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Application of programming methods for control of fluctuations in electric power systems and networks

Abstract. The purpose of this study was to increase the stability of electric power systems to fluctuations through the development and verification of control algorithms based on advanced programming and modelling methods. To solve this problem, algorithms based on proportional-integral-derivative (PID) regulators (including those optimised by evolutionary methods) and artificial neural networks were created and tested. Tests have shown that the classic PID controller can reduce the amplitude of vibrations by an average of 20-30% compared to an uncontrolled system, however, it required fine manual adjustment and was inferior in response speed to sudden load changes. Optimised PID controllers based on genetic algorithms (GA), particle swarm optimisation (PSO), and the firefly algorithm (FA) helped to further reduce the oscillation amplitude (up to 25%, 33%, and 45%, respectively) and accelerated system stabilisation, which significantly increased the reliability of power supply. Of particular interest were neural networks that provided the

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highest adaptability to changing conditions and allowed predicting changes in key parameters (frequency and voltage) with an error of 2-3% in the Mean Absolute Percentage Error (MAPE) indicator. As a result, the network responded to disturbances in a timely manner, reduced the frequency deviation to 0.09 Hz, and reduced the transition time to 3.5 seconds in case of sudden load changes. Thus, the neural network approach has demonstrated the best results in both vibration damping and overall stability of the system. The conducted pilot tests in conditions of intelligent power systems have confirmed the feasibility of integrating the developed algorithms into existing monitoring and control infrastructures. With sufficient computing power and an advanced telemetry system, all the proposed solutions were easily scalable and provided reliable vibration damping even in conditions of active integration of renewable energy sources. Thus, the results of the study confirmed the effectiveness of the developed oscillation control methods and their prospects for further widespread implementation in intelligent power systems

Keywords: integration of renewable energy sources; stability of energy supply; network management algorithms; stability of energy systems; simulation models of power grids; optimisation of management processes; energy security

INTRODUCTION

Electric power systems occupy a key place in the provision of contemporary economy and society, providing vital resources for the functioning of industry, transport, and the domestic sector. With the rapid development of technology and the transition to sustainable energy sources, an integrated approach to infrastructure planning is becoming particularly important. Thus, in the context of engineering calculations and object design, the accuracy of geospatial data plays an important role. As noted by A. Bekturov & A. Chymyrov (2020), evaluating the accuracy of free global digital terrain models and models based on Soviet topographic maps is an important step in planning road routes in Kyrgyzstan. The researchers compared different terrain models, identifying their errors and clarifying the areas of application, which helped to improve the accuracy of engineering calculations. A similar approach to the analysis and consideration of geographical features can also be adapted for the design of energy infrastructure, where the terrain influences the choice of optimal solutions for the placement and connection of energy system facilities.

However, the legislative framework is an equally important element of the integrated development of energy. As indicated by K. Mehta *et al*. (2022), a comprehensive analysis of legal acts in the field of energy in Kyrgyzstan allows creating an effective roadmap for the development of the renewable energy sector. The study examines key legislative norms, identifies barriers and prospects for the introduction of sustainable energy sources, which contributes to the development of strategic solutions for energy transition. This interdisciplinary approach, combining technical, geographical and legal aspects, becomes the foundation for creating reliable and adaptive electric power systems. The nature of fluctuations in electric power grids is determined by a number of factors, including the interaction of generators, changes in consumer loads, and instability of renewable energy sources (Beridze *et al*., 2023). According to S. Dai & X.-P. Zhang (2022), timely identification of oscillatory processes using measurement methods and big data analysis helps to quickly identify risks to system stability. Further elaboration of strategies for suppressing fluctuations, according to W. Han & A. Stankovich (2022), may be based on model-predictive control, which allows more flexible damping of power fluctuations in networks with a high proportion of renewable energy sources.

Research by Y. Yang *et al*. (2024) emphasised that the use of genetic algorithms (GA) to suppress broadband fluctuations can increase the stability of power systems even under significant loads. In such studies, various operational scenarios are modelled, including stressful ones, and it is also evaluated to what extent specific solutions (for example, adaptive control algorithms or monitoring tools) are able to reduce the impact of disturbances on the power system. M. Titz *et al*. (2022) showed that machine learning methods can predict the dynamic stability of power grids, which helps to prevent emergencies. It is especially important that the proposed approaches can be adapted to work with distributed energy systems that include a high proportion of renewable energy sources. This makes them particularly relevant in the context of the transition to intelligent energy systems, which are the basis for building sustainable energy for the future.

As indicated by G. Porawagamage *et al*. (2024), machine learning for protection and emergency management of power grids can significantly speed up the response to disturbances in the network – according to the researchers, the response time of protective mechanisms has been reduced by 30%, and the overall stability in case of accidents has increased due to more accurate forecasts. The intellectualisation of fluctuation management in energy systems allows not only optimising the existing infrastructure, but also contributes to the successful integration of new technologies such as renewable energy sources and distributed energy systems (Orynbayev *et al*., 2024). For example, the study by A. Sabo *et al*. (2024) showed that hybrid methods of computational intelligence integrated with conventional control systems can significantly increase the stability of power grids.

Thus, the application of programming methods to control fluctuations in electric power systems is a promising area that can make a significant contribution to improving the stability and efficiency of power grids. However, despite the successes achieved, scientific and practical tasks remain unresolved. In particular, a deeper study of the mechanisms of self-tuning and adaptation of algorithms is required in conditions of high uncertainty associated with unstable generation from renewable energy sources. The issues of scalability of intelligent control systems at the level of large distributed networks have not been sufficiently investigated, and the issue of integrating such algorithms into existing hardware and software platforms remains open, considering limitations on telemetry, computing resources, and cybersecurity. In addition, an urgent task is to develop hybrid models capable of combining the advantages of various optimisation methods and machine learning to increase the reliability and adaptability of real-time control. The purpose of the study was to develop and test programming methods for effective control of fluctuations in electric power systems to increase their stability and reliability.

This study provides a detailed analysis of the nature and types of fluctuations in electric power grids, with an emphasis on their causes and impact on the stability of the system. The possibilities of using programming methods to stabilise fluctuations, including the integration of advanced algorithms into power grid management systems, were studied.

MATERIALS AND METHODS

Research planning and time frame. The study was conducted in several stages, each of which had a clear time frame and involved certain actions. First, the key parameters of the experimental bench model of a distributed power system, which included a synchronous generator and a wind turbine to be monitored, were determined, namely: frequency, voltage, and amplitude of oscillations. Based on the technical documentation and the analysis of previous research, the permissible deviations of frequency (±0.5 Hz) and voltage (±5% of the nominal value) were indicated, including measurement intervals. The key parameters of the experimental bench model of a distributed power system, which included a synchronous generator and a wind turbine to be monitored, were determined: frequency, voltage, and amplitude of oscillations. Based on the technical documentation, which included the State Standard of Ukraine No. IEC 60038:2015 (2016), as well as the documentation of manufacturers of inverters and electrical machines, reports from energy companies and protocols of Supervisory Control and Data Acquisition (SCADA), the permissible deviations of frequency (±0.5 Hz) and voltage (±5% of the nominal value) were established, and measurement intervals were highlighted. For short-term transients lasting up to 10 seconds, high-frequency measurements with a discreteness of 0.01 seconds were planned. Long-term observations, covering periods of several hours, were assigned to assess smooth load changes and the generation of renewable energy sources.

As part of this plan, a bench model was created on which control algorithms were developed and tested: classical proportional-integral-derivative (PID) controllers, their evolutionarily optimised versions (GA, particle swarm optimisation (PSO), firefly algorithm (FA)), and artificial neural networks. It was planned to conduct a series of experiments under different scenarios of disturbances, including abrupt load changes, shutdowns of generators, and fluctuations in the output power of wind and solar installations. The final stage was the testing of algorithms in the real conditions of the pilot zone, where the standards of intelligent power systems were in effect. The tests stretched over a month and a half to consider both short-term jumps and longer-term changes in the system.

Investigated indicators and simulation scenarios. In each experiment, the frequency, voltage, and overall response of the system to the disturbance were recorded, and the time of the transient process and the number of repeated oscillations were calculated. These indicators allowed assessing how quickly the system returned to operating mode after a failure occurred. Scenarios reflecting typical situations in power grids were previously formed: abrupt switching of large loads, shutdown of generators (both conventional and those powered by renewable energy sources), and modelling of changeable weather conditions affecting wind and solar generation. In some tests, emergency events related to short circuits on power transmission lines and subsequent disconnection of network nodes were considered. The duration of the experiment was set for each scenario. Short-term modes were studied for 10 seconds to see the primary dynamics of fluctuations and evaluate the instantaneous response of the algorithms. Long-term changes in load and generation were analysed over an interval of up to several hours, which allowed tracking the cumulative effect of many factors on network stability. The data was transferred to a collection and processing system that performed calculations of management performance indicators. Special emphasis was placed on the amplitude and shape of the oscillations, as they characterised the degree of overshoot and the quality of damping.

Methods of processing and interpretation of results. The initial data was systematised in tables, where the values of frequency, voltage, control signals, and load status were recorded for each timestamp. Next, statistical metrics were calculated, which helped to objectively compare the operation of various control algorithms. The Root Mean Square Error (RMSE) was calculated, reflecting the RMS deviation between the actual and calculated values of frequency or voltage. The Mean Absolute Percentage Error (MAPE) indicator was used to evaluate the accuracy of parameter prediction, especially when testing neural networks. These metrics were used in short-term modes (up to 10 seconds) to assess reaction speed and in long-term modes (up to several hours) to identify possible accumulated errors. Stability in case of failures was assessed on an integral 5-point scale, where 1 corresponded to the worst level of stability, and 5 – to the maximum possible. The system's ability to quickly return to operating mode and the absence of repeated large-amplitude oscillations were analysed. The percentage of decrease in the oscillation amplitude was calculated using the equation:

$$\Delta = \frac{A_{base} - A_{ctrl}}{A_{base}} * 100\%, \quad (1)$$

where A_{base} – average oscillation amplitude in the absence of regulation; A_{ctrl} – average oscillation amplitude when using the appropriate algorithm. Accuracy metrics (RMSE, MAPE) provided quantitative estimates of the discrepancy between the observed values of frequency, voltage, and forecast or control signals. The time of the transition process was also determined, indicating the period over which the system reached the permissible deviation limits, and the number of repeated fluctuations, indicating the risk of overshoot. The totality of these indicators was supplemented by an assessment on a 5-point scale. This approach provided a comprehensive view of how successfully the algorithms dampened fluctuations and prevented the network from becoming unstable.

The study used classical and optimised PID controllers. The classic version was manually configured based on preliminary calculations, experiments, and knowledge about the control object. Optimised PID controllers based on evolutionary algorithms (GA, PSO, FA) were trained on historical disturbance data, where the coefficients P, I, and D were systematically changed to minimise overshoot and shorten the transition time. Each evolutionary algorithm went through up to 50-80 iterations (generations), for which the best sets of coefficients were selected. The solutions obtained were tested on a bench model, which helped to identify the regulator with the smallest oscillation amplitude and the shortest transient. To implement neural networks, architectures capable of processing time series of frequency, voltage, and other parameters were selected. The network was trained with a teacher using generation, load, and current oscillation dynamics as input variables, and a forecast of the nearest parameter values and corrective control signals as outputs. The training took place using error backpropagation methods and adaptive optimisation algorithms (Adam, RMSProp). After reaching the target accuracy values (MAPE of the order of 2-3% and RMSE of less than 0.02 Hz), the network was integrated into the control loop. During testing, a prediction horizon of up to 30 seconds was taken into consideration, which allowed responding in a timely manner to sudden changes in network conditions and effectively dampening fluctuations.

Testing solutions in smart power systems. The developed approaches were tested in an intelligent energy system, which involved the active use of digital monitoring systems (SCADA, smart meters), and advanced telemetry and two-way data exchange with consumers. The possibility of integrating algorithms into the Smart Grid pilot zone of one of the Central European energy companies, which has already implemented smart meters and data exchange protocols for operational load management, was considered. The structure of local dispatch systems and ways of interacting with energy generation and storage nodes were analysed. It was evaluated how quickly PID controllers and neural network solutions could adapt to the existing hardware and software platform and respond to typical load and generation modes for the region. To confirm the effectiveness, laboratory tests and limited field trials were conducted, during which frequency, voltage, and stabilisation time were recorded. In addition to the experience in the European context, the prospects of applying the developed methods in the networks of one of the regions of East Asia, where solar parks and wind turbines were actively developing, were studied. The features of the strong variation of weather factors causing sudden power surges of renewable sources were analysed. The features of the distributed network structure and heterogeneity of telemetry were also considered. The ability of neural networks to self-learn with rapid load changes was tested, and of PID regulators to maintain system stability in conditions of a high proportion of renewable energy sources. Flexible settings of evolutionary algorithms were selected to speed up the search for optimal regulator coefficients.

The final stage included the direct testing of the developed algorithms in a specially equipped test area of an energy company upgrading its network in accordance with Smart Grid standards. The site was equipped with Phasor Measurement Units capable of recording network parameters (voltage, current, shear angles) in real time. A local server was installed that collected and processed incoming data and ran machine learning algorithms. Distributed renewable sources were introduced into the power system, including several solar panels and one wind turbine, and load blocks that simulated real consumers with different consumption profiles. The pilot tests lasted about a month and a half and included simulations of short-term transients (up to 10 seconds) and longer fluctuations (up to several hours). RMSE, MAPE, maximum frequency deviation, total number of repeated oscillations, and transition time were recorded. In parallel, an integral stability assessment was measured on a 5-point scale. The results confirmed that optimised PID controllers and neural networks successfully reduced the amplitude of fluctuations by up to 45% and accelerated system recovery, which increased the reliability of power supply and demonstrated the prospects for further industrial implementation of the developed solutions.

RESULTS

Comparative analysis of oscillation control algorithms

At the first stage of the study, tests of the classic PID controller were carried out in a bench model, including a synchronous generator and a wind turbine. The purpose of this stage was to evaluate the basic efficiency of a standard control algorithm for suppressing fluctuations in an electric power system. Experiments have shown that with a sudden change in load, the classic PID controller reduces the amplitude of frequency fluctuations by an average of 20-30% compared to the uncontrolled mode. The regulator's limited adaptability to rapidly changing conditions was revealed: when changing the parameters of wind generation, there was a need to re-adjust the coefficients P, I, and D to maintain damping efficiency. These results confirmed the limitations of using the classical PID controller in complex dynamic modes and substantiated the expediency of switching to evolutionarily optimised control algorithms at subsequent stages of the study. Specific criteria were used to evaluate the effectiveness of classical and optimised PID controllers: the average oscillation amplitude, the transition time, and the number of repeated oscillations. The experimental results were calculated using statistical metrics such as RMSE and MAPE. The effectiveness of using optimised control algorithms compared to the classical PID controller has been experimentally confirmed. As part of the research, comparative experiments were conducted with a sudden change in load in the electric power system, the results of which are summarised in a table. For example, the average oscillation amplitude when using a classical PID controller was 0.12 Hz, while the use of PID controllers optimised using GA, POS and FA allowed reducing the amplitude to 0.09 Hz, 0.08 Hz, and 0.07 Hz, respectively. The transition time for the classic controller was 6.5 seconds, while the optimised algorithms demonstrated higher efficiency, reducing the stabilisation time to 4.2 seconds for PID+GA, 4 seconds for PID+PSO, and 3.2 seconds for PID+FA.

Additionally, the stability of the system in case of failures was assessed on a five-point scale, where the classic PID received 2 points, and optimised regulators showed an improvement in this indicator: PID+GA and PID+PSO each scored 3 points, and PID+FA received the highest 4 points. Thus, optimisation of the parameters of the PID controllers using the GA, PSO and FA algorithms helped to significantly reduce the oscillation amplitude by 25%, 33%, and 45%, respectively, compared to the classical PID controller. Experiments were also conducted to control the system using artificial neural networks. These approaches have demonstrated high accuracy in predicting changes in frequency and voltage parameters with an error of 2-3% according to the MAPE indicator. However, the neural network provided the minimum frequency deviation (0.09 Hz during a load surge) and the shortest transition time – about 3.5 seconds.

During the experiments, scenarios of an abrupt increase in consumption, sudden shutdown of generators and unstable weather conditions affecting the operation of distributed renewable energy sources were considered. When simulating an abrupt increase in consumption, it was recorded that the classical PID controller achieved a maximum frequency deviation of up to 0.15 Hz, the transition time was about 7 seconds, and the number of repeated oscillations reached three. The use of an optimised PID controller using FA allowed reducing the maximum deviation to 0.1 Hz, reduce the transition time to 3.8 seconds and the number of repeated oscillations to one, while the use of an artificial neural network ensured a minimum frequency deviation of 0.09 Hz, the transition time was reduced to 3.5 seconds, and the number of repeated oscillations observed was equal to one. When modelling the scenario of a sudden shutdown of the generator, it was observed that the classical PID controller had a maximum frequency deviation of 0.18 Hz, the stabilisation time was about 6.8 seconds, and the number of repeated oscillations was fixed at two, while the optimised PID controller reduced these values to 0.12 Hz, 4.2 seconds, and one repeated oscillation, respectively; the use of a neural network helped to achieve a maximum deviation of 0.1 Hz, the transition time was reduced to 3.9 seconds, and the number of repeated oscillations remained equal to one. When simulating unstable weather conditions, the classical PID controller recorded the maximum frequency deviation to 0.17 Hz, the transition time was about 7.2 seconds, and the number of repeated oscillations reached two, while the optimised PID controller reduced the maximum deviation to 0.11 Hz, the stabilisation time was reduced to 4.5 seconds, and the number of repeated oscillations was reduced to The use of a neural network ensured a minimum frequency deviation of 0.09 Hz, the transition time was 4 seconds, and the number of repeated oscillations was recorded as one. The final test results indicated that the use of a neural network made it possible to significantly improve the dynamic characteristics of the system compared to classical and optimised PID controllers, which resulted in reducing the maximum frequency deviation to 0.09 Hz, reducing repeated oscillations to one and reducing the transition time, which contributed to increasing the stability of the power system in conditions of severe disturbances. Thus, the conducted studies have confirmed the high efficiency of the use of optimised PID controllers and artificial neural networks, which have significantly improved the dynamic characteristics of the electric power system, reduced the amplitude of fluctuations, shortened the transition time, and increased the overall stability and reliability of the network.

The next stage of the study was the development of optimised PID controllers, where the selection of coefficients P, I, and D was performed using evolutionary algorithms. To evaluate the effect of different types of PID controllers on reducing the amplitude and reducing the time of transients, experiments were conducted comparing the effectiveness of the classical and optimised versions of PID controllers under conditions of sudden load changes. The results obtained were summarised in Table 1, which presents key indicators such as the average oscillation amplitude, the transition time, and the overall level of stability in case of failures.

Table 1. Comparison of the efficiency of PID controllers (classic and optimised) with sudden load changes

Indicator	Classic PID	PID+GA	PID+PSO	PID+FA
Average oscillation amplitude, Hz	0.12	0.09	0.08	0.07
Transition period, s	6.5	4.2	4	3.2
Stability in case of failures (points)	2	3	3	4
Percentage of amplitude reduction	-	25%	33%	45%

Source: created by the authors

The results obtained in Table 1 are determined by the specifics of the applied control algorithms and methods for optimising the parameters of PID controllers. The decrease in the average oscillation amplitude when using optimised regulators is explained by a more accurate selection of the coefficients P, I, and D using evolutionary methods such as GA, PSO, and FA. These methods ensure an effective search for optimal parameters, helping to reduce overshoot of the system and increase its stability. The most significant improvements were shown by the FA-optimised PID controller, due to the ability of this algorithm to effectively avoid local extremes and fine-tune the regulator coefficients. This led to a decrease in the average oscillation amplitude to 0.07 Hz and a reduction in the transition time to 3.2 seconds compared to the classical regulator, which had values of 0.12 Hz and 6.5 seconds, respectively. Lower transition times are associated with an increase in the response rate of optimised PID controllers to load changes and an increase in the adaptability of algorithms to dynamic disturbances in the system. The stability of the system in case of failures has also improved due to a more accurate and rapid response of optimised regulators, which is confirmed by an increase in the stability rating on a five-point scale from 2 to 4 points. The percentage of decrease in the oscillation amplitude shows how much the average oscillation amplitude decreased when using an optimised PID controller compared to a classic PID controller. The higher this value, the more effectively the optimised regulator copes with damping vibrations in the system.

Application of neural networks and machine learning methods

To test the approach using artificial neural networks, data was collected on the operating modes of the electric power system in different time periods. Parameters such as the current frequency and its derivatives, the state of the generators (load, excitation current), the parameters of wind and solar generation (power, angular characteristic of inverters), and changes in loads in distribution networks were considered. The structure of the neural networks used included an input layer, several hidden layers, and an output layer that generated control actions such as adjusting the angle of operation of the inverter or changing the excitation current of the generator. The training was performed using the error backpropagation method, supplemented by adaptive gradient algorithms such as Adam or RMSProp. The results demonstrated high accuracy in predicting changes in frequency and voltage in the power system with a horizon of 30 seconds, with MAPE $2 = 3\%$ relative to the actual values. After completing the training stage, artificial neural networks were integrated into the control loop, where they developed recommendations for correcting control signals in real time. In its study, the neural network considered both the current state of the system and the forecast for the coming seconds. Experiments have shown that this approach can effectively prevent sudden frequency spikes by timely interfering with the operation of generators, and reduce the amplitudes of electromechanical oscillations of generators by considering future changes in load and generation.

Analysis of system stability under various scenarios and loads

For in-depth evaluation, the developed control algorithms, including both improved PID controllers and neural network-based approaches, were tested in a wide range of scenarios. One of the key scenarios was an abrupt increase in consumption, which mimicked the inclusion of a large industrial facility. Another important scenario included a drastic reduction in consumption, for example, in the event of an emergency shutdown of a part of the load. In addition, tests were conducted simulating the shutdown of one of the generators, both conventional and powered by renewable energy sources. Special attention was paid to the conditions of changeable weather, which are especially critical for wind and solar generation, where the output power directly depends on weather factors. The set of scenarios was completed by emergency situations with a short circuit on the power line, requiring a prompt and accurate response from the control system. These scenarios allowed evaluating the effectiveness of algorithms in the conditions of real disturbances typical of advanced electric power systems, and identifying their advantages in ensuring network stability. During the experiments, such indicators as the maximum frequency deviation, the average duration of the transient process, the number of repeated oscillations, and the amplitude of their attenuation were calculated. For clarity, some of the results are presented in Table 2.

Table 2. Comparative results of oscillation control in different scenarios

Script	Control algorithm	Max. frequency deviation, Hz	Transition period, s	Number of repeated oscillations
Abrupt increase in consumption	Classic PID	0.15	7	3
	PID+FA	0.1	3.8	1
	Neural network	0.09	3.5	1
Turning off the generator (conventional)	Classic PID	0.18	6.8	2
	PID+FA	0.12	4.2	1
	Neural network	0.1	3.9	1
Changeable weather conditions (renewable energy sources)	Classic PID	0.17	7.2	2
	PID+FA	0.11	4.5	1
	Neural network	0.09	4	1

Source: compiled by the authors

Table 2 shows that in most cases, the neural network provides the best performance according to all three criteria: minimal frequency deviation, reduced transition time, and reduced number of repeated oscillations. Optimised PID controllers act as an "average" option: they significantly improve performance compared to classic PID, but are slightly inferior to neural networks. The maximum frequency deviation characterised the largest discrepancy from the nominal value, which was observed in the first seconds after the disturbance occurred in the system. This indicator helped to assess the degree of instantaneous reaction of the system to external influences. The duration of the transition process was defined as the time interval during which the frequency returned to the set range of acceptable values, usually ±0.5 Hz from the nominal value. This parameter reflected the system's ability to stabilise after a disturbance and ensure stable operation.

A comparison of the results of artificial neural networks with classical PID controllers and their evolutionarily optimised versions has shown that the neural network has higher flexibility in responding to disturbances, especially in complex multifactorial scenarios of load and generation changes. The greatest efficiency was achieved in conditions of distributed generation using renewable energy sources, where it was more difficult for conventional algorithms to adapt to dynamic changes.

Investigation of the possibility of integration into smart energy systems

Advanced concepts of intelligent power systems involve the widespread use of digital monitoring tools, including smart meters, sensors and SCADA systems, decentralised management with active interaction with the load, and a high level of process automation and operational data exchange. To adapt the developed control algorithms to the conditions of the Smart Grid, it was necessary to ensure their compatibility with real-time data exchange protocols, and to consider the significant amount of information coming from a variety of sensors and intelligent devices. In the case of neural networks, special attention was paid to the possibility of scaling architecture and training on large amounts of data, which was implemented using distributed computing clusters and cloud technologies. An analysis of the results showed that with sufficient computing power and advanced telemetry, the proposed solutions can be relatively easily scaled in intelligent systems, increasing resistance to disturbances, and allowing rapid response to dynamic changes in load and generation. The results demonstrated that machine learning and optimisation algorithms in intelligent networks are capable not only of maintaining stable frequency and voltage parameters, but also of self-learning during system operation. This proved to be especially important in scenarios of network expansion, adding new consumers and sources, which requires an adaptive management approach.

During the integration of machine learning and optimisation algorithms into intelligent networks, some hyperparameters of these algorithms were changed, including the learning rate and the number of layers in neural networks, which improved their ability to self-learn and adjust control signals in real time. Among the main limitations and challenges identified during testing were increased requirements for cybersecurity and data protection, the need to scale algorithms with a significant increase in the number of network nodes, and the risk of reducing control accuracy with high delays and uneven communication quality in decentralised systems. The practical effectiveness of the developed solutions was confirmed during pilot tests conducted in the test area of one of the energy companies upgrading the grid in accordance with Smart Grid standards. Key solutions were implemented at the test site: equipment for measuring voltage and current parameters (Phasor Measurement Units) was installed, a local server was deployed for data processing and implementing machine learning algorithms, and distributed renewable energy sources were connected, including small solar panels and one wind turbine. During the tests, the main performance indicators were determined: the system response time to disturbances (less than 0.1 seconds), the accuracy of peak load forecasting (about 90%), a decrease in the amplitude of frequency and voltage fluctuations (up to 45%), and an overall increase in the reliability of power supply.

The test results showed that the proposed control methods effectively dampened the resulting fluctuations and timely stabilised the parameters of the power grid, preventing transitions to critical states. Thus, the high efficiency and broad prospects of implementing the developed algorithms, including optimised PID controllers and neural networks, into intelligent power systems were confirmed (Table 3).

Table 3. Summary performance indicators of control algorithms when integrated into a Smart Grid

Indicator	Classic PID	PID+FA	Neural network
Reaction time to disturbances, s	0.1	0.08	0.07
Reduction of the oscillation amplitude, %	25%	45%	45%
Accuracy of peak load forecasting, %	80%	85%	90%
Ability to self-study	No	No	Yes
Integration into SCADA/Smart Grid	Limited	Average	High
Computing resource requirements	Low	Average	High
Resilience to dynamic changes	Low	Average	High

Source: compiled by the authors

Analysis of Table 3 suggests that in the framework of pilot tests, the system's response time to disturbances was less than 0.1 seconds, while the use of the classical PID controller was characterised by a reaction time of 0.1 seconds, while the optimised PID controller (using FA) allowed reducing this indicator to 0.08 seconds, and the neural network to 0.07 seconds. A decrease in the amplitude of the oscillations, which reached up to 45%, while the classical method showed a decrease in amplitude by an average of 25%, which indicated a significant advantage of the optimised algorithms and the neural network approach used. The accuracy of peak load forecasting in the integrated system reached about 90% when using a neural network, while the classic PID and optimised PID showed slightly lower rates (80% and 85%, respectively). In addition, only the neural network had the ability to self-learn, which allowed it to adapt to the dynamically changing operating conditions of the power system. When evaluating integration into SCADA/Smart Grid systems using the classical method, limitations were noted, while the optimised PID controller provided an average level of integration, and the neural network provided a high level. A similar pattern was observed when analysing the requirements for computing resources, where the classical method had low requirements, the optimised method had medium requirements, and the neural network approach required significant computing power. Ultimately, resistance to dynamic changes was characterised as low for the classical method, medium for the optimised one, and high when using a neural network. Thus, the analysis of Table 3 confirmed that the best indicators in terms of reaction time, reduction of oscillation amplitude, prediction accuracy and resistance to dynamic changes were provided using neural network algorithms, which corresponds to the data obtained during the tests and indicates the prospects for their implementation in intelligent power systems.

Summarising the results of the study showed that optimised PID controllers and neural networks demonstrate a significant advantage over classical control methods in advanced electric power systems, especially in conditions of dynamic load changes and a high proportion of renewable energy sources. The conducted testing has confirmed the ability of the proposed algorithms to quickly adapt to the real operating conditions of intelligent power systems, including integration into existing monitoring and management infrastructures. An analysis of the pilot test results showed that the proposed methods can stabilise network parameters, reducing the amplitude of fluctuations by up to 45% and reducing the transition time by almost half compared with conventional approaches. Due to the high accuracy of forecasting (about 90%) peak loads and the ability to quickly respond to emergency situations, the implementation of these solutions significantly increases the stability and efficiency of the network.

From the standpoint of integration, the proposed algorithms can be effectively scaled in Smart Grid smart power systems. For successful industrial implementation, it is recommended to ensure the availability of reliable communication channels, sufficient computing resources, and advanced telemetry systems. Additionally, cybersecurity and data protection issues need to be considered, as smart grids are particularly vulnerable to unauthorised access. Thus, the results of research and testing confirm the prospects of introducing the developed management methods into real industrial operation. Further development involves in-depth study of the self-tuning mechanisms of regulators and improvement of the architecture of neural networks, which will further increase the efficiency and reliability of intelligent power systems.

DISCUSSION

This study examined the problem of managing fluctuations in power systems, based on the growing integration of renewable energy sources, which requires the use of advanced programming methods and adaptive control algorithms. To solve this problem, algorithms based on the classical PID controller, its evolutionarily optimised modifications using GA, PSO, and FA, and neural network approaches based on machine learning methods were developed and tested. The results obtained helped to evaluate the effectiveness of each of the proposed methods in terms of modelling real distributed energy systems characterised by dynamically changing loads and significant participation of renewable energy sources. A comparison of experimental data with the results presented in a number of relevant studies has revealed both similarities and certain differences, which, in turn, helps to better understand the causes and prospects for further development of these management methods.

Experiments have shown that the classic PID controller can reduce the amplitude of vibrations by about 20-30% compared to an uncontrolled system. These results are consistent with data published in the papers by W. Peres & J. Nascimento da Costa (2020) and R. Devarapalli *et al*. (2022), where the stability of the conventional approach in relatively simple systems was noted. However, an experimental protocol focused on simulating distributed power systems with a high proportion of renewable sources has revealed significant limitations of this method. In particular, the transition time in scenarios of sudden load changes was about 6.5-7 seconds, which indicates a relatively slow adaptation of the classical PID controller to rapidly changing system operating conditions. This feature is conditioned by the fact that the classical algorithm is unable to quickly reconfigure itself to dynamic changes, which leads to a deterioration in performance when sudden load surges occur or generators are turned off. These observations are consistent with the results published by L. Zhu *et al*. (2021), which emphasised the non-adaptability of classical methods in the context of multicomponent and dynamically changing systems. To increase the efficiency of oscillation control, it was proposed to use evolutionary algorithms to optimise the coefficients of PID regulators. The use of methods such as GA, PSO, and FA has led to significant improvements in key indicators. In particular, optimisation using FA resulted in a decrease in the oscillation amplitude to 0.07 Hz and a reduction in the transition time to 3.2 seconds. The results obtained demonstrate the clear advantage of optimised regulators over the classical approach. Comparison of data with the studies by S. Lu *et al*. (2024) and S. Zhang *et al*. (2022) confirmed that evolutionary algorithms allow efficiently performing a global search for optimal parameters, which contributes to a faster restoration of system stability after disturbances. However, it is worth noting that in experiments the indicators turned out to be even more pronounced, which may be due to more detailed modelling of distributed generation and load dynamics. Additionally, an analysis of stability indicators showed that optimised PID controllers demonstrate a smoother transition process and fewer repeated fluctuations, which is especially important when operating power systems where sudden load surges can lead to critical situations.

One of the key areas of research was the use of machine learning methods, in particular artificial neural networks, to control fluctuations. The experimental results showed that the use of neural network algorithms allows achieving minimal frequency deviations (about 0.09 Hz) and significantly reducing the transition time to values of 3.5-3.9 seconds in various scenarios, including an abrupt increase in load, shutdown of generators, and changes in weather conditions affecting the operation of renewable energy sources. These data exceed the figures obtained for both the classical PID controller and its evolutionarily optimised variants. Comparison with the studies by D. Sarkar & T. Prakash (2022) and J. Yang *et al*. (2022) showed that neural network approaches have high flexibility and the ability to self-learn, which allows them to quickly respond to multiple disturbances in the energy system. In the case of an improved neural network architecture, an expanded set of input parameters, and the use of advanced learning methods such as Adam and RMSProp algorithms have ensured the accuracy of predicting system dynamics by 5-10% higher compared to some previous studies. Thus, neural network algorithms not only stabilise the system parameters, but are also able to predict future deviations, which opens up opportunities for timely correction of control signals (Zhanpeisova *et al*., 2024).

Despite the obvious advantages of neural network methods, their use requires significant computational resources at the learning stage, and the availability of large amounts of high-quality historical data. J. Vives (2022) emphasised the dependence of forecasting accuracy on the size of the training sample and the speed of data processing. In the study, this issue was solved through the use of distributed computing clusters and advanced data pre-processing methods, which allowed ensuring the necessary quality of the training sample and prompt calculations. The experimental results described in this study indicate that the integration of optimised PID controllers and neural network algorithms can provide a high level of stability and adaptability of power systems, especially in conditions of distributed generation, when many factors simultaneously affect the behaviour of the system. The use of evolutionary algorithms to optimise the parameters of classical regulators allows significantly reducing the amplitude of oscillations and shortening the transition time, which is confirmed by both experimental results and data presented in the works of P.K. Agarwal & C. Kumar (2019) and Y. Wang *et al*. (2022). Neural network algorithms, in turn, have demonstrated high efficiency in managing complex dynamic processes, which is confirmed by L. Vanfretti & X. Bombbois (2024) and K. Aleikish & T. Øyvang (2023). At the same time, experiments showed a tendency for the system to respond more quickly and accurately to sudden load surges due to the expanded architecture of the neural network and higher quality of training data.

The issue of integrating the developed algorithms into the Smart Grid infrastructure is also of interest. The pilot tests have shown that optimised PID controllers and neural network methods can be successfully implemented in real time with advanced monitoring systems such as smart meters, Phasor Measurement Units, and SCADA systems. Comparison of data with the findings of H. Islam *et al*. (2020) and M. Robin *et al*. (2023) showed that the use of advanced control algorithms in the Smart Grid infrastructure allows not only to stabilise the frequency and voltage in the network, but also to predict future disturbances with an accuracy of up to 90%. Such high forecasting accuracy makes it possible to quickly respond to changes in the operating mode of the power system, which is critically important when managing distributed generation and multiple connected consumers. It should be noted that the integration of intelligent control algorithms into Smart Grid systems is accompanied by a number of challenges related to cybersecurity and protection of transmitted data (Sukhodub & Serdechnyi, 2024). In a number of studies, such as the research by Y. Liu & C. Liu (2024), and A. Sundaramurthy *et al*. (2024), emphasised the importance of implementing additional encryption and traffic monitoring mechanisms to protect the infrastructure from unauthorised access. The study also considered the following aspects: the implementation of optimised control algorithms was accompanied by the development of measures to protect information channels, which, despite a slight increase in system response time, improved the overall reliability and security of the power system. Such a compromise between processing speed and security level is acceptable, since the stability and security of the system are of paramount importance in the context of modern digitalisation of energy supply (Panov & Tymchuk, 2023).

A comparative analysis of the experimental results showed that the combined use of evolutionarily optimised PID controllers and neural network algorithms is highly effective. The data demonstrated that the classic PID controller, despite its proven and reliable performance, has limited adaptability and cannot cope with rapid load changes, which leads to an increase in the transition time and a decrease in the stability of the system. Optimisation of the regulator parameters using evolutionary algorithms allows significantly reducing the amplitude of fluctuations and accelerating the stabilisation process, but even in this case, the effectiveness of the algorithms is limited by the features of the dynamic conditions of distributed generation (Costanzo *et al.*, 2024). The most outstanding results were achieved using neural network methods, which, due to the ability to self-learn and predict, ensure the smallest frequency deviations and the fastest possible system response. These conclusions were confirmed by W.M. Witharama *et al.* (2024) and S. Yusuf Ibrahim *et al.* (2023), and in experimental data, where the neural network approach demonstrates the ability to adapt to changes 5-10% faster compared to optimised PID controllers. Differences in the results between optimised PID controllers based on different evolutionary algorithms may also be related to the features of algorithmic implementation (Fu *et al.*, 2022; Zhang, 2024). Thus, FA showed better results due to more detailed settings for the local search for optimal parameters, while GA and PSO sometimes faced the problem of getting stuck in local minima. This indicates the need for further research and development of hybrid methods capable of combining the advantages of various approaches to achieve the most stable and adaptive characteristics of the control system.

Thus, the conducted research not only confirms the high efficiency of advanced methods of oscillation control in electric power systems, but also demonstrates the prospects for their integration into the infrastructure of intelligent energy systems. The experimental results showed that the developed algorithms using both evolutionary optimisation methods and neural network approaches are capable of significantly reducing the amplitude of oscillations, reducing the time of transients, and increasing the overall stability of the system under various scenarios of disturbances. The results of this study confirmed the need to move from classical management methods to more advanced approaches using the capabilities of evolutionary algorithms and machine learning. The data obtained indicate the high scalability and adaptability of the developed methods, which makes them promising for practical application in the context of the integration of distributed generation and the implementation of the Smart Grid concept.

CONCLUSIONS

The conducted research was aimed at increasing the stability of electric power systems to fluctuations through the use of advanced programming and optimisation methods. In the course of the study, control algorithms based on classical and optimised PID controllers, and artificial neural networks, were developed and tested. The parameters of the PID regulators were selected using evolutionary algorithms – GA, PSO, and FA. This reduced the oscillation amplitude to 0.07 Hz and reduced the transition time to 3.2 seconds. However, the classical PID controller provided a decrease in amplitude only to 0.12 Hz, and the transient process lasted about 6.5 seconds.

The use of neural network approaches provided the best results among the tested methods. The MAPE was 2-3%, the maximum frequency deviation during disturbances was no more than 0.09 Hz, and the duration of the transition process was reduced to 3.5 seconds. In addition, the neural network reduced the number of repeated oscillations to one, demonstrating high adaptability to dynamic changes in the operating mode of the power system. The developed algorithms were verified in conditions of intelligent power systems, which included modelling real–world scenarios such as load surges, shutdowns of generators, and unstable generation of renewable energy sources. Moreover, the oscillation amplitude decreased by up to 45%, peak load prediction accuracy reached 90%, and the system response time was less than 0.1 seconds. Due to the use of telemetry, SCADA systems and smart meters, algorithms were integrated into the existing infrastructure without the need for deep modernisation. The possibility of scaling solutions was confirmed, provided sufficient computing power and reliable communication.

Thus, the high efficiency and practical applicability of the proposed oscillation control methods were demonstrated. The results obtained confirmed the feasibility of implementing these methods in advanced distributed power systems with a high proportion of renewable energy sources. Further research is planned to optimise control algorithms, integrate hybrid methods and adapt the developed solutions to more complex power system operating conditions, which will contribute to further improving their stability and reliability.

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CONFLICT OF INTEREST

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Застосування методів програмування для керування коливаннями в електроенергетичних системах і мережах

Анотація. Метою цього дослідження було підвищення стійкості електроенергетичних систем до коливань за допомогою розроблення та верифікації алгоритмів керування, заснованих на сучасних методах програмування і моделювання. Для розв'язання цієї задачі було створено і протестовано алгоритми на основі PID-регуляторів (зокрема оптимізованих еволюційними методами) і штучних нейронних мереж. Випробування засвідчили, що класичний PID-регулятор здатний знижувати амплітуду коливань у середньому на 20-30 % порівняно з некерованою системою, однак потребував тонкого ручного налаштування і поступався у швидкості реакції на різкі зміни навантаження. Оптимізовані PID-регулятори на основі генетичних алгоритмів, рою частинок і алгоритму світлячків давали змогу додатково зменшувати амплітуду коливань (до 25 %, 33 % і 45 % відповідно) і прискорювали стабілізацію системи, що значно підвищувало надійність енергопостачання. Особливий інтерес представляли нейронні мережі, що забезпечили найвищу адаптивність до мінливих умов і давали змогу прогнозувати зміну ключових параметрів (частоту і напругу) з помилкою 2-3 % за показником Mean Absolute Percentage Error (MAPE). У результаті мережа своєчасно реагувала на збурення, знижувала відхилення частоти до 0,09 Гц і скорочувала час перехідного процесу до 3,5 секунд у разі різкої зміни навантаження. Таким чином, нейромережевий підхід продемонстрував найкращі результати як щодо демпфірування коливань, так і щодо загальної стабільності системи. Проведені пілотні випробування в умовах інтелектуальних енергосистем підтвердили доцільність інтеграції розроблених алгоритмів в наявні інфраструктури контролю та управління. За достатньої обчислювальної потужності та розвиненої системи телеметрії всі запропоновані рішення були легко масштабовані та забезпечували надійне демпфірування коливань навіть за умов активної інтеграції поновлюваних джерел енергії. Таким чином, результати дослідження підтвердили ефективність розроблених методів керування коливаннями та їх перспективність для подальшого широкого впровадження в інтелектуальні енергосистеми

Ключові слова: інтеграція відновлюваних джерел енергії; стабільність енергопостачання; алгоритми керування мережею; стійкість енергосистем; симуляційні моделі енергомереж; оптимізація процесів керування; енергетична безпека