This study's object is the processes of frequency and power adjustment in the power system of Ukraine, which is connected to parallel operation with a neighboring power system.

The current issues related to increasing the efficiency of secondary frequency and power adjustment in the unified power system of Ukraine, which operates in parallel with the European power system (ENTSO-E), have been considered. The factors associated with the introduction of renewable energy sources, the growing role of decentralized generation, and the need to take into account the limitations of internal tie-lines in the power system when distributing the load have been analyzed.

An analysis of approaches to automatic frequency and power adjustment was conducted; the shortcomings of existing solutions were identified, including simplification of the network topology, failure to take into account the technical limitations of power units and reserves, as well as limitations in internal controlled tie-lines.

An improved approach to secondary adjustment based on the method of predictive models has been proposed, which makes it possible to take into account these limitations and improve the efficiency of secondary frequency and power adjustment in the power system. The study of the processes was performed on a dynamic model of the power system with real parameters; the effectiveness of the proposed approach was confirmed by comparison with the conventional proportional-integral control law of the automatic frequency and power control system.

It has been shown that the implementation of the devised approach provides a reduction in frequency recovery time by 8% and prevents overloading of controlled sections, increasing the stability and reliability of the power system under the conditions of modern challenges. The has proposed approach made it possible to increase the efficiency of secondary frequency and power control in the power system

Keywords: frequency control, power flow limitation, model predictive control, power system stability

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IMPROVING THE EFFICIENCY OF SECONDARY LOAD FREQUENCY CONTROL IN A POWER SYSTEM CONSIDERING INTERNAL TIE-LINE POWER EXCHANGES

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1. Introduction

The parallel operation of the Unified Power System (UPS) of Ukraine with the European power system ENTSO-E imposes increased requirements on the quality of frequency adjustment, which is directly related to the efficiency of the automatic frequency and power adjustment system (AFPAS). According to a number of indicators, such as sensitivity, overshoot, the existing AFPAS does not meet the requirements. In addition, secondary frequency adjustment is carried out by involving individual units of hydropower plants, which are concentrated in one region of the country, while restrictions on the capacity of power transmission lines (internal cross-sections) are not automatically taken into account during adjustment. At the same time, a market for auxiliary services is being formed in Ukraine, which contributes to the involvement of a larger number of power plants in frequency adjustment processes. When engaging power plants that are geographically dispersed throughout the territory of Ukraine, there is a need to effectively involve power units at thermal power plants and hydropower units in frequency adjustment processes and at the same time optimize flow distribution during secondary frequency and power adjustment.

The active introduction of renewable energy sources (RES), in particular solar and wind power plants, significantly affects power flows along internal power transmission lines. Conventional systems provided for the transmission of electricity from powerful power plants to consumers through specific nodes and power transmission lines that were designed for predicted loads and directions of power flows. With the advent of decentralized RES, the structure of production and distribution has changed, namely, electricity can now be generated directly near end consumers or even in weakly connected parts of the network. This leads to the emergence of reverse flows, overloads of individual internal sections, increased losses, as well as instability of network operating modes due to unpredictable generation inherent in RES (dependence on weather conditions, time of day, etc.). The sensitivity of the system to emergency modes also increases, especially with large volumes of installed RES, which reduces the margin of stability and requires the implementation of new approaches to flow management. Similar conclusions are also confirmed by studies [1, 2], which emphasize the need to implement active power flow management.

Thus, research related to the development of methods and means of secondary frequency and power adjustment under the updated operating conditions of UPS is important and its results are needed to improve the efficiency of adjustment and the stability of the power system.

2. Literature review and problem statement

In studies related to secondary frequency and power control in power systems, approaches based on model predictive control (MPC) and various optimization algorithms are widely used.

In [3], a controller is proposed that combines MPC and the particle swarm optimization (PSO) algorithm. This approach makes it possible to reduce the number of calculations and increase the efficiency of the controller. However, the optimization parameters have fixed values, which can lead to suboptimal settings of the controller parameters under different conditions. The cited paper also does not consider the impact of restrictions on power flows between power system zones, as well as in the internal tie-lines of each zone. This is due to the fact that the model is centralized and single-zone, which significantly simplifies the topology and eliminates the need to control internal tie-lines. Taking into account such restrictions requires a more complex topology and complication of the mathematical model of the controller. In addition, the authors did not fully take into account the restrictions on secondary adjustment reserves, in particular, they did not consider the absolute restrictions on the available reserve and the rate of change of power of each station. This does not make it possible to assess the effectiveness of distributed secondary frequency and power control taking into account the real limitations of internal controlled sections and different types of power plants.

In [4], the use of a controller based on MPC for secondary frequency control in low-inertia power systems using data from monitoring and information transfer system (MITS) devices was proposed. In the work, the controlled load is involved in the adjustment, and power flows are taken into account through the Jacobi matrix, taking into account the limitations on the rate of change of load power and its limits. However, the limitations in controlled sections are not taken into account, despite the use of the 9-node scheme model. Also, only the controlled load is considered as secondary adjustment reserves, while conventional power plants, such as thermal power plants and hydroelectric power plants, do not participate in adjustment. Taking into account their operation would significantly complicate the model and the controller. Therefore, to increase the accuracy and practical significance of the proposed approach, it is necessary to improve the controller, taking into account the limitations on sections, technical characteristics of power plants, and frequency levels.

In study [5], secondary frequency control in an isolated power system with an adaptive controller based on MPC and fuzzy set theory is considered. There, internal cross-section restrictions are not taken into account due to the simplification of the model, which makes it possible to avoid a complex description of the network topology and does not complicate the controller. Restrictions on the control range of power plants are not fully taken into account in order to maintain the smoothness of parameter settings. Analysis of the speed of power generation restrictions is superficial since a detailed analysis would complicate the model. The lack of multi-zone coordination is explained by the desire to maintain the compactness of the algorithm for the local system and reduce computational costs. Despite this, the proposed approach could be improved by applying it to a multi-node model with control over the necessary cross-sections and restrictions on the reserves of secondary frequency and power control.

In work [6], a controller model based on MPC for secondary frequency control is built taking into account restrictions on intersystem flows and power plant units. However, internal tie-lines are not taken into account since their inclusion significantly complicates the optimization due to the large number of variables and constraints. Generator equivalence does not make it possible to take into account the technical limitations of individual units, their minimum and maximum levels, as well as restrictions on the rate of change of power. This is done to maintain the simplicity of the model and the speed of calculations, as well as because of the lack of complete information about power plants.

In study [7], restrictions on internal tie-lines, the range of secondary control reserves, and the rate of change of power were also not taken into account. This significantly limits the application of the MPC -based controller under actual conditions. The reasons are the complexity of modeling, the lack of detailed network topology, insufficient data on generators, and high computational costs. To overcome these shortcomings, it is important to expand the model by taking into account internal tie-lines, minimum and maximum generator power values, and dynamic restrictions on the change of reserve power.

In [8], the use of orthonormal Laguerre functions reduced the computational cost of stepwise optimization with a large forecast horizon. However, the constraints on the change in power of thermal and hydroelectric power plants were overestimated compared to real data. The actual system will respond more slowly, which may cause frequency fluctuations or delays. If the model allows for a fast change in power, less frequency control reserves are needed, but in reality they may not be enough when the units do not have time to develop the required power. Also, the constraints on internal controlled tie-lines are not taken into account. The authors used a simplified model with overestimated constraints to demonstrate the workability of the method at the initial stage.

In [9], a secondary frequency control strategy based on MPC for systems with wind power plants is proposed. However, the constraints on internal tie-lines are not considered, which is important for preventing overloads and modeling overflows. There is also no analysis of the generation and ramp-up constraints that determine the physical capabilities of power units. The authors probably simplified the model for analytical convenience and due to limited access to data, which makes it difficult to comprehensively take into account all constraints.

It can be concluded that most of the studies reviewed are based on simplified models that do not take into account the constraints on internal cross-sections, generation, and ramp-up. This reduces practical application in real multi-zone power systems with power plants of various types. Taking into account these constraints complicates modeling and optimization but is necessary to increase the accuracy and efficiency of frequency and power control.

Therefore, there is an urgent need for research that would address these unresolved problems. In particular, it is necessary to investigate the processes of secondary frequency and power control taking into account the constraints on internal cross-sections, real technical constraints of power units and hydropower units, including the rate of change of power. This will contribute to improving the stability of the power system and the efficiency of secondary frequency and power adjustment while increasing the share of renewable sources and complex network topology.

3. The aim and objectives of the study

The aim of our work is to define the processes of frequency and power adjustment in the power system, taking into account the existing restrictions on the internal sections of the power system, regulating stations to increase the efficiency of secondary frequency and power adjustment. This will make it possible to meet the requirements for frequency adjustment in the power system of European countries and increase the stability of the power system in Ukraine during secondary frequency and power adjustment.

To achieve the goal, the following tasks have been set:

– to devise an approach to secondary frequency and power adjustment based on MPM, which takes into account the restrictions on the internal controlled sections of the power system, the rate of change of the power of regulating stations and their available reserve;

– to investigate the efficiency of secondary frequency and power adjustment using the proposed approach.

4. The study materials and methods

The object of our study is the frequency control processes in the power system when disturbances occur in different parts of the power system according to the hypothesis in accordance with the N-1 criterion. The processes were studied at the system level and at stations involved in secondary frequency and power control. In addition, the frequency level in each coherent zone and power flows in internal controlled tie-lines were monitored.

The studies were conducted on a dynamic power system model (Fig. 1), while load equivalence was performed at 220 kV nodes, and RESs were taken into account through their equivalent representation in the form of load.

The designed dynamic model of the power system in the PowerFactory software includes 621 nodes, 279 synchronous generators at thermal power plants (TPPs) and hydroelectric power plants (HPPs), 350 power transmission lines with a voltage of 750–220 kV, 376 transformers, and 200 load nodes. The model built was validated on the basis of real data from the existing transient processes monitoring system (TPMS) [10], which confirmed its adequacy. The model contains intersystem lines with a neighboring power system and operates in parallel operation. Secondary frequency adjustment is carried out by AFPAS, which consists of two levels: system and station. The system level, when the frequency and setpoint of the controlled intersystem flow deviate, calculates the unscheduled task (controlling influence) in accordance with the adjustment law of the installed controller and distributes the value of the unscheduled task to the power plants participating in secondary adjustment. According to actual data, a PI controller of adjustment law is installed at the system level of AFPAS. The station level distributes the unscheduled task among the station modules, taking into account the number of those modules that participate in secondary frequency adjustment.

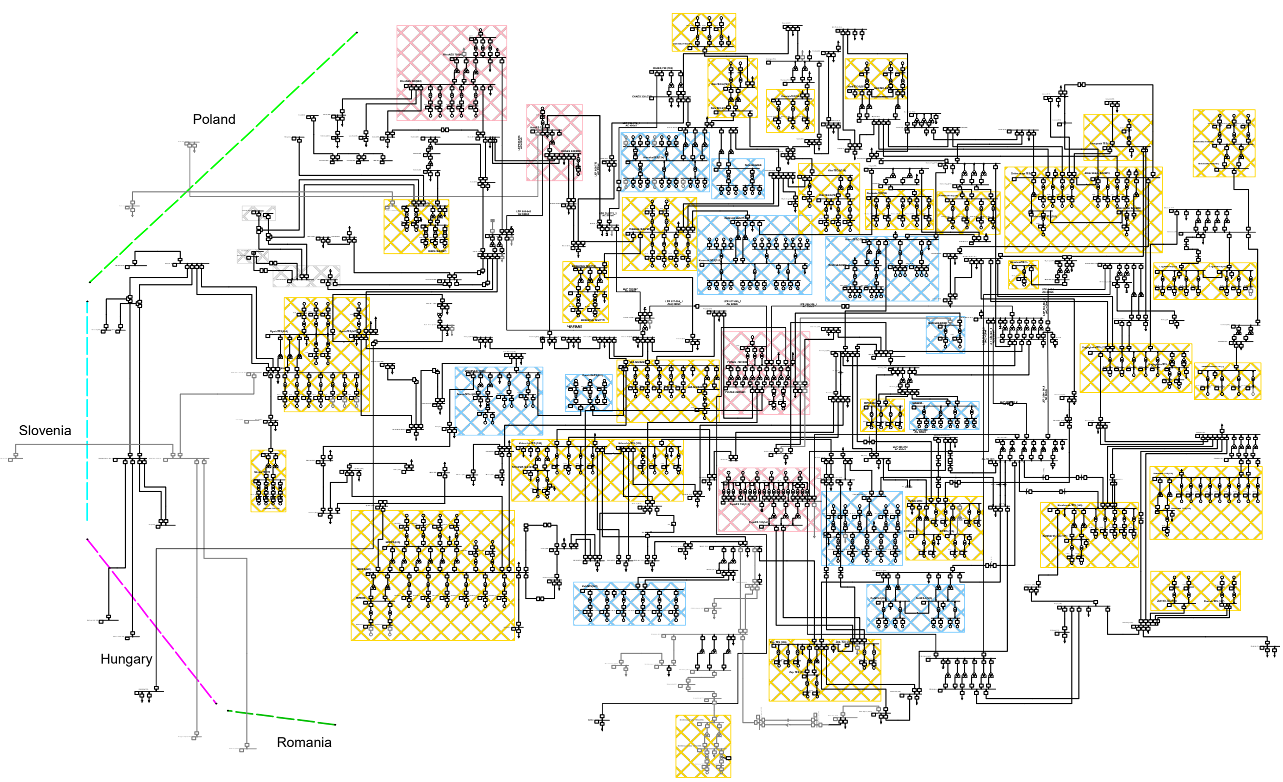

Fig. 1. Dynamic power system model

Secondary frequency control involves 4 thermal power plants (TPP-1, TPP-2, TPP-3, TPP-4) and 3 hydroelectric power plants (HPP-1, HPP-2, HPP-3,). It should be noted that the plants involved in secondary frequency and power control operate with the planned output power according to the mode, while simultaneously maintaining the established secondary control reserve. The magnitude of the disturbance was considered according to the N-1 principle. For the power system in Ukraine, this is the shutdown of the largest power unit in the power system with a capacity of 1000 MW. The shutdown of two nuclear power plants (NPPs) was considered, which are located in the central and southern regions of Ukraine and belong to different coherence zones (Zone 1, Zone 2, Zone 3) [11]. The shutdown of the NPP power unit for all studies occurred on second 3. Among the controlled tie-lines, 5 intra-system tie-lines with restrictions on the amount of active power flows were considered, given in Table 1.

In addition, power flows along the external tie-line (Tie-line-6) with the neighboring power system were considered.

Table 1

Limitation of power flows at controlled tie-lines

Tie-line	Maximum value, MW	Minimum value, MW	Regime value, MW
Tie-line-1	2055	1800	2001
Tie-line-2	1950	1500	1907
Tie-line-3	400	100	314
Tie-line-4	865	500	800
Tie-line-5	2910	2500	2856

5. Results of research on increasing the efficiency of secondary frequency and power adjustment taking into account the considered limitations

5. 1. Devising an approach to secondary frequency and power adjustment based on the method of predictive models

The goal of secondary frequency and power flow adjustment based on the predictive model is to determine the optimal sequence of changes in the active power generation settings from the control zones, which ensure:

– restoration of the frequency in each control zone to the rated value;

– maintenance of inter-zone power flows at a given level.

At each step k_i, the sequence of future control influences is considered

$$\Delta u(k_i), \Delta u(k_i+1), \ldots, \Delta u(k_i+N_c-1), \tag{1}$$

where $\Delta u(k)$ is the vector of changes in active power of generators in control zones, [MW], N_c – time horizon of control.

The current state of electric power system (EPS) is determined by state vector $x(k_i)$, which is formed from:

– $f_z(k_i)$ – value of frequency deviation in zone z from 50 Hz;

– $p_{ij}(k_i)$ – value of deviation of power flow between zones i and j from the given one;

– $e(k_i)$ – integral variables that reflect the accumulated error in flows.

The basis of control based on the predictive model is the calculation of system state vectors on time horizon N_p, which is defined as the following vector

$$x(k_i+m \mid k_i), \quad m=1,\ldots,N_p. \tag{2}$$

The calculation of vector (2) on horizon N_p is carried out using the linearized model of (EPS) (3). The calculated state vector (2) makes it possible to form a forecast of output variables (4) of the system (frequencies and inter-zone active power flows):

$$x(k+1)=Ax(k)+B\Delta u(k), \quad y(k)=Cx(k), \tag{3}$$

$$y(k_i+m \mid k_i)=CA^{N_p}x(k_i)+CA^{N_p-1}B\Delta u(k_i)+ \\ +\ldots+CA^{N_p-N_c}B\Delta u(k_i+N_c-1), \tag{4}$$

where A is the dynamics matrix, B is the control influence matrix, C is the output (observation) matrix, $y(k)$ includes $f_z(k)$ and $p_{ij}(k)$.

When solving the problem of finding vector (1) for secondary frequency control and power flows based on PMM, the following constraints must be taken into account.

Power constraints

$$p_z^{\min} \le u_z(k) \le p_z^{\max}. \tag{5}$$

Limitations on the speed of power change in the control zones

$$\frac{p_z^{\min}}{\Delta t} \le \frac{u_z(k)}{\Delta t} \le \frac{p_z^{\max}}{\Delta t}. \tag{6}$$

Restrictions on permissible frequency deviations

$$f_z^{\min} \le f_z(k) \le f_z^{\max}. \tag{7}$$

Restrictions on interzonal flows and overflows at controlled tie-lines

$$\left|p_{ij}(k)\right| \le p_{ij}^{\max}. \tag{8}$$

It should be noted that when implementing PMM in power systems, it is important to ensure the admissibility of the optimization problem even under modes when all strict constraints cannot be simultaneously met [12]. For this purpose, the PMM problem introduces mitigation variables (s_v), which allow temporary violations of certain technical constraints under the condition of their penalization in the objective function. For each constraint (5) to (8), the modified constraint with the application of mitigation is formed as

$$z_{\min}-s_v^z \le z(k) \le z_{\min}+s_v^z, \quad s_v^z \ge 0. \tag{9}$$

To avoid unjustified violations of the restrictions, all mitigations are included in the objective function as penalty terms

$$J(.)=\ldots+\rho_f s_v^f+\rho_p s_v^p+\rho_u s_v^u+\rho_{\Delta u} s_v^{\Delta u}, \tag{10}$$

where $\rho_* >> 0$ are the weighting factors that determine the "cost" of each type of violation. The larger of these factors forces the optimizer to fully comply with the corresponding constraint, if possible.

Thus, the objective control function according to the proposed approach is formulated as a quadratic functional

$$J(u_k)=\sum_{k=0}^{t_f}\left(z_k^T Q z_k+u_k^T R u_k+2z_k^T N u_k\right)+ \\ +\phi(x_t,t_f)+\rho s_v, \tag{11}$$

where:

– $z_k = y(k) - r(k)$ – vector of frequency and flow deviations from the given values;

– Q, R, N – weight matrices;

– $\phi(x_t, t_f)$ – penalty functions for the final state (can be zero).

Based on (11), in the process of adjustment based on PMM at each step of the formation of control influences, the quadratic programming problem is solved

$$\text{minimize } J(u_k) \text{ subject to } Mz_k \leq \gamma(z_k), \tag{12}$$

where:

– M is the matrix of constraints (activation of limits by frequency, power, overflows);

– $\gamma(z_k)$ – vector of limits;

– u_k – vector of changes in active powers by zones;

– z_k – vector of adjustment errors.

The implementation of a predictive control system for the tasks of automatic secondary frequency control and inter-zone power flows is based on the feedback principle: measurement → forecast → optimization → control action → data update. Five main stages are performed at each discrete time step k_i.

State estimation.

The state vector $x(k_i)$ is determined from current measurements of frequency deviations in each control zone and active power deviations on inter-zone connections. If necessary, internal variables, in particular the integrating components of PI controllers, can be estimated using filtering methods, for example, the Kalman filter.

Forecast construction.

Based on the linearized model of the electric power system (3), a forecast of the dynamics of states and outputs within forecasting horizon N_p is formed using a sequence of future control actions $\Delta u(k)$. The forecast of the system outputs – frequency deviations by zones and deviations of inter-zone flows – is constructed according to (4).

Solving the optimization problem.

The problem of minimizing the quadratic criterion (11) taking into account constraints (5) to (9) is solved as a quadratic programming problem. The input data are the current state $x(k_i)$ of the frequency and flow rate setpoints, the model matrices (A, B, C), the weighting factors (Q, R, N), and the permissible limits of the variables.

Application of the control influence.

Only the first element of the optimal vector ΔU, i.e., $\Delta u(k_i)$, is applied to the physical system. In the next step, the optimization is repeated based on the updated state.

Data update.

After the end of the sampling period Δt (usually 4–10 s), the system moves to a new step Δk_{i+1} and the cycle repeats.

In the supervisory control and data acquisition (SCADA) environment, the controller is implemented as an extension of AFPAS. The basic aspects of integration include the following:

– data collection and processing.

Input data (frequencies and active flows) come from a remote terminal unit (RTU), SCADA, or power measurement unit (PMU). Aggregation from multiple sources is used to increase accuracy. Data transmission is implemented according to IEC 60870-5-104, DNP3, or IEC 61850 standards to ensure integration with existing dispatch infrastructure, ensuring protocol compatibility;

– unscheduled task of changing the power of stations.

The calculated power changes are transmitted to the station level of AFPAS generator controllers or to the centralized power distribution module between zones;

– model adaptation.

The model matrices (A, B, C) are updated according to load changes or identification results based on actual data. It is possible to use aggregated zone models;

– discretization.

The controller discretization period is selected in accordance with the requirements of the ENTSO-E standards for secondary adjustment and, as a rule, is from 4 to 10 seconds.

The designed controller based on the proposed approach is implemented in the AFPAS system level.

5. 2. Research on the effectiveness of secondary frequency adjustment taking into account the considered limitations

To compare the effectiveness of secondary adjustment according to the proposed approach, studies were conducted using the controller in the system part of AFPAS based on the proposed MPC approach and the PI of the adjustment law.

Below are plots of the regime parameters that were recorded when the power unit of NPP-1, which is located in the central part of Ukraine, was shut down.

Fig. 2 shows a reduced plot of changes in the capacities of thermal power plants participating in secondary frequency adjustment.

The plot of changes in the capacities of hydroelectric power plants involved in the secondary regulation of frequency and power is shown in Fig. 3.

Fig. 4 shows the plots of changes in the internal controlled tie-lines of the power system.

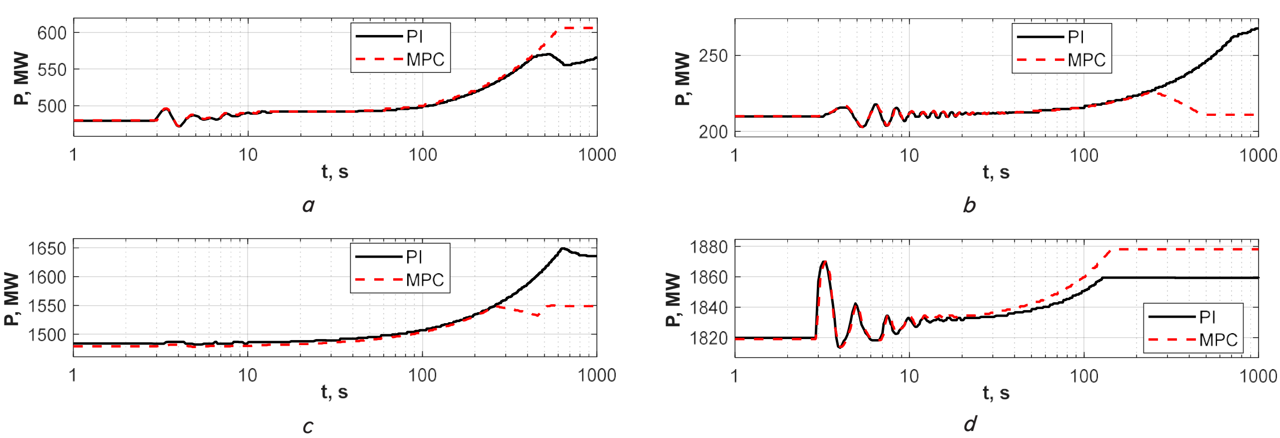

Fig. 2. Plot of changes in the capacities of thermal power plants: *a* – TPP-1; *b* – TPP-2; *c* – TPP-3; *d* – TPP-4

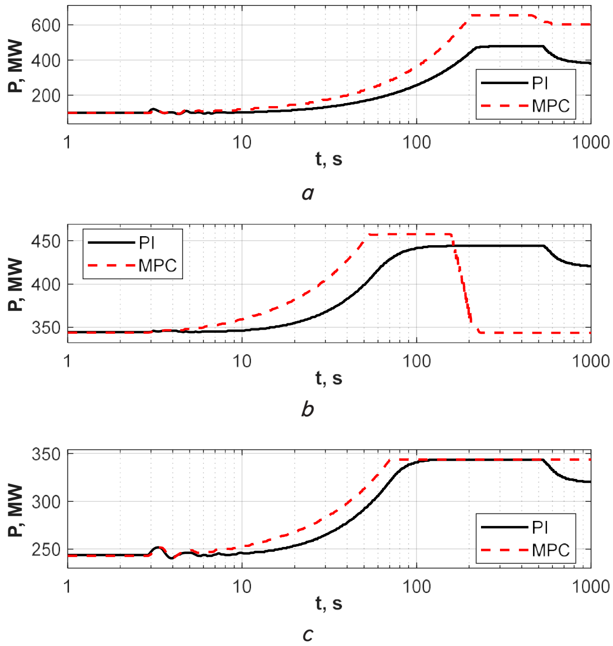

Fig. 3. Plot of changes in the capacity of hydroelectric power plants: *a* – HPP-1; *b* – HPP-2; *c* – HPP-3

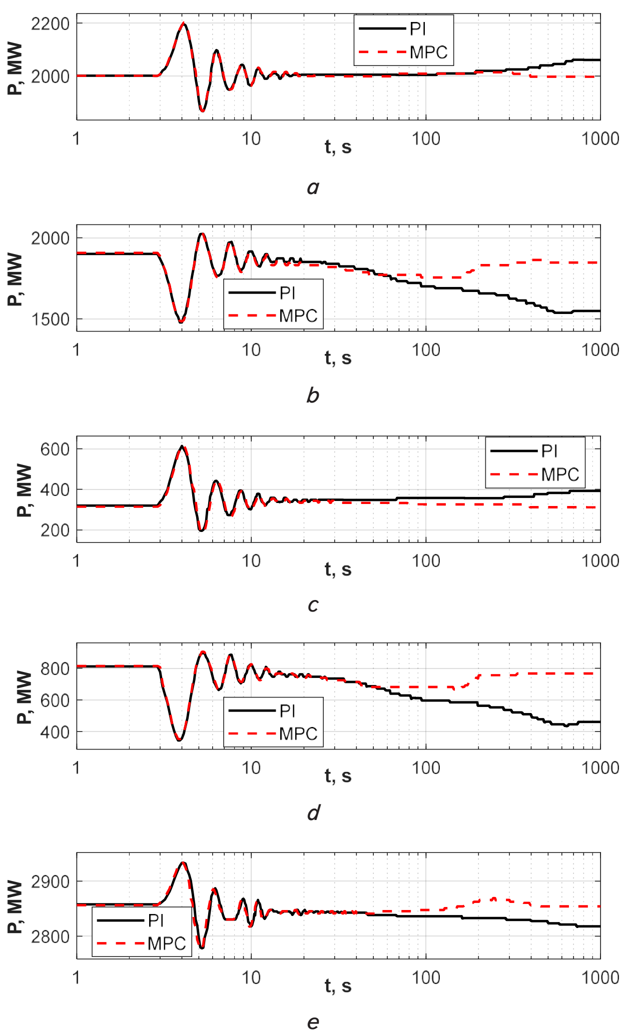

Fig. 4. Plot of changes in the capacity flows of controlled tie-lines: *a* – tie-line-1; *b* – tie-line-2; *c* – tie-line-3; *d* – tie-line-4; *e* – tie-line-5

The plot of changes in power flow through intersystem communication lines is shown in Fig. 5.

Fig. 6 shows a plot of frequency changes in three coherent zones of the power system.

Further studies were conducted during the shutdown of the nuclear power plant, which is located in the southern part of Ukraine.

Fig. 7 shows a plot of changes in the capacities of thermal power plants that participate in secondary frequency adjustment.

The plot of changes in the capacities of hydroelectric power plants involved in the secondary regulation of frequency and power is shown in Fig. 8.

Fig. 9 shows the plots of changes in the internal controlled tie-lines of the power system.

The plot of changes in power flow through intersystem communication lines is shown in Fig. 10.

Fig. 11 shows a plot of frequency changes in three coherent zones of the power system.

The generalized results of our research are given in Table 2.

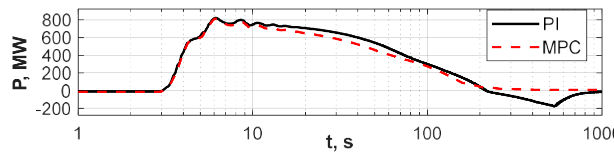

Fig. 5. Plot of changes in power flow through intersystem communication lines

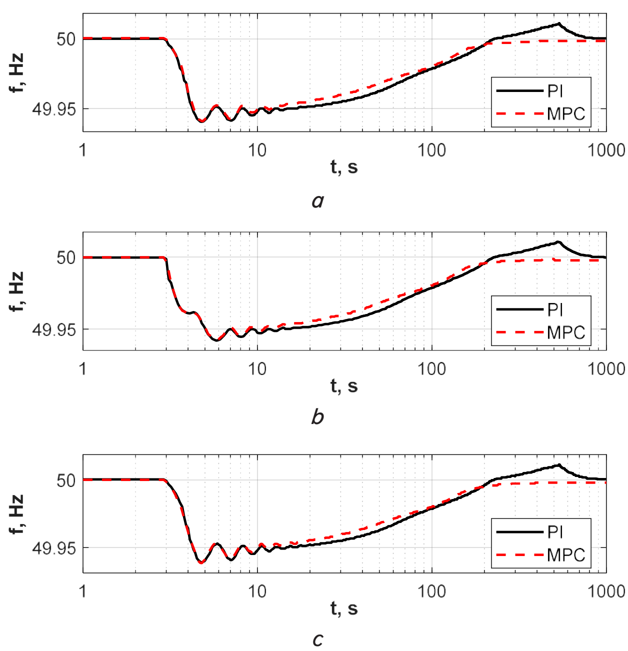

Fig. 6. Frequency change plot in controlled zones: *a* – zone-1; *b* – zone-2; *c* – zone-3

Table 2

Results of the current study

Disturbance	Approach to adjustment	Maximum dynamic frequency deviation, MHz	Frequency recovery time to 50 Hz ± 20 MHz, s	Adjustment time, s	Frequency overshoot, MHz
AEC-1	PI	59	106	228	11
	PMM	59	98	202	absent
AEC-2	PI	54	99	228	10
	PMM	53	91	195	absent

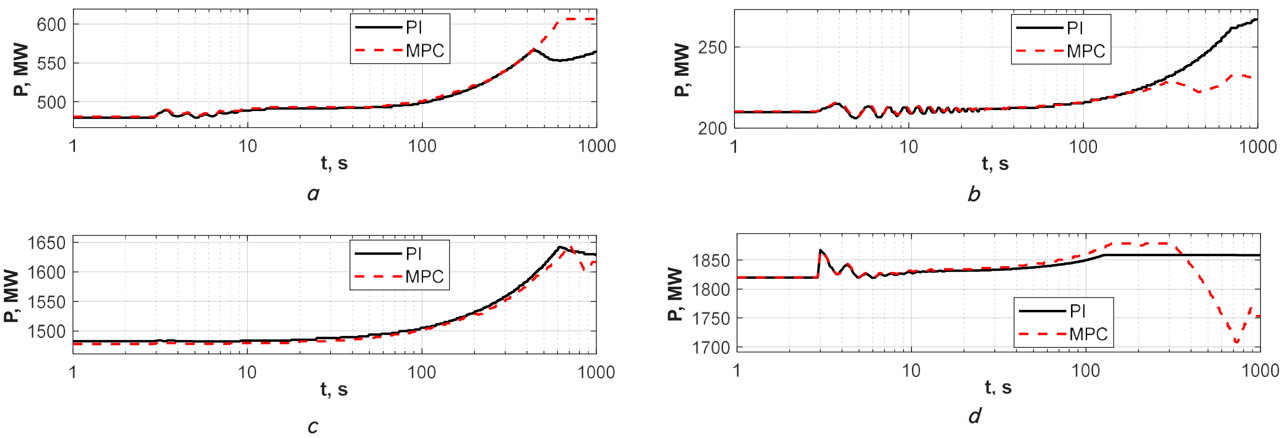

Fig. 7. Plot of changes in the capacities of thermal power plants: *a* – TPP-1; *b* – TPP-2; *c* – TPP-3; *d* – TPP-4

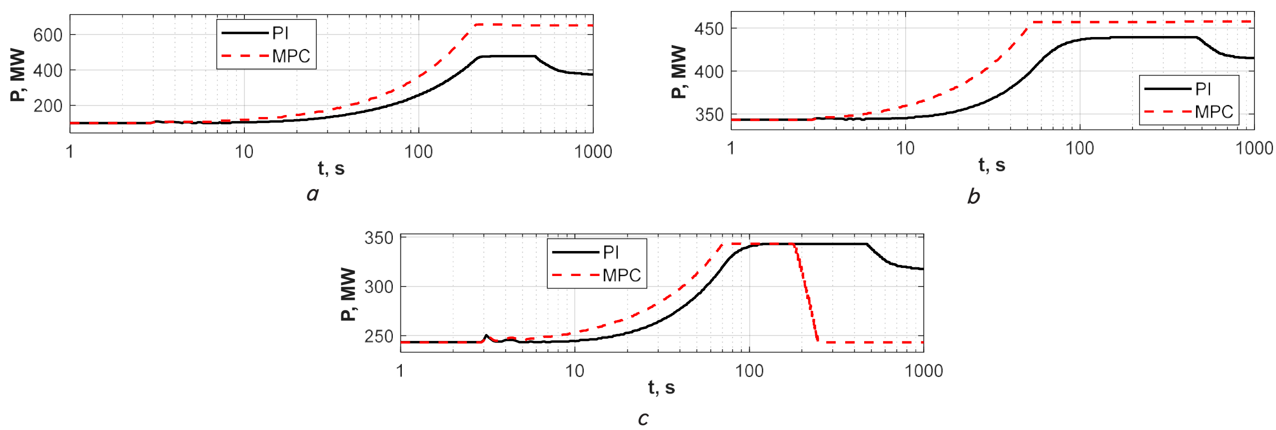

Fig. 8. Plot of changes in the capacity of hydroelectric power plants: *a* – HPP-1; *b* – HPP-2; *c* – HPP-3

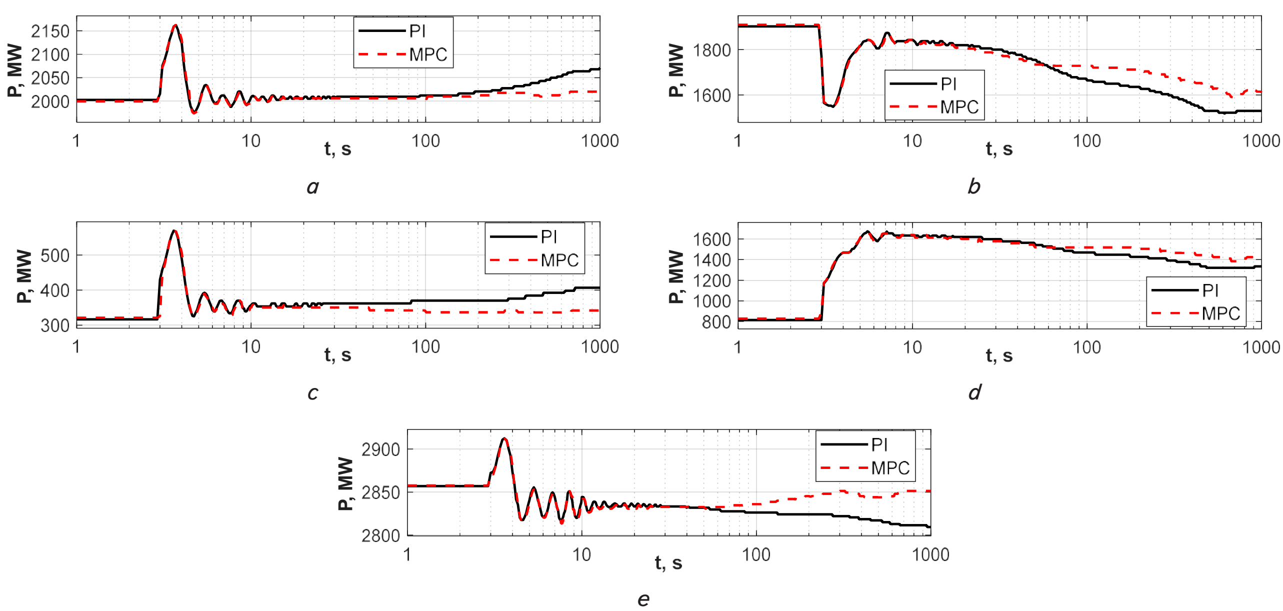

Fig. 9. Plot of changes in the capacity flows of controlled tie-lines: *a* – tie-line-1; *b* – tie-line-2; *c* – tie-line-3; *d* – tie-line-4; *e* – tie-line-5

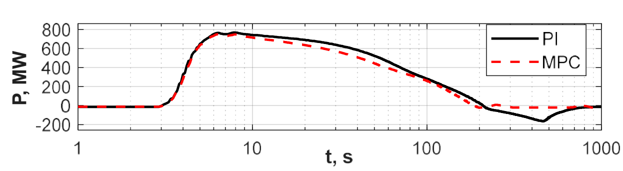

Fig. 10. Plot of changes in power flow through intersystem communication lines

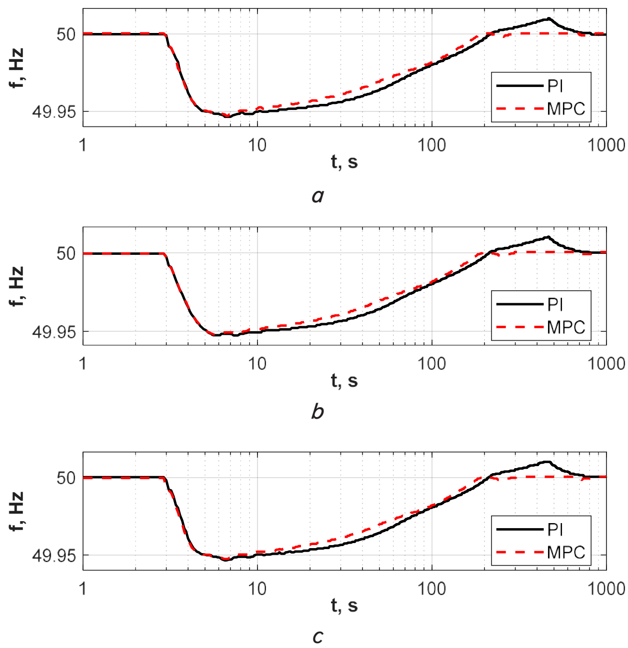

Fig. 11. Frequency change plot in coherent zones: *a* – zone-1; *b* – zone-2; *c* – zone-3

When using the proposed approach, there is no frequency overshoot during secondary frequency and power control.

6. Discussion of results related to the effectiveness of secondary frequency adjustment taking into account restrictions in controlled tie-lines

The proposed approach to secondary frequency and power adjustment based on PMM makes it possible to restore the frequency to the rated value and maintain power flows in controlled tie-lines in the specified ranges. The forecast of future states of the power system is formed using a linearized model, which makes it possible to take into account frequency deviations, power flows at controlled tie-lines, and accumulated integral control errors. By solving the quadratic programming problem with restrictions on the rate of change of power of stations, permissible frequency deviations and inter-zone flows, compliance with the technical requirements for the operation of the power system is ensured.

One of the features of the proposed approach is the introduction of mitigation variables, which make it possible to control temporary violations of constraints with appropriate penalties of the objective function. This makes the control system more flexible and stable even under complex transient regimes.

The implementation of the controller based on the proposed approach involves a five-stage structure, which includes assessing the current state, building a forecast, solving the optimization problem, applying control influence, and updating data in the next cycle. This sequence makes it possible to maintain high accuracy and speed of the algorithm. Integration of the controller in the SCADA environment using modern communication protocols ensures its compatibility with the existing dispatching infrastructure and a high level of process automation. An additional advantage is the ability to adapt the model to changes in network operating modes, which increases the reliability of adjustment. Aggregated zone models make it possible to reduce the complexity of calculations without losing accuracy.

In the event of a power unit outage at NPP-1, which is located in the central part of Ukraine, the operation of the emergency power control system with a PI controller in its system part leads to the fact that the thermal power plant (Fig. 2) and the hydroelectric power plant (Fig. 3) increase their active power. In the first minutes after the disturbance, the hydroelectric power plant uses its available reserve to the maximum, and the reserves at the thermal power plant are also involved. However, due to overshoot, the frequency level (Fig. 6) continues to increase, and the value of the balance of the flow with the adjacent power system becomes negative (Fig. 5), which forces the emergency power control system to generate a signal to unload the regulating units. This, in turn, leads to a decrease in the frequency, and the process is repeated.

During adjustment, an increase in active power flows is observed at the sections Tie-line-1 (Fig. 4, *a*) and Tie-line-3 (Fig. 4, *c*) due to the loading of the thermal power plant power units after the exhaustion of the hydroelectric power plant reserves. The operation of AFPAS with the PI adjustment law does not take into account the selective loading and unloading of regulating stations, taking into account the restrictions of controlled tie-lines. This leads to exceeding the maximum permissible flow values, which negatively affects the static and dynamic stability of the system.

The application of the proposed MPC approach makes it possible to more effectively, in comparison with the PI law of adjustment, involve the reserves of HPPs and TPPs for secondary frequency and power adjustment. It was established that the total reserves are sufficient to restore the frequency of (EPS) to the rated value and ensure the flow of active power with the adjacent power system at a minimum level close to zero. The operation of AFPAS with a controller based on the proposed PMM approach does not provide for the full loading of TPP-3 (Fig. 2, *c*) and TPP-2 (Fig. 2, *b*) since this could lead to an excess of power through Tie-line-1 (Fig. 4, *a*), which contradicts the established restrictions. Initially, the fastest HPP reserves are used (Fig. 3), after which, with the increase in the load on the less maneuverable TPP units, HPP reserves are released, which ensures optimal use of all maneuvering capabilities and at the same time preserves the reserves of primary frequency and power adjustment at the TPP. Adjustment occurs without overshoot (Fig. 6), the frequency recovery time has decreased by 7.5%, and the rates of change in power of the stations remain within permissible limits. Control over the flows of other sections (Fig. 4) prevents their overload, due to which the adjustment is assessed as successful.

Similar patterns were confirmed during the shutdown of the NPP-2 power unit in the southern region of Ukraine. The use of the PI-law of adjustment in the system part of AFPAS has made it possible to restore the frequency and the balance of the flow to the rated values. The maximum dynamic frequency deviation reached 54 MHz (Table 2). At the same time, significant overshoot was observed (Fig. 11), which is due to the integral component. This led to alternating settings of unplanned power and fluctuations in the power of the regulating stations (Fig. 7, 8). That also caused an increase in flows through tie-line-1, tie-line-3, and tie-line-4 (Fig. 9) simultaneously with an increase in TPP capacity since the controller did not take into account the restrictions on controlled tie-lines. Such an excess negatively affected the system stability margin.

At the same time, the application of the proposed approach during this disturbance confirmed its advantages.

It was established that the effective involvement of reserves made it possible to quickly restore the frequency and reduce the overflows to a minimum level. Full loading of TPP-3 and TPP-2 (Fig. 7) did not occur due to the introduced restrictions on overflows in the tie-lines, which prevented overloading of Tie-line-1 (Fig. 9, *a*). However, after establishing a stable regime, an excess of the overflow was observed on Tie-line-4, for the correction of which TPP-4 was partially unloaded. However, its reserves turned out to be insufficient. In this case, the AFPAS sequentially involved first the HPP reserves (Fig. 8, *a*), then the TPP reserves were activated, which ensured the optimal distribution of maneuvering capabilities and the preservation of primary reserves. Adjustment took place without overshoot (Fig. 11), the frequency restoration time decreased by 8%, the response speed met the requirements, and the controlled overflows remained within permissible limits.

The application of the proposed approach, in contrast to [13, 14], makes it possible to take into account restrictions on internal tie-lines, technical characteristics of stations, and increase the stability of power system during secondary frequency and power adjustment.

The limitation of the devised approach relates to the use of the model in MPC without automatic updating of its parameters. One of the disadvantages of this approach is the need to provide additional communication channels for transmitting the values of power flows along internal controlled tie-lines to the system level of AFPAS. However, further development of the smart grid infrastructure could provide conditions for eliminating this problem.

Further research may focus on improving the proposed approach by using an adaptive model in MPC, the parameters of which will be periodically updated according to the data from the TPMS devices.

7. Conclusions

1. The proposed approach to secondary adjustment based on a predictive model provides an optimal change in active power in the control zones to restore frequency and ensure inter-zone flows. This approach takes into account restrictions on internal controlled tie-lines, preventing their overloading and increasing the stability margin of the power system. Due to the introduction of variable mitigation and weight penalty functions, flexible response is ensured even when it is impossible to simultaneously fulfill all restrictions, which allows power system to effectively adapt to changing operating conditions and maintain stability under various disturbances. This approach increases the reliability and stability of the power system, providing more flexible control over power flows. Our approach provides integration of restrictions in real time, which makes it possible to adapt their values in accordance with changes in the system operating modes.

2. Analysis of the research results revealed that the operation of existing AFPAS with the PI-law of adjustment leads to overshoot (10 MHz) and exceeding the permissible overcurrent at the tie-lines, which negatively affects the static and dynamic stability reserve of the power system. AFPAS does not take into account restrictions on controlled overflows, which causes additional loading on TPPs and tie-lines while HPPs exhaust reserves too quickly. At the same time, the study of the proposed approach showed its advantages, namely the effective involvement of HPP and TPP reserves and optimal use of their maneuvering capabilities. The frequency recovery time was also reduced by 8%. The absence of overload at the main tie-lines was established, which increases the stability of the unified power system of Ukraine. Thus, the proposed approach has improved the efficiency of secondary frequency and power adjustment in the power system.

Conflicts of interest

The authors declare that they have no conflicts of interest in relation to the current study, including financial, personal, authorship, or any other, that could affect the study, as well as the results reported in this paper.

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Data availability

All data are available, either in numerical or graphical form, in the main text of the manuscript.

Use of artificial intelligence

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

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