T \cdot W_{AVR}^{U} \cdot W_{22} \cdot W_E + W_{11} \cdot W_{ASC} \cdot W_T + W_{21} \cdot W_{AVR}^{\omega} \times$$

$$\times W_E + W_{22} \cdot W_{AVR}^{U} \cdot W_E - W_{12} \cdot W_{ASC} \cdot W_{AVR}^{U} \cdot W_E \cdot W_T \cdot W_{21}. \quad (2)$$

where W_{11}, W_{22}, W_{12}, W_{21} are the complex transfer functions of the main channels and cross-connections of the generator; W_{AVR}^{U} is the complex transfer function of the voltage control channel of AVR:

$$W_{AVR}^{U} = \frac{0.5(j\omega)}{(0.5(j\omega)+1)} \cdot \left[k_{0u} - \frac{k_{1u}0.02(j\omega)}{0.06(j\omega)+1}\right], \quad (3)$$

where W_{AVR}^{ω} is the complex transfer function of the frequency control channel of AVR:

$$W_{AVR}^{\omega} = \frac{1+0.5(j\omega)}{0.5(j\omega)} \cdot \left[\frac{k_{0\omega}2(j\omega)}{(2(j\omega)+1)(0.02(j\omega)+1)} + \frac{k_{1\omega}0.05(j\omega)}{0.05(j\omega)+1}\right], \quad (4)$$

where $W_T = \frac{-(j\omega)+1}{0.5(j\omega)+1}$ is the complex transfer function of a hydroturbine; $W_E = \frac{1}{0.001(j\omega)+1} \cdot \frac{1}{0.025(j\omega)+1}$ is the complex transfer function of the thyristor excitation system; $W_{ASC} = \left(k_p + \frac{k_i}{0.1(j\omega)} + \frac{k_d(j\omega)}{0.01(j\omega)+1}\right) \cdot \frac{0.5(j\omega)+1}{0.5(j\omega)^2+6.5(j\omega)+1}$ is the complex transfer function of the ASC, given the PI controller and servomotor. Using the obtained polynomial, the optimal settings of the AVR were determined: k_{0u} = 50, k_{1u} = 0.16, $k_{0\omega}$ = 5.67, and $k_{1\omega}$ = 1.58.

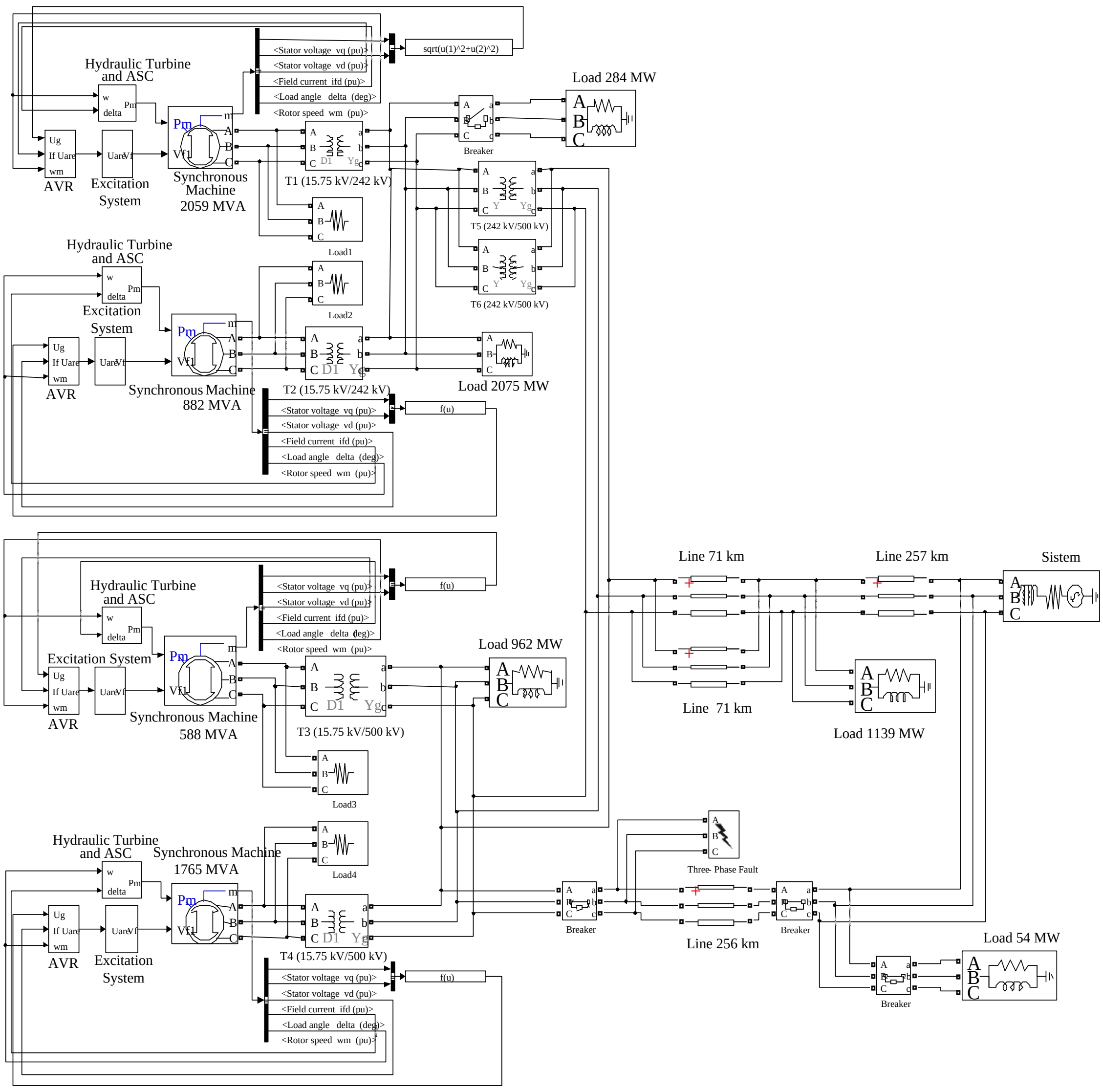


Figure 4. The scheme of the simulation model in MATLAB

The results of the simulation are presented in Figures 5–7. The stability analysis of the power plant at issue, with a focus on intra-group movement, was carried out by monitoring the change in the mutual angles of the generator rotors (Figure 5) with introduced disturbances in the form of connection and disconnection of the 284+j20 MVA load on 220 kV buses. The oscillogram shows that the internal oscillations quickly attenuate, which indicates the effectiveness of the proposed method for tuning the AVR and ASC.

As seen in the oscillograms of the voltage (Figure 6(a)) and speed of the generator rotor (Figure 6(b)), the AVR and ASC tuned in this way provide acceptable damping of electromechanical oscillations. At the same time, the use of the self-tuning lead-lag element in the ASC [33] significantly improved the quality indicators of voltage and frequency control: there is no voltage oscillation and frequency overshoot; the maximum deviation of these parameters is significantly reduced.

The effect of the developed method of coordinated tuning of the AVR and ASC on the transfer capability of the 71 km line was determined (Figure 3). For this purpose, the load was increased by successively increasing the power flow. In this case, the load grew in a power-balanced manner with the frequency remaining practically unchanged, which made it possible to reach the boundary of the stability region. The results of multiple simulations, which involved changes in the power flow and frequency for various AVR and ASC tuning methods (Figure 7), were used to determine the stability margin factor for active power. When tuning the AVR without considering the influence of ASC, the factor was K_{marg} = 26%, while with the coordinated tuning, the transmitted power limit increased and, as a result, the stability margin reached K_{marg}= 32 %.

Figure 8 shows the simulation results for a temporary short-circuit fault on the 256 km line (see Figure 3), which was cleared by disconnecting it from both ends after 0.5 seconds. The results are presented in terms of generator terminal voltage and rotor speed. Based on the results, it can be concluded that the application of the self-tuning lead-lag compensator in the AVR ensures stable operation of the power plant generators under this contingency.

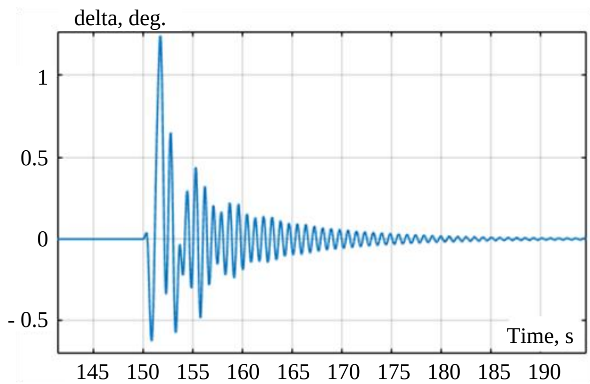


Figure 5. Oscillogram of changes in mutual angles of generator rotors

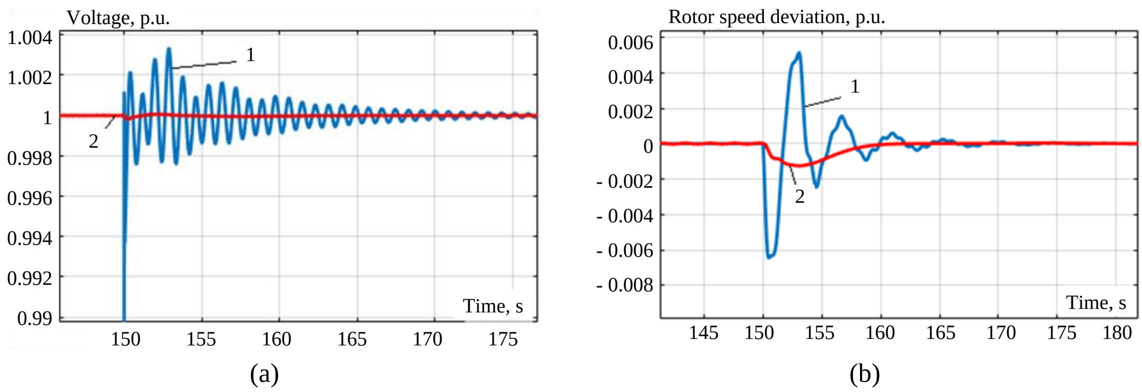


Figure 6. Oscillograms of changes in voltage: (a) rotor speed and (b) of the generator: 1 – AVR and ASC without a predictive element; 2 – AVR and ASC with a predictive element

Thus, the simulation model of the power plant built in MATLAB allows us to study the intra-group movements of generators and the capabilities of the proposed methods and algorithms for tuning the AVR and ASC systems. The developed method for the coordinated tuning of the AVR and ASC systems improves the damping properties of electromechanical oscillations in the EPS and increases its stability margin. The use of the self-tuning lead-lag compensator in the AVR significantly improves the regulation quality of both generator terminal voltage and rotor speed, while also ensuring the dynamic stability of the generators.

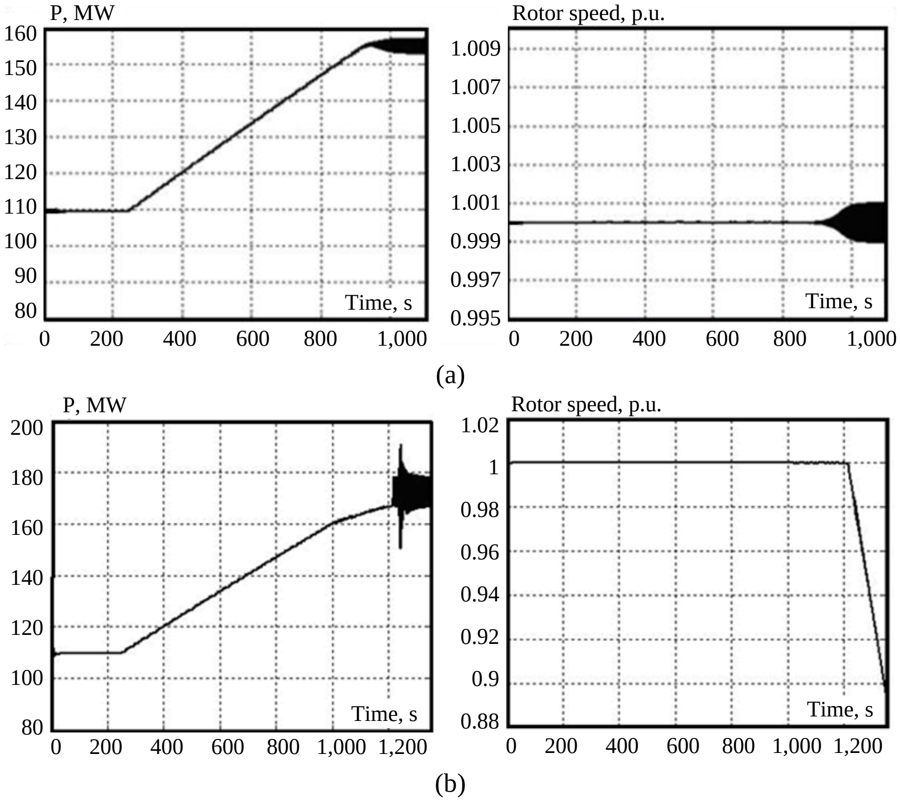
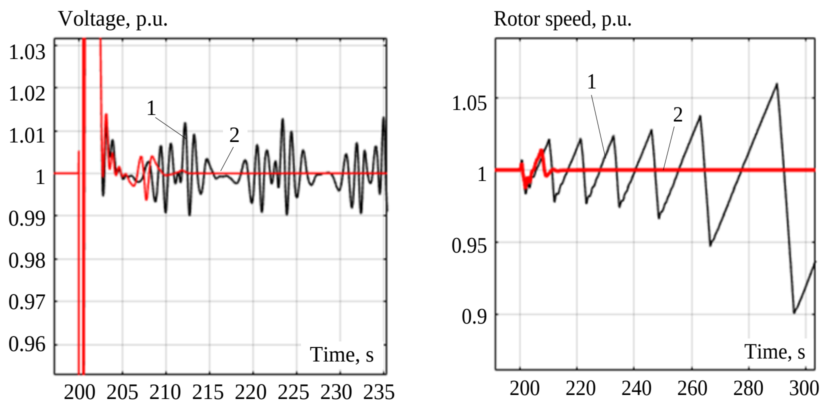


Figure 7. Determining the transmitted power limit for a 71 km line: (a) for non-coordinated tuning of AVR and ASC and (b) for coordinated tuning of AVR and ASC



(a) (b)

Figure 8. Change in (a) voltage and (b) generator rotor speed during a temporary short-circuit and the disconnection of the 256 km line: 1 - Generator AVR without the self-tuning lead-lag compensator; 2 - Generator AVR with the self-tuning lead-lag compensator

5. CONCLUSION

The research and modeling findings indicate that: The model of a power plant operating in parallel with an EPS, proposed within the study, demonstrates effective damping of oscillations under large disturbances when the AVR and ASC coefficients are tuned using the proposed method and the self-tuning lead-lag element. An analysis of the stability of the power plant, focused on intra-group movement of generators to adjust the mutual angles of the generator rotors in response to the disturbances introduced in the form of connection and disconnection of loads on the 220 kV buses has revealed that internal oscillations in the system rapidly decay. This indicates the effectiveness of the proposed method for tuning the AVR and ASC of a group of parallel generators. The use of the self-tuning lead-lag element in the ASC significantly improved the quality indicators of voltage and frequency control: there is no voltage oscillation and frequency overshoot; the maximum deviation of these parameters is markedly reduced. In the illustrative case study, the coordinated tuning of the AVR and ASC provided a 6% increase in the transmitted power limit and, as a consequence, an enhancement of the EPS stability margin.

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AUTHOR CONTRIBUTIONS STATEMENT

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C : **C**onceptualization
M : **M**ethodology
So : **So**ftware
Va : **Va**lidation
Fo : **Fo**rmal analysis
I : **I**nvestigation
R : **R**esources
D : **D**ata Curation
O : Writing - **O**riginal Draft
E : Writing - Review & **E**diting
Vi : **Vi**sualization
Su : **Su**pervision
P : **P**roject administration
Fu : **Fu**nding acquisition

CONFLICT OF INTEREST STATEMENT

Authors state no conflict of interest.

DATA AVAILABILITY

The data that support the findings of this study are available from the corresponding author, [KS], upon reasonable request.

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