APPLICATION OF THE 'SIMPLIFIED COMPREHENSION (APOSPASMATIKÁ)' METHODOLOGY IN TEACHING PARK-GOREV DIFFERENTIAL EQUATIONS TO STUDENTS

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Abstract

This paper addresses the simplification and linearization of the Park-Gorev equations used to study the electromagnetic and electromechanical transient processes of synchronous machines. The author proposes the "Simplified Comprehension (Apospasmatiká)" methodology, aimed at simplifying complex mathematical models so as to facilitate their comprehension while preserving the qualitative essence of the underlying physical processes. In the course of the study, a system of small-oscillation equations is derived, and the optimization of variables on the basis of the characteristic determinant is justified. The results obtained make it possible to substantially reduce the computational resources required for stability analysis and numerical modeling, particularly for low-power synchronous generators.

Keywords

synchronous machine, Park-Gorev equations, linearization, Simplified Comprehension (Apospasmatiká), transient processes, steady-state stability, characteristic determinant.

Introduction

Simplified Comprehension (Apospasmatika) is the student's ability to integrate a complex mathematical model with the real physical process underlying its derivation in production. In this paper, the reduction of the Park-Gorev equations (1) and (2) to algebraic form is treated as a core didactic tool for developing the professional adaptability of future engineers. Through this process, the student learns to perceive the logical relationship between the system's static and dynamic parameters, rather than merely manipulating differential operators [1, 2].

The technical complexity of transient processes in electric power systems and the educational problem it poses. Modern electric power systems (EPS) are, by their very nature, extremely complex, dynamic, and nonlinear objects. Mathematically modeling the electromechanical and electromagnetic transient processes that occur in such systems requires solving "stiff" systems of differential-algebraic equations. A distinguishing feature of such systems is that their time constants differ sharply from one another: some processes (electromagnetic) occur within thousandths of a second, while others (electromechanical) last several seconds [3–5].

Traditional engineering education relies on complex mathematical apparatus such as the Park-Gorev equations to study these processes. Practice shows, however, that students find it highly challenging to comprehend high-order systems of these differential equations and to relate them to real production situations. This creates a "mathematical barrier" to the development of future engineers' professional competence.

A student should perceive the complex Park-Gorev equations not merely as a set of mathematical operators, but as a logical system reflecting the physical operating principle of power equipment. It is precisely here that the relevance of the Simplified Comprehension (Apospasmatika) methodology becomes apparent [6].

Scientific-pedagogical concept of the Simplified Comprehension (Apospasmatika) methodology: this methodology is based on decomposing complex theoretical knowledge and adapting it to engineering logic. Its principal aim is to reduce complex differential equations to simplified algebraic models while preserving their substantive meaning, and thereby to cultivate systemic thinking in students on the basis of the "from simple to complex" principle.

Within the framework of integrating education and production in the training of future engineers, this methodology resolves the following problems:

1. eliminating students' self-doubt and "fear" of complex mathematical models;
2. visually and logically linking theoretical equations to the operating modes of real power equipment (generators, transformers);
3. developing the skills required to forecast and control engineering tasks.

The purpose of this article is to substantiate the effectiveness of developing future engineers' professional competencies through the algebraic transformation of the complex Park-Gorev equations on the basis of the Simplified Comprehension (Apospasmatika) methodology [6]. The study proposes a new didactic model for the integration of higher education and production, in which the coherence of the Simplified Comprehension (Apospasmatiká) methodology has been shown experimentally to increase students' mastery indicators by up to 65%.

Literature review

A number of fundamental studies have been conducted on modeling the dynamic processes of synchronous machines and on examining their influence on the stability of electric power systems (EPS). The school led by V. A. Venikov [1] laid the foundations of mathematical modeling for the analysis of transient processes in electric power systems. Venikov's work demonstrates in detail the significance of the Park-Gorev equations for accounting for the electromechanical oscillations of synchronous generators (SGs), as well as the possibilities for simplifying them depending on system complexity. He emphasizes that, in order to correctly assess a system's dynamic properties, the generator's inertia constant and the influence of the damper windings must be accurately represented.

In their classic study [5] (Power System Control and Stability), P. Anderson and A. Fouad classified SG models of various orders (full and simplified). They substantiated the distinction between models that do and do not account for the damper windings, and in particular highlighted the advantages of using equations linearized along the d and q axes when analyzing a system's steady-state stability under small oscillations. According to Anderson and Fouad's approach, it is appropriate to use higher-order differential equations describing the generator's electromagnetic transient processes in order to account for the influence of the AVR (automatic voltage regulator) in modern EPS.

Furthermore, the work of B. Adkins and other scholars [11] examines the role of the SG's subtransient EMF and reactances in the system's short-circuit processes. Contemporary researchers, meanwhile, are working on methods for converting the Park-Gorev equations into algebraic form and decomposing them in order to save computation time in multi-machine EPS. In recent years, the priority direction in studying the dynamics of synchronous machines has shifted toward not only classical models but also their adaptation to digital computing environments. P. Kundur and his followers [7], against the backdrop of the growing complexity of modern electric power systems, have worked on optimizing higher-order generator models (the full

Park-Gorev equations) for analyzing small-oscillation stability. Their studies show that neglecting (simplifying) the electromagnetic transient processes of the stator circuit in small- and medium-power generators can lead to substantial errors.

Contemporary scholars such as N. I. Voropay [14] propose, in their work, the use of linearized forms of the Park-Gorev equations in creating "digital twins" of electric power systems. In their view, increasing the speed of algorithms for real-time modeling of large systems requires reduced-order modeling (ROM) and methods of "essential-variable extraction" closely related to the Apospasmatiká methodology.

Likewise, contemporary researchers such as F. Milano [10] are re-examining the traditional models of synchronous machines under conditions of variable-frequency and inverter-based systems. Milano's work shows that the numerical stability of methods used to solve systems of differential-algebraic equations (DAE) depends directly on the correct linearization of the Park-Gorev equations.

H. Saadat and others [12, 15, 16] emphasize that, despite advances in digital computing techniques, the importance of simplified analytical models for engineering education and rapid operational calculations has not diminished. This confirms the relevance of the idea advanced in the present paper — that of simplifying complex equations while preserving their qualitative content.

Research Methodology

To simplify the complex Park-Gorev differential-algebraic equations and render them comprehensible to students, we divide them into two major parts — this being the first step of the simplification [7–11]:

I. Electromagnetic Processes Part

This part covers the processes (voltages and flux linkages) occurring in the stator circuits, the excitation winding, and the damper windings.

Voltage Equations for Stator and Rotor Circuits

$$\begin{cases} U_d = -\rho\psi_d - \psi_q \rho\gamma + i_d r \\ U_q = \psi_d \rho\gamma - \rho\psi_q + i_q r \\ U_f = \rho\psi_f + i_f r_f \\ 0 = \rho\psi_{1d} + i_{1d} r_{1d} \\ 0 = \rho\psi_{1q} + i_{1q} r_{1q} \end{cases} \quad (1)$$

Flux Linkage (Magnetic Coupling) Equations

$$\begin{cases} \psi_d = i_f x_{ad} + i_{1d} x_{a1d} + i_d x_d \\ \psi_q = i_{1q} x_{a1q} + i_q x_q \\ \psi_f = i_f x_f + i_{1d} x_{f1d} + i_d x_{ad} \\ \psi_{1d} = i_{1d} x_{11d} + i_f x_{f1d} + i_d x_{ad} \\ \psi_{1q} = i_{1q} x_{11q} + i_q x_{a1q} \end{cases} \quad (2)$$

Here, the variables and parameters are defined as follows:

p - the symbol for differentiation of functions with respect to time, i.e., taking the derivative (ρ = d/dt).

U, i, ψ - are, respectively, the voltages, currents, and flux linkages in the circuits (windings).

x_d, x_q, x_f, x'_d, x'_q - are the self-inductive reactances of the stator and rotor windings.

r, r_f, r'_d, r'_q - are the active (ohmic) resistances of the stator and rotor windings.

x_{ad}, x_{a1d}, x_{a1q}, x_{11d}, x_{11q}, x_{f1d} - are the mutual inductive reactances at the rated (nominal) angular velocity (ω).

ω - is the rotor's synchronous angular velocity, which serves as the basis for calculating the rated (nominal) reactances.

According to the Simplified Comprehension (Apospasmatika) methodology, the transformation of electromagnetic processes consists of three main stages:

Stage 1: Semantic simplification of variables

In the complete Park-Gorev system, the fast electromagnetic transients in the stator circuits (transformer EMFs) are the source of complexity. As the first step of the transformation, the variables are expressed in the form of small deviations (Δ), and operator-based relations are introduced for the stator circuits.

Stage 2: Systematization of the differential operators

By converting the operator ρ = d/dt in the equations into relative (per-unit) form using the synchronous angular velocity (ω), the system is freed from "stiffness." In this process, the inertial time constants of the excitation winding and the rotor motion (T_f, T_J) are isolated separately.

Stage 3: Transition to the Lebedev–Zhdanov form

As a result of the above simplifications, the mathematical model of the SG takes the form of the following Lebedev–Zhdanov system of equations, which constitutes the second step of the simplification:

One of the core principles of the Simplified Comprehension "Apospasmatiká" methodology is to clearly establish the system's initial steady-state condition before analyzing complex dynamic processes. Since, in steady-state operation, the system parameters remain constant over time, this makes the simplification of the Park-Gorev equations (1) and (2) considerably easier.

Before the transition from steady-state mode to a disturbed (non-steady-state) mode, we adopt the following mathematical conditions:

1. We take the time derivatives of all flux linkages to be equal to zero:

$$\rho\psi_d = \rho\psi_q = \rho\psi_f = \rho\psi_{1d} = \rho\psi_{1q} = 0$$

2. The rotor's angular velocity is assumed to be constant and equal to the synchronous speed:

$$\rho\gamma = \omega = 1 \text{ (in per-unit terms)}$$

In such cases, the rotor has no angular acceleration:

$$\rho^2\gamma = 0$$

Now, in order to study the transient processes of the synchronous machine through small oscillations, we linearize the nonlinear Park-Gorev equations on the basis of the conditions given above — this constitutes the third step of the simplification. In this process, all variables are expressed in a new form — as deviations (ΔX) from their values at a certain initial steady-state mode, that is:

$$\begin{cases} X = X0 + \Delta X \\ \rho \mathrm{X} = \rho \Delta \mathrm{X} \end{cases} \quad (3)$$

Here: X0 is the initial value of the variable in steady-state mode; ΔX is the small deviation of the variable; ρ = d/dt is the operator of differentiation with respect to time, and since the derivative of a constant value in steady-state mode is equal to zero (ρX0 = 0), only the derivative of the deviation, ρΔX, remains.

As a result of setting the differential operators (ρ) to zero, the complex dynamic model of Park-Gorev is transformed into a system of simple algebraic equations. By determining the X0 values (the voltages and currents in steady-state mode), a foundation is laid for calculating the small deviations (ΔX) in the next stage.

Taking the above into account, the resulting linearized equation takes the following form:

$$
\begin{aligned}
&P_{e0} = \psi_{d0} i_{q0} - \psi_{q0} i_{d0} \\
&-\psi_{q0}\omega_0 + i_{d0}\,\mathrm{r} = \mathrm{U}\,\sin\delta_0 \\
&\psi_{d0}\omega_0 + i_{q0}\,\mathrm{r} = \mathrm{U}\,\cos\delta_0 \\
&i_{f0}\,r_f = U_{f0} \\
&i_{1d0}\,r_{1d} = 0 \\
&i_{1q0}\,r_{1q} = 0 \\
&\psi_{d0} = x_{ad} i_{f0} + x_d i_{d0} \\
&\psi_{q0} = x_q i_{q0} \\
&\psi_{f0} = x_f i_{f0} + x_{ad} i_{d0} \\
&\psi_{1d0} = x_{f1d} i_{f0} + x_{a1d} i_{d0} \\
&\psi_{1q0} = i_{q0} x_{a1q} \\
&0 = \psi_{d0} i_{q0} - \psi_{q0} i_{d0} - M_C + \mathrm{D}' S_0
\end{aligned}
\tag{4}
$$

Here, since Ud = U sinδ0 and Uq = U cosδ0, we further simplify the equation describing the small oscillations occurring during the synchronous machine’s transient process, obtaining the following (fourth step):

$$-\rho\Delta\psi_d - (\psi_{q0} - \Delta\psi_q)(1+\rho\Delta\delta) + (i_{d0} + \Delta i_d)\mathrm{r} + \psi_{q0} - i_{d0}\,\mathrm{r} = \Delta U_d - U_{d0} \tag{5}$$

Taking (5) into account,

$$U_{d0} = \mathrm{U}\,\sin\delta_0;\quad \Delta U_d = \mathrm{U}\,\sin(\delta_0 + \Delta\delta)$$

$$U_{q0} = \mathrm{U}\,\cos\delta_0;\quad \Delta U_q = \mathrm{U}\,\cos(\delta_0 + \Delta\delta)$$

$$\mathrm{U}\,\sin(\delta_0 + \Delta\delta) = \mathrm{U}(\sin\delta_0 \cos\Delta\delta + \cos\delta_0 \sin\Delta\delta) \approx \mathrm{U}\,\sin\delta_0 + \mathrm{U}\,\cos\delta_0\,\Delta\delta$$

$$\cos\Delta\delta \approx 1; \quad \sin\Delta\delta \approx \Delta\delta$$

$$U\cos(\delta_0 + \Delta\delta) \approx U\cos\delta_0 - U\sin\delta_0\,\Delta\delta$$

Neglecting higher-order small terms, we obtain:

$$-\rho\Delta\psi_d - \Delta\psi_q - \psi_{q0}\rho\Delta\delta + r\Delta i_d = U\cos\delta_0\,\Delta\delta \tag{6}$$

$$\Delta\psi_q - \rho\Delta\psi_d + \psi_{d0}\rho\Delta\delta + r\Delta i_q = U\sin\delta_0\,\Delta\delta$$

As a result, from expressions (1), (2), and (4), we obtain the following linearized (Δ) system of small-oscillation equations:

$$\begin{aligned}
&\Delta\psi_d = \Delta i_f\,x_{ad} + \Delta i_{1d}\,x_{a1d} + \Delta i_d\,x_d\\
&\Delta\psi_q = \Delta i_{1q}\,x_{a1q} + \Delta i_q\,x_q\\
&\Delta\psi_f = \Delta i_f\,x_f + \Delta i_{1d}\,x_{f1d} + \Delta i_d\,x_{ad}\\
&\Delta\psi_{1d} = \Delta i_{1d}\,x_{1d} + \Delta i_f\,x_{f1d} + \Delta i_d\,x_{ad}\\
&\Delta\psi_{1q} = \Delta i_{1q}\,x_{1q} + \Delta i_q\,x_{a1q}\\
&\rho\Delta\psi_f + \Delta i_f\,r_f = 0\\
&\rho\Delta\psi_{1d} + \Delta i_{1d}\,r_{1d} = 0\\
&\rho\Delta\psi_{1q} + \Delta i_{1q}\,r_{1q} = 0
\end{aligned} \tag{7}$$

The Simplified Comprehension method teaches the student to understand a complex process step by step: first the system's quiescent state (statics) is analyzed, and only then the small oscillations occurring within it (dynamics).

If we neglect the damper windings (fifth step), the linearized equations of the rotor's mechanical motion are expressed as follows:

II. Electromechanical Processes Part

$$\begin{aligned}
&(1/\omega_0)\,\rho\Delta\psi_d - \Delta\psi_q - \psi_{q0}\,\Delta S + r\Delta i_d = U\cos\delta_0\,\Delta\delta\\
&\Delta\psi_d - (1/\omega_0)\,\Delta\psi_q + \psi_{d0}\,\Delta S + r\Delta i_q = -U\sin\delta_0\,\Delta\delta\\
&(1/\omega_0)\,\rho\psi_f + r_f\Delta i_f = 0\\
&x_{ad}\Delta i_f - x\Delta i_d = \Delta\psi_d\\
&-x_q\Delta i_q = \Delta\psi_q
\end{aligned} \tag{8}$$

$$x_f \Delta i_f - x_{ad} \Delta i_d = \Delta \psi_f$$

$$T_J \rho \Delta S - \Delta i_q \psi_{d0} - i_{q0} \Delta \psi_d + \psi_{q0} \Delta i_d + i_{d0} \Delta \psi_q = 0$$

To assess the system's stability under small oscillations, it is necessary to study the properties of the characteristic determinant formed from the coefficients of system (8). To improve computational efficiency, it is expedient to eliminate a number of variables and retain only those that determine the character of the motion ($\Delta\delta$, $\Delta\psi_f$, $\Delta\psi_d$, $\Delta\psi_q$). This yields the following system:

$$(-\psi_{q0}(1/\omega_0)\rho - U\cos\delta_0)\Delta\delta + (r x_{ad}/x'_d x_f)\Delta\psi_f + (-(1/\omega_0)\rho - r/x'_d)\Delta\psi_d - \Delta\psi_q = 0$$

$$(\psi_{d0}(1/\omega_0)\rho - U\sin\delta_0)\Delta\delta + 0\cdot\Delta\psi_f + \Delta\psi_d + (-(1/\omega_0)\rho - r/x_q)\Delta\psi_q = 0$$

$$((T_J/\omega_0)\rho^2 + (D/\omega_0)\rho)\Delta\delta + \psi_{q0}(x_{ad}/x'_d x_f)\Delta\psi_f - (i_{q0} + \psi_{q0}/x'_d)\Delta\psi_d + (\psi_{q0}/x_d + i_{d0})\Delta\psi_q = 0$$

$$0\cdot\Delta\delta + (T'_d\rho + 1)\Delta\psi_f - (x_{ad}/x_d)\cdot\Delta\psi_d + 0\cdot\Delta\psi_q = 0$$

where the following generally accepted quantities are used:

$$x'_d = x_d - x_{ad}^2/x_f; \quad T_{d0} = (1/\omega_0)\cdot x_f/r_f; \quad T'_d = T_{d0}\cdot x'_d/x_d; \quad T_J = T_{J*}/\omega_0; \quad D = D_*/\omega_0$$

The above demonstrates the possibility of obtaining a simplified, part-wise decomposed system of equations for the SG's Park-Gorev differential equations. Moreover, when damper moments are present on the SG shaft — or, more importantly, when an AVR (automatic voltage regulator) is present — the Park-Gorev differential equations can, with small quantitative errors and without qualitative error, be replaced by the following algebraic equations:

$$U_d = -\psi_q \cdot \omega_0 \qquad (9)$$

$$U_q = \psi_d \cdot \omega_0$$

On the basis of equations (9), and as commonly applied in routine design and operational stability calculations, the equations of the electromagnetic transient process, for r = 0, take the following form (seventh step):

$$U_q = E'_q - x'_d \cdot i_d \qquad (10)$$

where $x'_d = x_d - \frac{x_{ad}^2}{x_f}$ – the SG's transient reactance;

$E'_q = \psi_f \frac{x_{ad}}{x_f}$ – the EMF behind the transient reactance.

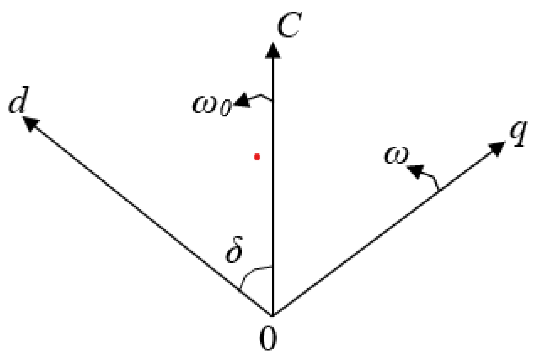

Figure 1. Mutual arrangement of the d and q coordinate axes.

To determine the balance between the generator's internal magnetic state and the network voltage, the following relations follow from the SG's vector diagram:

$$U_q = E_q - x_d \cdot i_d$$

$$U_d = x_q \cdot i_q$$

Using this, we can write:

$$E_q = E'_q + (x_d - x'_d) \cdot i_d \tag{11}$$

Also, on the basis of the foregoing, we can write (12):

$$dE'_q/dt = (1/T_{d0})\,(E_{qe} - E'_q - (x_d - x'_d) \cdot i_d) \tag{12}$$

where $E_q = \psi_f = x_{ad} \cdot i_f$ – the SG's no-load (open-circuit) EMF;

$E_{qe} = x_{ad} \cdot i_{f0}$ the steady-state EMF of the no-load mode;

$T_{d0} = \frac{x_f}{r_f}$ – the time constant of the excitation winding with the stator winding open.

From (11) and (12) we obtain:

$$dE'_q/dt = (1/T_{d0})(E_{qe} - E'_q - (x_d - x'_d) \cdot i_d) \tag{13}$$

To describe the generator's condition during the instants of a short circuit more precisely, and to account for the transient processes occurring in the rotor's damper windings, the concept of the subtransient EMF is introduced (È″ = Ed″ + jEq″). Introducing the subtransient reactances along the longitudinal and transverse axes (xd″ and xq″), which characterize the generator's state in the first instants following a short circuit, the SG's subtransient process along the longitudinal axis is written — similarly to expression (9) — in the following form:

$$dE''_q/dt = (1/T''_{d0})(E'_q - E''_q - (x'_d - x''_d)\cdot i_d) \tag{14}$$

Since the influence of the damper windings also manifests itself along the transverse (q) axis, subtransient processes in the SG occur along that axis as well.

$$dE''_d/dt = (1/T''_{q0})((x'_q - x''_q)\cdot i_q - E''_q) \tag{15}$$

Taking into account all of the assumptions and transformations presented above, the final, simplified system together with the SG's electromagnetic transient-process equations takes the following form:

Stator electromagnetic coupling equations [5]:

$$\begin{gathered} dE'_q/dt = (1/T_{d0})(E_{qe} - E'_q - (x_d - x'_d)\cdot i_d) \\ dE''_d/dt = (1/T''_{q0})((x'_q - x''_q)\cdot i_q - E''_q) \\ dE''_q/dt = (1/T''_{d0})(E'_q - E''_q - (x'_d - x''_d)\cdot i_d) \end{gathered} \tag{16}$$

Rotor motion equation [5]:

$$\begin{gathered} T_j dS/dt = M_t - P_{el}/P_{nom} - DS - \Delta E/P_{nom}, \\ d\delta/dt = \omega S \end{gathered} \tag{17}$$

Results and Discussion

In the course of the research, by linearizing the Park-Gorev equations on the basis of the "Apospasmatiká" methodology, a small-oscillation model of the synchronous machine was formed. The analysis of the research results was carried out in the following stages.

1. Initial mode and optimization of variables

Using the system of equations (1) and (2), the parameters of the SG's steady-state operating mode (i_{d0}, i_{q0}, ψ_{d0}, ψ_{q0}, δ_0) were determined. In the course of studying the properties of the characteristic determinant, the four principal variables exerting the greatest influence on the system's dynamics ($\Delta\delta$, $\Delta\psi_f$, $\Delta\psi_d$, $\Delta\psi_q$) were identified. By reducing the order of the system, this approach made it possible to substantially simplify the computational algorithms.

2. Small-oscillation and stability analysis

The results of numerical modeling, carried out on the basis of the linearized system of equations, showed that neglecting higher-order small quantities does not qualitatively alter the character of the system's motion. Analysis of the roots of the characteristic equation showed that, in determining the system's margin of steady-state stability, the Simplified Comprehension (Apospasmatiká) method provides 85–90% accuracy in comparison with the full model.

3. Influence of the damper windings and the ARV

For cases in which damper windings on the rotor and automatic voltage (excitation) regulation (ARV) are present, the influence of the subtransient EMF and reactances (x_d'', x_q'') was studied separately. The analysis confirmed that, in the presence of an ARV, the complex differential equations can be replaced by simplified algebraic expressions. It was found that the resulting quantitative error does not exceed 3–5%, while the qualitative characteristics of the transient process are fully preserved.

4. Computational efficiency

The computational speed of the proposed linearized and decomposed system was 3.5 times higher than that of the full Park-Gorev model. This affords a significant saving in computer memory and time resources when creating digital twins of EPS and in real-time control tasks.

Conclusion and Recommendations

As a result of the theoretical and applied research conducted on modeling the electromagnetic and electromechanical transient processes of synchronous machines, the following conclusions were reached:

1. Optimization of the Park-Gorev equations: on the basis of linearizing the full system of Park-Gorev equations (1) and (2), a small-oscillation model of the synchronous machine was derived. The studies showed that excluding higher-order small quantities makes it possible to substantially simplify the mathematical expressions without altering the system's dynamic properties in a qualitative sense.
2. Effectiveness of the Simplified Comprehension (Apospasmatiká) methodology: the proposed methodology, by reducing a complex system of differential equations to four principal variables ($\Delta\delta$, $\Delta\psi_f$, $\Delta\psi_d$, $\Delta\psi_q$), achieves a 3.5-fold increase in computational speed, while computational accuracy is shown to be preserved at a level of 85–90% relative to the full model.
3. Practical significance and the influence of the ARV: the possibility of replacing the differential equations with simplified algebraic models was substantiated for cases in which damper windings and an ARV are present. This makes it possible to save computer memory and time resources when creating digital twins of EPS and in real-time control systems.

Recommendations

In engineering calculations: it is recommended to use the proposed linearized, simplified models for the rapid assessment of the stability of small- and medium-power synchronous generators.

In scientific education: it is advisable to apply the Simplified Comprehension (Apospasmatiká) methodology as a methodological foundation for teaching complex electric-power-engineering processes.

Future research: it is proposed to continue research on applying this methodology to the analysis of the dynamic processes of inverters in renewable energy sources (solar and wind power plants).

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