UDC 621.3
DOI: 10.15587/2706-5448.2024.314219

Viktoriia Kryvda,
Maksym Maksymov,
Viktor Zubak,
Andrii Ivaneiev,
Ruslan Ryaboshapka

DEVELOPMENT OF THE MODEL AND IMPROVEMENT OF THE METHOD OF AUTOMATED CONTROL OF STEAM TURBINE PARAMETERS TO MINIMIZE THE POWER IMBALANCE IN THE ENERGY SYSTEM TO INCREASE ITS EFFICIENCY

The object of research is the process of regulating power imbalances due to automated control of steam turbine parameters. The work solves the problem of minimizing power imbalances in the electric power system by developing a model of automated control of steam turbine parameters. This will ensure high-quality regulation of frequency and power, increase the efficiency and stability of the electric power system, and provide a new management method for reliable power supply to consumers.

The paper analyzes existing models and methods of power imbalance regulation, develops a dynamic model of automated control of K-300-240 steam turbines, which includes a mechanical-hydraulic system, a steam boiler and a steam superheater. As a result of the study, an improved power regulation method was proposed, which ensures efficient operation of the electric power system. The evaluation of the effectiveness of the regulation of imbalances was carried out on the basis of the proposed criterion of the efficiency of electricity supply and consumption, which is based on the convolution of partial criteria into the general criterion of the efficiency of electricity supply. The following criteria were proposed as partial criteria for electricity supply and consumption: volume criterion, quality criterion, and electricity supply efficiency criterion. The research results indicate the need for a reserve on each steam turbine in the amount of 10 % of its nominal power, which is explained by the assessment of the efficiency of electricity supply among the considered modes of operation of the systems. The presence of a power reserve on each steam turbine in the amount of 10 % of their nominal power ensures the most efficient power supply within the considered modes of operation of the power system, taking into account disturbances and as an imbalance of power generation and power consumption. The obtained research results can be applied in the strategy of primary regulation of power imbalances in the electric power system, thanks to the creation of a power reserve in the amount of 10 % of the nominal power on each steam turbine, and the organization of automated control of steam turbine parameters.

Keywords: *electric power system, efficiency, reliability, quality, frequency regulation, disturbance, unbalance, steam turbine, primary regulation.*

Received date: 09.09.2024
Accepted date: 29.10.2024
Published date: 31.10.2024

How to cite

Kryvda, V., Maksymov, M., Zubak, V., Ivaneiev, A., Ryaboshapka, R. (2024). Development of the model and improvement of the method of automated control of steam turbine parameters to minimize the power imbalance in the energy system to increase its efficiency. Technology Audit and Production Reserves, 5 (1 (79)), 19–29. https://doi.org/10.15587/2706-5448.2024.314219

1. Introduction

For the reliable and efficient operation of the electric power system (EPS), it is necessary that the quality indicators correspond to the normative values. One of the key indicators of the quality of electrical energy (EE) in the EPS is the frequency. Its value directly depends on the balance of power generation and consumption. The nominal value of the frequency in the unified energy system (UES) of Ukraine is 50 Hz. Since the load in the UES is constantly changing, there is a need to constantly maintain the frequency within acceptable limits due to the change in the generating power that can be developed by turbine units at thermal power plants (TPP), hydroelectric power plants (HPP), etc. Normative conditions regarding the quality of EE for UES of Ukraine are regulated [1, 2] and are:

– for systems that are synchronously connected to the UES of Ukraine – 50 Hz±1 % during 99.5 % of the time per year and 50 Hz+4 % (–6 %) during 100 % of the time;
– for systems without synchronous connection to the UES of Ukraine – 50 Hz±2 % during 99.5 % of the time per year and 50 Hz±15 % during 100 % of the time.

ISSN 2664-9969

In connection with the increase in the number of energy-intensive devices, the unevenness of the daily schedule of EE consumption and various disturbances of the EE requires constant and effective frequency regulation to ensure its reliability and stable operation.

In addition, an important factor is the obsolescence of generating units and the lack of capacity reserves at many TPPs and HPPs. Mostly, most generators work beyond their design life, which reduces their efficiency and reliability. This development makes it difficult to maintain the stability of EPS, since outdated units have less ability to quickly respond to changes in load and frequency.

Due to the active growth of the load in the EPS, most generating plants are forced to work at 100 % of their capacity, leaving no reserve to compensate for sudden load changes or emergency situations. Under normal operating conditions of the EPS, the reserve capacity is used to balance the differences between the generating and the consumed capacity.

Failure to maintain power balance in the EPS can lead to frequency deviation, emergency situations, avalanche-like frequency drop, cascading outages and ultimately loss of synchronization in the EPS and collapse. All this leads to significant economic losses for the country, which are associated with the downtime of enterprises and the restoration of energy supply after the effects of disturbances.

The aim of research is to increase the efficiency of power system operation by reducing the power imbalance between generation and consumption by developing a model for automated control of steam turbine parameters. This will ensure high-quality power regulation, increase the efficiency and stability of the power system, and provide a new management method for reliable energy supply to consumers.

Tasks related to the fulfillment of the set goal:
- to analyze existing models and methods of power imbalance regulation in the power system;
- to develop a dynamic model of automated control of steam turbine parameters to minimize power imbalances in the power system;
- to improve the method of regulating power imbalances to ensure efficient, reliable and stable operation of the energy system;
- to develop criteria for evaluating the effectiveness of power imbalance regulation in the power system.

2. Materials and Methods

2.1. Existing methods of regulating power and frequency imbalance. In the EPS, the balance between generation and consumption capacities must be constantly maintained within permissible values. Any deviation from this balance leads to a change in frequency, which can negatively affect the stability and reliability of the power system.

To regulate the power imbalance in the EPS, it is customary to use the following methods:
- primary frequency regulation;
- secondary frequency regulation;
- tertiary frequency regulation.

As additional methods are used:
- use of energy storage systems;
- demand regulation;
- automatic frequency unloading.

The primary frequency adjustment is intended to restore the power balance or maintain the frequency deviation as a result of disturbances in the EPS. All generating power plants (PP) with primary capacity reserves must participate in primary regulation. The duration of the primary adjustment is approximately 30 s [3, 4].

The principle of operation of the primary regulation is as follows: when the frequency deviates due to an increase in the load, the automatic speed regulators (ASRs) of the turbines react to the generating PPs by changing the generation power in the power system within the limits of the available primary power reserve.

Primary regulation requires coordinated operation of all generating power plants in the EPS, regardless of their parameters and characteristics.

After the primary adjustment, the secondary adjustment comes into effect, which, although slower, provides more accurate frequency adjustment. The secondary adjustment is intended to restore the frequency to the nominal value of 50 Hz, as well as to release the engaged primary power reserve. Specially allocated PPs, such as maneuverable HPPs, hydro-accumulating power plants (HAPPs), participate in secondary regulation, as these plants have the ability to quickly change their capacity. The duration of secondary regulation is approximately 30 seconds to 15 minutes after its activation.

The principle of operation of the secondary adjustment is as follows: after the primary adjustment, the residual frequency deviation is analyzed. If necessary, the frequency is adjusted by adjusting the power of the generators or introducing additional reserves. Also, secondary regulation ensures restoration of power reserves that could be used during primary regulation [3–6].

Tertiary regulation is intended for long-term provision of power balance and restoration of all reserves that were used during primary and secondary regulation. The principle of operation of tertiary regulation is as follows: after the completion of primary and secondary regulation, an analysis of the residual frequency deviation is performed. If necessary, the load is redistributed between different generating units, in particular, additional sources such as thermal power plants or gas turbines are involved [7].

Tertiary regulation ensures long-term maintenance of the frequency within nominal values and restoration of reserves to ensure the EPS stability for a long period. It completes the frequency stabilization process started by the primary and secondary regulation, ensuring the EPS readiness for further changes and disturbances. Thanks to the tertiary regulation, the EPS can function safely and reliably even in conditions of variable operation modes, guaranteeing the stability and reliability of the energy supply.

The use of energy storage systems for frequency regulation in EPS plays an increasing role in ensuring the stability of the power system, in particular in frequency regulation. They are able to quickly respond to changes in the balance between generation and consumption of EE. At times when generation exceeds consumption, energy storage systems can accumulate this excess, which helps to avoid a sharp increase in the frequency in the network and reduces the load on the generators of traditional PPs. In the event that consumption exceeds generation, the frequency in the system is reduced. At this point, the energy storage system can quickly release the accumulated energy to maintain the frequency within the nominal values.

The following are used as energy storage systems: hydroelectric power station, supercapacitors, lithium-ion batteries, etc. As a rule, the gas station is used for secondary and tertiary regulation to restore the frequency to the nominal value after the action of the primary regulation by the ASR devices of the turbines. Accumulator power plants are able to instantly supply electricity, stabilizing the EPS, but have a high cost and a short service life.

In the absence of fast-acting rotating and maneuverable power reserves, or their connection time exceeds the time required to maintain the frequency drop, automatic frequency unloading (AFU) is activated, the main principle of which is multi-stage disconnection of the least responsible parts of consumers [8]. The AFU levels operation differ in the setting of the operation frequency.

AFU 1 response time from 0.3 s to 0.5 s with frequency settings from 48.5 Hz to 46.5 Hz. The main task of AFU 1 is to prevent a sharp decrease in frequency at the time of the accident.

The operation of AFU 1 is characterized by a frequency reduction rate of up to 1.7 Hz/s and a power deficit of no more than 30 % of consumption. In the case of severe accidents with a frequency reduction rate of more than 1.7 Hz/s and a power deficit of more than 30 % of consumption, AFU 1 is supplemented by a second start at the speed of AFU-1Ш [2, 9, 10].

AFU 2 is activated after the frequency is reduced and set at 47.5–48.5 Hz. The main task of AFU 2 is to restore the frequency to an acceptable value above 49.2 Hz. The activation time of AFU 2 settings is equal to 3 s between settings and is 5–90 s. When restoring a frequency higher than 49.2 Hz, it is considered that the EPS can work for a long time to maintain its stability [2, 9, 10].

2.2. The existing model of primary and secondary frequency regulation in an isolated power system. The operation principle of the primary regulation is as follows: when the frequency deviates due to an increase in the load, the ASR turbines react to the generating PPs by changing the generation power in the EPS within the limits of the available primary power reserve.

Primary regulation requires the coordinated operation of all generating PPs in the power system, regardless of their parameters and characteristics.

Fig. 1 shows the structural diagram of the primary frequency control in an isolated EPS [11–13].

The block diagram of the primary frequency control consists of the following blocks: a speed controller, a turbine and an equivalent EPS. Modeling of structural diagram elements is performed by the transfer function.

When the load ΔP_L changes in the EPS, a frequency deviation $\Delta w(s)$ occurs. The speed controller analyzes the difference between the set value $\Delta w_{ref}(s)$ and the current $\Delta w(s)$ of the frequency. If $\Delta w_{ref}(s)$ deviates from $\Delta w(s)$, the controller adjusts the position of the turbine valve ΔP_v in order to return the frequency to the nominal value. The turbine, in turn, adjusts the mechanical power $\Delta P_m(s)$ delivered to the generator to ensure a match between the current and required frequency values. The equivalent EPS, which takes into account the inertia of the masses and the load, converts the change in mechanical power into a change in frequency $\Delta w(s)$, which is again fed to the regulator input, forming a closed feedback loop.

The mathematical model of the primary frequency control system in an isolated EPS is described by the following transfer function [11]:

$$\frac{\Delta\omega(s)}{-\Delta P_L(s)}=\frac{(1+sT_H)(1+sT_T)}{(2H_s+D)(1+sT_H)(1+sT_T)+1/R}, \quad (1)$$

where T_H, T_T – time constants of delays caused by the speed controller and the turbine, respectively, s; ΔP_L – load change, c.u.; $\Delta\omega$ – frequency deviation, c.u.; H_s – moment of inertia of the generator, s; D – damping coefficient of the system, c.u.; R – permanent regulator, acting.

The operation principle of primary regulation in an isolated EPS based on a mathematical model developed in MATLAB Simulink with the following system parameters:
- turbine capacity (S_T) – 300 MW;
- turbine time constant (T_T) – 0.5 s;
- time constant of the regulator (T_H) – 0.2 s;
- power system load inertia time constant (H_s) – 5 s;
- adjusting the speed of the regulator (R) – 0.5 c.u.

The mathematical model of primary frequency regulation in an isolated EPS is shown in Fig. 2.

When a disturbance occurred at the 10th second of the simulation, the load in the EPS increased by 60 MW, which corresponds to 0.2 c.u. As a result of the effect of turbine ASR, the frequency in the EPS stabilized and a new established mode occurred at the value of 49.53 Hz.

The result of the simulation of the primary regulation in the isolated EPS is shown in Fig. 3.

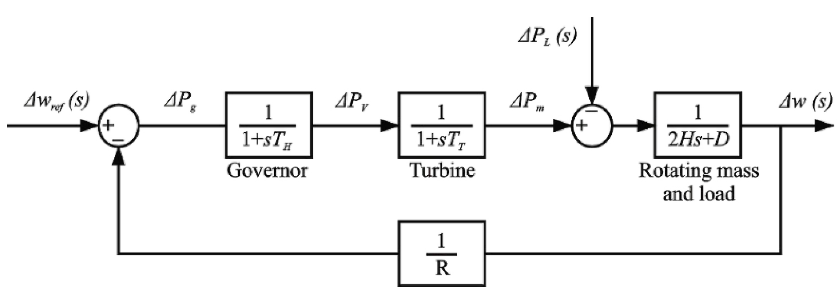

Fig. 1. Block diagram of the primary frequency regulation in an isolated EPS

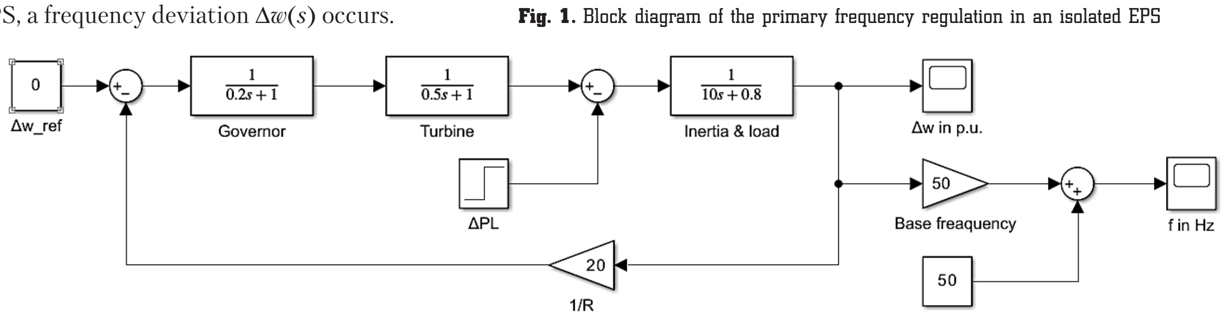

Fig. 2. Mathematical model of the primary frequency regulation in an isolated EPS, executed in the Matlab Simulink software complex

ISSN 2664-9969

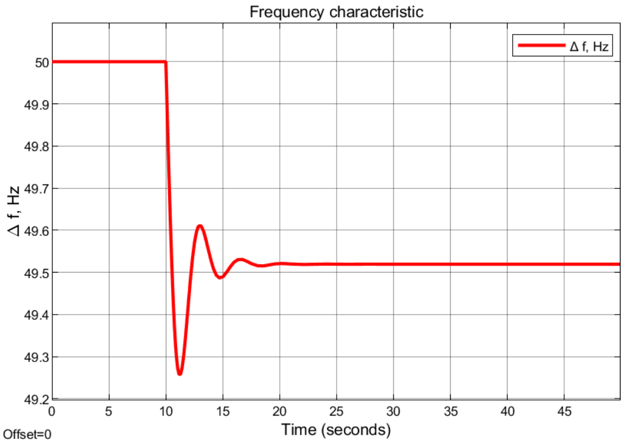

Fig. 3. Frequency regulation during the action of the primary regulation in an isolated EPS

The rate of change of frequency in the EPS depends on its inertia. The greater the inertia of the system, the slower the frequency changes, and the more time it takes to stabilize it. Thus, the inertia of the system plays a key role in determining the response time to disturbances, which ultimately affects the overall EPS stability.

To restore the frequency to the nominal value of 50 Hz after the action of the primary regulation, the secondary regulation is used.

Specially allocated PPs, such as maneuverable HPPs and HAPPs, participate in secondary regulation, as these plants have the ability to quickly change their capacity. The time of action of the secondary regulation is approximately 30 s to 15 min after its activation, which depends on the scale of the disturbance and the speed of the system's response.

The principle of operation of the secondary regulation is as follows: after the completion of the primary regulation, an analysis of the residual deviation of the frequency from the nominal value is performed. If necessary, the frequency is adjusted by adjusting the power of the generators or introducing additional reserves. Secondary regulation also restores power reserves that could have been used during primary regulation.

Fig. 4 shows a block diagram of the primary and secondary frequency regulation in an isolated EPS [11, 13].

The mathematical model of the system of primary and secondary frequency regulation in an isolated EPS is described by the following transfer function [11]:

$$\frac{\Delta\omega(s)}{-\Delta P_L(s)}=$$
$$=\frac{s(1+sT_H)(1+sT_T)}{s(2H_s+D)(1+sT_H)(1+sT_T)+K_I+s/R}, \quad (2)$$

where K_I – the gain of the integral regulator.

To display the principle of operation of primary and secondary regulation, the mathematical model of an isolated EPS in MATLAB Simulink is considered and shown in Fig. 5.

After the completion of the primary frequency adjustment, at 25 seconds of the simulation, the secondary adjustment begins. As a result of the action of the secondary regulation, the frequency in the EPS is restored to the nominal value of 50 Hz, a new stationary mode is established, which is characterized by a balance of generation and consumption capacities.

The result of the combined action of primary and secondary frequency regulation in an isolated EPS is shown in Fig. 6.

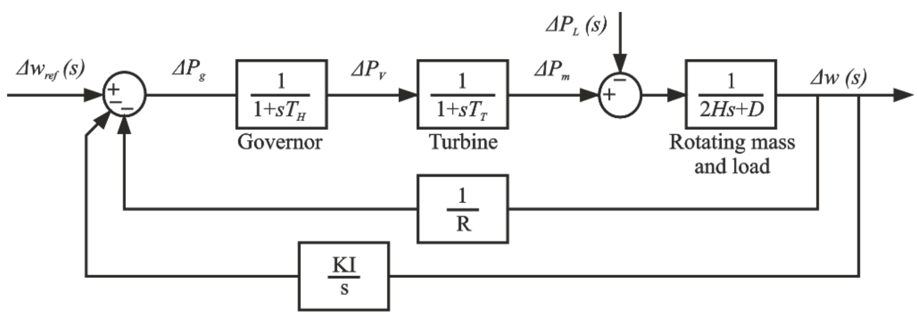

Fig. 4. Block diagram of primary and secondary frequency regulation in an isolated EPS

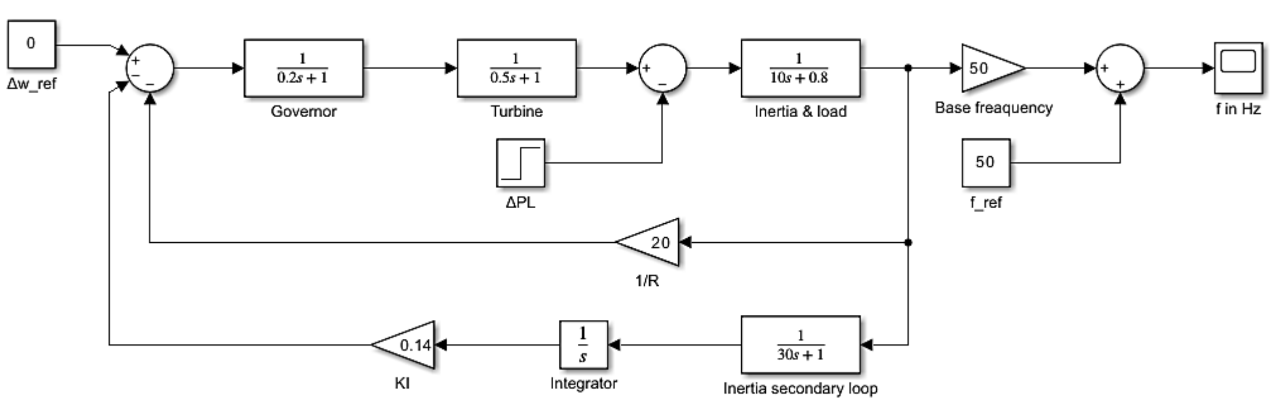

Fig. 5. Mathematical model of primary and secondary frequency regulation in an isolated EPS, performed in the Matlab Simulink software complex

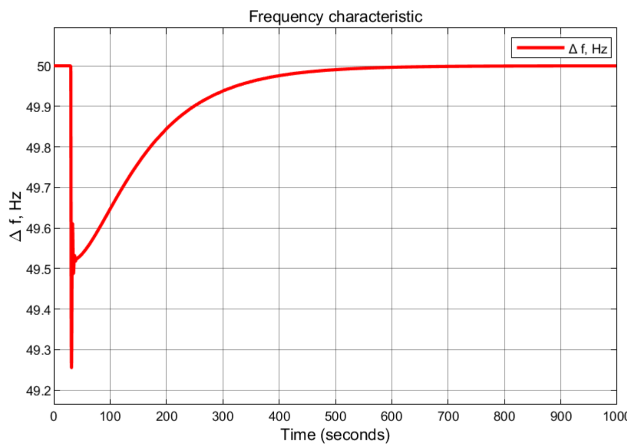

Fig. 6. Frequency regulation under the action of the primary and secondary regulation in an isolated EPS

2.3. Existing steam turbine model. A simplified diagram of a steam turbine and its components operating on an isolated load is shown in Fig. 7 [14]. The presented scheme consists of a steam boiler, a mechanical-hydraulic speed control system, high, medium and low-pressure cylinders, has one superheater and a bypass pipeline.

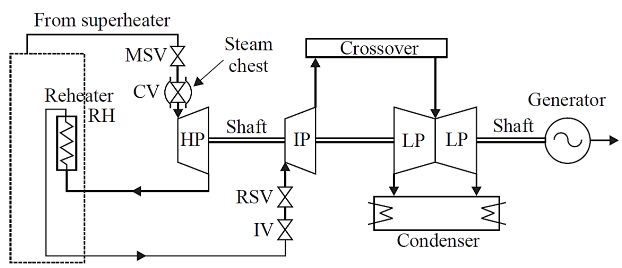

Fig. 7. Simplified diagram of a steam turbine

The operation principle of a steam turbine is as follows. The high pressure and temperature steam produced in the steam boiler by burning fuel and heating water first enters the high-pressure cylinder (HPC), passing through the main control valves that control the flow and pressure of the steam. After that, it passes through the medium-pressure cylinder (MPC) and finally, through the low-pressure cylinder (LPC). At the exit from the turbine, the steam enters the condenser, where it cools and turns into a liquid state. Condensed water is pumped by a condensate pump into a steam generator for reheating and turning into steam, completing the cycle.

The block diagram of the steam turbine shown in Fig. 8 [14–16].

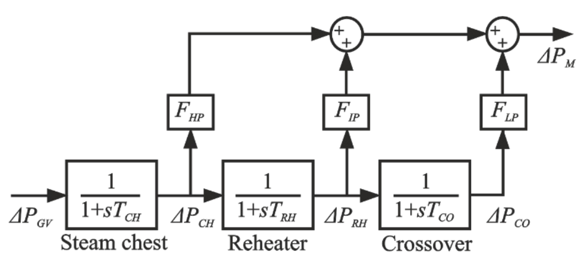

Fig. 8. Block diagram of a steam turbine with one superheater and high, medium and low-pressure cylinders and a bypass pipeline

T_{SC}, T_{RH} and T_{CO} values reflect the delays caused by the steam boiler and inlet pipe, superheater and cross pipe, respectively. The power shares of the high F_{HP}, medium F_{IP}, and low pressure F_{LP} cylinders determine what contribution each cylinder makes to the total power output of the steam turbine.

The mathematical model of a steam turbine is described by the following transfer function [16]:

$$\frac{\Delta P_M(s)}{\Delta P_{GV}(s)}= \left[\frac{F_{LP}}{T_{CH}T_{RH}T_{CO}s^3+((T_{CH}+T_{RH})T_{CO})s^2+(T_{CH}+T_{RH}+T_{CO})s+1}+ +\frac{F_{HP}}{T_{CH}s+1}+\frac{F_{IP}}{T_{CH}T_{RH}s^2+(T_{CH}+T_{RH})s+1}\right], \quad (3)$$

where T_{CH}, T_{RH}, T_{CO} – the time constants of the delays caused by the steam boiler, superheater and cross pipeline, respectively, s; F_{HP}, F_{IP}, F_{LP} – shares of power developed in high-, medium- and low-pressure cylinders, respectively, c.u.; ΔP_M – change in the mechanical power of the steam turbine, c.u.; ΔP_{GV} – valve position change, %.

Determining the parameters of a steam turbine is usually a very complicated process, due to the lack of parameters for turbines in the public domain. According to [14, 17], the parameters for steam turbines are recommended to be taken as follows: T_{CH}=0.1–0.4 s; T_{RH}=4–11 s; T_{CO}=0.3–0.5 s; F_{HP}=0.22; F_{IP}=0.4; F_{LP}=0.3.

2.4. The existing model of the mechanical-hydraulic control system. The mechanical-hydraulic system for regulating the speed of rotation of a steam turbine consists of a proportional speed controller, a speed relay of a hydraulic servo motor, and valves controlled by the controller. The main task of the speed controller is to regulate and maintain the set speed of rotation of the steam turbine.

The model of the mechano-hydraulic speed control system in a block form is shown in Fig. 9 [17].

The speed relay is presented as an integrator with a time constant T_{SR} and direct feedback, which allows to control the speed of rotation to correct speed deviations.

The servomotor moves the valves and is represented as an integrator with a time constant T_{SM} and direct feedback. The values $S_{VOPEN}, S_{VCLOSED}, S_{VMAX}$ and S_{VMIN} represent the speed limits and valve position, respectively.

The gain factor K_G is used to adjust the speed of rotation of the steam turbine. The larger K_G, the smaller the deviation from the set speed.

The signal P_{ref} in the regulation system reflects the target value for controlling system parameters.

The model of the mechanical-hydraulic system of regulating the speed of a steam turbine in the vector-matrix form [16]:

$$\frac{d}{dt}\begin{bmatrix}\Delta P_{GV}\\ \Delta P_{SR}\end{bmatrix}=\begin{bmatrix}-\frac{1}{T_{SM}} & \frac{1}{T_{SM}}\\ 0 & -\frac{1}{T_{SR}}\end{bmatrix}\cdot\begin{bmatrix}P_{GV}\\ \Delta P_{SR}\end{bmatrix}+\begin{bmatrix}0 & 0\\ \frac{1}{T_{SR}} & \frac{-K_G}{T_{SR}}\end{bmatrix}\cdot\begin{bmatrix}P_{ref}\\ \Delta\omega_r\end{bmatrix}. \quad (4)$$

According to [17], the parameters for the mechanical-hydraulic system are recommended to be taken as follows: K_G=20; T_{SR}=0.1 s; T_{SM}=0.2–0.3 s; S_{VOPEN}=0.1 c.u./s; $S_{VCLOSED}$=1.0 c.u./s.

ISSN 2664-9969

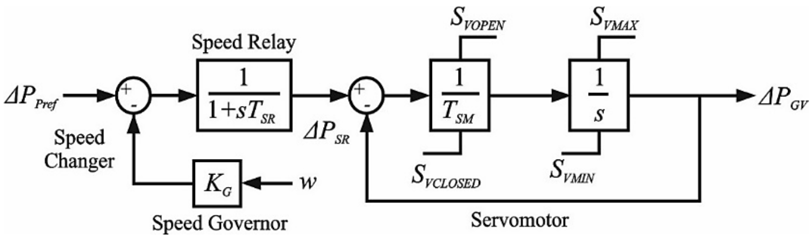

Fig. 9. Block diagram of the mechanical-hydraulic system of steam turbine rotation speed regulation

2.5. Criterion of efficiency of electricity supply and consumption. To evaluate the efficiency of electricity supply, a generalized indicator is used, which is formed by the method of convolution of partial criteria [18], namely:

– volume of electricity supply (C_S);
– quality of electricity supply (C_f);
– efficiency of electricity supply (C_{ef}).

The criterion of the volume of electricity supply is calculated according to the formula:

$$C_S = \frac{V_{c.e}}{V_{s.e}}, \quad (5)$$

where $V_{c.e}$ – the required amount of electricity for consumption, MWh; $V_{s.e}$ – volume of supplied electricity, MWh.

The quality criterion of electricity supply is defined as:

$$C_f = \frac{f_a}{f_n}, \quad (6)$$

where f_a – the volume of the actual frequency value, Hz·h; f_n – the volume of the nominal value of the frequency, Hz·h.

Criterion of efficiency of electricity supply and consumption:

$$C_{ef} = \frac{V_{c.e}}{V_{s.e} + V_b + (V_b \cdot C)}, \quad (7)$$

where V_b – the amount of electricity that is borrowed in case of a shortage of electrical energy or sold in the case of excess generation according to the principle of the banking system, MWh; C – the percentage that is introduced for the use of electricity.

According to the ideal point method, it is proposed to perform a convolution of partial criteria C_S, C_f, C_{ef}, which belong to one group and express the efficiency of electricity supply.

The general criterion of power supply efficiency is formed on the basis of partial criteria C_S, C_f, C_{ef}, according to the ideal point method:

$$C_r = \sqrt{\sum_{i=1}^{n} (C_i - C_{id.i})^2},$$
$$i = \overline{1, n}, \quad (8)$$

where C_i – the value of partial criteria; $C_{id.i}$ – the values of partial criteria at an ideal point – a fictitious point in n-dimensional space, in which the values of partial criteria reach an extremum (in this case, a minimum).

3. Results and Discussion

3.1. Modeling of power system operation modes. Consider the model of an isolated EPS operating on an isolated load. Four K-300-240 steam turbines operating in parallel with a nominal capacity of 300 MW each are used as generating units. The steam turbine model is executed according to the block diagram shown in Fig. 8. The speed regulator of the steam turbine is modeled by a mechanical-hydraulic speed regulator, the block diagram of which is shown in Fig. 9. The general model of the K-300-240 steam turbine and its components working on an isolated load, made in the MatLab Simulunk environment, is shown in Fig. 10.

When modeling a steam turbine, it is assumed that the steam pressure in the steam boiler is constant. The K-300-240 steam turbine model is shown in Fig. 11. The model of the mechanical-hydraulic system for regulating the speed of rotation of the K-300-240 steam turbine is shown in Fig. 12.

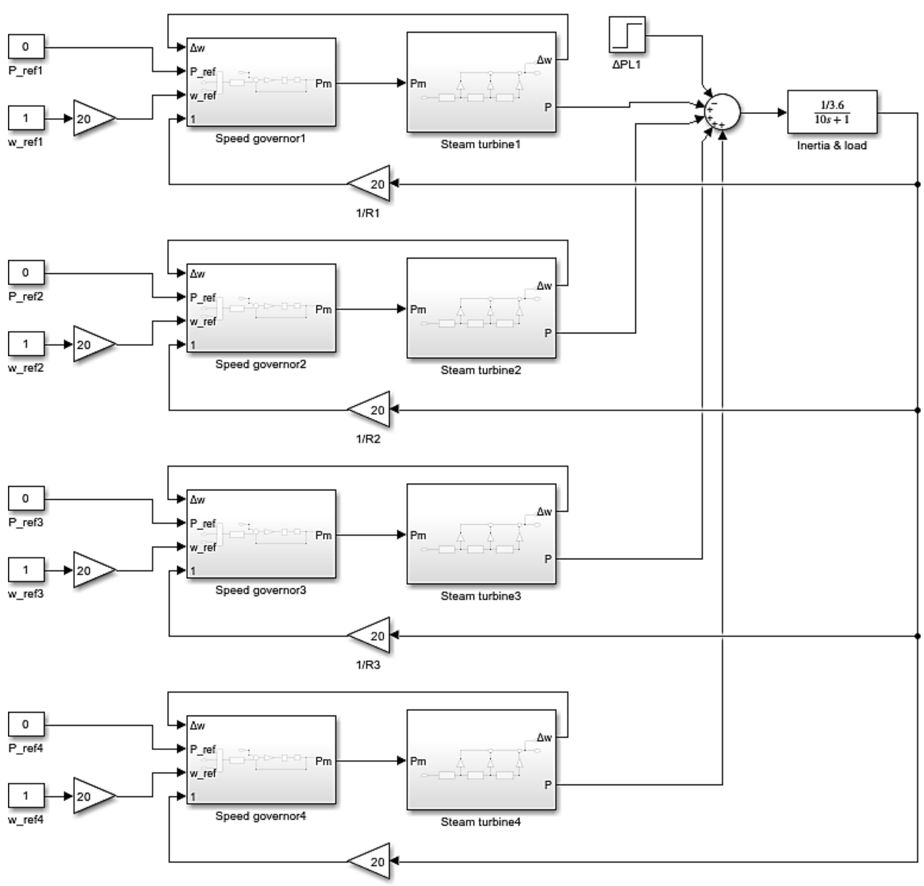

Fig. 10. A model of EPS operating on an isolated load

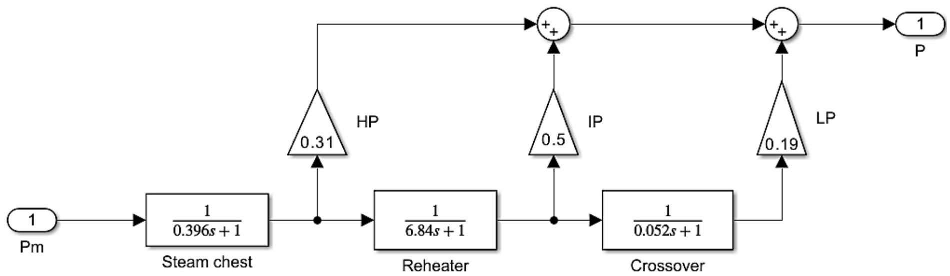

Fig. 11. K-300-240 steam turbine model

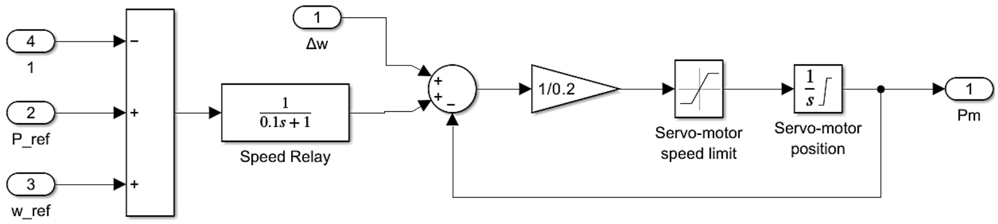

Fig. 12. Mechanical-hydraulic system for regulating the speed of rotation of a steam turbine

For further evaluation of the efficiency of the electric power system, operation modes 1–5 are considered. They are given in the Table 1.

Table 1

Operation modes of the electric power system

No.	Geneation power (P_g, MW)	Load power (P_l, MW)	Distur-bance time (t_d, s)	Distur-bance (P_d, MW)	Reserve (P_r, MW)	Nominal frequency (f_n, Hz)	Set fre-quency (f_s, Hz)
1	1080	1080	–	–	–	50	–
2	1080	1080	70	120	120	50	50
3	1080	1080	70	120	60	50	47.2
4	1080	1080	70	240	120	50	44.5
5	1080	1080	70	240	240	50	50

3.1.1. Operation mode No. 1. Four turbines operate with a capacity of 270 MW each, for a load of 1080 MW. In the normal operation mode, the power balance is performed, and the frequency in the EPS is 50 Hz. The EPS has a power reserve of 30 MW on each of the turbines (10 % of the turbine's nominal power), which is typical for primary frequency regulation. There is no disturbance in the EPS. The frequency characteristic and power characteristic are shown in Fig. 13, 14, respectively.

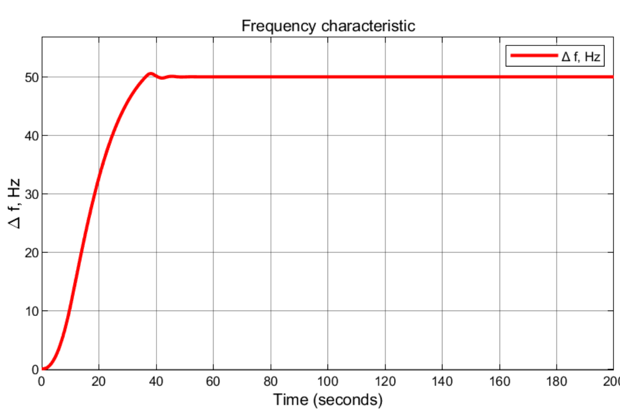

Fig. 13. Frequency characteristics of the turbine with power balance

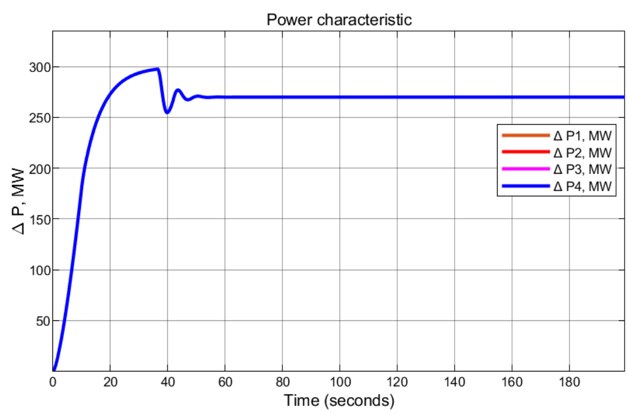

Fig. 14. Characteristics of turbine power at power balance

3.1.2. Operation mode No. 2. Four turbines operate with a capacity of 270 MW each, for a load of 1080 MW. In the normal mode of operation, the power balance is performed, and the frequency in the EPS is 50 Hz. The EPS has a power reserve of 30 MW on each of the turbines (10 % of the turbine's nominal power), which is typical for primary frequency regulation. At a time of 70 s, a disturbance is simulated by connecting a load of 120 MW. After the occurrence of an ASR disturbance, the turbine increases the generation capacity of the steam turbines to 300 MW each. The new established system operation mode and power balance are performed. The action of primary regulation is shown in Fig. 15, 16.

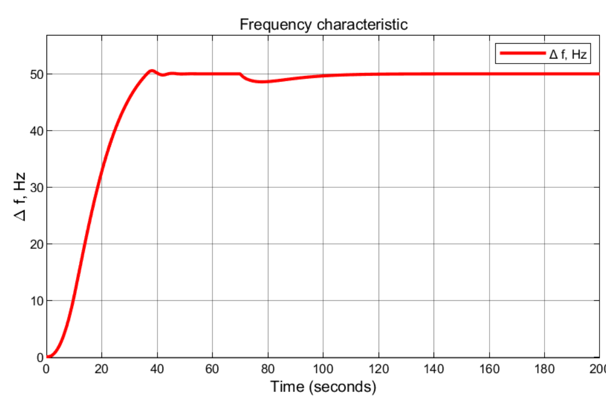

Fig. 15. Frequency characteristic of the turbine at 120 MW disturbance

 ISSN 2664-9969

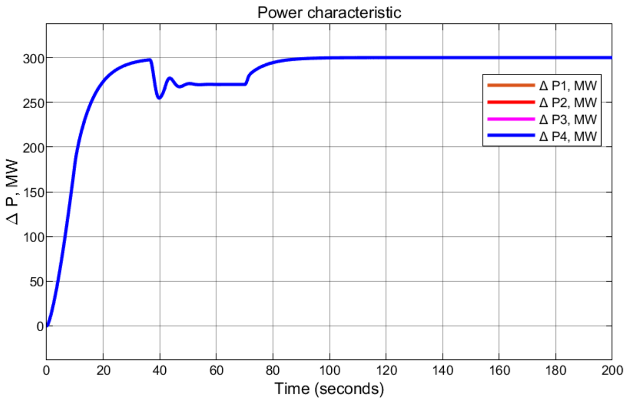

Fig. 16. Characteristics of the turbine power at a disturbance of 120 MW

3.1.3. Operation mode No. 3. Four turbines operate with a capacity of 270 MW each, for a load of 1080 MW. In the normal mode of operation, the power balance is performed, and the frequency in the EPS is 50 Hz. Only two turbines with a power reserve of 30 MW each take part in the primary regulation. At a time of 70 s, a disturbance is simulated by connecting a load of 120 MW. The effect of primary regulation by turbines T1 and T2 is shown in Fig. 17, 18.

As a result of insufficient power reserve, the frequency is held and a new set mode is established at the value of 47.2 Hz.

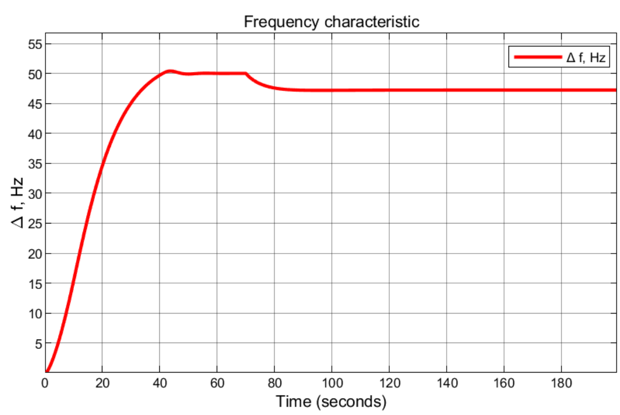

Fig. 17. Frequency characteristics of the turbine with a disturbance of 120 MW and a shortage of generation capacity

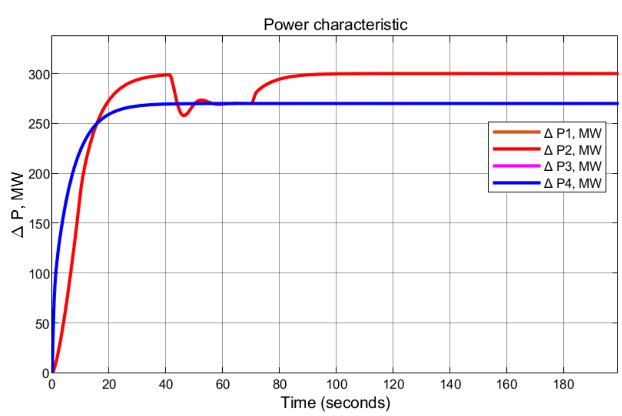

Fig. 18. Characteristics of the turbine power at a disturbance of 120 MW and a deficit of generation power

3.1.4. Operation mode No. 4. Four turbines operate with a capacity of 270 MW each for a load of 1080 MW. In the normal mode of operation, the power balance is performed, and the frequency in this case is 50 Hz. The EPS has a power reserve of 30 MW on each of the turbines. At 70 seconds, a 240 MW load connection disturbance is simulated. After the occurrence of an ASR disturbance, the turbine increases the generation capacity of the steam turbines to 300 MW each. The action of the primary regulation holds the frequency, but it is not enough to restore it to the nominal value. The action of primary regulation is shown in Fig. 19, 20.

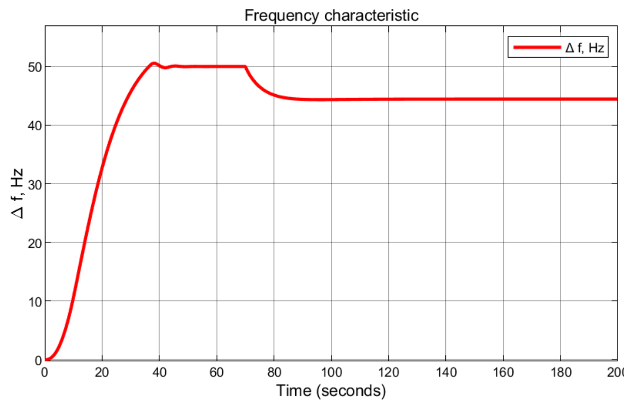

Fig. 19. Frequency characteristics of the turbine with a disturbance of 240 MW and the action of the primary regulation

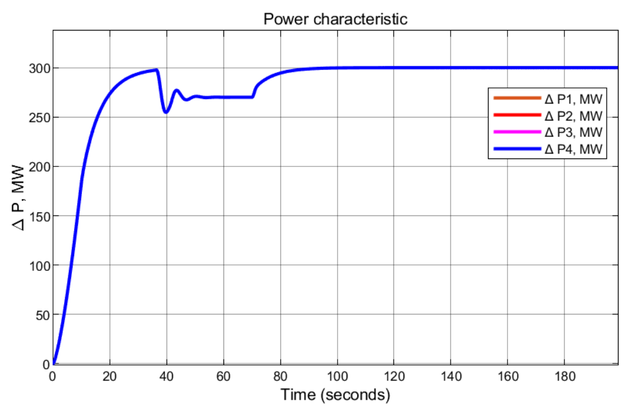

Fig. 20. Characteristics of the turbine power at a disturbance of 240 MW and the action of the primary regulation

3.1.5. Operation mode No. 5. Four turbines operate with a capacity of 270 MW each for a load of 1080 MW. In the normal mode of operation, the power balance is performed, and the frequency in this case is 50 Hz. The EPS has a capacity reserve of 30 MW on each of the turbines. At a time of 70 s, a disturbance is simulated by connecting a load of 240 MW. After the occurrence of a disturbance, ASR increases the generation capacity of steam turbines to 300 MW each. The primary control action holds the frequency, but is not enough to restore it to the nominal value, so at 70 seconds of the simulation, the hot backup is connected, namely the 120 MW turbine, which provides frequency restoration and power balance. The action of primary regulation is shown in Fig. 21, 22.

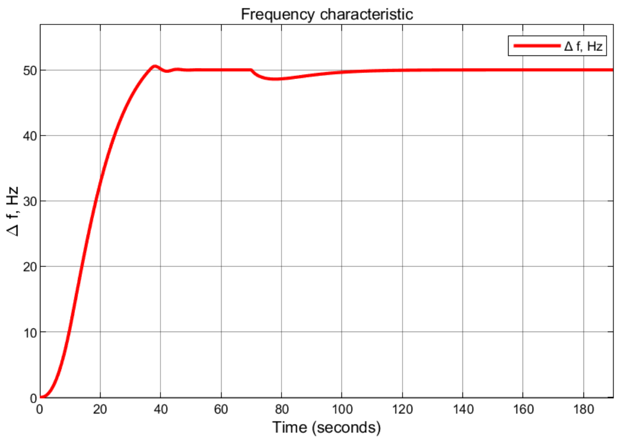

Fig. 21. Frequency characteristics of the turbine during a disturbance of 240 MW and the action of the primary regulation, taking into account the connection of the hot reserve

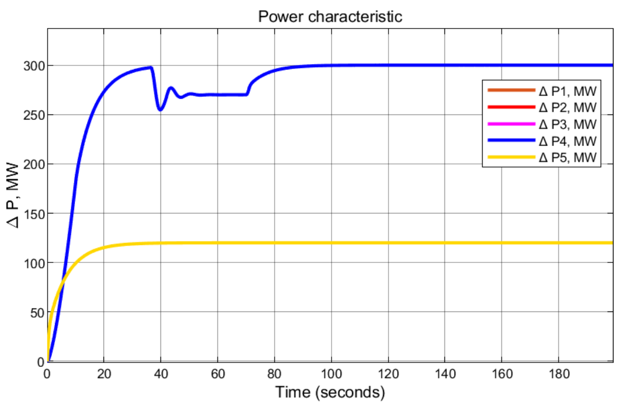

Fig. 22. Characteristics of the turbine power at a disturbance of 240 MW and the action of the primary regulation, taking into account the connection of the hot reserve

3.2. Efficiency evaluation of electricity supply and consumption. Efficiency evaluation of electricity supply and consumption is carried out for operation mode No. 2. In the normal operation mode, four turbines operate with a capacity of 270 MW each for a load of 1080 MW. Each of the turbines has a power reserve of 30 MW, which is 10 % of the nominal power of the turbine. At a time of 70 s, a disturbance is simulated by connecting a load of 120 MW. After the occurrence of a disturbance, the generation capacity of steam turbines increases to 300 MW each under the ASR action. At 110 s, a new stable mode of operation of the system and the balance of power generation and consumption is established. The characteristics of power generation and consumption of EPS are given in Fig. 23, 24, respectively.

The volume of supplied electricity ($V_{s.e}$, MW·h) is located as the area of the figure described by points A, C, D, according to Fig. 23, and is $V_{s.e}$=47334.3 MW·h.

The volume of consumed electricity ($V_{c.e}$, MW·h) is calculated as the square area at points A, B, C, D, according to Fig. 24, and is $V_{c.e}$=48000 MW·h.

The EPS frequency characteristic is shown in Fig. 25, 26.

The volume of the actual value of the frequency (f_a, Hz·h) is found as the area of the figure described by points A, B, C, D, according to Fig. 25, and is f_a=1962.2 Hz·h.

The volume of the required frequency value (f_r, Hz·h) is calculated as the area of the square at points A, B, C, D, according to Fig. 26, and is f_r=2000 Hz·h.

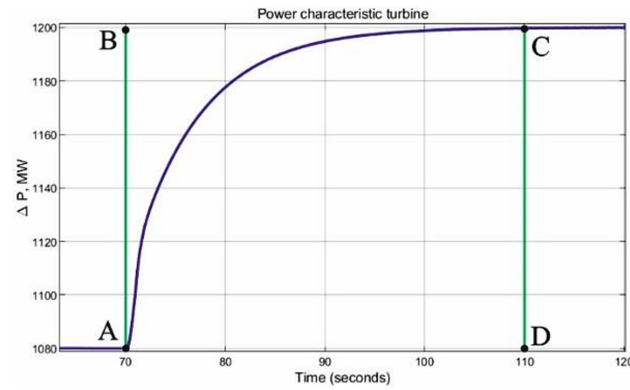

Fig. 23. Characterization of EPS power generation capacity

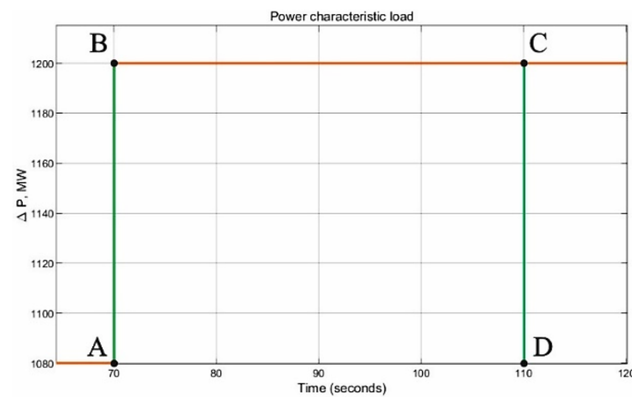

Fig. 24. Characteristics of EPS power consumption

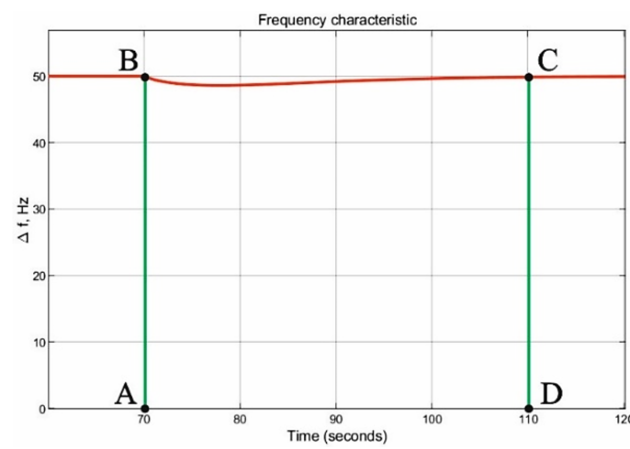

Fig. 25. EPS frequency characteristics under the action of a disturbance

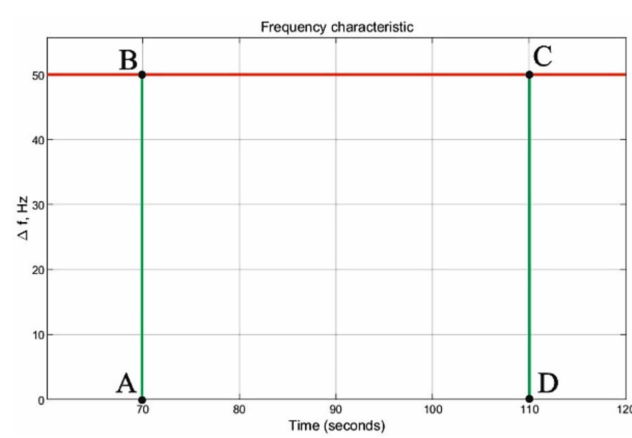

Fig. 26. EPS necessary frequency characteristics

 ISSN 2664-9969

The result of calculations of the efficiency of electricity supply for operation modes 1, 2, 3, 5 is given in the Table 2.

Table 2

The result of electricity supply efficiency calculations for operation modes 1, 2, 3, 5

Calculated values	Operation modes			
	No. 1	No. 2	No. 3	No. 5
$V_{s.e}$, MW·h	43220.8	47334.3	45277.5	51755.1
$V_{c.e}$, MW·h	43220.8	48000	48000	52825.6
f_n, Hz·h	2000	2000	2000	2000
f_a, Hz·h	2000	1962.2	1894.5	1944.7
V_b, MW·h	0	0	2722.46	0
C_n	1.0	0.986	0.94	0.98
C_f	1.0	0.981	0.95	0.97
C_{ef}	1.0	0.986	0.84	0.98
C_r	0	0.046	0.27	0.068

Operation mode No. 1 is an ideal case of supply and consumption of EE, without disturbances in the EE, as $V_{s.e}=V_{c.e}=43220.8$ MW·h, hence the partial criterion of EE supply is $C_n=1$, this indicates the balance of generation capacity and consumption. At the same time, the partial quality criteria of EE supply are $C_f=1$, that is, there are no frequency deviations in the network, the frequency is 50 Hz. The partial supply efficiency criterion $C_{ef}=1$ indicates that the supply and consumption of EE is maximally efficient. So, the general efficiency criterion is $C_r=0$, which is an ideal value.

Operation mode No. 2 reflects operation mode No. 1, but taking into account the occurrence of a 120 MW disturbance at 70 seconds of simulation. The partial criteria for the supply of EE is $C_n=0.986$, which means lack of EE release in the amount of 665.7 MW·h, which is associated with the inertia of steam turbines when increasing the generation capacity. At the 110th second of the simulation, the generation power of the steam turbines reaches the required value, a new set mode is executed, in which the power balance is performed. Partial criteria for the quality of electricity supply is $C_f=0.981$. A partial criterion for delivery efficiency is $C_{ef}=0.986$. Therefore, the general efficiency criterion is $C_r=0.046$.

Operation mode No. 3. In normal operation mode, four turbines operate at a capacity of 270 MW each. Power regulation is performed by two turbines. At 70 seconds, a disturbance of 120 MW is simulated. The partial criterion for the supply of EE is $C_n=0.94$, which means a lack of EE release in the amount of 2722.5 MW·h. At 110 seconds, the generating power of the two steam turbines reaches a maximum value of 300 MW each. At the same time, the power balance is not established in the EPS, as there is not enough generation power reserve. Partial quality criteria of EE supply is $C_f=0.95$. A partial criterion for delivery efficiency is $C_{ef}=0.84$. Therefore, the general efficiency criterion is $C_r=0.27$.

Operation mode No. 5. In normal operation mode, four steam turbines operate at a capacity of 270 MW each. Power regulation is performed by only two turbines. At 70 seconds, a disturbance of 240 MW is simulated. Since the ASR action of the steam turbines is not enough to restore the power balance in 70 seconds, a steam turbine with a capacity of 120 MW is connected. Partial criteria for the EE supply $C_n=0.98$, which means a lack of EE release in the amount of 1070.5 MW·h, which is associated with the inertia of steam turbines when increasing the generation capacity. At the 110th second of the simulation, the generation power of the steam turbines reaches the required value, a new set mode is executed, in which the power balance is performed. Partial quality criteria of EE supply are $C_f=0.97$. A partial criterion for delivery efficiency is $C_{ef}=0.98$. Therefore, the general efficiency criterion is $C_r=0.068$.

The developed model of automated control of parameters of steam turbines according to operation mode No. 2 demonstrated the highest efficiency among the considered operation modes according to the evaluation of the efficiency of EE supply and consumption. The implementation of this model in the strategy of regulating power imbalances in the EPS will allow not only to increase the accuracy and speed of frequency regulation, but also to significantly reduce the power imbalance, especially in cases of sudden frequency changes. The model can be implemented at TPPs with large-capacity steam turbines, providing prompt response to frequency fluctuations due to a power reserve of 10 % of the nominal power of each turbine. This will ensure stable EE generation in conditions of variable load and disturbances. In addition, the model can be adapted for other types of turbines used in EPS, in order to optimize energy consumption processes and improve the overall efficiency of power supply.

Limitations of the study. Implementation of the proposed method of automated control of steam turbine parameters may require modernization of existing turbines, updating of their control systems and provision of appropriate power reserve, which in turn requires significant financial investment and time expenditure.

The influence of martial law conditions. Due to security risks and instability, much of the research was conducted remotely, which limited opportunities for personal collaboration with colleagues. This led to the use of mostly theoretical and simulation approaches to evaluate the results. During the research, difficulties related to power outages and unstable access to the Internet repeatedly arose, which slowed down the work process and extended the deadlines for some stages of the work.

A promising direction of further research is the integration of the developed control system with battery stations and other energy storage systems to increase the efficiency of response to power imbalance and reduce its magnitude to acceptable values.

4. Conclusions

As a result of the rapid decrease in the frequency in the EPS, it is necessary to increase the generation of electric power as soon as possible in order to maintain and restore the frequency. Having analyzed the existing methods of power regulation, primary regulation, as well as energy storage systems, increase EE generation in a short period of time. The duration of the primary adjustment is approximately 30 seconds. The operating time of battery stations is approximately 1 second. Primary power regulation is performed by all generating PPs that have a reserve of primary power, thus providing an appropriate reserve on existing PPs, it is possible to perform power regulation depending on the disturbance caused by the PPs. Accumulator stations require large economic costs and have a short service life, which is characterized by the properties of accumulator batteries.

A dynamic model of the automated control of parameters of the K-300-240 steam turbine was developed, which consists of a mechanical-hydraulic system for regulating the speed of rotation of the steam turbine, a steam boiler, a superheater and a cross pipeline.

For effective power regulation in the EPS, it is necessary that each of the steam turbines has a power reserve of 10 % of the nominal power of the turbine. This principle of EPS operation was considered and described as mode of operation No. 2.

A method was developed to assess the efficiency of the EE supply and consumption, which is based on the convolution of partial criteria into a general criterion of the efficiency of electricity supply. The following criteria were proposed as partial criteria for electricity supply and consumption: volume criterion, quality criterion, and electricity supply efficiency criterion. Operation mode No. 1 according to the general criterion of power supply efficiency is considered as an ideal case, in the absence of disturbances in the EPS. The closest to the reference value of the efficiency criterion, taking into account disturbances in the EPS, is operation mode No. 2 with the general criterion of power supply efficiency.

Conflict of interest

The authors declare that they have no conflict of interest in relation to this study, including financial, personal, authorship, or any other, that could affect the study and its results presented in this article.

Financing

The study was conducted without financial support.

Data availability

The manuscript has no associated data.

Use of artificial intelligence

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

References

1. *Pro zatverdzhennia Kodeksu system rozpodilu* (2018). Postanova NKREKP No. 310. 14.03.2018. Available at: https://zakon.rada.gov.ua/laws/show/v0310874-18 Last accessed: 05.09.2024
2. *Elektricheskaia energiia. Normy kachestva elektricheskoi energii v sistemakh elektrosnabzheniia obshchego naznacheniia: GOST 13109-97.* Chinnii vid 01.01.2000 (1999). Kyiv: Izd-vo standartov, 31.
3. Iandulskii, O. S., Steliuk, A. O., Lukash, M. P.; Iandulskii, O. S. (Eds.) (2010). *Avtomatichne reguliuvannia chastoti ta peretokiv aktivnoi potuzhnosti v energosistemakh.* Kyiv: NTUU "KPI", 88.
4. *ENTSO-E Operation Handbook. Policy 1* (2009). Load-Frequency Control and Performance, 28.
5. Kryvda, V. I., Zubak, V. V., Maksymov, M. M. (2024). Model for maintaining the operability of the power system under conditions of its imbalance. *Electrical and Computer Systems, 40 (116),* 13–24. https://doi.org/10.15276/eltecs.40.116.2024.2
6. *Rehulyuvannya chastoty v elektrychnykh systemakh.* Available at: https://forca.com.ua/knigi/navchannya/regulyuvannya-chastoti-v-elektrichnih-sistemah.html
7. Fesiuk, O. V. (2015). Optimal load of power units for third step of regulation of their capacity. *Teoriia optymalnykh rishen,* 79–84.
8. Pavlovsky, V., Steliuk, A. (2015). Influence estimation of the frequency protection of nuclear power plant units on system survivability and frequency stability of Ukrainian power system. *Tekhnichna elektrodynamika, 6,* 53–57.
9. Bazhenov, V. M., Odiehov, M. M. (2022). *Avtomatyka elektroustanovok elektroenerhetychnykh system.* Kharkiv: Planeta-Print, 186.
10. Holota, A. D. (2006). *Avtomatyka v elektroenerhetychnykh systemakh.* Kyiv: Vyshcha shkola, 367.
11. Saadat, H. (2010). *Power System Analysis.* PSA Publishing.
12. Majeed, F. A. A. (2021). Steam Turbine Governor (STG) Controller Design Based on Particle Swarm Optimization (PSO). *IOP Conference Series: Materials Science and Engineering, 1105 (1),* 012050. https://doi.org/10.1088/1757-899x/1105/1/012050
13. Pal, I., Kumar, A. (2018). *Load Frequency Control of Multi-Area Power System with PI Controller.* Gautam Buddh University.
14. Eremia, M., Shahidehpour, M. (Eds.) (2013). *Handbook of Electrical Power System Dynamics: Modeling, Stability, and Control.* John Wiley Sons. https://doi.org/10.1002/9781118516072
15. Dynamic Models for Steam and Hydro Turbines in Power System Studies (1973). *IEEE Transactions on Power Apparatus and Systems, PAS-92 (6),* 1904–1915. https://doi.org/10.1109/tpas.1973.293570
16. Tuaimah, F., M. Al-Rawi, N., A. Mahmoud, W. (2014). Steam Turbine Governor Design based on Pole Placement Technique. *International Journal of Computer Applications, 92 (13),* 51–55. https://doi.org/10.5120/16073-5306
17. Vahidi, B., Tavakoli, M., Gawlik, W. (2007). Determining Parameters of Turbine's Model Using Heat Balance Data of Steam Power Unit for Educational Purposes. *IEEE Transactions on Power Systems, 22 (4),* 1547–1553. https://doi.org/10.1109/tpwrs.2007.907509
18. Suvorov, V., Zubak, V. (2023). Model for monitoring and evaluation of the effectiveness of the electric power system of the country. *Electrical and Computer Systems, 38 (114),* 15–21. https://doi.org/10.15276/eltecs.38.114.2023.2

Viktoriia Kryvda, *PhD, Associate Professor, Head of Department of Postgraduate and Doctoral Studies, Department of Electricity and Energy Management, Odesa Polytechnic National University, Odesa, Ukraine, ORCID: https://orcid.org/0000-0002-0930-1163*

Maksym Maksymov, *Doctor of Technical Sciences, Professor, Head of Department of Software and Computer-Integrated Technologies, Odesa Polytechnic National University, Odesa, Ukraine, ORCID: https://orcid.org/0000-0002-7536-2570*

✉***Viktor Zubak,*** *PhD Student, Department of Software and Computer-Integrated Technologies, Odesa Polytechnic National University, Odesa, Ukraine, e-mail: viktorzubak172@gmail.com, ORCID: https://orcid.org/0000-0002-6981-645X*

Andrii Ivaneiev, *PhD Student, Department of Software and Computer-Integrated Technologies, Odesa Polytechnic National University, Odesa, Ukraine, ORCID: https://orcid.org/0009-0001-7618-3769*

Ruslan Ryaboshapka, *PhD Student, Department of Software and Computer-Integrated Technologies, Odesa Polytechnic National University, Odesa, Ukraine, ORCID: https://orcid.org/0009-0004-2068-0290*

✉*Corresponding author*