Algorithmic methods of constructing the space of parameter increments in automated control systems of energy processes

Maria Yukhimchuk[†], Viacheslav Kovtun[†], Yurii Horchuk[†,*], Vladyslav Lesko[†]

Vinnytsia National Technical University, Khmel'nyts'ke Hwy, 95, Vinnytsia, 21000, Ukraine

Abstract

The article discusses algorithmic methods for constructing the space of parameter increments in control systems for automated energy processes. Automation of power processes is an important task of modern energy, which requires accurate analysis of parameter changes in real time. The space of parameter increments allows us to identify patterns of changes in dynamic systems and predict their behavior.

Two approaches to the construction of the incremental space are proposed: preliminary numerical integration of the stored values of state variables and parallel integration of the state and sensitivity equations. The first approach is based on the use of numerical integration methods, such as the Runge-Kutta method, which provides an effective analysis of the stable modes of automated systems. The second approach, which takes into account generalized derivatives, allows analyzing systems with discontinuities and abrupt changes in parameters.

The possibility of applying the developed algorithms in automated systems for monitoring and controlling energy facilities is analyzed. The use of the proposed methods makes it possible to improve the accuracy of forecasting changes in parameters, optimize the distribution of energy resources and ensure adaptive control of power grids. The combination of algorithmic methods with machine learning technologies opens up prospects for the creation of intelligent control systems that can adapt to changing operating conditions.

The results of the study confirm the effectiveness of the proposed methods and can be used to develop modern software solutions in the field of automation of energy systems.

Keywords

algorithmic methods, space of parameter increments, control systems, machine learning, optimization, automated monitoring systems, adaptive control.

1. Introduction

Modern power systems are characterized by high complexity and dynamism of the processes taking place in them. Optimal control of such systems requires an accurate analysis of parameter changes over time, which allows timely response to load fluctuations, energy losses and other factors that affect the efficiency of power facilities [1].

One of the approaches to analyzing the dynamics of automated energy processes is to build a space of parameter increments, which allows identifying patterns of changes in the system and predicting its behavior. The use of algorithmic methods to build such spaces opens up new opportunities for optimizing the operation of automated energy facilities (power plants, distribution networks, etc.) [2].

Modern studies propose various methods of analyzing the incremental space, including machine learning methods [3], optimization algorithms [4], and numerical computing methods [5]. The combination of these approaches makes it possible to create automated monitoring and control systems that improve the efficiency of energy processes [6, 8-11].

The purpose of this article is to analyze algorithmic methods for constructing the space of parameter increments in automated energy process control systems, to assess their efficiency and

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* Corresponding author.

† These authors contributed equally.

umcmasha@gmail.com (M. Yukhimchuk); kovtun_v_v@vntu.edu.ua (V. Kovtun), yurii.horchuk@gmail.com (Y. Horchuk); lesko.v.o@vntu.edu.ua (V. Lesko)

0000-0002-8131-9739 (M. Yukhimchuk); 0000-0002-7624-7072 (V. Kovtun), 0009-0005-2761-6520 (Y. Horchuk); 0000-0002-5477-7080 (V. Lesko)

possibilities of application in industrial conditions.

The novelty of the article is as follows:

The paper introduces the space of parameter increments as a means of solving non-classical problems of assessing the stability of automated power systems. This is a new approach to analyzing the impact of changes in primary parameters on system behavior.

The use of generalized derivatives for piecewise continuous functions in modelling state variables of automated energy processes, which allows to take into account systems with discontinuities and abrupt changes.

Two algorithmic methods for constructing the space of parameter increments are proposed:

- direct numerical integration with the preservation of state variables, which is effective for stable dynamic regimes;
- parallel integration of the state and sensitivity equations, which provides better forecasting accuracy in systems with discontinuities.

The methods are adapted for industrial conditions, in particular for automated control systems of energy facilities,

Combining algorithmic methods with machine learning, which opens up prospects for creating intelligent energy control systems.

Thus, the article proposes a new conceptual approach to the analysis of the dynamics of energy systems, develops efficient algorithms and justifies their practical application.

2. Analysis of algorithmic methods for constructing the space of parameter increments in automated control systems of energy processes

Modern energy systems, such as power plants, distribution networks and renewable energy infrastructures, require efficient automated control to ensure stability and optimal use of resources. One of the key aspects of such control is the analysis of the dynamics of changes in system parameters, which allows predicting its behavior and adapting operating modes to load fluctuations or other external factors [1]. The space of parameter increments acts as a powerful tool for such analysis, as it reflects the sensitivity of the system to changes in the primary parameters and provides a basis for building control models [8-11].

Algorithmic methods for constructing the space of parameter increments are based on the calculation of sensitivity functions that describe the dependence of system state variables on its primary parameters. These functions can be obtained by numerical integration of sensitivity equations, which are linear differential equations with variable coefficients [2]. For small and medium-sized generation and consumption sources, it is important to choose an integration method that takes into account both computational efficiency and accuracy of the results. Let's consider two main approaches:

1. Pre-integration with preservation of state variables.

2. Parallel integration of the state and sensitivity equations.

The first approach involves the preliminary calculation of the system behavior in the state variable space with the subsequent determination of sensitivity functions based on the stored numerical arrays [3]. Its advantage is the ability to use standard numerical methods, such as the Runge-Kutta method, implemented in software packages such as MATLAB, SciLAB. However, in distribution networks, where the amount of data can be significant (for example, when monitoring distribution networks in real time), this method requires significant memory resources, which can make it difficult to use in cloud computing environments with limited resources.

The second approach, based on the parallel integration of the state and sensitivity equations, reduces the memory requirement, but increases the order of the system of differential equations being integrated [4]. This can lead to an increase in computational complexity. In such conditions, it is necessary to take into account generalized derivatives and jump conditions, which complicates the algorithms but ensures the correctness of the analysis for automated systems typical for the energy sector (for example, when switching operating modes of turbines or generators).

Assessment of the effectiveness of these methods in industrial conditions depends on the specific application scenario. For systems with continuous dynamics (e.g., stable operating modes of thermal power plants), the direct method of numerical integration is quite effective due to its simplicity and the possibility of implementation on standard equipment [5]. At the same time, for systems with discontinuities (e.g., sudden changes in load in distribution networks), parallel integration allows for more accurate behavioral forecasting, although it requires adaptation of algorithms to the specifics of the equipment.

The possibilities of applying these methods in distribution networks are significant. They can be integrated into automated monitoring and control systems, increasing the efficiency of energy processes by responding to changes in parameters in a timely manner. For example, in distribution networks, algorithms for constructing the incremental space can help optimize the distribution of electricity, reducing losses [2, 6, 7]. Combined with machine learning methods, these approaches open up prospects for creating intelligent control systems that can adapt to changes in real time [3, 8-11].

3. Development of algorithms for constructing the space of parameter increments

The space of parameter increments can be reduced to finding partial derivatives (which determine the corresponding sensitivity functions). However, for piecewise continuous functions that define Y(X(t), P(t), t) [7], the construction of sensitivity functions requires solving the problem of differentiability of functions that are nondifferentiable in the classical sense. This problem is solved by the notion of a generalized derivative, which exists for piecewise continuous functions with a finite number of discontinuities of the first kind. Recall that for a piecewise continuous function f(t) with a finite number of discontinuities of the first kind at points t_i, the generalized derivative is found by using the expression:

$$\frac{Df}{dt} = \frac{df}{dt} + \sum_{i=1}^{\ell} \Delta f_i \delta(t - t_i) \ , \qquad (1)$$

where $\frac{df}{dt}$ is the ordinary derivative at points of continuity, δ(t) is the delta function,

$$\Delta f_i = \Delta f(t_i) = f(t_i + 0) - f(t_i - 0). \qquad (2)$$

If a piecewise continuous function depending on the parameter f(t, α) is given, such that

$$f(t,\alpha) = \begin{cases} f_1(t,\alpha), & t_0 < t < t_1(\alpha) \\ f_2(t,\alpha), & t_1(\alpha) < t < T < \infty, \end{cases} \qquad (3)$$

where the functions $f_1(t, \alpha)$ and $f_2(t, \alpha)$ have a derivative in the classical sense with respect to t and α, the generalized derivative is defined by the expression:

$$\frac{Df}{\partial\alpha} = \frac{\partial f}{\partial\alpha} - \Delta f(t_1) \frac{dt_1}{d\alpha} \delta(t - t_0) \ , \qquad (4)$$

which is determined at each fixed value of the parameter .a

If the coordinate of the break point does not depend on the parameter a, then $\frac{dt_1}{d\alpha} = 0$ follows from (4) that the generalized derivative and the ordinary and it partial derivative coincide.

It is possible to obtain constructive results in the description of systems by numerical integration of the sensitivity equations of dynamic systems. It is known that the sensitivity equations are linear ordinary differential equations with variable coefficients. To integrate them, one can use the methods of fundamental systems, conjugate systems, direct numerical integration, etc. It should be remembered that due to the fact that the sensitivity functions of dynamic systems are determined not only by time t, but also by the value of the finite-dimensional vector of state variables Y(X(t),P(t),t), two approaches can be used to implement various methods of integrating differential equations:

a) preliminary integration of the equations describing the behavior of the system in the space of state variables while preserving the values of Y(X(t),P(t),t), ($t \in [t_0, T]$) in the form of numerical arrays of discrete values with some step Δt , followed by obtaining the sensitivity function;

b) parallel integration of equations describing the behavior of systems in the space of variable states.

It should be noted that the implementation of the first approach requires a significant amount of cloud storage, and the implementation of the second approach is associated with an increase in the order of the system of differential equations being integrated.

To develop algorithms for constructing the space of parameter increments, let us assume that the dynamic system is described by the equation of the form:

$$\dot{Y} = F(Y,t,P); Y(t_0) = Y_0, \tag{5}$$

where $P = \left| p_1, p_2, \cdots, p_p \right|^T$ - the vector of initial parameters

When (5) is fulfilled, the sensitivity functions $u_j(t) = \dfrac{\partial Y(t,P)}{\partial P_j}$ are solutions of the differential sensitivity equations:

$$\begin{aligned} &\dot{u}_j = B(Y,t)u_j + C_j(Y,t), \\ &u_j(t_0) = \frac{dY_0}{dP_j} - F(Y_0, t_0, P_j)\frac{dt_0}{dP_j}, (\mathrm{j} = 1,2,\cdots, p), \end{aligned} \tag{6}$$

where $B(Y,t) = \dfrac{\partial F(Y,t,P)}{\partial Y}$; $„_j(Y,t) = \dfrac{\partial F(Y,t,P)}{\partial P_j}$.

Naturally, when describing systems, the right-hand sides of equations (5) are continuous on the interval $[t_0, T]$, which is considered, so the solutions of equations (6) will be continuous. In this case, the values of the sensitivity matrix can be calculated by the usual method of direct numerical integration, the corresponding flowcharts of the algorithms are shown in Figures 2 and 3.

If the system is dynamic and described by equations with a discontinuous right-hand side (5), then the use of direct numerical integration methods to find the sensitivity functions is complicated.

Suppose that the dynamics of the system for intervals, $t_{i-1} < t < t_i (i = \overline{1, \ell}),$ is described by various differential equations in the space of state variables of the form:

$$\dot{Y} = F_i(Y,t,P), \tag{7}$$

and the switching surfaces are described by the scalar equations

$$f_i(Y,t,P)=0 \ . \qquad (8)$$

When the right-hand side of equation (7) changes (the moment of switching), the solution of this equation Y(t) undergoes discontinuities defined by the relations:

$$Y_i^+ = \Phi_i(Y_i^-, t_i, P), \qquad (9)$$

where . $Y_i^+ = Y(t_i+0), Y_i^- = Y(t_i-0)$

When conditions (7) - (9) are met, it is shown [7] that the sensitivity vectors satisfy the equation:

$$\dot{U}_j = B_i(Y,t)U_j + C_{ij}(Y,t) \, t_{i-1} < t < t_i \ , \qquad (10)$$

under initial conditions

$$\dot{U}_j(t_\cdot) = \frac{dY_\cdot}{\partial P_j} - F_i(Y_\cdot^+, t_\cdot, P) \times \frac{dt_\cdot}{dP_j} \ , \qquad (11)$$

where .$Y_i^+ = Y(t+0)$

In this case, the transitions from one equation (10) to another are "stitched together" by means of jump conditions containing generalized functions.

We emphasize that under conditions (7)-(9), the space of parameter increments is constructed by solving the system of equations (10), provided that (11) is satisfied, and the behavior of the system is described by (11).

Taking into account the above, we present two algorithms for constructing the space of parameter increments, which differ in the way the sensitivity matrix is found.

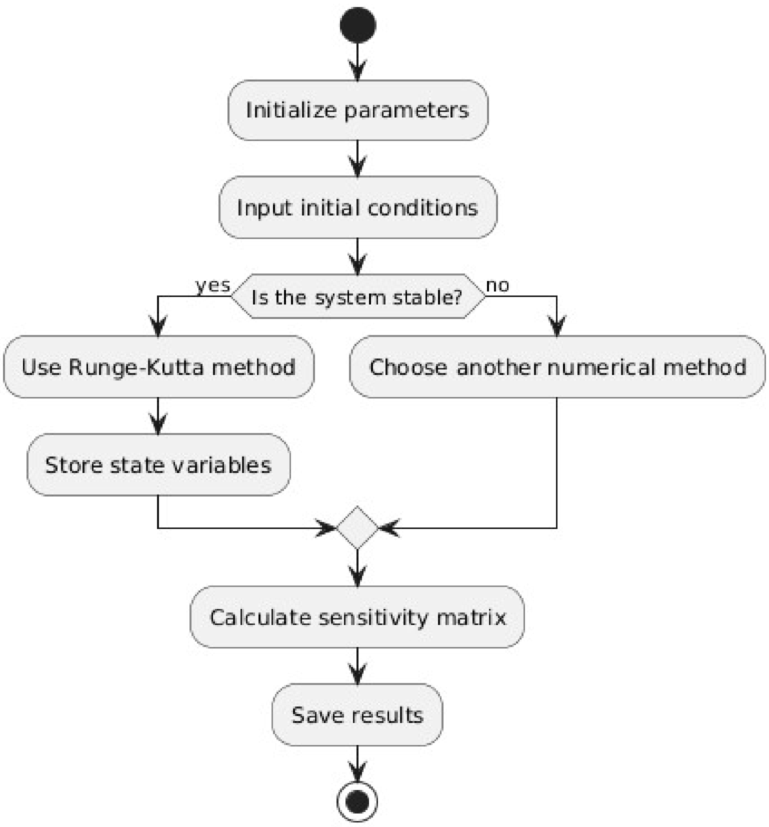

Figure 1: UML - diagram of finding the sensitivity matrix by direct numerical integration with preliminary integration and memorization of the values of the variable states of systems.

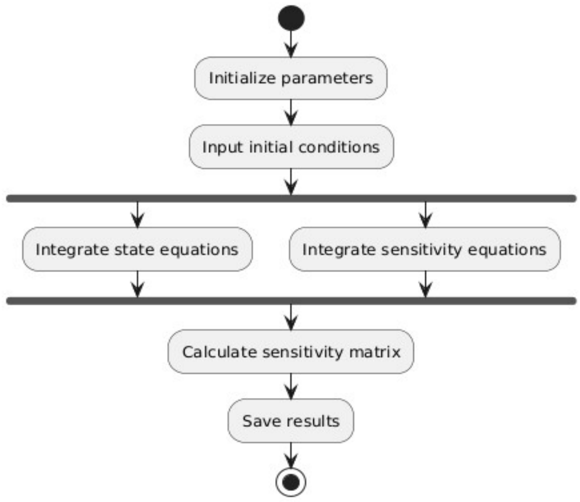

Figure 2: UML diagram of finding the sensitivity matrix by parallel numerical integration of equations describing the behavior of the system in the space of state variables and sensitivity equations.

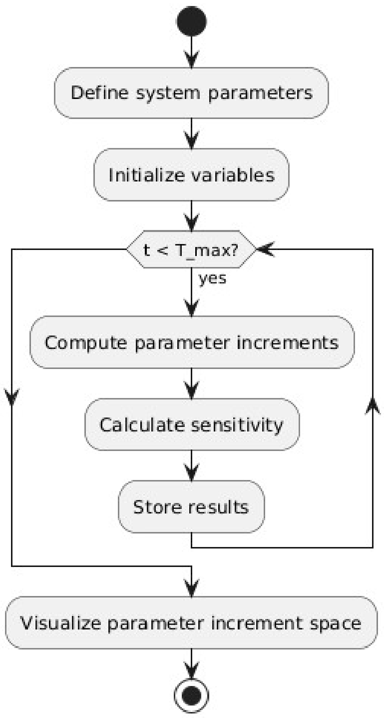

Figure 3: UML diagram of the space of parameter increments when obtaining the sensitivity matrix by direct numerical integration.

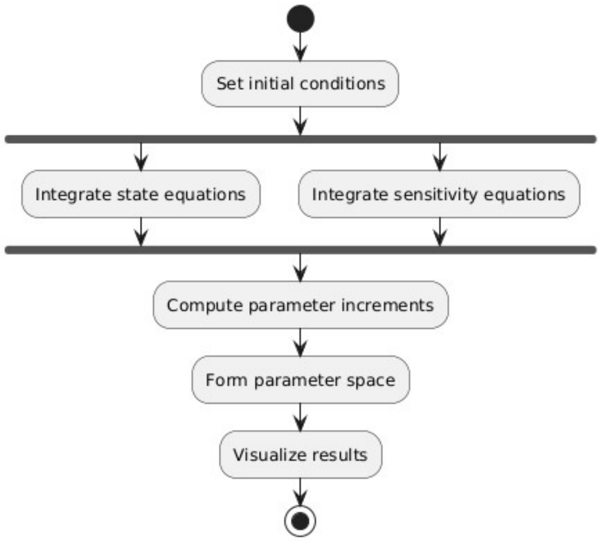

Figure 4: UML diagram of the space of parameter increments when obtaining the sensitivity matrix by parallel numerical integration.

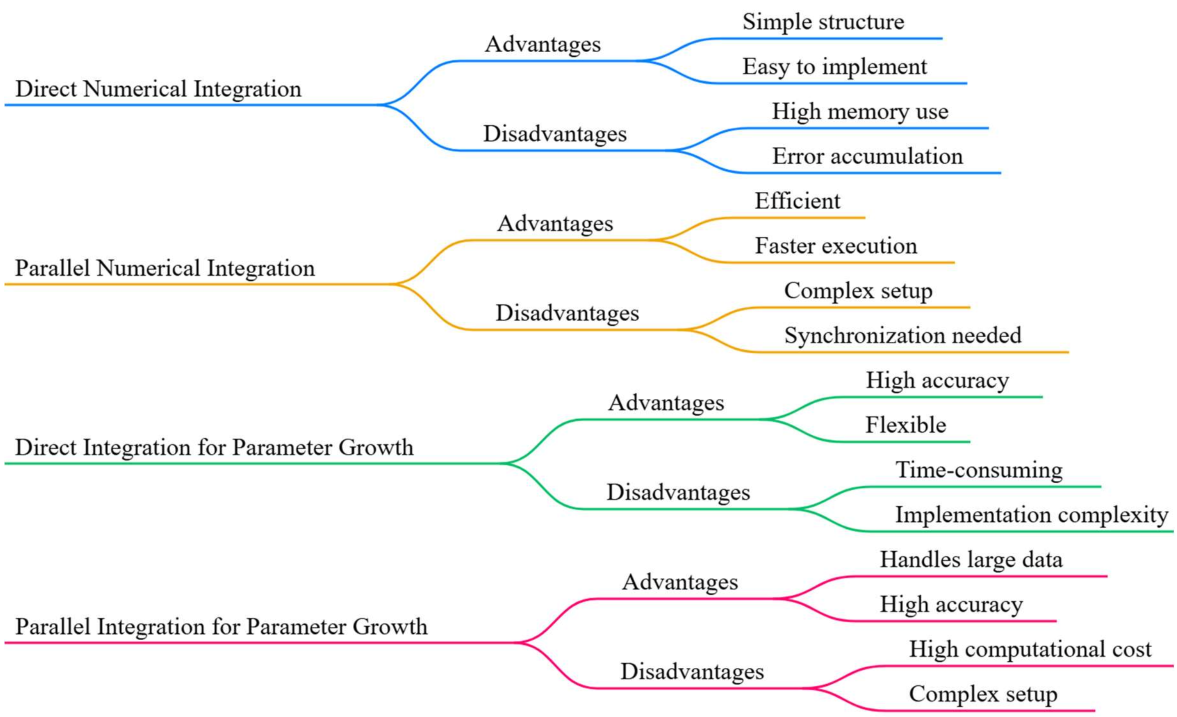

Figure 5: Comparison of UML diagrams of the developed algorithms.

Both approaches to constructing the space of parameter increments have their advantages and disadvantages. Direct numerical integration is easier to implement but requires more memory, which can be critical in large systems. Parallel integration, although more complex, provides better memory efficiency and accuracy for systems with discontinuities.

The choice between these methods depends on the specifics of the task, the amount of data and the requirements for forecasting accuracy. The development of algorithms that combine both approaches can be the optimal solution for modern automated energy process control systems.

With the help of the developed algorithms, we will build a graph of the impact of changes in the mode (load) parameters in the power system on its sensitivity, Figure 6.

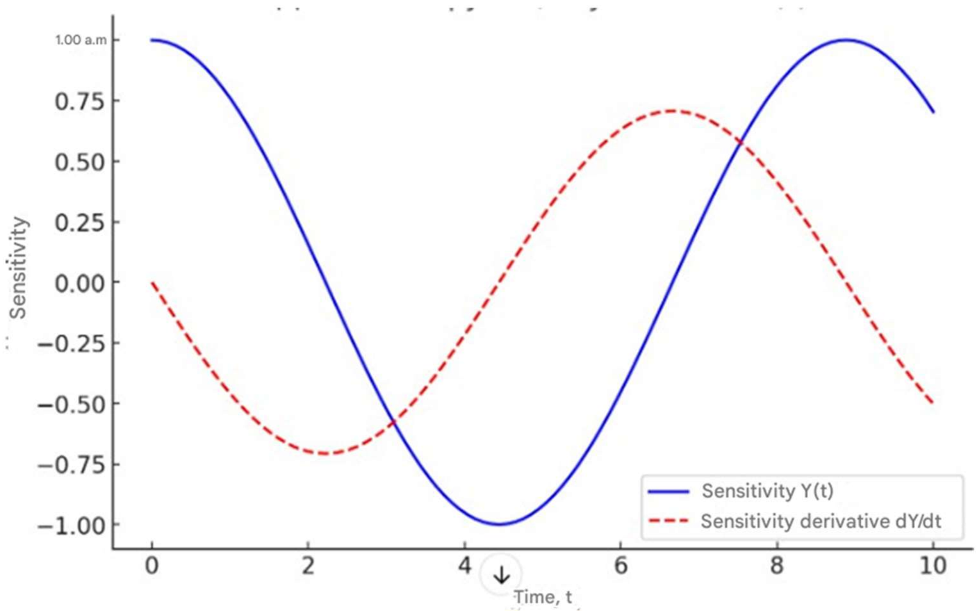

Figure 6: Sensitivity of the power system to changes in mode (load) parameters

This graph shows how the system reacts to changes in the object's state parameters: at first, the reaction rate is high, then it stabilizes, and eventually becomes less sensitive to small fluctuations. Such analysis is critical for automated control of power systems, which helps:

1. Optimize the balance of generation and consumption.
2. Reduce energy losses.
3. Improve the reliability of electricity supply.

To summaries, the space of parameter increments is a space along the coordinate axes of which the corresponding sensitivity functions to changes in the primary parameters of systems and the values of these parameters are plotted [8- 10]. The construction of such a space is mainly reduced to algorithms for finding the corresponding sensitivity functions.

Figure 7 shows a graph of the sensitivity of changes in boiler temperature and system steam pressure over time to changes in system load.

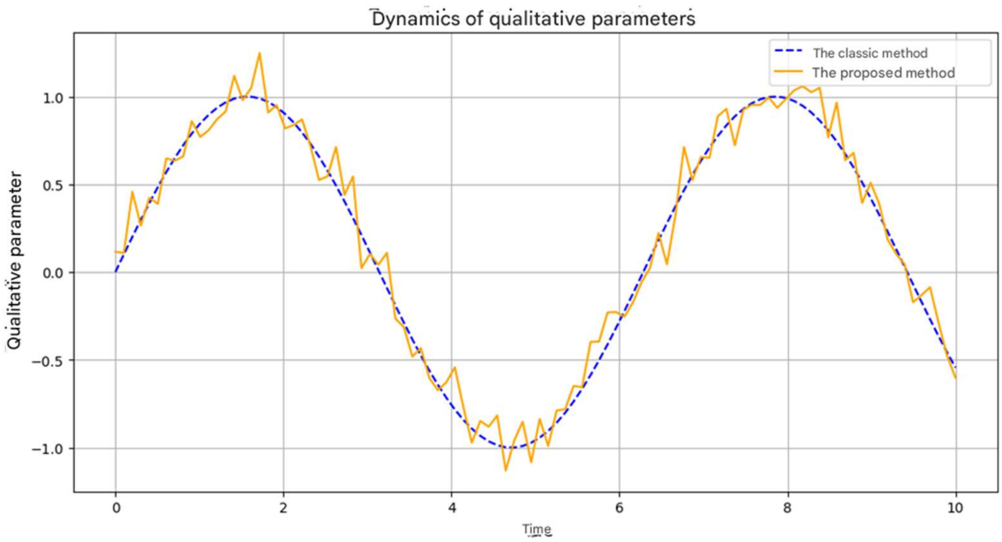

Figure 7: Sensitivity of changes in boiler temperature and steam pressure to changes in network parameters (load).

As we can see, the proposed method allows us to more accurately predict temperature changes under conditions of sharp load fluctuations, which is critical for preventing emergencies and timely adjusting the fuel supply to maintain optimal operating conditions.

Figure 8 shows a sensitivity graph that shows how changes in electricity consumption in one of the distribution network districts affect the overall grid voltage.

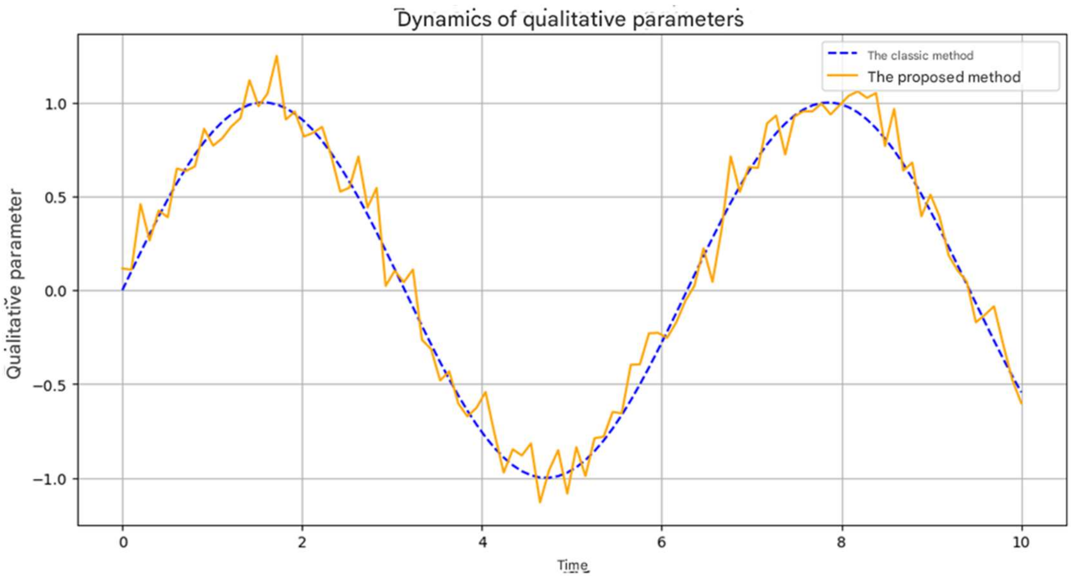

Figure 8: Sensitivity of grid disturbances to voltage

This method can help to identify patterns in system behavior more quickly, which is important for optimizing the control of distribution networks.

Figure 9 shows an interactive graph for monitoring the operation of a wind farm. The graph shows how wind speed affects electricity production and equipment status in real time.

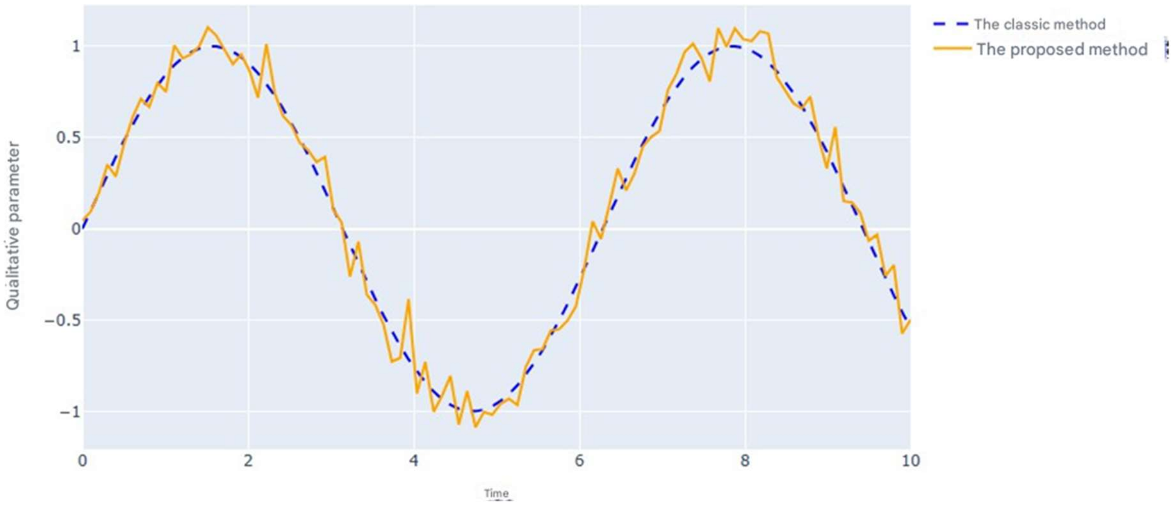

Figure 9: Impact of wind speed changes on wind farm operation

The proposed method allows for the creation of interactive graphs, which increases the convenience of data analysis and allows for a faster response to changes in operating conditions for optimal control of wind farm operation.

Thus, Figures 6-9 show that the proposed method provides significant advantages in analyzing the dynamics of quality parameters in energy systems. They allow not only to identify patterns, but also to adapt control decisions in real time, which is critical for ensuring the efficiency and reliability of energy processes.

4. Conclusions

The article substantiates the expediency of introducing the space of parameter increments as a means of solving non-classical problems of assessing the stability of automated power systems. This approach is explained by the need to analyze the impact of changes in the primary parameters on the behavior of the system at fixed initial states. This method is especially relevant for modern power facilities where dynamic load changes or changes in operating modes are commonplace.

The mathematical foundations of the new space are created, which include the use of generalized derivatives for piecewise continuous functions and numerical integration of sensitivity equations for continuous state vectors. It is shown that the proposed space provides a more accurate representation of the behavior of automated control systems compared to traditional methods, especially in the conditions of discontinuities typical for energy processes. The advantages of this approach lie in its adaptability to systems with different dynamics, which opens up opportunities for universal application.

Constructive algorithms for building models in the space of parameter increments have been developed, based on two approaches to finding sensitivity matrices: direct numerical integration with preliminary preservation of state variables and parallel integration of state and sensitivity equations. Both methods are analyzed in detail in terms of their computational efficiency and applicability to industrial conditions. In particular, it is found that the direct method is optimal for systems with stable dynamics, while the parallel approach is better suited for systems with discontinuities, ensuring accurate forecasting under conditions of limited resources.

In addition to the theoretical results, the practical significance of the developed methods is assessed. The algorithms can be integrated into automated control systems for energy facilities, such as power plants or distribution networks, to improve their efficiency and reliability. For example, in real time, they can optimize equipment operation modes, reduce energy losses and adapt the system to changing operating conditions. The combination of these algorithms with modern technologies such as machine learning and cloud computing creates prospects for the development of intelligent control systems that meet the requirements of the energy sector of the future.

Declaration on Generative AI

During the preparation of this work, the authors used X-GPT-4 and Gramby in order to: Grammar and spelling check. Further, the author(s) used X-AI-IMG for figures 3 and 4 in order to: Generate images. After using these tool(s)/service(s), the author(s) reviewed and edited the content as needed and take(s) full responsibility for the publication's content.

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