REPORTING METHODOLOGY AND ALGORITHM OF MODES OF COMPLEX ENERGY SYSTEMS WITH PHASE COORDINATES

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Abstract

A mathematical model, algorithm and program have been developed to study any types of complex asymmetric steady-state modes and transient processes of a multi-machine power system with a renewable energy source in phase coordinates, the results of which can be used in the operational control of power system operating modes with any type of emergency automation. The developed methodology and software package can also be used in industry to check the possibility of long-term operation in the considered asymmetrical mode from the point of view of the operating conditions of the system generators and electrical receivers, to determine the need to use baluns, to select their parameters and installation locations, to ensure the efficiency of asymmetrical modes , as well as for conducting various tests and analyzing accidents that have occurred.

Keywords: power system, asymmetrical steady-state modes, transient processes, emergency automation, relay protection

I. Introduction

At present, methods and algorithms for calculating steady-state and transition modes of complex power systems are used in the replacement scheme of a symmetrical three-phase system. When modeling switching processes in non-symmetrical short-circuit and incomplete phase modes, instead of asymmetry, it is performed by adding a shunt or additional resistance. In modern conditions, where the integration of renewable energy sources and digital technologies into the energy system takes place, solving the mentioned problem with traditional methods and algorithms becomes significantly more complicated, and sometimes in complex asymmetric modes, when the transposition of electric transmission lines is not considered, when the parameters of the line and other elements of the system differ in phase, in substations when three-phase transformers are connected with special schemes, it is quite difficult and sometimes impossible to solve. At the same time, carrying out non-symmetric settled and transition modes in a fictitious two-axis coordinate system using transformation formulas significantly increases modeling and reporting errors and makes adequate decision-making difficult for mode control. Taking into account the above, the issue of expressing mode parameters in phase coordinates (a, b, c) during the calculation and study of steady and transition modes appears as an actual solution [1-4].

It should be noted that the advantage of the (a,b,c) coordinate system over other calculation systems, especially the $d,q,0$ system, is that all mode quantities correspond to real-time values, and re-transformation and calculation of the results are not required to obtain the phase quantities.

The solution of the given problem in phase coordinates is quite universal, as the modeling of various types of non-symmetrical short-circuits and settled symmetric modes is relatively easy, and the simplicity of the reporting algorithm allows the use of modern high-performance computing systems. In this case, the main difficulty is to design a three-phase replacement scheme for the elements of the power system in non-symmetrical quasi-steady and transition modes. Therefore, the replacement schemes and mathematical models of the main elements of the power system (generator, transformer, power transmission line, load) for the calculation of non-symmetric modes were presented in [5-11], respectively.

In order to solve the problem posed in the conditions of integration of renewable energy sources, first, the calculation of the non-symmetrical settled mode is carried out in the phase coordinates, and here the pre-accident mode will differ significantly from the linear scheme of the mode due to the reasons we mentioned above. In the next stage, generators in a multi-machine complex energy system are combined with the algorithm of reporting transition processes in phase coordinates, taking into account the complete Park-Gorev equations [12-15].

In the work under review, the equations for the stator windings of conventional and wind generator machines are used in the (a,b,c) coordinate system, and for the rotor quantities, the $d,q,0$ system is used. The periodic coefficients in the equations of synchronous and asynchronous machines are calculated as the angle between the stator and rotor axes in each interval of the mathematical solution of the equations. It should be noted that since their periodic coefficients are expressed as $\sin\gamma$ and $\cos\gamma$, their calculation does not cause any difficulties.

In order to express each three-phase element in phase coordinates, their description with a suitable three-phase replacement scheme was used in the calculation methodology. In this case, the operation of the complex transformation coefficient in different branching cases is taken into account for voltage regulation in power transformers and autotransformers. For the purpose of reporting, a matrix of nodal equations is established for separate elements of the energy system, and based on it, the results of the report are used not only for tuning relay protection and automation devices but also for more complex issues, in other words, mode symmetrization.

II. Solving the system of nodal equations in phase coordinates for the study of symmetric and non-symmetric regimes of the complex energy system

The steady-state mathematical model of a three-phase network is analogous to the model of a single-line network and is a system of nonlinear mathematical equations with complex coefficients and variables. All known methods can be used to solve it [16-18].

The well-known Gauss-Seidel method was used to solve the system of nodal voltage equations in the form of a current balance and the system of nodal equations written in the form of a matrix.

$$|\dot{Y}||\dot{U}|=|\dot{I}|$$

Data for nodes is given as $P_L + jQ_L$ load power for each phase, and for generators as $P_G + jQ_G$ corresponding to each phase or $P_G, |\dot{U}_G|$. As in a single-line circuit, a node is taken as a balancing node, for which the emf's are assumed to be 120º from each other in the three phases. The voltage at the balancing node is determined according to the following expression:

$$\begin{vmatrix} \dot{Y}_{11} & \dot{Y}_{12} & \dot{Y}_{13} & -\dot{Y}_0 \\ \dot{Y}_{21} & \dot{Y}_{22} & \dot{Y}_{23} & -\dot{Y}_0 \\ \dot{Y}_{31} & \dot{Y}_{32} & \dot{Y}_{33} & -\dot{Y}_0 \\ -\dot{Y}_0 & -\dot{Y}_0 & -\dot{Y}_0 & 3\dot{Y}_0+\dot{Y}_{N0} \end{vmatrix} \begin{vmatrix} \dot{U}_1 \\ \dot{U}_2 \\ \dot{U}_3 \\ 0 \end{vmatrix} = \begin{vmatrix} \dot{S}_1/\dot{U}_1 + & \dot{Y}_1 E_a^{бал} \\ \dot{S}_2/\dot{U}_2 & a^2\dot{Y}_1 E_a^{бал} \\ \dot{S}_3/\dot{U}_3 & a^2\dot{Y}_1 E_a^{бал} \\ 0 & \end{vmatrix} \tag{1}$$

here $a = 1\angle 120^0 = e^{j2\pi/3}$; $\dot{Y}_1$, $\dot{Y}_2$, $\dot{Y}_0$ – forward, reverse and zero sequence conductors; U_1, U_2, U_3 – forward, reverse and zero sequence voltages; S_1, S_2, S_3 – the full powers of individual phases; E_a^{bal} – is the EMF of the balancing node.

In this case, the following restrictions are taken into account according to voltage and power:

$$\begin{gathered} P_{i\min} \le P_{Gi} \le P_{i\max}, \\ Q_{i\min} \le Q_{Gi} \le Q_{i\max}, \\ \dot{U}_{i\min} \le |\ \dot{U}_i\ | \le \dot{U}_{i\max}. \\ i = 1, 2, 3, \ldots, n \end{gathered}$$

The allowable limits characterize the change of active power Pi, reactive power Qi and voltage modulus $|\ \dot{U}_i\ |$ at node i. The algorithm uses the procedure of accelerated accumulation of the iteration process, where the new acceleration coefficient ωnew is recalculated depending on the given number of iterations of the old coefficient ω start.

$$\omega^{new} = \frac{2}{1 + \sqrt{1 - \dfrac{(\omega^{start} + \lambda - 1)^2}{\omega^{start} - \lambda}}} \tag{3}$$

here

$$\lambda = \sqrt{\frac{\sum_{i=1}^{n} |\ \Delta \dot{U}_1^{(k+1)}\ |^2}{\sum_{i=1}^{n} |\ \Delta \dot{U}_1^{(k)}\ |^2}} \tag{4}$$

The value of the acceleration coefficient is taken in the range $1 \le \omega \le 2$. The iteration process ends after the given precision is met.

Considering the given expression, an algorithm and software were developed for the calculation of asymmetric modes in multi-machine complex systems with renewable energy sources, according to which the equations of the energy system elements are expressed in phase coordinates.

III. Determination of currents and voltages in phase coordinates in asymmetric regimes of power systems

Calculation of short-circuit currents and single-phase modes can be performed based on the results of calculating the previous short-circuit pre-emergency mode. In this case, you can simultaneously simulate any type of short circuit, including short circuit through impedance. Short circuits and phase breaks are taken into account directly when drawing up nodal equations. At the same time, all the necessary information is entered into the computer, taking into account the capacitive conductivities of the corresponding component lines, the resistance of the component transformers (autotransformers); resistances included in the neutral of transformers, generators, etc. The phase discontinuity of a branch can also be replaced by including an infinitely large resistance in it [19,20].

In the conductivity matrix $|\dot{Y}|$, the short circuit is quite simply taken into account through transition resistance. To do this, it is enough to set the value of the contact resistance in the source data. When modeling a fault in the nodes of the system circuit, it is necessary to set a pre-provided code for the fault type. To calculate short-circuit currents and open-phase modes, the Gauss-Seidel method was used.

IV. Modeling in phase coordinates of transient processes in complex regulated power systems.

The equations of synchronous machines are modeled using the full Park–Gorev equations and simplified Lebedev–Zhdanov equations, taking into account electromagnetic transient processes in the rotor circuits [21-26]

The initial equations for calculating the modes of a synchronous machine in coordinates *a*, *b*, *c* are the following differential equations for the stator winding voltages:

$$\left.\begin{array}{l} p\psi_a = e_a - i_a r_a \\ p\psi_b = e_b - i_b r_b \\ p\psi_c = e_c - i_c r_c \end{array}\right\}, \tag{5}$$

where ψ_a, ψ_b, ψ_c – flux linkage of the stator winding phases; i_a, i_b, i_c – stator winding phase currents; r_a, r_b, r_c – active resistance of stator winding phases; e_a, e_b, e_c – voltage at the terminals of the generator stator phase windings; $p = \frac{d}{d\tau}$ – differentiation operator with respect to synchronous time $\tau = 2\pi ft$.

To this system of equations one should add the stress equations for the rotor circuits and the rotor motion equations:

$$\left.\begin{array}{c} p\psi_f = e_f - i_f r_f \\ p\psi_{kd} = -i_{kd} r_{kd} \\ p\psi_{kq} = -i_{kq} r_{kq} \\ pS = \dfrac{1}{H}\left(M_m + M_e\right) \\ p\theta = S \end{array}\right\}, \tag{6}$$

where $\left.\begin{array}{c} \psi_f, \psi_{kd}, \psi_{kq} \\ i_f, i_{kd}, i_{kq} \\ r_f, r_{kd}, r_{kq} \end{array}\right\}$ – flux linkage of current and active resistance of the excitation winding and damper circuits along the longitudinal and transverse axes; e_f – voltage applied to the excitation winding; S – slip; H – inertial constant in el. rad; M_m – load torque on the shaft of a synchronous machine; M_e – electromagnetic torque of synchronous machine; θ – working angle (angle between the transverse axis of the rotor and the representing vector of phase voltages.

To solve systems of equations (4) and (5) on a PC using any of the well-known numerical methods of Runge–Kutta, Adams Euler, etc. [3] it is necessary that the number of variables equals the number of equations. Experience shows that it is advisable to express all currents through the flux linkage of the circuits. For this purpose, well-known relationships obtained from calculations of symmetric modes using the Park–Gorev equations are used [3].

$$\left.\begin{array}{c} i_d = a\psi_d - b\psi_f - c\psi_{kd} \\ i_q = g\psi_q - h\psi_{kq} \\ i_f = -b\psi_d + d\psi_f - e\psi_{kd} \\ i_{kd} = -c\psi_d - e\psi_f + f\psi_{kd} \\ i_{kq} = -h\psi_q + k\psi_{kq} \\ i_0 = \dfrac{\psi_0}{x_0} \end{array}\right\}, \tag{7}$$

where the coefficients a,b,c,d,e,f,g,h,k are expressed through the machine parameters as follows:

$$\left.\begin{array}{l} a = \dfrac{X_f X_{kd} - x_{ad}^2}{\Delta}; \ f = \dfrac{X_d X_f - x_{ad}^2}{\Delta}; \\ b = \dfrac{x_{ad} X_{kd} - x_{ad}^2}{\Delta}; g = \dfrac{X_{kq}}{X_q X_{kq} - x_{aq}^2}; \\ c = \dfrac{x_{ad} X_f - x_{ad}^2}{\Delta}; h = \dfrac{x_{aq}}{X_q X_{kq} - x_{aq}^2}; \\ d = \dfrac{X_d X_{kd} - x_{ad}^2}{\Delta}; k = \dfrac{X_q}{X_q X_{kq} - x_{aq}^2}; \\ e = \dfrac{X_d x_{ad} - x_{ad}^2}{\Delta}; \end{array}\right\} \tag{8}$$

$$\Delta = X_d\left(X_f X_{kd} - x_{ad}^2\right) - x_{ad}\left(x_{ad} X_{kd} - x_{ad}^2\right) - x_{ad}\left(x_{ad} X_f - x_{ad}^2\right).$$

The parameters included in these expressions represent the mutual or complete reactivity of the circuits.

$$X_f = x_{ad} + x_f; \quad X_{kd} = x_{ad} + x_{kd}; \quad X_{kq} = x_{aq} + x_{kq};$$
$$X_d = x_{ad} + x_e; \quad X_q = x_{aq} + x_l;$$

To transition from stator currents i_d, i_q, i_0 to phase values i_a, i_b, i_c we use the known relations.

$$\left.\begin{array}{l} i_a = i_0 + i_d \cos\gamma - i_q \sin\gamma; \\ i_b = i_0 + i_d \cos(\gamma - \rho) - i_q \sin(\gamma - \rho); \\ i_c = i_0 + i_d \cos(\gamma + \rho) - i_q \sin(\gamma + \rho); \end{array}\right\} \tag{9}$$

$$\left.\begin{array}{l} \psi_0 = \dfrac{1}{3}(\psi_a + \psi_b + \psi_c); \\ \psi_d = \dfrac{2}{3}[\psi_a \cos\gamma + \psi_b \cos(\gamma - \rho) + \psi_c \cos(\gamma + \rho)]; \\ \psi_q = \dfrac{2}{3}[\psi_a \sin\gamma + \psi_b \sin(\gamma - \rho) + \psi_c \sin(\gamma + \rho)]; \end{array}\right\} \tag{10}$$

where $\rho = \frac{2\pi}{3}$ =120° for a machine with symmetrically arranged three-phase windings, $\gamma = \tau + \theta + \frac{\pi}{2}$ – the angle between the stationary axis of phase a and the rotating longitudinal axis of the rotor.

V. Modeling in phase coordinates of transient processes in complex regulated power systems.

The block diagram of the algorithm for calculating asymmetric modes and transient processes in phase coordinates is shown in Figure 1.

As a result of calculating symmetrical or asymmetrical modes for each phase, the following are determined: modules and voltage angles in nodes, flows of active and reactive power along lines and transformers, losses in each element and in the system as a whole, generation of reactive power in those nodes where voltage modules are specified and other information if necessary.

When calculating short circuit (SC) modes, the output information is also displayed on the display screen in tabular form and includes: currents at the short circuit point, residual voltages in the circuit nodes and their phases, currents or power flows along the branches, including losses in each element and in the system generally.

In this work, it is possible to perform calculations during a short circuit at an intermediate point of a branch without introducing additional nodes into the design diagram.

To illustrate the performance of the developed methodology and program for calculating symmetrical and complex-asymmetrical modes in complex multi-machine power systems, let us consider several examples for a specific circuit shown in Figure 2. As can be seen, a 10 MW wind turbine is integrated into the system through a T3 transformer.

All necessary data for the system under study are presented in Tables 1 ÷ 3. The values are presented in p. u. and reduced to $S_b = 100MVA$. Transformers T1-T3 have a connection diagram Y0/Δ. Transformers T4 and T5 have three-phase-two-phase and star-zigzag connection schemes, respectively.

Tables 4 and 5 present the results of calculating symmetrical and asymmetrical modes in phase coordinates, where the load was represented by $P_L + jQ_L = \text{const}$. Note that the voltage values in the secondary windings of a three-phase-two-phase transformer are distributed as follows:

$$\dot{U}_{a2-a1} = (\dot{U}_{41} - \dot{U}_{43}),\ \dot{U}_{в2-в1} = (\dot{U}_{42} - \dot{U}_{44}),\ \text{where}$$

$$\dot{U}_{a2-a1} = 0{,}855\angle 83{,}15^\circ - 0{,}197\angle -76{,}996^\circ = 1{,}0424\angle 86{,}83^\circ;$$

$$\dot{U}_{в2-в1} = 0{,}836\angle -5{,}011^\circ - 0{,}209\angle -175{,}166^\circ = 1{,}043\angle -3{,}05^\circ.$$

A comparison of the calculation results presented in Tables 4 and 5 indicates that the levels of voltage values in the nodes are different due to the different representations of loads in the nodes of the circuit.

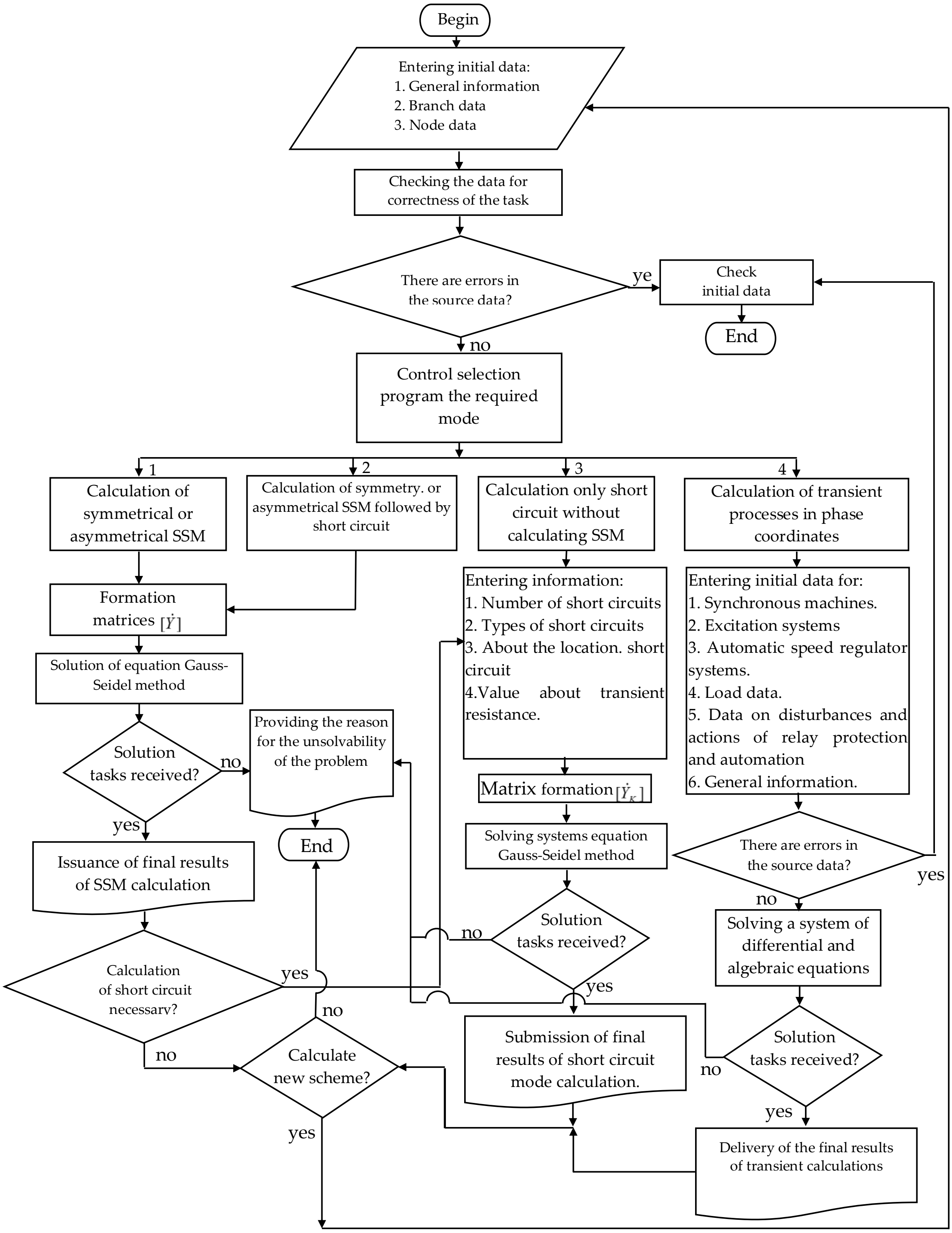


Figure 1: *Block diagram of the algorithm for calculating power system modes in phase coordinates*

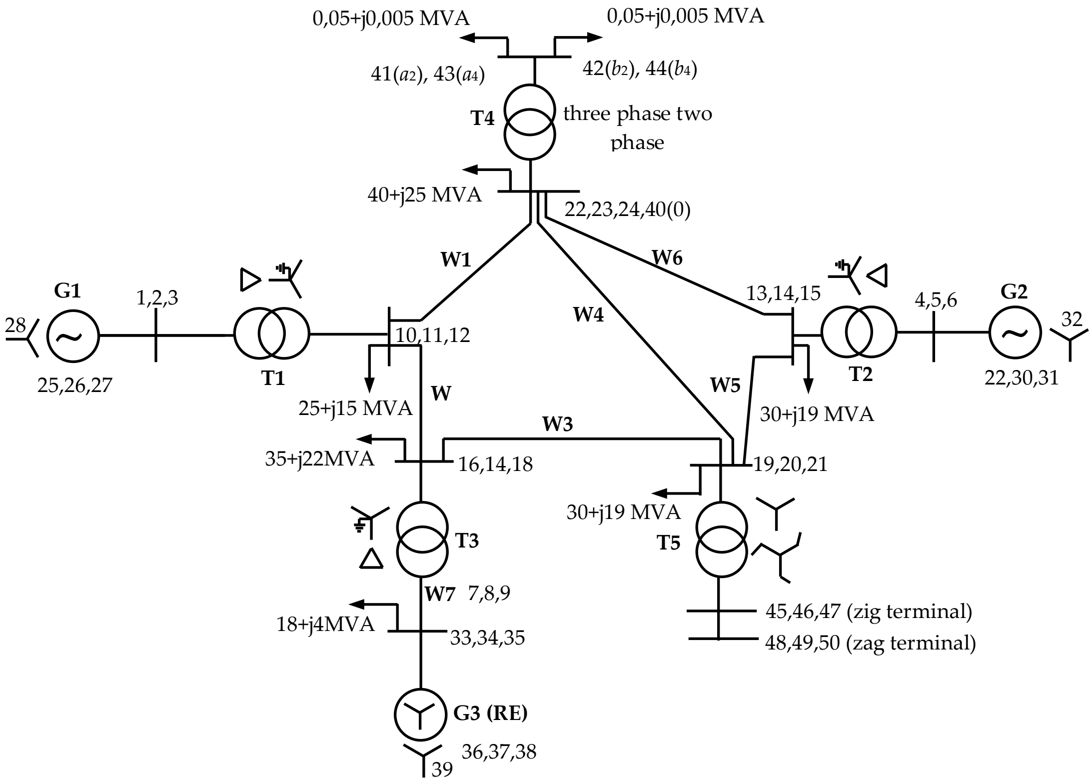


Figure 2: *Scheme of the studied multi-machine power system with renewable energy sources*

Table 1: *Initial data of power transmission lines of power systems (p.u.)*

art node	End node	Positive sequence resistors			Zero sequence resistances		
		R_1	X_1	B_1	R_0	X_0	B_0
10, 11, 12	22, 23, 24	0,0145	0,0660	0,0108	0,0456	0,1944	0,0058
10, 11, 12	16, 17, 18	0,0110	0,0496	0,0080	0,0342	0,1458	0,0050
16, 17, 18	19, 20, 21	0,0091	0,0413	0,0068	0,0285	0,1215	0,0043
19, 20, 21	22, 23, 24	0,0056	0,0248	0,0041	0,0171	0,0729	0,0025
19, 20, 21	13, 14, 15	0,0035	0,0155	0,0021	0,0114	0,0486	0,0027
13, 14, 15	22, 23, 24	0,0013	0,0330	0,0054	0,0228	0,0972	0,0034
7, 8, 9	33, 34, 35	0,0073	0,0330	0,0054	0,0228	0,0972	0,0034

Table 2: *Initial data of system generators (p.u.)*

Start node	End node	Positive sequence resistors		Zero sequence resistances	
		R_1	X_1	R_0	X_0
1, 2, 3	25, 26, 27	0,0	0,0967	0,0	0,0467
4, 5, 6	29, 30, 31	0,0	0,17	0,0	0,085
33, 34, 35	36, 37, 38	0,0	0,17	0,0	0,085

The obtained results of calculating the asymmetric mode indicate that the noted violations of the symmetric mode do not cause deep violations of the level of asymmetry of the mode parameters in the network circuit and such a mode is acceptable.

The calculation results for a single-phase short circuit at the generator terminals are presented in Figure 3, where a complete coincidence with the experimentally taken curves of the transition process was obtained.

Table 3: *Initial data of power transformers (p.u.)*

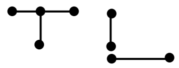
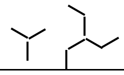
Start node	End node	Connection type	*X*
1, 2, 3	10, 11, 12		0,0533
4, 5, 6	13, 14, 15		0,12
7, 8, 9	16, 17, 18		0,16
22, 23, 24	41, 42, 43, 44		0,09(X_M) 0,16(X_T)
19, 20, 21	45, 46, 47 48, 49, 50		0,17

Table 4: *Calculation results of the symmetrical mode in phase coordinates*

Start node	End node	P (MW)	Q (MVAr)	Start node	End node	P (MW)	Q (MVAr)
1	25	-32,373	-15,122	25	1	32,373	16,230
2	26	-32,306	-14,879	26	2	32,306	15,976
3	27	-32,497	-14,971	27	3	32,497	16,081
4	29	-19,985	-9,405	29	4	19,985	10,151
5	30	-20,105	-9,534	30	5	20,105	10,292
6	31	-19,912	-9,582	31	6	19,912	10,329
10	16	12,079	3,889	16	10	-12,063	-4,690
11	17	12,106	3,965	17	11	-12,090	-4,768
12	18	11,943	4,030	18	12	-11,926	-4,833
10	22	12,317	5,404	22	10	-12,292	-6,470
11	23	12,230	5,382	23	11	-12,207	-6,452
12	24	12,103	5,536	24	12	-12,077	-6,610
13	19	6,511	1,803	19	13	-6,509	-2,090
14	20	6,437	1,662	20	14	-6,436	-1,950
15	21	6,466	1,749	21	15	-6,465	-2,037
13	22	4,002	0,986	22	13	-4,001	-1,568
14	23	3,912	0,880	23	14	-3,911	-1,463
15	24	3,974	0,972	24	15	-3,973	-1,555
16	19	4,617	3,748	19	16	-4,614	-4,470
17	20	4,489	3,649	20	17	-4,487	-4,373
18	21	4,444	3,785	21	18	-4,440	-4,508
19	22	0,996	0,186	22	19	-0,996	-0,626
20	23	0,924	0,139	23	20	-0,924	-0,579
21	24	0,988	0,203	24	21	-0,988	-0,643
7	33	-3,966	-6,288	33	7	3,969	5,701
8	34	-4,024	-6,332	34	8	4,028	5,745
9	35	-3,837	-6,442	35	9	3,841	5,856
33	36	-10,047	-8,021	36	33	10,047	8,272
34	37	-10,074	-8,038	37	34	10,075	8,292
35	38	-9,881	-8,178	38	35	9,880	8,428

Table 5: *Calculation results for the asymmetric mode in phase coordinates*

Start node	End node	P (MW)	Q (MVAR)	Start node	End node	P (MW)	Q (MVAR)
1	25	-38,839	-21,470	25	1	38,839	23,199
2	26	-32,511	-20,268	26	2	32,511	21,553
3	27	-37,071	-15,517	27	3	37,072	16,920
4	29	-24,543	-10,624	29	4	24,543	11,722
5	30	-16,229	-12,413	30	5	16,229	13,057
6	31	-19,228	-4,594	31	6	19,228	5,183
10	16	12,622	4,220	16	10	-12,605	-5,008
11	17	15,593	5,171	17	11	-15,566	-5,913
12	18	13,322	7,676	18	12	-13,295	-5,419
10	22	11,936	5,932	22	10	-11,913	-6,993
11	23	14,615	6,308	23	11	-14,580	-7,324
12	24	12,881	8,829	24	12	-12,844	-9,824
13	19	8,625	1,825	19	13	-8,523	-2,105
14	20	4,315	2,852	20	14	-4,314	-3,139
15	21	5,362	-1,541	21	15	-5,361	1,260
13	22	5,114	1,095	22	13	-5,111	-1,671
14	23	1,412	1,713	23	14	-1,411	-2,293
15	24	2,381	-2,027	24	15	-2,381	1,458
16	19	3,321	4,121	19	16	-3,319	-4,942
17	20	5,276	3,489	20	17	-5,272	-4,203
18	21	4,866	5,752	21	18	-4,861	-6,446
19	22	1,068	0,315	22	19	-1,067	-0,753
20	23	-0,993	0,455	23	20	0,994	-0,892
21	24	-0,400	-1,603	24	21	0,400	1,175
7	33	-3,408	-7,157	33	7	3,412	6,575
8	34	-2,302	-5,661	34	8	2,305	5,068
9	35	-4,268	-5,472	35	9	4,270	4,882
33	36	-10,082	-9,145	36	33	10,083	9,429
34	37	-8,970	-7,701	37	34	8,970	7,914
35	38	-10,947	-7,463	38	35	10,947	7,732

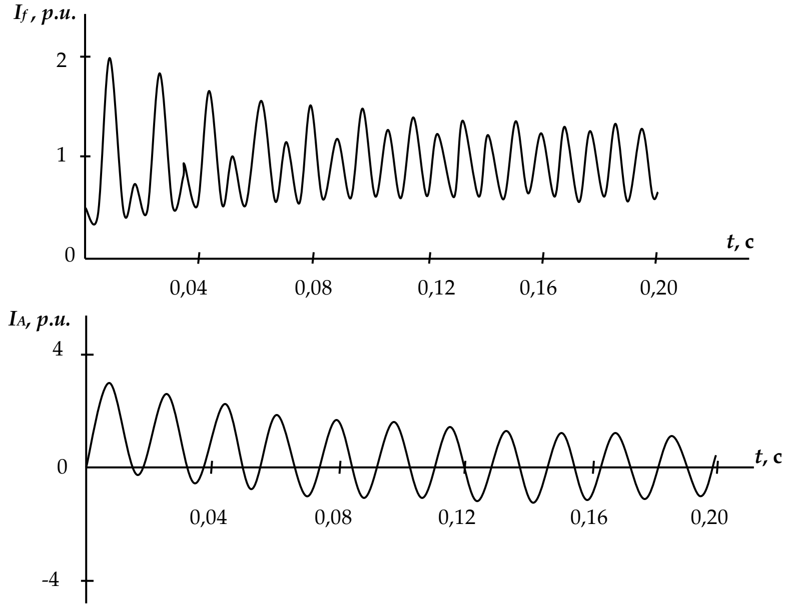


Figure. 3: *Current in the field winding (a) and in phase A (b) with a single-phase short circuit*

VI. Conclusions

1. A mathematical model of a power system with a renewable energy source, an algorithm and a program have been developed for studying any types of longitudinal-transverse, complex asymmetric steady-state modes, short-circuit modes and transient processes in phase coordinates and a dialogue complex created on its basis, which can be used in operational dispatch control operating modes of power systems for any type of emergency automation.

2. The developed methodology and complex program can be used in industry to solve the following practical problems: to test the possibility of long-term operation in the considered asymmetrical mode from the point of view of the operating conditions of EPS generators and power receivers; to determine the need to use baluns, to select their parameters and installation locations, to ensure the efficiency of asymmetrical modes; for carrying out various tests, analyzing accidents that have occurred; for selecting response parameters and assessing the sensitivity of relay protection devices, parameters of automation devices.

3. The obtained comparative results of calculating the symmetrical and asymmetrical modes of power systems indicate that the levels of voltage values in the nodes are different due to the different representations of loads in the nodes of the circuit. The noted violations of the symmetrical mode do not cause deep violations of the level of asymmetry of the mode parameters in the network circuit and such a mode is acceptable.

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