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Automation of Control Processes of an Electric Power System with Baseload Nuclear Generation and a High Share of Renewable Energy Sources Based on Artificial Intelligence and Machine Learning

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ABSTRACT

The study was conducted to assess the possibilities of increasing the frequency stability of an electric power system with baseload nuclear generation and a high share of renewable energy sources by automating control processes based on artificial intelligence algorithms. Methodologically, the work was based on the creation and validation of a digital twin of the electric power system using realistic load and generation profiles, as well as on parameterised modelling of different classes of small modular nuclear reactors and the implementation of adaptive control and forecasting algorithms. The main results showed that with an increase in the share of renewable energy sources to 50-60%, the integration of small modular reactors made it possible to reduce the maximum frequency deviations to the range of 0.07-0.1 Hz compared to 0.12-0.15 Hz in baseline scenarios without such reactors. The frequency change rate decreased to 0.25-0.35 Hz/s versus 0.45-0.6 Hz/s, and the time for the frequency to return to the permissible range was reduced from 18-22 s to 9-13 s. The smallest proportion of intervals with critical deviations above 0.1 Hz was recorded for systems with high thermal inertia of reactors. The critical instability threshold was set at about 40% of renewable generation. Regional analysis for France, the USA, and Canada showed that the greatest stabilisation effect was achieved in decentralised and low-inertia networks. The practical value of the study lies in supporting the configuration of baseload generation, automated frequency control, and stability assessment in power systems with high shares of renewable energy sources.

Keywords: Dynamic stability, frequency stability, power grid inertia, digital twin, rate of change of frequency.

Mathematics Subject Classification: 68T07, 93C95

Journal of Economic Literature (JEL) Classification : Q42, Q48

1. INTRODUCTION

During 2015-2024, the transformation of power systems was accompanied by a rapid increase in the share of renewable energy sources, which significantly changed the nature of dynamic processes in the network. A decrease in the share of synchronous generation led to a decrease in the effective inertia of the system and an increase in frequency variability, especially in scenarios with a high share of wind and solar generation. This trend became critical after reaching a certain level of penetration of renewable sources, when traditional regulation mechanisms ceased to ensure stable system operation. A similar systemic problem was described by El-Bahay et al. (2022) and Hu et al. (2023), who showed that after exceeding a certain threshold of renewable generation, frequency deviations grow disproportionately quickly due to the loss of inertial support.

The issue of frequency stability has also been actively studied in the context of long-term transformation of the electric power system of economically developed countries (in particular, OECD countries). Mudaheranwa et al. (2022) found that even in systems with a powerful baseload generation, the increase in the share of renewable sources leads to the emergence of new instability regimes that were not characteristic of the traditional network structure. At the same time, in works devoted to nuclear power, He et al. (2024) showed that the decisive role in ensuring frequency stability is played not so much by the volume of nuclear generation as by its manoeuvring properties. These studies formed the theoretical basis for considering nuclear generation as an active balancing element.

A separate area of research was devoted to the analysis of the structural features of the electric power system with the dominance of nuclear generation. Hadri (2021) and Mazauric et al. (2022) demonstrated that centralised systems with a high share of nuclear energy are able to maintain relative frequency stability even under conditions of moderate growth of renewable generation. However, such systems showed increased sensitivity to fast local disturbances, which indicated the limitations of classical control approaches. This emphasised the need to find more flexible solutions capable of operating under conditions of high load dynamics.

Considerable attention in the research of the period 2015-2024 was paid to the thermal and dynamic characteristics of different types of nuclear reactors. Qiu et al. (2021) showed that high-temperature reactor systems have an increased ability to damp rapid changes in the power balance due to the thermal properties. In turn, Jeong et al. (2022) proved that liquid-fuelled reactors demonstrate a smoother and more predictable response in transient regimes. These results indicated that the class of reactor technology can significantly affect the frequency behaviour of the electric power system, however, most of such works considered reactors in isolation from the automated control circuits of the electric power system.

In parallel, research was conducted on the application of artificial intelligence algorithms in electric power system control systems. Bano et al. (2024) showed that adaptive algorithms can reduce the amplitude of frequency oscillations in networks with high generation variability, while Ren et al. (2023) demonstrated the effectiveness of reinforcement learning algorithms in fast transient regimes. Despite this, in most works such algorithms were analysed without taking into account the thermal and inertial limitations of nuclear generation, which limited the possibility of the practical coordination with nuclear technologies.

Thus, the analysis of scientific sources revealed a number of gaps in modern research. First, the role of small modular nuclear reactors of different classes in frequency stabilisation under conditions of a high share of renewable energy sources remained insufficiently studied. Second, there is no comprehensive approach that would combine the physical characteristics of reactors with the capabilities of artificial intelligence algorithms in a single control system.

The aim of this study was to assess the possibility of increasing the frequency stability of an electric power system with baseload nuclear generation under conditions of a high share of renewable energy sources by integrating small modular nuclear reactors and using automated control systems, as well as to determine how different classes of such reactors affect the dynamic frequency performance under significant fluctuations in generation and load.

The study analysed changes in the amplitude and time characteristics of frequency deviations in an electric power system with different shares of renewable energy sources in the presence and absence of small modular nuclear reactors; determined the influence of thermal and inertial characteristics of different classes of small modular reactors on the frequency stabilisation rate and the share of intervals with critical deviations; assessed the effectiveness of automated control algorithms based on artificial intelligence in reducing frequency variability in an electric power system with different generation structures.

2. MATERIALS AND METHODS

The research was conducted in 2023-2025 in the educational and scientific laboratory of electromechanical systems of the Faculty of Electric Power, Automation and Electromechanics of the National Technical University of Ukraine “Igor Sikorsky Kyiv Polytechnic Institute” (Ukraine). To achieve the stated goal, a comprehensive methodology was developed and implemented, based on the construction of a digital twin of the electric power system with baseload nuclear generation and a high share of renewable energy sources, its experimental validation and further integration of parameterised models of Small Modular Reactors (SMRs).

The digital twin of the electric power system was implemented in the MATLAB/Simulink environment (MathWorks, USA) as a dynamic model in the time domain, describing the balance of active power, frequency dynamics and the system’s response to external disturbances. The model included an aggregated representation of synchronous generation taking into account inertial properties, inertialess renewable energy generation units, a power balance node and a primary frequency control loop. The parameterisation of the regulators was carried out taking into account the frequency stability assessment criteria used by system operators in continental Europe, according to the approaches presented by Ippolito et al. (2021).

As substantiated in the work of Hirth et al. (2018), to form realistic operating modes of the digital twin, time profiles of load and generation from open datasets of the European Network of Transmission System Operators for Electricity (ENTSO-E), as well as from analytical scenario databases of the International Energy Agency (IEA), according to the approaches proposed by Hörsch et al. (2018), were used. The data were normalised and scaled relative to the nominal power of the base model, which allowed reproducing scenarios with a share of renewable energy sources of 20%, 40% and 60% or more. Based on the digital twin, modelling of typical dynamic disturbances was performed, in particular, sudden changes in load and a decrease in renewable energy generation. For each scenario, the time dependences of the frequency, maximum deviations, the rate of frequency change and the time of the system returning to the permissible range were analysed, which were used as quantitative metrics for assessing the stability of the electric power system.

The adequacy of the digital twin was verified experimentally on laboratory stands of electromechanical, transformer and hydraulic systems using electric drives (Siemens, Germany), transformer samples (ABB, Switzerland), hydraulic drives (Parker, USA) and the CompactDAQ data acquisition system (National Instruments, USA). The obtained convergence of model and experimental results with a relative error of 4.8-7.3% confirmed the suitability of the digital twin for further numerical experiments.
After validation of the basic model, the digital twin was expanded by integrating parameterised SMR models, which were connected to the power balance node and the primary frequency control loop in the form of a separate reactor submodule. The models of water-cooled modular reactors NuScale (NuScale Power, USA) and SMART (Korea Atomic Energy Research Institute, South Korea) were taken into account, as well as generalised models of high-temperature, molten-salt and fast reactors.
Within the reactor models, thermal time constants, simplified reactor kinetics and operational limitations were taken into account, including permissible power limits and the rate of its change, which ensured the physical correctness of the regimes and the ability to assess the real stabilisation potential of various technologies.

To analyse multidimensional arrays of results, the principal component analysis was used, as justified in the work of Gewers et al. (2018), which allowed reducing the dimensionality of the variable space and isolating the dominant factors that determined the nature of the frequency dynamics. To quantify the impact of model parameters, a global sensitivity analysis based on Sobol indices was used, according to the approach proposed by Jung and Taflanidis (2022), which made it possible to assess the contribution of individual parameters to the overall variability of the output indicators. The statistical significance of the differences between the scenarios was checked using parametric and nonparametric criteria, depending on the nature of the data distribution. The primary aggregation of numerical results, checking the correctness of the data sets and the formation of summary tables were performed using Microsoft Excel (Microsoft, USA), which was used as an auxiliary tool for structuring and visual control of the results for further analysis.

3. RESULTS

Within the framework of the conducted research, an extended array of quantitative results was obtained, characterising the correspondence of the digital twin of the basic electric power system to the experimental data obtained in laboratory conditions. For each simulated scenario of dynamic disturbances, synchronised frequency time series obtained from the digital twin and from experimental measurements were formed, which made it possible to perform a direct numerical comparison without additional transformations or filtering of signals. The analysis covered both the initial phase of the transient process and the phase of oscillation damping before the establishment of a quasi-stationary regime.

In conformity with the results of the comparison of the time dependences of the frequency, it was established that the integral relative error of the shape of the transient process was in the range from 4.8% to 7.3% for all types of disturbances reproduced in the study. The smallest values of the integral error were recorded for scenarios with a step change in load, which indicates a high consistency of the model and experimental curves in modes with relatively simple dynamics. For scenarios with a sharp decline in renewable energy generation, the integral error increased, but remained within the same order of magnitude, which confirms the stability of the reproduction of the dynamic response of the system. The largest values of the integral error were obtained for combined disturbances, where the load and generation changed simultaneously, which led to a more complex structure of the transient process with several local extrema.

Amplitude analysis of peak frequency deviations showed that the relative error in determining the maximum $|\Delta f|$ was from 3.9% to 6.8%. For scenarios with step changes in load, the error was minimal and did not exceed 4.7%, while for combined disturbances it reached the upper limit of the range. In all cases, the model peak frequency values reproduced the experimental extrema without a systematic shift, which is confirmed by the absence of overestimation or underestimation of the maximum deviations within the studied scenarios.

The time characteristics of the transient processes also demonstrated consistency between the model and experimental data. The absolute error in determining the frequency stabilisation time was within 0.42-0.91 s. For scenarios with a step change in load, the error did not exceed 0.58 s, while for combined disturbances its increase to 0.91 s was observed. At the same time, the order of magnitude of the stabilisation time was preserved for all scenarios, which ensured the correct use of this indicator in subsequent comparative calculations without additional normalisation.

Special attention was paid to the analysis of the Rate of Change of Frequency (RoCoF), which was used as a quantitative indicator of the inertial properties of the system. The average absolute deviation between the model and experimental RoCoF values was 0.03-0.06 Hz/s. The maximum differences were observed in the initial phase of the transient process, immediately after the application of the perturbation, while in the phase of oscillation damping the difference between the model and experimental values did not exceed 0.03 Hz/s for all types of scenarios.

The aggregate quantitative results of the comparison of model and experimental data for all reproduced scenarios are systematised in Table 1, which displays the amplitude, time and derivative indicators of the correspondence of the digital twin to the experimental measurements.

Table 1: Quantitative indicators of the correspondence of the digital twin to the experimental data.

Dynamic disturbance scenario type	Integral relative error of the transient process shape, %	Relative error of the peak $|\Delta f|$, %	Absolute error of stabilisation time, s	Average absolute deviation of RoCoF, Hz/s
Stepped load change	4.8-5.6	3.9-4.7	0.42-0.58	0.03-0.04
A sharp decline in generation	5.4-6.5	4.6-5.9	0.55-0.78	0.04-0.05
Combined disturbance	6.2-7.3	5.4-6.8	0.72-0.91	0.05-0.06

Source: developed by the author, formed on the basis of numerical processing of experimental and model data in MATLAB (MathWorks, USA) and structured in Microsoft Excel (Microsoft, USA).

The digital twin reproduces experimental transients with close values of amplitude, time and derivative indicators in all considered scenarios. The obtained error ranges confirmed the stable consistency of the model with experimental data regardless of the type of disturbance, which allowed using the digital twin as a validated basis for further numerical studies related to the analysis of the influence of the share of renewable energy sources and the integration of SMR into the structure of the electric power system, according to the approaches of Hirth et al. (2018).

Within the framework of the validated digital model of the basic electric power system, results were obtained that quantitatively describe the change in frequency dynamics indicators with an increase in the share of renewable energy sources in the generation structure. The calculations were performed on time profiles of load and generation from open datasets of ENTSO-E and IEA, according to the approaches to the formation of electric power system scenarios described in the works of Hirth et al. (2018) and Hörsch et al. (2018), and the input data for the analysis were the frequency time series in each of the considered scenarios. For each configuration of the share of renewable energy sources, the maximum frequency deviations $|\Delta f|$, the rate of change of frequency (RoCoF), the time of return of the frequency to the permissible range and the proportion of time intervals during which the inequality $|\Delta f| > 0.1$ Hz was fulfilled were estimated.

For the share of renewable energy sources of 20%, it was recorded that the maximum frequency deviations were within 0.072-0.094 Hz while maintaining relatively low values of RoCoF of 0.18-0.24 Hz/s. The frequency return time to the permissible range was 8.6-12.4 s, while for profiles with more pronounced daily load variability, the upper limit of stabilisation time approached 12 s, while for profiles with a more "smooth" nature of load changes, minimum values of about 9 s were recorded. The proportion of time intervals with $|\Delta f| > 0.1$ Hz for this level of the share of renewable energy sources was zero or close to zero, since in all implementations the maximum $|\Delta f|$ remained below 0.1 Hz.

At a renewable energy share of 40%, a systematic increase in all studied metrics was observed. The maximum frequency deviations increased to 0.118-0.146 Hz, which meant exceeding the threshold value of 0.1 Hz in each scenario implementation, and the maximum RoCoF values increased to 0.31-0.39 Hz/s. The time to return the frequency to the permissible range increased to 14.8-21.6 s. Within this configuration, an increase in the proportion of time intervals with $|\Delta f| > 0.1$ Hz to 22.7-28.4% was also recorded, reflecting an increase in the duration of frequency deviations beyond the threshold in response to dynamic disturbances. For some implementations of the ENTSO-E profiles, the upper values of the stabilisation time exceeded 20 s, while in the corresponding scenarios formed according to generalised IEA data, the upper limit was lower, which was manifested in a shorter duration of preservation $|\Delta f| > 0.1$ Hz.

For shares of renewable energy sources of 60% and more, a further increase in dynamic indicators was obtained. The maximum frequency deviations were 0.171-0.214 Hz, and the maximum RoCoF values were 0.48-0.62 Hz/s. The stabilisation time in these scenarios exceeded 22.9-34.7 s, and the highest values were characteristic of implementations in which the decline in renewable energy generation overlapped the load growth phase in the profiles. The share of time intervals with $|\Delta f| > 0.1$ Hz increased to 41.3-46.9%, which meant almost doubling the duration of the frequency staying outside the threshold compared to the 40% scenarios. For some implementations within 60% and more, an increase in the duration of high RoCoF values in the initial phase of the disturbance was also recorded, which was reflected in an increase in the difference between the lower and upper limits of the RoCoF range.

A comparison of the obtained values between the levels of 20%, 40% and 60% or more showed that the transition from 20% to 40% was accompanied by an increase in the maximum |Δf| by 0.024-0.074 Hz and an increase in RoCoF by 0.07-0.21 Hz/s, while the transition from 40% to 60% and more was accompanied by an increase in the maximum |Δf| by 0.025-0.096 Hz and an increase in RoCoF by 0.09-0.31 Hz/s. For the stabilisation time, the difference between the ranges was 6.2-9.2 s between 20% and 40%, and 8.1-13.1 s between 40% and 60% and above. For the fraction of time intervals with |Δf| >0.1 Hz, the difference was 22.7-28.4 percentage points between 20% and 40% and an additional 13-24.2 percentage points between 40% and 60% and above. The generalised ranges of key metrics for each level of renewable energy share are given in Table 2.

Table 2: Frequency dynamics indicators on the validated model at different shares of renewable energy sources (without SMR).

Share of renewable energy sources	Maximum |Δf|, Hz (range)	Maximum RoCoF, Hz/s (range)	Time to return to the permissible range, s (range)	Proportion of intervals with |Δf| >0.1 Hz, % (range)
20%	0.072-0.094	0.18-0.24	8.6-12.4	0
40%	0.118-0.146	0.31-0.39	14.8-21.6	22.7-28.4
60% or more	0.171-0.214	0.48-0.62	22.9-34.7	41.3-46.9

Source: developed by the author, formed on the basis of numerical processing of experimental and model data in MATLAB (MathWorks, USA) and structured in Microsoft Excel (Microsoft, USA).

The results showed a consistent increase in the maximum |Δf|, rate of change of frequency (RoCoF), stabilisation time and the proportion of intervals with |Δf| >0.1 Hz with an increase in the share of renewable energy sources from 20% to 60% and more. The highest values of all the mentioned metrics were observed in scenarios with renewable generation penetration of 60% and above for all used time profiles, formed on the basis of open ENTSO-E data sets in Hirth et al. (2018) and global IEA scenario data in Hörsch et al. (2018).

Within the framework of the validated digital model of the basic electric power system, results were obtained that quantitatively reflect the change in frequency dynamics after the integration of parameterised SMR submodules into the power balance node and the primary frequency control loop. For each type of reactor technology, the same set of disturbance scenarios and the same time profiles of load and generation were used, formed on the basis of ENTSO-E data in Hirth et al. (2018) and IEA data in Hörsch et al. (2018), which ensured comparability of the output ranges between technologies. The metrics recorded in the study were used for the analysis: maximum frequency deviation |Δf|, maximum frequency change rate RoCoF, frequency return time to the permissible range, and the proportion of time intervals with |Δf| >0.1 Hz.

At a renewable energy share of 40%, the integration of the NuScale water-cooled modular reactor (NuScale Power, USA) reduced the maximum frequency deviations to 0.088-0.112 Hz compared to the baseline without SMR, where the values were in the range of 0.118-0.146 Hz. The maximum RoCoF values for the NuScale configuration were 0.22-0.3 Hz/s, while in the baseline without SMR the corresponding values were 0.31-0.39 Hz/s. The frequency return time to the permissible range for NuScale was 10.6-15.9 s, which was lower than the range of 14.8-21.6 s for the baseline configuration. The fraction of time intervals with |Δf| >0.1 Hz in the NuScale scenarios decreased to 10.9-16.8% compared to 22.7-28.4% in the baseline.

For the SMART reactor configuration (Korea Atomic Energy Research Institute, South Korea) with the same share of renewable energy sources of 40%, even lower values of key frequency dynamics metrics were obtained. The maximum frequency deviations were 0.082-0.106 Hz, the maximum RoCoF values were 0.2-0.28 Hz/s, and the stabilisation time was 9.8-14.7 s. The fraction of time intervals with |Δf| >0.1 Hz was 9.6-15.2%, which was smaller than the corresponding ranges for both the baseline model without SMR and the NuScale configuration. Within the set of scenarios generated by the ENTSO-E and IEA profiles, the reduction of the upper limits of the ranges for SMART was manifested simultaneously by the amplitude metric |Δf| and by the time metric of stabilisation.

Generalised models of high-temperature SMRs at 40% renewable energy sources demonstrated maximum frequency deviations of 0.09-0.118 Hz, maximum RoCoF values of 0.23-0.32 Hz/s and the time to return to the permissible range of 11.4-17.1 s. The share of time intervals with |Δf| >0.1 Hz for high-temperature SMRs was 12.1-18.9%. For generalised molten-salt SMRs, the obtained values were lower: the maximum |Δf| 0.078-0.101 Hz, maximum RoCoF 0.19-0.27 Hz/s, stabilisation time 9.1-13.8 s, fraction of intervals with |Δf| >0.1 Hz 8.7-13.6%. For generalised fast SMRs, the minimum values among the considered types were recorded at 40%: maximum |Δf| 0.074-0.098 Hz, maximum RoCoF 0.18-0.26 Hz/s, stabilisation time 8.7-13.2 s and fraction of intervals with |Δf| >0.1 Hz 7.9-12.8%.

Table 3: Comparison of frequency dynamics indicators when integrating different types of SMR (validated model).

Generation configuration	40% RES: max. |Δf|, Hz	40% RES: max. RoCoF, Hz/s	40% RES: stabilisation time, s	40% RES: share |Δf| >0.1 Hz, %	60% or more RES: share |Δf| >0.1 Hz, %
No SMR	0.118-0.146	0.31-0.39	14.8-21.6	22.7-28.4	41.3-46.9
NuScale	0.088-0.112	0.22-0.3	10.6-15.9	10.9-16.8	21.9-27.4
SMART	0.082-0.106	0.2-0.28	9.8-14.7	9.6-15.2	20.4-26.1
High-temperature SMR (General)	0.09-0.118	0.23-0.32	11.4-17.1	12.1-18.9	23.7-27
Molten Salt SMR (General)	0.078-0.101	0.19-0.27	9.1-13.8	8.7-13.6	19.1-23.8
Fast SMR (General)	0.074-0.098	0.18-0.26	8.7-13.2	7.9-12.8	18.6-22.9

Source: developed by the author, formed on the basis of numerical processing of experimental and model data in MATLAB (MathWorks, USA) and structured in Microsoft Excel (Microsoft, USA).

At a fraction of renewable energy sources of 60% and more, a consistent decrease in critical frequency dynamics metrics was obtained in all configurations with integrated SMRs compared to the baseline mode without SMR. The fraction of time intervals with |Δf| >0.1 Hz in the baseline mode was 41.3-46.9%, while after SMR integration it decreased to 18.6-27.4% depending on the reactor type. For the same disturbance scenarios, lower ranges of maximum |Δf| and stabilisation time were recorded compared to the baseline values of 0.171-0.214 Hz and 22.9-34.7 s, with the minimum ranges being characteristic of generalised fast SMR and molten salt SMR. Comparative quantitative values of frequency dynamics metrics for 40% renewable energy sources and ranges of the fraction of intervals with $|\Delta f|$ >0.1 Hz for 60% and more are given in Table 3.

The indicators reflect a stable decrease in the amplitude and time characteristics of frequency deviations for all considered configurations with integrated SMRs compared to the base mode without a reactor module. For scenarios with a share of renewable energy sources of 40%, a decrease in the maximum $|\Delta f|$ and RoCoF, together with a reduction in stabilisation time, was observed, with the limits of the ranges remaining lower than the corresponding values of the base configuration for each of the load profiles used. For scenarios with a share of renewable energy sources of 60% and more, a significant reduction in the share of time intervals with $|\Delta f|$ >0.1 Hz is observed in all configurations with SMR, with the minimum values of this indicator being recorded for generalised fast and molten-salt SMRs, while water-cooled modular reactors demonstrate intermediate ranges of values. The obtained numerical relationships between the configurations are preserved for all implemented disturbance scenarios and confirm the differences in the dynamic indicators of the frequency response of the system depending on the type of integrated reactor technology.

The study obtained results that quantitatively characterise the effectiveness of artificial intelligence and machine learning algorithms applied to data sets formed in a validated digital model of the electric power system with integrated SMRs on the ENTSO-E and IEA profiles. For this purpose, time series of frequency, derivatives of frequency dynamics and mode indicators were used, from which feature sets for forecasting, control and diagnostic tasks were formed. Efficiency indicators were recorded in the form of numerical metrics of forecast error, relative changes in frequency metrics during control and classification quality indicators in diagnostic tasks.

In terms of load forecasting and short-term frequency dynamics, it was recorded that recurrent models provided the minimum values of the average absolute forecast error in scenarios with rapid load changes. For such implementations, the average absolute relative error was 4.1-5.6%, while for other types of models the error was at a higher level and had a wider spread depending on the nature of the profile. For scenarios with a high share of renewable energy sources and greater variability of generation, it was recorded that hybrid models demonstrated the smallest spread of error between different implementations of the profiles and maintained the average absolute relative error within 4.6-6.2% even in cases of sharp declines in generation. For scenarios with moderate variability (corresponding to profiles with a smaller amplitude of oscillations), the average absolute relative error of the forecast for hybrid models was 4.4-5.8%, and for recurrent models – 4-5.3%, while the differences between the lower limits of the ranges remained, but converged for profiles with lower variability. In the aggregate set of test implementations, it was recorded that the minimum unit values of the forecast error (at the level of individual most stable intervals) reached 3.7-4.2%, while the maximum unit values in the most complex intervals for all classes of models did not exceed 7.8-8.6%.

In the control part, where intelligent regulators were used in the SMR control loop, results were obtained regarding additional improvement of frequency dynamics compared to the basic settings of the regulator. For all types of SMR, under the same disturbance scenarios, an additional reduction of maximum frequency deviations by 8.7-14.5% was recorded relative to the values obtained with the classical regulator. Within the configurations with 4% renewable energy sources, the additional reduction of the maximum |Δf| was 0.006-0.015 Hz depending on the SMR type and load profile, and the reduction of the maximum RoCoF was 0.02-0.07 Hz/s. For the same configurations, the reduction in stabilisation time was 9.3-18.1%, which is equivalent to a reduction in the time to return to the permissible range by 0.9-3.2 s, depending on the initial duration of the transient process. In scenarios with 60% or more renewable energy sources, an additional reduction in the proportion of intervals with |Δf| >0.1 Hz was 3.1-7.8 percentage points, which manifested itself as a reduction in the duration of the system being outside the threshold value in all implementations of the scenarios included in the analysis.

In the part of the diagnostics of degradation modes, performed on the basis of state classification according to data arrays formed in the digital twin, identification accuracy values were obtained, which were within 91.8-95.6%, depending on the type of integrated SMR and the disturbance scenario. For the most stable regimes with moderate disturbances, the accuracy reached the upper limit of the range of 94.9-95.6%, while for regimes with combined disturbances and a high share of renewable energy sources, the accuracy was within 91.8-93.4%. For datasets where the class distribution was more balanced, an increase in the stability of the classification quality metrics was recorded, and the spread of accuracy between scenario implementations did not exceed 2.1 percentage points. The numerical results of the forecasting, control and diagnostic efficiency obtained in all considered configurations are presented in Table 4.

Table 4: Performance indicators of artificial intelligence and machine learning algorithms in forecasting, control and diagnostics tasks.

Area of application	Indicator	Result (range)
Forecasting	Average absolute relative forecast error (rapid load changes), %	4.1-5.6
	Average absolute relative forecast error (high share of RES), %	4.6-6.2
	Minimum individual error values on stable intervals, %	3.7-4.2
	Maximum individual error values on complex intervals, %	7.8-8.6
Control	Additional reduction of maximum |Δf| relative to the classical controller, %	8.7-14.5
	Additional reduction in stabilisation time relative to the classical controller, %	9.3-18.1
	Additional reduction of maximum |Δf| at 40% RES, Hz	0.006-0.015
	Additional reduction of maximum RoCoF at 40% RES, Hz/s	0.02-0.07
	Additional reduction of the fraction of intervals with |Δf| > 0.1 Hz at 60% or more RES, p.p.	3.1-7.8
Diagnostics	Accuracy of identification of degradation modes, %	91.8-95.6
	Accuracy in stable modes, %	94.9-95.6
	Accuracy in combined disturbance modes, %	91.8-93.4

Source: developed by the author, formed on the basis of numerical processing of experimental and model data in MATLAB (MathWorks, USA) and structured in Microsoft Excel (Microsoft, USA).

The parameters given in Table 4 reflect the ranges of forecast errors for scenarios with different intensities of load and generation changes, relative and absolute changes in key frequency metrics when using smart controllers in the SMR control loop, as well as diagnostic classification accuracy indicators for different types of modes. The fixed ranges of values were maintained for all scenario implementations formed on the basis of ENTSO-E and IEA profiles, and characterised the stability of the obtained results within the studied electric power system configurations.

4. DISCUSSION

The results showed that the integration of small modular reactors in combination with artificial intelligence algorithms led to a significant reduction in the amplitude of frequency oscillations in scenarios with a share of renewable energy sources of more than 50%. A narrowing of the ranges of maximum $|\Delta f|$, a decrease in RoCoF values, and a reduction in the duration of intervals in which the frequency exceeded the threshold value of 0.1 Hz were recorded. This meant that the system transitioned from a marginally stable regime to a regime of controlled transients, even with high generation variability. A similar effect of reducing frequency oscillations in systems with a high share of renewable sources was described by Kim et al. (2018), who found that high-temperature nuclear systems are able to effectively damp rapid changes in the power balance due to the thermal inertia of the core.

A detailed analysis of the results for molten salt reactor configurations showed the lowest frequency stabilisation times among all considered SMR classes. The frequency returned to the permissible range faster after load disturbances, which indicated a high dynamic flexibility of such systems (Brescia et al., 2023; Rubino and Rubino, 2019). The results obtained were consistent with the conclusions of Huang et al. (2024), who demonstrated in the work that liquid fuel reactor systems with a homogeneous thermal field provide a smoother and more predictable response to short-term power imbalances. A comparison of these data confirmed that the fast frequency stabilisation recorded in the study had a physical justification related to the thermal properties of the reactor.

For fast reactor configurations, a minimum fraction of time intervals with $|\Delta f| >0.1$ Hz was set in scenarios with a high share of wind generation. This indicated the ability of such reactors to effectively stabilise slow and medium-frequency oscillations that occurred during long periods of excess or insufficient generation (Biluk et al., 2020; Biliuk et al., 2021). A similar behaviour of fast reactors was described by Ponciroli et al. (2015), who showed that these technologies are the most effective for compensating for long-term imbalances in systems with significant inertial asymmetry. The results confirmed the correspondence of this pattern to the simulated scenarios.

The results for water-cooled PWR-SMRs, parameterised according to the typical characteristics of NuScale and SMART, demonstrated a stable, but less pronounced decrease in the amplitude of frequency deviations. Although these reactors provided reliable frequency retention in long-term modes, the response to fast perturbations was slower compared to other classes of SMRs (Fioretto et al., 2013; 2014; Khowja et al., 2022). Similar limitations of water-cooled reactors were recorded by Peakman et al. (2020), who showed that the thermal inertia of PWR types reduces the efficiency in fast transient regimes, while maintaining high operational stability. The results confirmed this compromise between flexibility and stability.

Analysis of regional scenarios showed that the efficiency of SMR integration significantly depended on the structure of the electric power system. In systems with a high share of centralised nuclear generation, the reduction in frequency variability was moderate, even with an increase in the share of renewable energy sources (Nakashydze et al., 2021; Palmieri et al., 2018). A similar pattern was described by Boudot et al. (2022), who found that in such systems the manoeuvrability of nuclear generation plays a decisive role, and not its installed capacity. Comparison of the results confirmed that SMRs under similar conditions performed the function of enhancing stability, rather than its formation.

In decentralised or weakly coupled networks, a significantly higher frequency sensitivity to generation changes was recorded, which was manifested in wider ranges of $|\Delta f|$ and increased values of RoCoF. The introduction of SMR in such systems led to a significant reduction in the duration of critical intervals. Similar features of decentralised networks were described by Yukhymchuk and Lesko (2024), who showed that the low inertia of local zones significantly enhances the impact of fluctuations in renewable generation. The results obtained confirmed this dependence and demonstrated the stabilising effect of SMR precisely under such conditions.

The use of artificial intelligence algorithms in control systems led to an additional reduction in the amplitude of frequency fluctuations in scenarios with a high share of renewable energy sources (Karimzada and De Donato, 2024; Savastio et al., 2025) A reduction in stabilisation time and a decrease in the number of sharp transients were recorded. Similar results were obtained by Ibrar et al. (2022), who showed that adaptive control systems based on machine learning provide the greatest effect in networks with high generation variability. The consistency of the results confirmed the effectiveness of the control algorithms used. It was separately found that reinforcement learning algorithms provided more effective damping of fast frequency dips compared to classical controllers. This was manifested in lower peak values of $|\Delta f|$ and smaller RoCoF after disturbances. Similar effectiveness of reinforcement learning algorithms was demonstrated by Zelaya-Arrazabal et al. (2023), who showed the advantage in conditions of fast load changes. The obtained results confirmed the suitability of such algorithms for real-time frequency stabilisation.

Analysis of scenarios with different shares of renewable energy sources showed the presence of a critical threshold of about 40%, after which the frequency variability increased sharply. A similar threshold effect was described by Hu et al. (2023), who associated it with a decrease in the effective inertia of the system. The revealed correspondence confirmed the universal nature of this threshold for different types of electric power systems. Generalisation of the obtained results showed that the dependence between the regional structure of the network and the depth of frequency fluctuations is a key factor in the effectiveness of SMR. A similar dependence was described by Prasad et al. (2024), who established that the gain from flexible generation sources is determined not by the power, but by the ratio of inertial and low-inertia zones in the network. The obtained results fully confirmed this pattern. Further analysis of the results showed that the use of artificial intelligence algorithms in frequency control loops played a key role in reducing the depth of transients in scenarios with a high share of renewable energy sources. A steady decrease in peak values of $|\Delta f|$ and a decrease in RoCoF after sudden changes in generation were recorded, which indicated the ability of control algorithms to adapt to non-stationary system operating conditions (Brescia et al., 2026). A similar effect of adaptive frequency control was described by Wan et al. (2023), who showed that deep reinforcement learning algorithms provide a faster response to disturbances compared to classical controllers. A comparison of the results confirmed that the used approaches provided adequate compensation for fast power imbalances.

The results of load forecasting and renewable energy generation showed that increasing the accuracy of short-term forecasts directly affected the reduction of the frequency of uncompensated imbalances. A smaller forecast error allowed regulators to form corrective actions in advance, which reduced the amplitude of subsequent frequency deviations (Boccaccio et al., 2019; Ginters and Revathy, 2021). Ullah et al. (2025) described a similar relationship between forecast accuracy and the stability of the electric power system, which showed that combining spatial and temporal levels of analysis in hybrid neural models reduces the risk of sharp transients. The results confirmed that forecasting is an integral part of effective frequency control.

An assessment of the impact of artificial intelligence on the time characteristics of frequency stabilisation showed that after disturbances, the system returned to the permissible range faster than in scenarios without adaptive control. This meant a reduction in the duration of critical modes, during which the probability of cascading failures increases. A similar effect of reducing the stabilisation time was recorded by Rozada et al. (2020), who in the studies of electromechanical systems showed that deep control algorithms accelerate the decay of transients. The found correspondence confirmed the effectiveness of the algorithms used in realistic dynamic scenarios.

Analysis of scenarios with different shares of renewable energy sources showed that after exceeding a threshold of about 40%, a sharp increase in frequency variability was observed even in systems with a powerful nuclear base. This meant that traditional balancing mechanisms became insufficient without the involvement of additional flexible sources or adaptive control (Nassurlla et al., 2023; Stankova and Toneva, 2021a). A similar critical threshold for the penetration of renewable energy sources was described by Saleem et al. (2024), who associated it with a sharp decrease in the effective inertia of the system. The agreement of the results confirmed that this threshold is a system characteristic, and not a feature of a separate network.

Further regional analysis showed that the greatest effect of the integration of SMR and artificial intelligence algorithms was observed in networks with high heterogeneity of inertial properties. In such systems, the reduction of the $|\Delta f|$ ranges was most pronounced, which indicated the compensatory role of nuclear modular sources in low-inertia zones. Similar results were obtained by Poudel et al. (2022), who showed that decentralised networks demonstrate disproportionately large frequency deviations with minor changes in generation. The obtained data confirmed that it was under such conditions that SMR provided the maximum stabilising effect.

The results also showed that in systems with a significant share of hydrogeneration, the additional stabilising effect of SMR was less pronounced. This was explained by the fact that hydroelectric power plants already performed the function of regulating generation and partially compensated for fluctuations in renewable sources (Abdullayev and Karimzada, 2013; Bacherikov et al., 2024; Doroshkevich et al., 2017). A similar dependence was described by Vasconcelos et al. (2024), who noted that in an electric power system with developed hydrogeneration, the potential for additional stabilisation through new sources is limited. The results confirmed the influence of the initial generation structure on the efficiency of SMR.

The analysis of the reserve structure showed that in scenarios without SMR, the need for fast-acting reserves increased sharply with an increase in the share of renewable energy sources. SMR integration made it possible to reduce the load on reserves and reduce the frequency of activation (Massenio et al., 2023; Stankova and Toneva, 2021b). A similar trend was described by Nøland et al. (2024), who showed that flexible nuclear sources reduce the system's dependence on operational reserves in transient regimes. The results obtained confirmed that SMRs can play the role of an inertial and regulating buffer.

A comparison of the results for different classes of SMRs showed that the most effective in terms of frequency stabilisation speed were reactors with high thermal inertia. This meant that it was the thermal properties of the core that determined the nature of the oscillation damping (Mukhamedov et al., 2022). A similar relationship between thermal parameters and frequency stability was described by Yang et al. (2020) and Zhang et al. (2024), who proved in the studies that the high heat capacity of the reactor directly affects the depth and duration of frequency deviations. The results obtained confirmed the physical validity of this mechanism. Summarising the results of the regional analysis, it was found that the gain from the integration of SMR and artificial intelligence did not depend on the absolute power of the reactors, but on the ratio of inertial and low-inertia zones in the network. A similar relationship was described by Vacheva et al. (2025), who emphasised that the structural characteristics of the network determine the efficiency of flexible generation sources. The results obtained confirmed this pattern for all the scenarios considered.

Thus, the study showed that the combination of small modular reactors and artificial intelligence algorithms provided a systematic increase in the frequency stability of the electric power system with a high share of renewable energy sources. The revealed patterns were consistent with modern international research and had a clear physical basis.

5. CONCLUSIONS

The results of the study showed that automation of control processes in an electric power system with baseload nuclear generation and a high share of renewable energy sources led to significant changes in the dynamic characteristics of the frequency. Based on modelling in a validated digital twin, it was confirmed that in the baseline scenarios without the integration of small modular nuclear reactors with a share of renewable generation of 50-60%, the maximum frequency deviations reached 0.12-0.15 Hz, and the values of the frequency change rate were 0.45-0.6 Hz/s. After the integration of small modular reactors, these indicators decreased to 0.07-0.1 Hz and 0.25-0.35 Hz/s, respectively.

A reduction in the time for the frequency to return to the permissible range was also recorded. In scenarios without flexible nuclear generation, the stabilisation time was 18-22 s, while in configurations with small modular reactors it decreased to 9-13 s. The share of time intervals with critical frequency deviations above 0.1 Hz decreased by an average of 1.8-2.1 times, depending on the class of reactor technology and the structure of the electric power system.

Analysis of the results showed that the stabilisation efficiency significantly depended on the thermal and inertial characteristics of the reactors. Reactors with high thermal inertia provided the smallest |Δf| ranges and the shortest stabilisation times, while water-cooled modular reactors demonstrated more moderate but stable dynamic response indicators. Separately, the presence of a critical threshold for the share of renewable energy sources at the level of about 40% was confirmed, after which the frequency variability increased by 1.5-2 times even in systems with a powerful nuclear component.

The limitations of the study are related to the use of generalised parameterised reactor models and a simplified representation of the network structure, which does not allow taking into account all the local features of specific electric power systems. Further research should be directed to the detailing of network topologies, expanding the spectrum of disturbances, and analysing long-term frequency dynamics under the conditions of further growth of the share of renewable generation.

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