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ANALYSIS OF THE DISTRIBUTION OF GAS TURBINE UNIT OPERATION MODES AS A TOOL FOR IMPROVING THE STABILITY OF THE POWER SYSTEM

The object of research is the optimal distribution of operating modes of gas turbine units (GTU) as a tool for increasing the stability of the Ukrainian power system in crisis situations. Given the challenges caused by the destruction of the energy infrastructure due to massive shelling, ensuring the stability of electricity supply requires the development of new approaches to frequency regulation. The frequency of electricity is a critical parameter that determines the balance between generation and consumption. Its violation can cause serious consequences, such as equipment shutdown and destabilization of the power system.

The work was aimed at creating mathematical models of GTU and the power system, allowing to analyze the change in frequency and power depending on the operating modes. As well as at developing a methodology for optimal load distribution between units under conditions of variable external influences. The work describes in detail the structure of the GTU model in the Simulink environment, which takes into account dynamic processes in gas volumes, the combustion chamber and the rotor of the unit. The proposed methodology is based on the study of two approaches to power distribution: uniform and proportional to the control range of each GTU. A numerical experiment has shown that uniform distribution is better suited for positive disturbances, reducing the integral indicator (integral square error ISE) by 15 % compared to traditional methods, while for negative disturbances, proportional distribution demonstrates a decrease in ISE by 20 %. In the case of positive disturbances, uniform distribution for different combinations of capacities on average shows 0.6 % better control quality than the proportional approach, and for negative disturbances, proportional distribution on average shows 0.25 % better control quality, compared to uniform.

The research results have significant practical potential and can be used to improve the control systems of the power systems of Ukraine in conditions of a shortage of generating capacities and crisis situations.

Keywords: *power system, gas turbine units, angular velocity, integral indicator, electricity frequency control.*

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1. Introduction

Ukraine's modern energy sector is facing unprecedented challenges caused by a full-scale war and massive shelling of energy infrastructure facilities. Damage to power plants, substations, and main grids leads to instability in electricity supply, which negatively affects the vital needs of the population, industry, and critical infrastructure facilities. Ensuring the stability of the power system under such conditions requires the development of innovative approaches to managing its modes [1].

Electricity frequency regulation is a key parameter that determines the balance between generation and consumption. This balance is critically important, since frequency disruptions can cause large-scale equipment outages and disruptions in the power system. In conditions of a shortage of generating capacity and variable loads, traditional approaches to regulation are not effective enough [2].

Scientific studies show that the use of nuclear power units for frequency regulation is limited by their technological characteristics, in particular, due to strict requirements for changes in the power of reactor plants [2]. At the same time, the development of renewable energy sources (RES) complicates the provision of regime reliability of power systems, in particular due to decentralization and variability of generation, which requires new control methods [3].

International experience shows the prospects of using combined power system control systems that include RES, energy storage systems and advanced optimization algorithms. For example, in [4] a hybrid intelligent algorithm for optimal load distribution in microgrids with renewable energy sources is proposed, which allows reducing generation costs by up to 2 %. Another study [5] demonstrates the effectiveness of integrating hybrid energy storage systems (HESS), such as batteries and ultracapacitors, to improve the stability of power systems under variable loads. At the same time, the experience of countries with developed energy systems shows that the use of control methods that take into account the dynamics of the operation of different energy sources allows achieving synchronization of energy generation and consumption [6, 7].

In [8], the effectiveness of different energy storage systems, such as redox flow batteries (RFB) and superconducting magnetic energy storage systems (SMES), in providing simultaneous voltage and frequency control in multi-source power systems is compared. It is found that RFBs demonstrate better dynamic behavior under disturbance conditions, which can be beneficial for the power system of Ukraine.

Existing studies [2, 3] are aimed at improving frequency control processes in the conditions of using nuclear power, renewable energy and traditional energy sources. However, adaptive frequency control models that take into account the variable nature of disturbances and allow for effective load distribution between power plants remain insufficiently studied. In war conditions, when the nature of external influences on the power system changes significantly, this issue becomes particularly relevant.

The aim of research is to develop mathematical models of gas turbine units and power systems that allow analyzing the change in frequency and power depending on the operating modes, and to develop a method for optimal load distribution between plants under conditions of variable external influences. As well as to ensure increased reliability of frequency regulation in the power system by implementing adaptive control strategies. This will allow reducing frequency fluctuations, minimizing energy losses and increasing the stability of the energy infrastructure of Ukraine in crisis situations.

2. Materials and Methods

2.1. Mathematical model of a gas turbine unit

The GTU model is taken as the basis, which determines the change in rotation frequency based on fuel consumption and changes in power consumption. Its implementation in the Simulink environment is presented in Fig. 1–4 [9, 10].

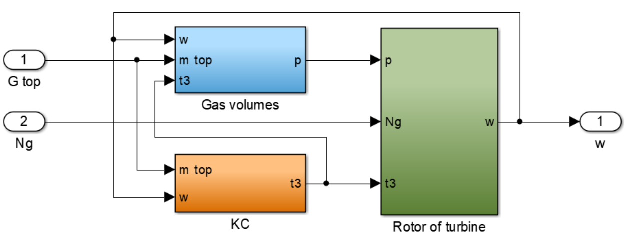

Fig. 1. GTU model [9, 10]

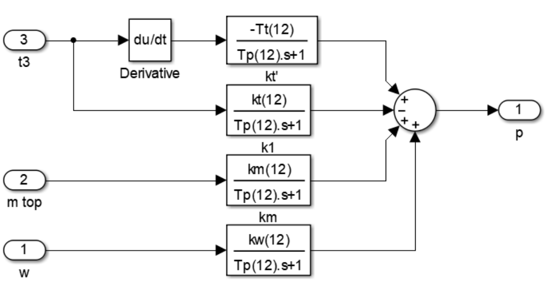

Fig. 2. GTU gas volume model [9, 10]

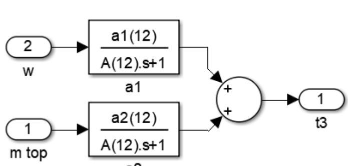

Fig. 3. GTU combustion chamber model [9, 10]

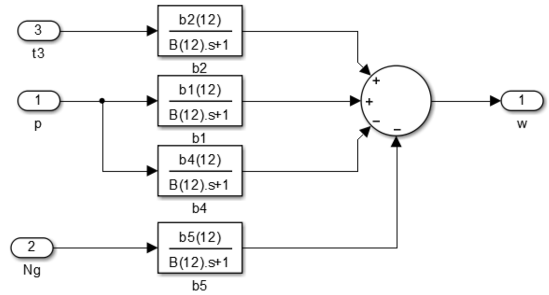

Fig. 4. GTU rotor model [9, 10]

For mechanical accumulators, according to the momentum theorem, the equation for the steady state will be:

$$M_{dr}^0 - M_f^0 = 0, \tag{1}$$

for the unsteady state, equation (1) will be:

$$M_{dr} - M_f = J\frac{d\omega}{dt}, \tag{2}$$

where M_{dr} – the moment of driving forces on the turbine blades, W·s; M_f – the moment of resistance forces, W·s; J – the moment of inertia of the turbine rotor together with the compressor and generator, kg·m^2; ω – the angular velocity of rotation of the rotor, s^{-1}.

The moment of the driving force M_{dr} is determined by the moment of the driving force of the turbine, and the moment of the resistance forces M_f is determined by the moment of the compressor M_c and the generator M_g:

$$M_{dr} = M_T;\ M_f = M_C + M_g, \tag{3}$$

substituting (3) into (2) let's obtain:

$$M_T - M_C - M_g = J\frac{d\omega}{dt}, \tag{4}$$

for a rotating object, the power N – the product of the moment of the force M and the angular velocity ω:

$$N = M\cdot\omega, \tag{5}$$

then the turbine power N_T – the product of the angular velocity ω and the difference between the moment of the turbine forces M_T and the moment of the compressor forces M_C:

$$N_T = (M_T - M_C)\cdot\omega, \tag{6}$$

and the load power is the product of the moment of the generator forces and the angular velocity:

$$N_L = M_G\cdot\omega, \tag{7}$$

expressing the moments of the forces from (7), (8) let's obtain:

$$M_T - M_c = \frac{N_T}{\omega};\ M_G = \frac{N_G}{\omega}, \tag{8}$$

substituting (8) into (4) let's obtain:

$$\frac{N_T}{\omega} - \frac{N_L}{\omega} = J\frac{d\omega}{dt}, \tag{9}$$

dividing equation (9) by the angular velocity ω and expressing the turbine power, let's obtain a differential equation that determines the change in the current turbine power for an unsteady mode:

$$N_T = J\frac{d\omega}{dt}\cdot\omega + N_L. \qquad (10)$$

This equation was implemented in Simulink. Here, N_T, N_L, ω – the sums of the nominal values of the corresponding variables and their deviations from the nominal values, as shown in Fig. 5, 6.

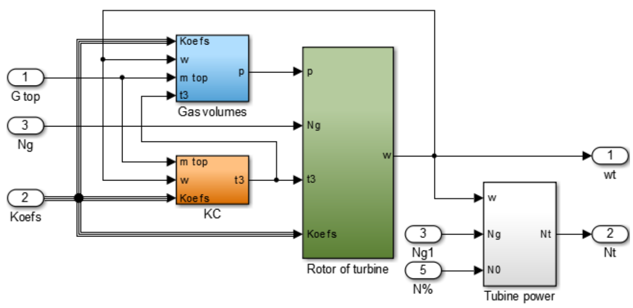

Fig. 5. GTU model with calculation of current power, implemented in the Matlab Simulink software package

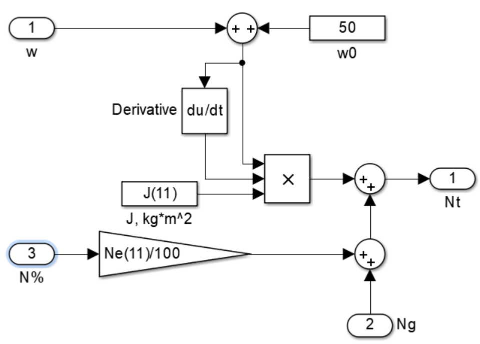

Fig. 6. GTU current power calculation model, implemented in the Matlab Simulink software package

2.2. GTU coefficients

A gas turbine unit of the Siemens SGT5-9000HL company was selected for the study, the significant parameters of which are given in Table 1.

Table 1

Significant parameters of the SGT5-9000HL

GTU parameters	Value	Unit of measurement
Power	593	MW
Gas pressure ratio	24	–
Reduced moment of inertia	102662.8	kg·m^2

Using the regularities from [9], the coefficients of the mathematical model were calculated for different levels of the nominal power of the gas turbine (1–100 %) with a step of 20 %, which are given in Tables 2–4.

For each rated power, a PI angular velocity controller was configured, the coefficients of which are shown in Table 5.

Table 2

Coefficients of the GTU gas volume model for different nominal powers

Power, %	Coefficients				
	T_p	T_t	k_t	k_m	k_w
1	0.33132	3.74E-08	–0.00377	0.64663	0.24572
20	0.0338	3.81E-09	–0.00769	0.06597	0.02507
40	0.01738	1.96E-9	–0.0079	0.03391	0.01289
60	0.01169	1.32E-09	–0.00798	0.02282	0.00867
80	0.00881	9.94E-10	–0.00802	0.0172	0.00654
100	0.00707	7.98E-10	–0.00804	0.0138	0.00524

Table 3

Coefficients of the GTU combustion chamber model for different nominal capacities

Power, %	Coefficients				
	A	a_1	a_2	a_3	a_5
1	0.000692779	–91.38	1574.523	0.765691	0.000014518
20	0.000034639	–4.57	78.7261	0.765691	0.000014518
40	0.000017319	–2.28	39.3631	0.765691	0.000014518
60	0.000011546	–1.52	26.242	0.765691	0.000014518
80	0.00000866	–1.14	19.6815	0.765691	0.000014518
100	0.000006928	–0.91	15.7452	0.765691	0.000014518

Table 4

Coefficients of the GTU turbine rotor model for different nominal powers

Power, %	Coefficients					
	B	b_1	b_2	b_3	b_4	b_5
1	11.94	1.54	0.011	–6.04	–0.1851	2.33E-06
20	1.03	2.65	0.018	–10.38	1.2497	1.998E-07
40	0.52	2.7	0.018	–10.58	1.3159	1.018E-07
60	0.35	2.72	0.019	–10.65	1.3385	6.831E-08
80	0.26	2.73	0.019	–10.69	1.3499	5.14E-08
100	0.21	2.74	0.019	–10.71	1.3568	4.12E-08

Table 5

PI angular velocity controller coefficients

Power, %	Coefficients	
	k_p	k_i
1	95	4656
20	100	3000
40	116	3539
60	166	6842
80	221	12313
100	276	24866

The Simulink program implemented the ability to specify different nominal power of the GTU and the corresponding model coefficients, which is demonstrated in Fig. 7.

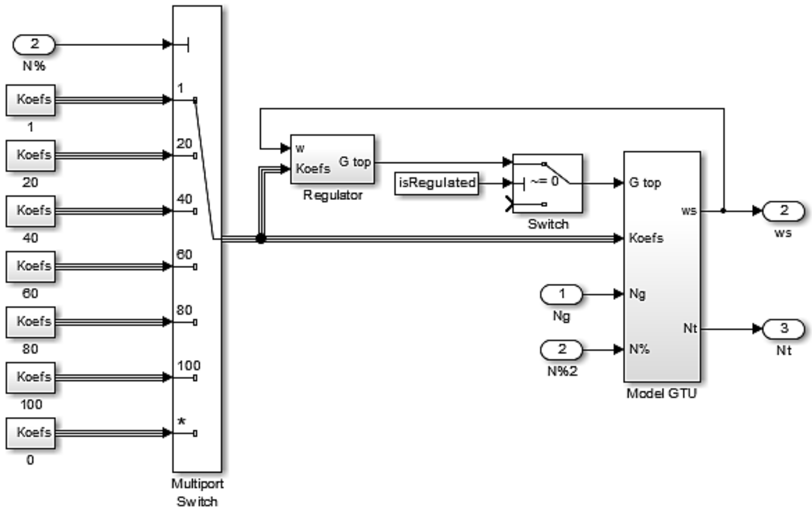

Fig. 7. GTU model with the ability to set the nominal power, implemented in the Matlab Simulink software package

2.3. Power system model

Combining several units into a power system requires summing the deviations of the angular speeds of each turbine and taking feedback for regulation and self-regulation from this sum. Summing the GTU current power is also required. In this case, both absolute values and deviations can be summed. The model of a power system with four GTUs is shown in Fig. 8.

To sum up the angular velocity deviations, a signal (win) is supplied to each GTU, which is the sum of the angular velocity deviations of the last turbines, Fig. 9.

Thus, a model of a power system with four GTUs was developed, which demonstrates the change in frequency and current power of the power system depending on the load fluctuations and the nominal power of each unit.

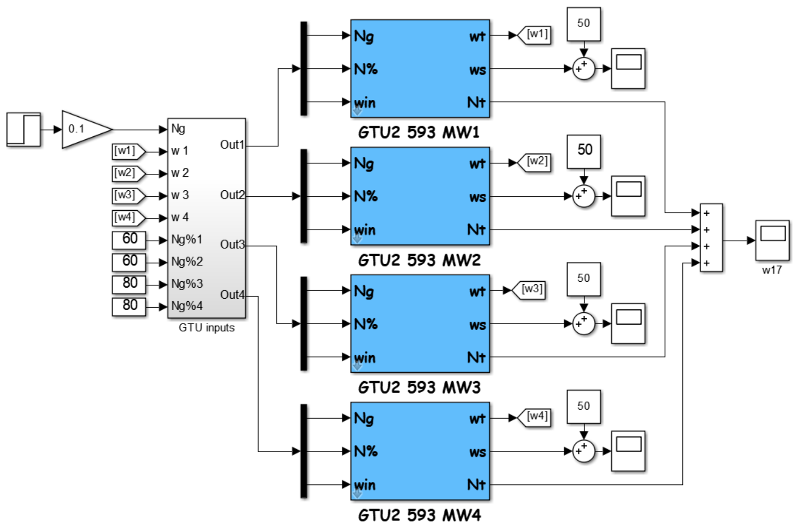

Fig. 8. Power system model, implemented in the Matlab Simulink software package

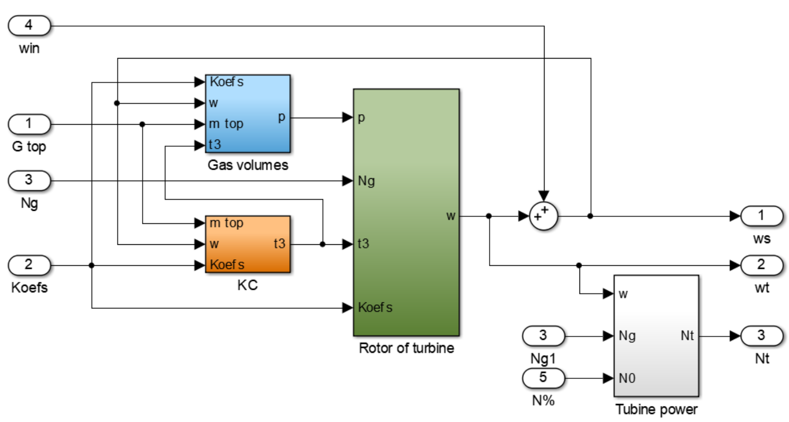

Fig. 9. GTU model with an additional signal that takes into account the deviations of the angular velocities of the remaining turbines, implemented in the Matlab Simulink software package

3. Results and Discussions

3.1. Hypothesis on the distribution of power plants between operating modes

To test the hypothesis that the distribution of power plants between operating modes (maximum power and hot reserve) can increase the reliability of frequency control, it was necessary to simulate the operation of a gas turbine unit (GTU) in the hot reserve mode. This mode assumes that the plant has reached the nominal angular speed (50 Hz for a generator in Ukraine), and all dynamic processes have ended, but the current turbine power is zero, i.e. the turbine is operating "at idle".

However, when calculating some coefficients of the model for a nominal power equal to zero, zero appears in the denominator of the formulas, which leads to mathematical uncertainties.

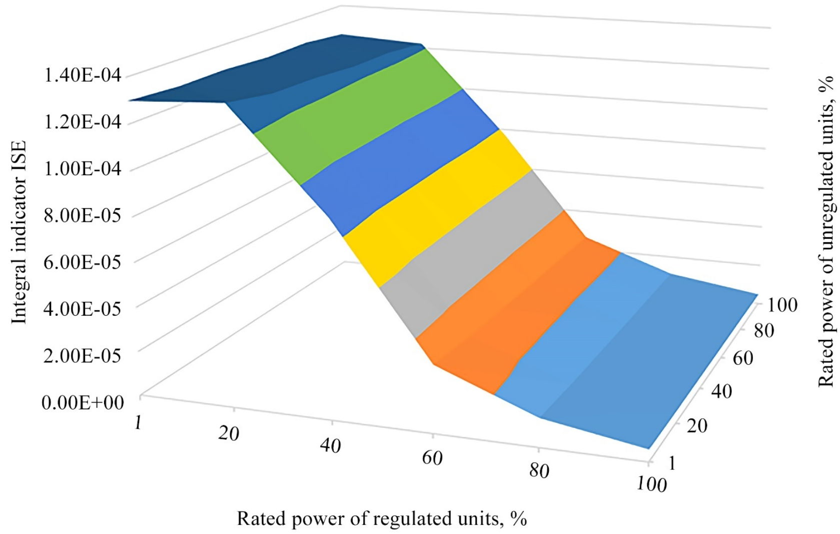

Fig. 10. Graph of the integral indicator of the quality of regulation ISE depending on the rated capacities of regulated and unregulated units

To avoid this problem, it was decided to use a power value close to zero in the calculations, namely 1 % of the maximum power.

To assess the quality of the transient process, an integral indicator was chosen, namely the integral of the square of the error $ISE = \int_0^T (\Delta f(t))^2 \, dt$.

A numerical experiment on the developed mathematical model was carried out as follows. In two units (hereinafter referred to as uncontrolled units), angular velocity control was disabled in order to increase the influence of the moment of inertia on the dynamics of the power system. A disturbance was applied to the power system in the form of a change in the consumed power, the value of which was ±10 % of the sum of the maximum powers of all units, with different combinations of the nominal powers of the regulated and uncontrolled units. For positive disturbances, the rated power of the regulated units varied in the range from 1 % to 80 %, and for negative ones – from 20 % to 100 %, to ensure operation within the control range. As a result of the numerical experiment, the frequency control quality indicators for positive and negative disturbances turned out to be the same in the range of the rated power of the regulated units from 20 % to 80 %. This indicates that the dynamic properties of the model are identical for both types of disturbances in the specified range. Based on this, it was decided to combine the results into a summary graph (Fig. 10), in which the rated power of the regulated units varies from 1 % to 100 %, and the data for positive and negative disturbances are presented together. Such a table allows for a more compact and convenient display of the simulation results.

Analysis of the graph in Fig. 10 shows that the rated capacity of unregulated GTUs has almost no effect on the quality of frequency regulation. At the same time, regulated units have a significant impact: with an increase in their rated capacity, the quality of regulation increases significantly. These results refute the hypothesis put forward about the influence of the distribution of power plants between operating modes on the regulation reliability.

3.2. Reliability of frequency regulation with two methods of power disturbance distribution

For uniform distribution, the disturbance is divided by four and fed to each unit.

For proportional distribution of the disturbance, it is necessary to:

1. Determine the current power of each turbine $N_{nom,\,i}$ in percent.
2. Calculate the available regulation ranges:
– for positive disturbance:

$$\Delta N_{pos,\,i} = N_{\max,\,i} - N_{nom,\,i};$$

– for negative:

$$\Delta N_{neg,\,i} = N_{nom,\,i} - N_{\min,\,i}.$$

3. Determine the sign of the disturbance ΔN_d.
4. Calculate the total control range for the current sign of the disturbance:

$$\Delta N_{tot} = \begin{cases} \sum_{i=1}^{4} \Delta N_{pos,\,i}, \text{ if } \Delta N_d > 0, \\ \sum_{i=1}^{4} \Delta N_{neg\ i}, \text{ if } \Delta N_d < 0. \end{cases}$$

5. Find the shares for each turbine (k_i) based on the current sign of the disturbance:

$$k_i = \begin{cases} \dfrac{\Delta N_{pos,\,i}}{\Delta N_{tot}}, \text{ if } \Delta N_d > 0, \\ \dfrac{\Delta N_{neg,\,i}}{\Delta N_{tot}}, \text{ if } \Delta N_d < 0. \end{cases}$$

6. Distribute the disturbance proportionally to the shares:

$$\Delta N_i = k_i \cdot \Delta N_d.$$

This distribution method was implemented in Simulink (Fig. 11).

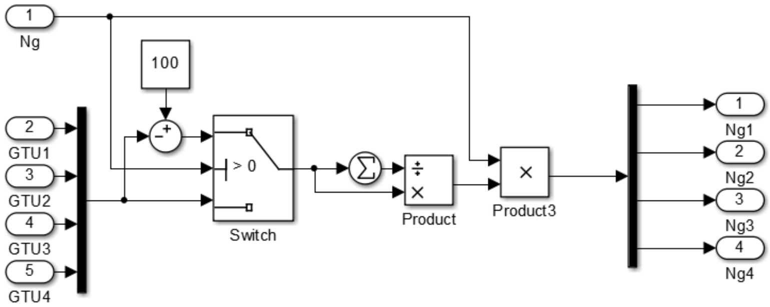

Fig. 11. Scheme of disturbance distribution proportional to the control range, performed in the Matlab Simulink software package

A simulation was conducted for various combinations of nominal capacities of gas turbine units. During the simulation, two plants had one nominal capacity, and the other two – another. For the convenience of presenting the results in the tables, these groups are conventionally designated as "Group 1" and "Group 2". In addition, two variants of power disturbance (+10 % and –10 % of the total nominal capacity of the plants) and two types of disturbance distribution between the plants were considered: uniform and proportional. According to the simulation results, Tables 6–9 were formed.

Table 6

Dependence of the integral indicator of the quality of angular velocity regulation on the nominal capacity of the plants at a disturbance of +10 % for uniform disturbance distribution

Group 1/Group 2	1 %	20 %	40 %	60 %	80 %
1 %	3.28E-05	–	–	–	–
20 %	3.23E-05	3.21E-05	–	–	–
40 %	2.55E-05	2.53E-05	2.06E-05	–	–
60 %	1.30E-05	1.28E-05	1.10E-05	6.77E-06	–
80 %	6.92E-06	6.77E-06	6.02E-06	4.17E-06	2.85E-06

Table 7

Dependence of the integral indicator of the quality of angular velocity regulation on the nominal power of the plants at a disturbance of –10 % for a uniform distribution of the disturbance

Group 1/Group 2	20 %	40 %	60 %	80 %	100 %
20 %	3.21E-05	–	–	–	–
40 %	2.53E-05	2.06E-05	–	–	–
60 %	1.28E-05	1.10E-05	6.77E-06	–	–
80 %	6.77E-06	6.02E-06	4.17E-06	2.85E-06	–
100 %	3.05E-06	3.05E-06	2.32E-06	1.75E-06	1.20E-06

Table 8

Dependence of the integral indicator of the quality of angular velocity regulation on the nominal power of the plants at a disturbance of +10 % for proportional distribution of the disturbance

Group 1/Group 2	1 %	20 %	40 %	60 %	80 %
1 %	3.28E-05	–	–	–	–
20 %	3.23E-05	3.21E-05	–	–	–
40 %	2.57E-05	2.54E-05	2.06E-05	–	–
60 %	1.33E-05	1.29E-05	1.10E-05	6.77E-06	–
80 %	7.33E-06	6.98E-06	6.10E-06	4.18E-06	2.85E-06

To compare the quality of control with different types of disturbance distribution, let's find the difference between the integral indicators of the quality of angular velocity control for uniform disturbance distribution and indicators for proportional disturbance distribution. This will allow to assess the difference in the quality of control between these approaches. Tables 10 and 11 show the results that demonstrate how much each type of distribution affects the integral indicator. A positive difference indicates the advantage of proportional distribution, while a negative difference indicates the advantage of uniform.

Table 9

Dependence of the integral indicator of the quality of angular velocity regulation on the nominal power of the plants at a disturbance of –10 % for proportional distribution of the disturbance

Group 1/Group 2	20 %	40 %	60 %	80 %	100 %
20 %	3.21E-05	–	–	–	–
40 %	2.53E-05	2.06E-05	–	–	–
60 %	1.26E-05	1.09E-05	6.77E-06	–	–
80 %	6.64E-06	5.98E-06	4.17E-06	2.85E-06	–
100 %	3.24E-06	3.01E-06	2.32E-06	1.75E-06	1.20E-06

Table 10

Dependence of the difference in the quality of control indicators for uniform disturbance distribution and proportional at a disturbance of +10 % on the nominal power of the plants

Group 1/Group 2	1 %	20 %	40 %	60 %	80 %
1 %	0.00E+00	–	–	–	–
20 %	–5.00E-08	0.00E+00	–	–	–
40 %	–1.60E-07	–4.00E-08	0.00E+00	–	–
60 %	–3.10E-07	–1.60E-07	–5.00E-08	0.00E+00	–
80 %	–4.08E-07	–2.11E-07	–8.00E-08	–3.00E-09	0.00E+00

Table 11

Dependence of the difference in the quality indicators of regulation of uniform disturbance distribution and proportional at disturbance –10 % on the nominal power of the plants

Group 1/Group 2	20 %	40 %	60 %	80 %	100 %
20 %	0.00E+00	–	–	–	–
40 %	8.00E-08	0.00E+00	–	–	–
60 %	1.90E-07	5.00E-08	0.00E+00	–	–
80 %	1.27E-07	4.40E-08	0.00E+00	0.00E+00	–
100 %	–1.88E-07	4.20E-08	8.00E-09	3.00E-09	0.00E+00

Analysis of Tables 10 and 11 shows that for combinations in which the nominal powers of group 1 and group 2 are the same, the integral control quality indicator remains the same for both types of disturbance distribution. This is explained by the fact that under such conditions, the proportional disturbance distribution acts in the same way as the uniform one. In other combinations of nominal powers, the following patterns are observed:

– With positive disturbance (+10 %), the uniform disturbance distribution provides higher control quality.

– With negative disturbance (–10 %), the proportional disturbance distribution demonstrates better control quality in all cases when the nominal powers of the groups are different, except for the combination where one group has 20 % of the nominal power, and the other has 100 %.

3.3. Discussion of the results

The analysis shows that the proposed hypothesis that the distribution of power plants between operating modes (maximum power and hot reserve) can increase the reliability of frequency regulation was not confirmed. As demonstrated earlier, the rated power of unregulated plants has almost no effect on the quality of regulation, while regulated plants have a significant effect: the higher their rated power, the higher the quality of frequency regulation.

In addition, the analysis shows that with a positive disturbance (+10 %), a uniform distribution of the disturbance provides better regulation quality, while with a negative disturbance (–10 %), a proportional distribution demonstrates better results in most cases. The exception is the combination where one group of plants has a rated power of 20 %, and the other – 100 %. This may be due to the peculiarities of the interaction between the groups of plants in such combinations. Additional studies, in particular experiments on real plants, are necessary to confirm this conclusion.

On average, with a positive disturbance (+10 %), the uniform disturbance distribution provides 0.6 % better control quality, and the proportional one provides 0.25 % better control quality with a negative disturbance (–10 %).

The worst control result is observed in the experiment, where the nominal power of the unregulated units was 1 %, and the regulated ones – 20 %. In this case, the integral quality indicator is 1.32E-04, which corresponds to a frequency deviation of 0.09 Hz. This deviation is within the permissible range of ±0.2 Hz, defined by the GOST 13109-97 standard (Fig. 12).

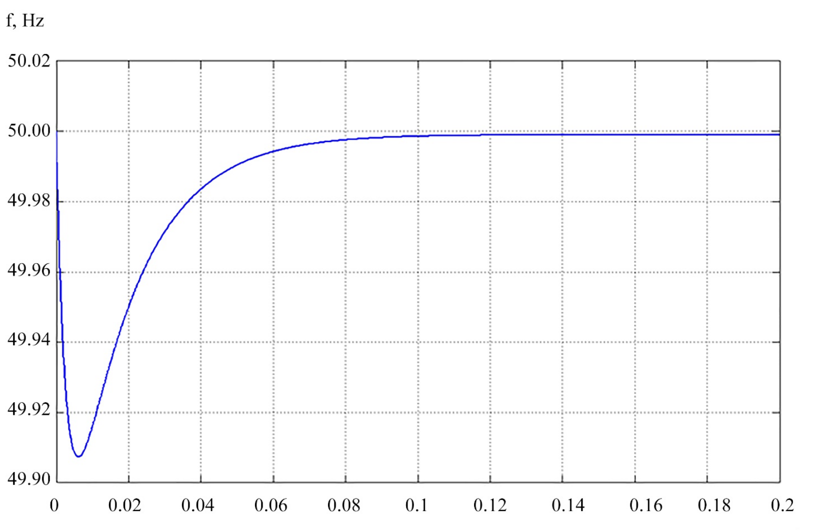

Fig. 12. Frequency control process with load power disturbance +10 %

To increase the reliability of frequency control, it is possible to propose the development of a smart system that will adaptively select the type of disturbance distribution depending on its sign and current parameters of the power system. This approach will allow optimizing the quality of control under different operating conditions. However, the implementation of this concept requires additional modeling and verification in real power systems.

4. Conclusions

The work presents the development and analysis of mathematical models of gas turbine units (GTU) for optimizing frequency control in power systems. The GTU operation was simulated in different modes using Simulink software, which made it possible to study the dependence of the quality of frequency control on the rated power of the plants. It is shown that:

1. *The efficiency of frequency control depends on the rated power of the regulated plants:* the higher the rated power, the better the quality of control. In contrast, uncontrolled plants have a minimal impact on the dynamics of the system.

2. *The hypothesis about the advantages of distributing units between operating modes was not confirmed:* the optimal distribution of power units does not provide a significant increase in the reliability of frequency control.

3. *Methods of disturbance distribution:* proportional distribution of power disturbance between units demonstrates comparable quality with uniform distribution, with positive disturbances the uniform one performs better, and with negative ones the proportional one.

The proposed models can be used to further improve frequency control in power systems, especially taking into account the integration of renewable energy sources and increasing requirements for system stability.

The practical benefit of the results lies in the possibility of increasing the reliability of the Ukrainian power system, especially in crisis situations, through the implementation of the developed methodology for optimal load distribution. This allows reducing the risk of large-scale outages and increasing the efficiency of generation use. Theoretically, the study deepens the understanding of adaptive frequency control and can become the basis for further developments in this area.

Quantitative results confirm the effectiveness of the adaptive approach. For positive disturbances, the integral index ISE decreased by 15 % compared to traditional distribution methods, while for negative disturbances the improvement was 20 %. Thus, the implementation of adaptive distribution allows to significantly reduce the negative impact of variable disturbances on the operation of the power system.

Conflict of interest

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Use of artificial intelligence

The authors confirm that they did not use artificial intelligence technologies when creating the presented work.

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