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DEVELOPMENT OF MATHEMATICAL MODELS OF ELEMENTS OF ELECTRICAL POWER SYSTEMS BASED ON THE TECHNOLOGY OF SYNCHRONIZED PHASOR MEASUREMENTS

221.01. ENERGY SYSTEMS AND TECHNOLOGIES

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CONTENT

CONCEPTUAL GUIDELINES OF RESEARCH

The actuality and the importance of the research topic. Currently, the electric power system (EPS) of the Republic of Moldova is characterized by an increasing share of distributed generation, a low level of modernization of electrical equipment, a high degree of wear and tear and poor financing for maintenance and repair activities. The effectiveness of managing such a system directly depends on the accuracy and reliability of both the information received about the state of the system and the mathematical models used to describe it. Numerous studies (works by A.Z. Gamm, T.B. Zaslavskaya, V.I. Idelchik, V.Z. Manusov, N.A. Melnikov, A.S. Novikov, S.I. Palamarchuk, M. Gavrilaș, J.W. Rittenhouse, J. Zaborszky, etc.) prove that the parameters of the equivalent schemes, based on which there are formed mathematical models can change under the influence of external factors during operation. At the same time, creating new equivalent schemes or updating existing ones is difficult due to the inadmissibility of full-scale experiments and the impossibility of physical modeling in the required volume. In this context, the development of synchronized phasor measurement (SPM) technologies will provide a significant boost to the improvement of the mathematical modeling of EPS.

Synchronized phasor measurement technology is based on the use of special devices (PMU - Phasor Measurement Unit) [1], which perform high-precision measurement of voltage phasors in nodes and currents from branches incident to these nodes. Each such measurement is time-synchronized using a satellite navigation system (GPS and/or GLONAS), which provides a "timestamp" of the observed network at any point in time. Thus, based on a system of synchronized phasor measurement devices, informational support is provided both for the power system management process and for the process of updating the mathematical models of the EPS. In conditions when in the Republic of Moldova, two important projects are being implemented in parallel in order to increase the security of electric power supply (the project for the synchronous connection of the EPS from the Republic of Moldova and Ukraine with the ENTSO-E system, as well as the integration project of interconnection of Moldavian EPS to the Romania's EEA by construction 400 kV power lines), the issues regarding the large-scale use of SPM technology and the improvement of mathematical models of the national EPS are becoming more actual and much more important. Thanks to the implementation of SPM technology, the Moldavian system operator will receive accurate and reliable tools for managing network operating regimes, for monitoring and diagnosing equipment, for quick response to network failures and breakdowns. With the improvement of information technologies and the introduction of automated computer systems, it will be possible to identify automatically the parameters of equivalent schemes without interfering with the technological process of equipment operation, as well as the automatic generation of databases about equipment parameters without operator participation.

Thus, it is necessary to carry out research on the identification of the parameters of the EPS elements based on the SPM data. For economic and technical reasons, as a rule, PMUs are not installed in every node of the network, so the problem of determining the critical nodes (from the point of view of EPS observability) where PMUs should be installed arises. For the same reason, it is necessary to consider the issues regarding the simultaneous use of data from SPM and traditional measurement systems for the analysis of EPS operating regimes. Special attention to these issues is also given in this research.

The purpose of the work is to develop methods and algorithms for mathematical modeling of EPS elements based on the implementation of SPM technology.

In order to achieve the purpose, the following **main objectives** were established:

1. Justification of real ranges of changes in the values of the parameters of power lines and power transformers, as well as the identification of the factors that have the most significant impact on these modifications;

2. Analysis of scientific works and research on the possibilities of using PMU measurements for solving practical problems in the field of electric power;

3. Development and research of methods for determining passive parameters of equivalent circuits of power lines and power transformers based on the use of SPM technology;

4. Development of algorithms for the optimal placement of PMU devices, taking into account ensuring the observability of EPS and minimizing the costs of purchasing and installing of these devices;

5. Research of the proposed algorithms for the optimal placement of PMUs on the possibility of increasing the reliability and calculation speed of the steady state mode of operation of the EPS;

6. Research of the possibility of simplifying the process of the EPS static state estimation by using PMU data.

The objects of the research are mathematical models of power lines and power transformers for voltage classes of 35-330 kV, information and measurement infrastructure, IEEE test schemes.

The subject of the research is methods and techniques for identifying the parameters of the equivalent schemes of the elements of the SEE, algorithms for the optimal placement of the PMUs, as well as methods for the accelerated calculation of steady state mode and the estimation of the static state of the electrical network.

When conducting the study, there were used various forms of writing the nodal equations describing the operating modes of the elements in the EPS, optimization methods and the method of determining nodal voltages. RastrWIN software was used to perform calculations, including for IEEE test schemes.

The novelty and scientific originality of the thesis: methods for identifying the passive parameters of the equivalent circuits of power lines and power transformers were developed, based on synchronized phasor measurements made in one or two modes, algorithms were developed for the optimal placement of SPM devices , which, in addition to ensuring the minimum number of PMUs for placement in network nodes, can improve the reliability and speed of calculations of the steady state mode and static state estimation due to the significant simplification of the system of equations describing the analyzed mode.

The theoretical significance. This study makes scientific contributions to the calculation and analysis of the EPS steady state modes, to the methodology for determining the passive parameters of equivalent schemes without full-scale tests, as well as to the development of mathematical models for optimizing the placement of PMUs in EPS nodes.

Applicative value. For the first time, a classification of methods for determination of the parameters of EPS elements based on the use of SPM technology was developed. The classification is based on the division of methods according to the original equations used to identify the parameters of the equivalent schemes of the EPS elements. The correlation formulas between the equivalent schemes of a transformer with two windings in the form of T, Γ and Π and the fundamental parameters of the quadrupole are obtained. Algorithms developed for the optimal placement of PMUs can be used both to determine the minimum number of nodes for the placement of SPM devices and to increase the speed and quality of steady state calculations and static state estimation in EPS.

The main scientific results submitted for defense.

1. Identification methods of power line parameters, based on MFS technology performed in one or two operating regimes are developed for different forms of representation of the equivalent scheme of power lines (with distributed and concentrated parameters).
2. For different forms of representation of the equivalent scheme of power transformers with real or complex transformation ratios, methods of identifying the parameters of two- and three-winding transformers based on synchronized phasor measurements have been developed.
3. By using the method of determining nodal voltages, there were developed algorithms for the optimal placement of PMUs in the EPS nodes that ensure the observability of

the network with a minimum number of devices installed in the network nodes.

4. The use of a matrix of nodal admittances of a special structure, in the framework of the calculation in the steady state mode, with the combined use of data from the PMU and SCADA devices can significantly reduce and facilitate the calculation of the steady state mode, as well as the process of static state estimation of the EPS.

Implementation of scientific results. Research results can be used by system operators to create active-adaptive models of EPS, to create methodologies for equipment diagnostics during operation, to determine the minimum number of PMUs installed in networks of different voltage classes, with the condition that the full observability of the EPS is ensured, in order to perform accelerated steady state calculations and to simplify the static state estimation process when PMU and SCADA measurements are used in combination.

Approval of the results. The results obtained in the thesis were presented and discussed in conferences and forums of national and international level, in total seven. The results obtained are published in eight scientific works.

Key words: synchronized phasor measurements, mathematical models, equivalent circuit parameters, power line, power transformer, power grid observability, steady state calculation, static state estimation.

CONTENT OF THE THESIS

In the **Introduction**, the actuality and importance of the research topic, the scientific novelty of the work, theoretical and applicative value of the obtained results are presented; the purpose of the thesis is indicated and the main research objectives are formulated.

In **Chapter I**, it is demonstrated that the mathematical models of the electrical network elements play a primary role in the problems of operating mode management. Mathematical modeling is done by solving direct and inverse problems. The direct problem involves conducting research on the model to extract useful knowledge, if the structure and parameters of the model are known. The inverse problem consists in development of mathematical models based on the results of observations of the behavior of the modeling object. The modeling compartment that solves the inverse problem is called identification [2].

The identification problem is divided into 2 components: determining the structure (structural identification) and determining the parameters (parametric identification). In the first case, an object (system element, control object, technological process element, etc.) is subjected to external influences, its reactions are analyzed and a mathematical model is obtained (description of its structure and parameters). The parametric identification of objects solves the problem of determining the parameters with a previously known structure of the object's mathematical model [3].There is given special attention to parametric identification problems in this study.

Currently, the parameters of equivalent schemes, as a rule, are determined using catalog and reference data. During the lifetime of the equipment, it is considered that these parameters do not change. In turn, an analysis of researches in the field of studying the nature of changes in passive parameters and the causes of errors showed that the passive parameters of equivalent schemes depend on many factors and can change under their influence within significant limits during operation.

The main reasons that affect the accuracy of determining the passive parameters of electric lines are the use of simplified equivalent schemes, technological deviations of parameters, as well as changes in external weather conditions and other causes.

Table 1 presents the error values of the power line parameters and the main reasons for their occurrence.

It should also be noted that there is inaccuracy that occurs when representing power transformers in any form of equivalent diagram presentation. The most accurate is the T-shaped equivalent circuit, and the most commonly used Γ-shaped equivalent circuit does not take into account the fact that no-load current flows through the primary winding.

Table 1. Errors in the calculation of passive parameters of the equivalent scheme for OHTL [4]

Reason	Maximum error, in %			
	R	*X*	*G*	*B*
1. Skin effect	+(1-3)	-	+1	-
2. Temperature changes	±16	-	-	+(2-3)
3. Meteorological factors	+20	±3	+(4-40)	+(3-20)
4. Technological elements	±1	±(2-3)	±11	±1
5. Lightning protection cables	+1	+(2-3)	-	±(1-9)
6. Conductivity of the earth	-	±3	-	-
7. Phase transposition	-	±6	-	+(2-4)
8. Parallel OHTLs	-	-(4-6)	-	+(3-4)
9. Simplification of the equivalent scheme	-	-	-(5-6)	-
10. Frequency modification	-	±0,5	-	±0,5
11. Length of OHTL's route	±(0,8-1)	±(0,8-1)	-	-
12. Non-linearity of characteristics	-	-	±(8-20)	-
13. Construction and installation tolerances	-	±0,5	-	±(2-4)
14. Other sources	-	±1	±(2-3)	±0,7
15. Total maximum error, %	-16..+20	-10..+8	-20..+40	-4..+20

Table 2 presents the causes and values of the errors of the passive parameters in the equivalent schemes for transformers.

Table 2. Errors in the calculation of the parameters of the equivalent schemes of the transformers [4]

Reason	Maximum error, in %			
	R	*X*	*G*	*B*
1. Simplification of the equivalent scheme	-	±2	±2	±4
2. Construction tolerances	+(10-20)	±10	+15	±30
3. Temperature changes	+12	-	-	-
4. Non-linearity of characteristics	-	-	±(9-12)	+45
5. Voltage regulation under load	±16	±11	-	-
6. Wear and tear	-	-	+15	-
7. Total maximum error, %	-16..+20	-15..+15	-12..+24	-15..+45

Changes in the parameters of the equivalent schemes of overhead lines and power transformers, as the main and most widespread elements of EPS, lead to inaccuracies in the calculation of short-circuit currents, the determination of fault locations, the adjustment of relay protection settings and emergency automation.

The traditional concept of creation of equivalent schemes does not reflect the changes of analyzed parameters and objects during operation. Consequently, the calculated values of currents and voltages in normal and fault conditions differ significantly from the measured values. This happens due to the lack of feedback between objects and their mathematical models, which does not allow reflecting changes in the passive parameters of EPS elements during their operation. Thus, it is demonstrated that during operation, the passive parameters of the EPS elements must be updated. The high economic costs and the impossibility of disconnecting from the network explain the impossibility of conducting physical experiments on the elements of the network during their operation in order to update their parameters. Therefore, the novel methods of updating the parameters of power lines and power transformers during their operation become particularly relevant and necessary.

For this reason, the new methods are implemented to identify the parameters of network elements in real time. A high degree of automation of the technological process, the improvement of the measurement system and the appearance of synchronized phasor measurements provide the technical opportunity to perform parameter identification automatically, without interfering with the technological process of equipment operation, as well as to generate automatically databases with equipment parameters without operator participation.

SPM technology has two key features [5]. First of all, the measurement of the operation mode parameters is carried out in connection with a high-precision exact time signal, since the measurement results are converted into digital form and provided with a UTC time stamp. Time synchronization accuracy is micro- and nanoseconds. In the information collection center, it is possible to compare all measurements with the same time stamp, and thus obtain a snapshot of the parameters of the EPS operating mode at any moment in time. In traditional telecontrol and SCADA systems, the accuracy of time synchronization varies from 0.1 to 4 s, which leads to an unpredictable time lag between the stamps of measurements made at different power stations and makes it difficult to compare the results obtained for different nodes of the EPS. Secondly, the measurements have phasor form, that is, not only the effective values of the currents and voltages are measured, but also their phase angles.

According to the standard architectural solution [6], the SPM system consists of several synchronized phasor measurement units (PMU) located in EPS nodes and phasor measurement concentrators (PDC), where further data processing will be performed. In addition, if PMUs are integrated into smart electronic devices that directly perform other functions (relay protection and automation terminals), it is recommended to place the concentrator directly at the power station. In general, according to the recommendations of SPM equipment manufacturers, phasor measurement concentrators should be installed at each level of the hierarchical architecture where requests to use phasor measurement data packets by third-party applications may occur.

The effect of the introduction of SPM technology is expressed in [7]:

- improving the quality of IT support for operational and dispatching staff in managing the EPS

operating mode;
- increasing the accuracy of calculations of the steady state operation mode based on the verified mathematical models of the electrical equipment and the network;
- increasing the stability of the operation of generating equipment, associated with the timely detection and damping of low-frequency oscillations, determining the correct operation and setting the automatic control of the generator's excitation;
- reducing the number of technological disruptions in the EPS, which occur as a result of the violation of static or dynamic stability, in the timely identification and assessment of the consequences of the increase in load of the EPS operation mode;
- increasing the precision of the emergency control due to the use of the voltage phase angles in the operation algorithms of the emergency automation.

As part of the reconstruction of relay protection and metering circuits with the financial support of USAID and USEA, until 2025, PMUs synchronized with GPS will be installed at the most essential power stations of the EPS in the Republic of Moldova, which will ensure the measurement of voltage and frequency in the nodes, as well as the currents of outcoming lines. The data from the PMUs will be sent to the control center of the State Enterprise "Moldelectrica" and will be used in various applications, including the static state estimation, the calculation of the transmission capacity of the power lines in real time, the analysis of static and dynamic stability.

In the Moldavian electric power system, there is currently a high degree of physical and moral wear and tear of the equipment of power plants and power stations (more than 60% have a service life of more than 30 years) and of high-voltage lines in the transmission networks of Republic of Moldova. (67.5% have been in operation for over 40 years) [8]. For this reason, tools for evaluating the parameters of equivalent schemes based on SPM data will have a great practical role, allowing the preventive identification of faults and failures of power lines and transformers, as well as the creation of appropriate mathematical models of these elements of the network. Such important aspects as the synchronization of the electrical energy systems of Ukraine and the Republic of Moldova with the European Continental Energy System ENTSO-E made in March 2022, as well as the stimulation of the development of renewable energy sources accelerate the processes of implementation and development of SPM technologies in the Republic of Moldova.

In **Chapter II**, based on an analysis of researches in the field of identification of passive parameters of EPS elements, as well as taking into account own studies, for the first time the classification of existing methods of identification of passive parameters of equivalent schemes for power lines and power transformers was carried out.

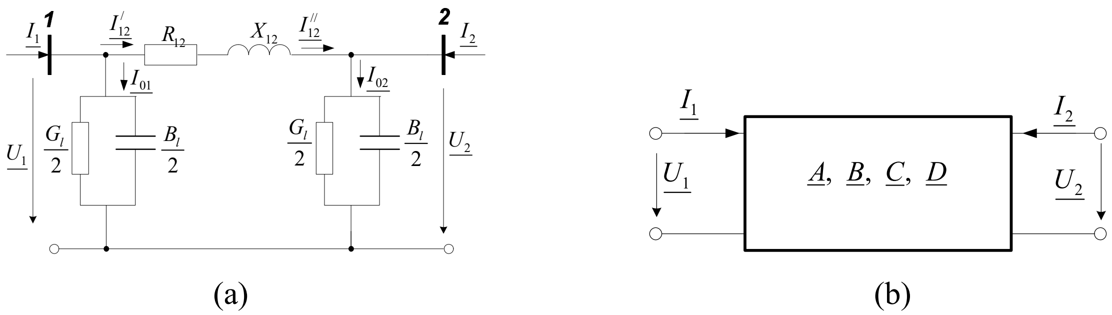

Fig. 1. Equivalent scheme of OHTL (a) in П-form; (b) in the form of a quadrupole

For the identification of passive parameters, classical models of power lines with concentrated parameters (Fig. 1 (a)) or with distributed parameters (Fig. 1 (b)) are used. In this case, a distinctive feature of the proposed methods is the use of phasor measurements of voltages and currents at the ends of the line, obtained synchronously in one or two operating modes of the line.

When the П-shaped equivalent scheme is used for power lines, it is proposed to use the node current balance method to calculate the longitudinal and transversal parameters of the line,

- according to the data of the measurements made in a single mode:

$$\begin{cases} I_{1a} = -G_{21}U_2\cos\delta_2 - B_{21}U_2\sin\delta_2 + G_{22}U_1; \\ I_{1r} = -B_{21}U_2\cos\delta_2 + G_{21}U_2\sin\delta_2 + B_{22}U_1; \\ I_{2a} = G_{21}U_1\cos\delta_2 - B_{21}U_1\sin\delta_2 - G_{22}U_2; \\ I_{2r} = B_{21}U_1\cos\delta_2 + G_{21}U_1\sin\delta_2 - B_{22}U_2. \end{cases} \tag{1}$$

- according to the data of the measurements made in two operating modes:

$$\begin{cases} I_{2a}^{(1)} = G_{21}U_1^{(1)}\cos\delta_2^{(1)} - B_{21}U_1^{(1)}\sin\delta_2^{(1)} - G_{22}U_2^{(1)}; \\ I_{2a}^{(2)} = G_{21}U_1^{(2)}\cos\delta_2^{(2)} - B_{21}U_1^{(2)}\sin\delta_2^{(2)} - G_{22}U_2^{(2)}; \\ I_{2r}^{(1)} = B_{21}U_1^{(1)}\cos\delta_2^{(1)} + G_{21}U_1^{(1)}\sin\delta_2^{(1)} + B_{22}U_2^{(1)}; \\ I_{2r}^{(2)} = B_{21}U_1^{(2)}\cos\delta_2^{(2)} + G_{21}U_1^{(2)}\sin\delta_2^{(2)} - B_{22}U_2^{(2)}. \end{cases} \tag{2}$$

If there are known synchronized values of the power at the ends of the line, it is proposed to use the method of power balance at the nodes:

- according to the data of the measurements made in a single mode:

$$\begin{cases} P_1 = -G_{21}U_1U_2\cos\delta_2 - B_{21}U_1U_2\sin\delta_2 + G_{22}U_1^2; \\ Q_1 = -B_{21}U_1U_2\cos\delta_2 + G_{21}U_1U_2\sin\delta_2 + B_{22}U_1^2; \\ P_2 = G_{21}U_1U_2\cos\delta_2 - B_{21}U_1U_2\sin\delta_2 - G_{22}U_2^2; \\ Q_2 = B_{21}U_1U_2\cos\delta_2 + G_{21}U_1U_2\sin\delta_2 - B_{22}U_2^2; \end{cases} \tag{3}$$

- according to the data of the measurements made in two operating modes:

$$
\begin{cases}
P_2^{(1)} = G_{21}U_1^{(1)}U_2^{(1)}\cos\delta_2^{(1)} - B_{21}U_1^{(1)}U_2^{(1)}\sin\delta_2^{(1)} - G_{22}\left(U_2^{(1)}\right)^2; \\
P_2^{(2)} = G_{21}U_1^{(2)}U_2^{(2)}\cos\delta_2^{(2)} - B_{21}U_1^{(2)}U_2^{(2)}\sin\delta_2^{(2)} - G_{22}\left(U_2^{(2)}\right)^2; \\
Q_2^{(1)} = B_{21}U_1^{(1)}U_2^{(1)}\cos\delta_2^{(1)} + G_{21}U_1^{(1)}U_2^{(1)}\sin\delta_2^{(1)} + B_{22}\left(U_2^{(1)}\right)^2; \\
Q_2^{(2)} = B_{21}U_1^{(2)}U_2^{(2)}\cos\delta_2^{(2)} + G_{21}U_1^{(2)}U_2^{(2)}\sin\delta_2^{(2)} - B_{22}\left(U_2^{(2)}\right)^2.
\end{cases} \tag{4}
$$

By solving the systems of equations (1)-(4) the longitudinal and transversal admittance values are determined. Knowing the active conductances G_{22} and G_{21}, as well as the capacitive susceptances B_{22} and B_{21}, there are determined:

$$\frac{G_l}{2} = G_{22} - G_{21}; \quad \frac{B_l}{2} = B_{21} - B_{22}. \tag{5}$$

Knowing values G_{12} and B_{12}, the parameters of the longitudinal branch R_{12} and X_{12} can be determined:

$$R_{12} = \frac{G_{12}}{G_{12}^2 + B_{12}^2}; \quad X_{12} = \frac{B_{12}}{G_{12}^2 + B_{12}^2}. \tag{6}$$

In the case of using an equivalent scheme of a power line with distributed parameters in the form of a passive quadrupole, it is assumed that the coefficients of the quadrupole are calculated using the formulas derived for the case

- of using the measurements, made in a single mode:

$$\underline{A} = \frac{\underline{U}_1^2 \cdot \underline{I}_2 + \underline{U}_1 \cdot \underline{U}_2 \cdot \underline{I}_1}{\underline{U}_2^2 \cdot \underline{I}_1 + \underline{U}_1 \cdot \underline{U}_2 \cdot \underline{I}_2}; \ \underline{B} = \frac{\underline{U}_1^2 \cdot \underline{U}_2 - \underline{U}_2^3}{\underline{U}_2^2 \cdot \underline{I}_1 \cdot \sqrt{3} + \underline{U}_1 \cdot \underline{U}_2 \cdot \underline{I}_2 \cdot \sqrt{3}}; \ \underline{C} = \frac{\underline{U}_2 \cdot \underline{I}_1^2 \cdot \sqrt{3} - \underline{U}_2 \cdot \underline{I}_2^2 \cdot \sqrt{3}}{\underline{U}_2^2 \cdot \underline{I}_1 + \underline{U}_1 \cdot \underline{U}_2 \cdot \underline{I}_2} \tag{7}$$

- of using the measurements, made in a two operating modes:

$$
\begin{gathered}
\underline{A} = \frac{\underline{U}_1^{(1)} \cdot \underline{I}_2^{(2)} - \underline{U}_1^{(2)} \cdot \underline{I}_2^{(1)}}{\underline{U}_2^{(1)} \cdot \underline{I}_2^{(2)} - \underline{U}_2^{(2)} \cdot \underline{I}_2^{(1)}}; \qquad \underline{B} = \frac{\underline{U}_1^{(1)} - \underline{A} \cdot \underline{U}_2^{(1)}}{\sqrt{3} \cdot \underline{I}_2^{(1)}} = \frac{\underline{U}_1^{(2)} - \underline{A} \cdot \underline{U}_2^{(2)}}{\sqrt{3} \cdot \underline{I}_2^{(2)}}; \\
\underline{C} = \frac{\sqrt{3} \cdot \left(\underline{I}_1^{(1)} \cdot \underline{I}_2^{(1)} - \underline{I}_1^{(2)} \cdot \underline{I}_2^{(1)}\right)}{\underline{U}_2^{(1)} \cdot \underline{I}_2^{(2)} - \underline{U}_2^{(2)} \cdot \underline{I}_2^{(1)}}.
\end{gathered} \tag{8}
$$

Next, the parameters of the longitudinal and transverse branches of the power line are determined using the formulas:

$$\underline{Z}_{12} = R_{12} + jX_{12} = \underline{B}; \quad \underline{Y}_{12} = G_{12} - jB_{12} = 2 \cdot \frac{\underline{A} - 1}{\underline{B}}. \tag{9}$$

Table 3 shows the results obtained for the parameters of the equivalent scheme of a 110 kV transmission line with a length of 100 km, made with conductor brand AC-185/43, with the horizontal arrangement of the phase conductors at a distance of 5 m, with different line load factors (k_l).

Table 3. Comparison of the results of determining the parameters by different methods for the OHTL 110 kV

Applicated method	k_l	Determined parameter		
		R, Ω	**X, Ω**	**B, μS**
Real values	-	15,6	41,4	282
Balance of powers (with data from one mode)	1	15,6	41,4	282
Balance of powers (with data from two modes)	1/0,9	15,601	41,4	282,08
Balance of currents (with data from one mode)	1	15,6	41,4	281,(9)
Balance of currents (with data from two modes)	1/0,9	15,601	41,4	282,08
Quadrupole (with data from one mode)	1	15,6	41,4	282
Quadrupole (with data from two modes)	1/0,9	15,6	41,4	282

For transformers with two windings, it is possible to use Г-, П- and T-shaped equivalent schemes (Fig. 2 (a), (b), (c) respectively). In addition, to determine the passive parameters of the two-winding transformer, it is proposed to use the scheme of active quadrupole (Fig. 2 (d)).

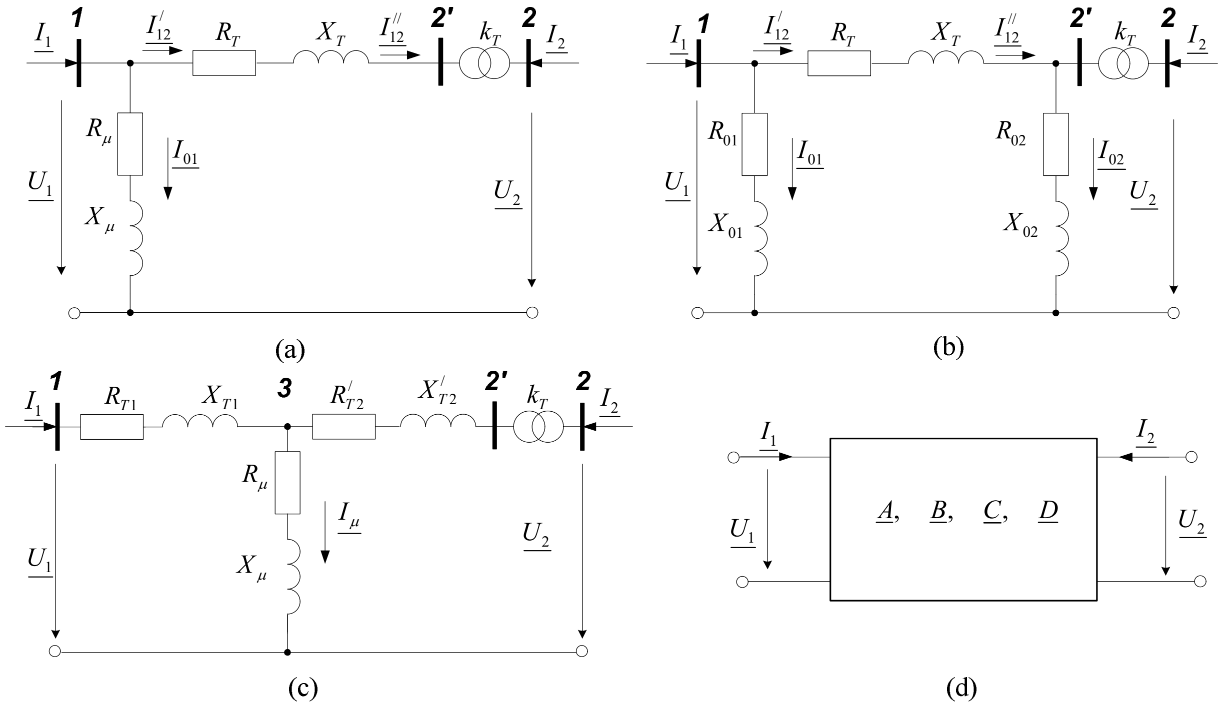

Fig. 2. Presentation of the transformer with two windings (a) with the Г-shaped equivalent scheme; (b) with the П-shaped equivalent scheme; (c) with the T-shaped equivalent scheme; (d) in the form of a quadrupole.

For the Г-shaped equivalent scheme, there are obtained expressions for the calculation of parameters using the method of balance of currents at the nodes:

$$\begin{cases} J_{a1}^{(1)} = U_1^{(1)} G_{t\mu} - k_t^{(1)} U_2^{(1)} G_t \cdot \cos\delta_2^{(1)} - k_t^{(1)} U_2^{(1)} B_t \sin\delta_2^{(1)}; \\ J_{r1}^{(1)} = U_1^{(1)} B_{t\mu} + k_t^{(1)} U_2^{(1)} G_t \cdot \sin\delta_2^{(1)} - k_t^{(1)} U_2^{(1)} B_t \cos\delta_2^{(1)}; \\ J_{a1}^{(2)} = U_1^{(2)} G_{t\mu} - k_t^{(2)} U_2^{(2)} G_t \cdot \cos\delta_2^{(2)} - k_t^{(2)} U_2^{(2)} B_t \sin\delta_2^{(2)}; \\ J_{r1}^{(2)} = U_1^{(2)} B_{t\mu} + k_t^{(2)} U_2^{(2)} G_t \cdot \sin\delta_2^{(2)} - k_t^{(2)} U_2^{(2)} B_t \cos\delta_2^{(2)}. \end{cases} \tag{10}$$

or the method of balance of powers at the nodes:

$$\begin{cases} P^{(1)} = U_1^{2(1)} G_{t\mu} - k_t^{(1)} U_1^{(1)} U_2^{(1)} G_t \cdot \cos\delta_2^{(1)} - k_t^{(1)} U_1^{(1)} U_2^{(1)} B_t \sin\delta_2^{(1)}; \\ Q^{(1)} = U_1^{2(1)} B_{t\mu} + k_t^{(1)} U_1^{(1)} U_2^{(1)} G_t \cdot \sin\delta_2^{(1)} - k_t^{(1)} U_1^{(1)} U_2^{(1)} B_t \cos\delta_2^{(1)}; \\ P^{(2)} = U_1^{2(2)} G_{t\mu} - k_t^{(2)} U_1^{(2)} U_2^{(2)} G_t \cdot \cos\delta_2^{(2)} - k_t^{(2)} U_1^{(2)} U_2^{(2)} B_t \sin\delta_2^{(2)}; \\ Q^{(2)} = U_1^{2(2)} B_{t\mu} + k_t^{(2)} U_1^{(2)} U_2^{(2)} G_t \cdot \sin\delta_2^{(2)} - k_t^{(2)} U_1^{(2)} U_2^{(2)} B_t \cos\delta_2^{(2)}, \end{cases} \tag{11}$$

and also by the quadrupole method:

$$\begin{cases} \underline{U}_1^{(1)} = \underline{U}_2^{(1)} \cdot \underline{A} + \sqrt{3} \cdot \underline{J}_2^{(1)} \underline{B}; \\ \underline{J}_1^{(1)} = \dfrac{\underline{U}_2^{(1)}}{\sqrt{3}} \cdot \underline{C} + \underline{J}_2^{(1)} \underline{D}; \\ \underline{U}_1^{(2)} = \underline{U}_2^{(2)} \cdot \underline{A} + \sqrt{3} \cdot \underline{J}_2^{(2)} \underline{B}; \\ \underline{J}_1^{(2)} = \dfrac{\underline{U}_2^{(2)}}{\sqrt{3}} \cdot \underline{C} + \underline{J}_2^{(2)} \underline{D}. \end{cases} \tag{12}$$

In addition, there were obtained expressions for calculating the parameters of the Г-, П- and T-shaped equivalent schemes of two-winding transformers when they are represented in the form of an active quadrupole (Table 4).

Table 4. Expressions for determining passive parameters of two-winding transformers with Г-, П- and T-shaped equivalent schemes

Г-shaped equivalent schemes		
$\underline{a} = \dfrac{\underline{U}_1 \cdot \underline{J}_1 \overset{*}{\underline{k}}_t + \underline{U}_2 \cdot \underline{J}_2 \cdot \underline{k}_t - \lvert \underline{k}_t \rvert^2 \cdot \underline{U}_2 \cdot \underline{J}_1}{\underline{J}_2 \cdot \underline{U}_1}$	$\underline{A} = \underline{k}_t$	$\underline{B} = \dfrac{\underline{U}_1 - \underline{k}_t \cdot \underline{U}_2}{\sqrt{3} \cdot \underline{J}_2}$
$\underline{C} = \dfrac{\left(\overset{*}{\underline{k}}_t \cdot \underline{J}_2 - \lvert \overset{*}{\underline{k}}_t \rvert^2 \cdot \underline{J}_1 \right) \cdot \sqrt{3}}{\underline{U}_1 \cdot \overset{*}{\underline{k}}_t}$	$\underline{D} = \dfrac{1}{\overset{*}{\underline{k}}_t} \cdot \underline{a}$	$\underline{Z}_t = \underline{B} \cdot \overset{*}{\underline{k}}_t$ $\underline{Z}_\mu = \dfrac{\underline{a} - 1}{\underline{Z}_t}$
П-shaped equivalent schemes		

$\underline{a}=\dfrac{\underline{U}_1\cdot\underline{J}_1\,\overset{*}{\underline{k}}_t+\underline{U}_2\cdot\underline{J}_2\cdot\underline{k}_t}{\underline{J}_2\cdot\underline{U}_1+\left\lvert\underline{k}_t\right\rvert^2\cdot\underline{U}_2\cdot\underline{J}_1}$	$\underline{A}=\underline{a}\cdot\underline{k}_t$	$\underline{B}=\dfrac{\underline{U}_1^2-\underline{k}_t^2\cdot\underline{U}_2^2}{\sqrt{3}\cdot\left(\underline{J}_2\cdot\underline{U}_1+\underline{J}_1\cdot\underline{U}_2\cdot\left\lvert\underline{k}_t\right\rvert^2\right)}$
$\underline{C}=\dfrac{\left(\left(\overset{*}{\underline{k}}_t\right)^2\cdot\underline{J}_1^2-\underline{J}_2^2\right)\cdot\sqrt{3}\cdot\underline{k}_t}{\left(\underline{J}_2\cdot\underline{U}_1+\underline{J}_1\cdot\underline{U}_2\cdot\left\lvert\underline{k}_t\right\rvert^2\right)\cdot\overset{*}{\underline{k}}_t}$	$\underline{D}=\dfrac{1}{\overset{*}{\underline{k}}_t}\cdot\underline{a}$	$\underline{Z}_t=\underline{B}\cdot\overset{*}{\underline{k}}_t$ $\underline{Z}_0=2\cdot\underline{Z}_{01}=2\cdot\underline{Z}_{02}=\dfrac{\underline{a}-1}{2\cdot\underline{Z}_t}$
T--shaped equivalent schemes		
$\underline{a}=\dfrac{\underline{U}_1\cdot\underline{J}_1\,\overset{*}{\underline{k}}_t+\underline{U}_2\cdot\underline{J}_2\cdot\underline{k}_t}{\underline{J}_2\cdot\underline{U}_1+\left\lvert\underline{k}_t\right\rvert^2\cdot\underline{U}_2\cdot\underline{J}_1}$	$\underline{A}=\underline{a}\cdot\underline{k}_t$	$\underline{B}=\dfrac{\underline{U}_1^2-\underline{k}_t^2\cdot\underline{U}_2^2}{\sqrt{3}\cdot\left(\underline{J}_2\cdot\underline{U}_1+\underline{J}_1\cdot\underline{U}_2\cdot\left\lvert\underline{k}_t\right\rvert^2\right)}$
$\underline{C}=\dfrac{\left(\left(\overset{*}{\underline{k}}_t\right)^2\cdot\underline{J}_1^2-\underline{J}_2^2\right)\cdot\sqrt{3}\cdot\underline{k}_t}{\left(\underline{J}_2\cdot\underline{U}_1+\underline{J}_1\cdot\underline{U}_2\cdot\left\lvert\underline{k}_t\right\rvert^2\right)\cdot\overset{*}{\underline{k}}_t}$	$\underline{D}=\dfrac{1}{\overset{*}{\underline{k}}_t}\cdot\underline{a}$	$\underline{Y}_\mu=\dfrac{\underline{C}}{\underline{k}_t}$ $\underline{Z}_t=\dfrac{2\cdot\left(\underline{a}-1\right)}{\underline{Y}_\mu}$

The methods presented by the expressions of table 4 can be used to calculate the passive parameters of two-winding transformers with a complex or real value of the transformation ratio. In this case, it is necessary to use the measurements made on both sides of the transformer in two operating modes. Thanks to the expressions presented in table 4, it is possible to calculate the passive parameters of a two-winding transformer when using the Γ-, Π- and T-shaped equivalent scheme, by calculating the coefficients of a quadrupole using a single measurement mode.

In order to identify the passive parameters of three-winding transformers and autotransformers, it is proposed to use the simplified equivalent schemes shown in Fig. 3.

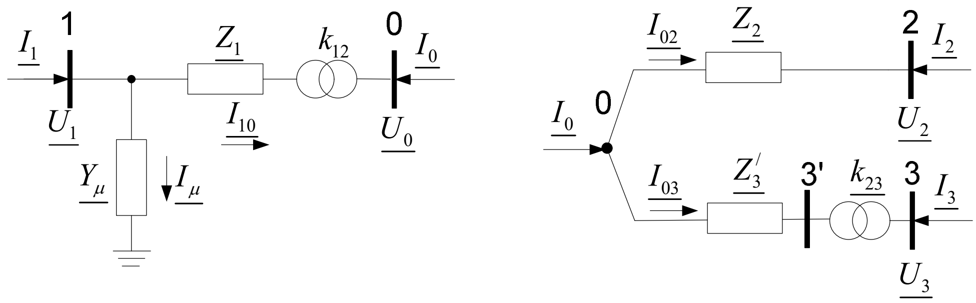

Fig. 3. Simplified equivalent scheme of a three-winding transformer

Taking into account that $R_1=R_2=R_3$, but $X_2=0$ for three-winding transformers, a system of eight equations with eight unknowns is formed:

$$\left\{\begin{array}{c}
-J_1' + G_\mu \frac{U_1}{\sqrt{3}} + \frac{J_2'}{k_{12}} + \left(\frac{\sqrt{3}}{2}J_3' - \frac{1}{2}J_3''\right)\frac{1}{k_{13}} = 0; \\
-J_1'' - B_\mu \frac{U_1}{\sqrt{3}} + \frac{J_2''}{k_{12}} + \left(\frac{1}{2}J_3' + \frac{1}{2}J_3''\right)\frac{1}{k_{13}} = 0; \\
U_1 - 2\sqrt{3}J_2' \frac{R_1}{k_{12}} + \sqrt{3}J_2'' \frac{X_1}{k_{12}} - \left(\frac{3}{2}J_3' - \frac{\sqrt{3}}{2}J_3''\right)\frac{R_1}{k_{13}} + \left(\frac{\sqrt{3}}{2}J_3' + \frac{3}{2}J_3''\right)\frac{X_1}{k_{13}} - U_2' k_{12} = 0; \\
-\sqrt{3}J_2' \frac{X_1}{k_{12}} - 2\sqrt{3}J_2'' \frac{R_1}{k_{12}} - \left(\frac{\sqrt{3}}{2}J_3' + \frac{3}{2}J_3''\right)\frac{R_1}{k_{13}} - \left(\frac{3}{2}J_3' - \frac{\sqrt{3}}{2}J_3''\right)\frac{X_1}{k_{13}} - U_2'' k_{12} = 0; \\
U_2' k_{12} + \sqrt{3}J_2' \frac{R_1}{k_{12}} - \left(\frac{\sqrt{3}}{2}U_3' - \frac{1}{2}U_3''\right)k_{13} - \left(\frac{3}{2}J_3' + \frac{\sqrt{3}}{2}J_3''\right)\frac{R_1}{k_{13}} - \left(\frac{\sqrt{3}}{2}J_3' - \frac{3}{2}J_3''\right)\frac{X_3}{k_{13}} = 0; \\
U_2'' k_{12} + \sqrt{3}J_2'' \frac{R_1}{k_{12}} - \left(\frac{1}{2}U_3' + \frac{\sqrt{3}}{2}U_3''\right)k_{13} + \left(\frac{\sqrt{3}}{2}J_3' + \frac{3}{2}J_3''\right)\frac{R_1}{k_{13}} - \left(\frac{3}{2}J_3' + \frac{\sqrt{3}}{2}J_3''\right)\frac{X_3}{k_{13}} = 0; \\
P_1 - P_2 - P_3 - G_\mu U_1^2 - 3J_1^2 R_1 + \frac{6}{\sqrt{3}}J_1' U_1 R_1 G_\mu - \frac{6}{\sqrt{3}}J_1'' U_1 R_1 B_\mu - U_1^2 R_1 G_\mu^2 - U_1^2 R_1 B_\mu^2 - 3\frac{J_2^2}{k_{12}^2}R_1 - 3\frac{J_3^2}{k_{13}^2}R_1 = 0; \\
Q_1 - Q_2 - Q_3 - B_\mu U_1^2 - 3J_1^2 X_1 + \frac{6}{\sqrt{3}}J_1' U_1 X_1 G_\mu - \frac{6}{\sqrt{3}}J_1'' U_1 X_1 B_\mu - U_1^2 X_1 G_\mu^2 - U_1^2 X_1 B_\mu^2 - 3\frac{J_3^2}{k_{13}^2}X_3 = 0.
\end{array}\right. \quad (13)$$

The results of determining the parameters using these methods are compared with the real (catalogue) data of overhead lines and power transformers with two and three windings, good results were obtained, which confirms the reliability of the proposed methods.

Chapter III explains that from a technical and economic point of view it is not efficient to install PMU devices in each node of the analyzed electrical network, since it is possible to achieve network observability with fewer points where PMU devices should be installed. A system is observable when its state variables can be determined from a set of available information [9]. The problem of optimal placement of PMUs involves determining the minimum number of PMUs and their installation locations in order to ensure full observability of the EPS.

The thesis proposes a new approach for the optimal placement of PMUs based on the method of determining nodal voltages [10, 11]. The system of nodal equations can be written in matrix form as follows [12, 13]:

$$\left[\underline{Y}_n\right]_{trans} \cdot \left[\underline{U}_n\right] = \begin{bmatrix} \underline{Y}_{pp} & \underline{Y}_{pq} \\ \underline{Y}_{qp} & \underline{Y}_{qq} \end{bmatrix} \cdot \begin{bmatrix} \underline{U}_p \\ \underline{U}_q \end{bmatrix} = \begin{bmatrix} \underline{J}_p \\ \underline{J}_q \end{bmatrix}, \quad (14)$$

where $\left[\underline{Y}_n\right]_{trans}$ - the transfigured nodal admittance matrix;

$\left[\underline{U}_n\right]$ - matrix of nodal voltages for all nodes of the electrical network, determined with relation to network neutral.

The transition from the matrix of nodal admittances $\left[\underline{Y}_n\right]$, which corresponds to the initial numbering of the electrical network nodes, to the matrix $\left[\underline{Y}_n\right]_{trans}$ is achieved by changing some lines and columns guided by the following rules:

- in the matrix of nodal admittances $\left[\underline{Y}_n\right]$, any two lines *i* and *k* can replace each other with the simultaneous modification of the matrix components $\left[\underline{J}_n\right]$;
- in the matrix of nodal admittances $\left[\underline{Y}_n\right]$, any two columns *s* and *r* can replace each other with the simultaneous modification of the components $\left[\underline{U}_n\right]$.

Since the submatrix $\left[\underline{Y}_{qq}\right]$ has a special structure and if the elements of the column matrix $\left[\underline{U}_p\right]$ are known, the elements of the submatrix $\left[\underline{U}_q\right]$ can be determined very quickly, as the unknown variables.

Regarding the process of dividing the nodal admittance matrix into submatrices, the following requirements are imposed:

- to reduce the investment costs for the installation of PMUs, the rank of the submatrix $\left[\underline{Y}_{qq}\right]$ should be maximum;

- to significantly simplify the calculation of the static state of the electrical network, in most cases, when possible, it is necessary to use linear equations for the determination of the unknown variables. To do this, it is necessary to move (if possible) the elements of the main diagonal of the matrix $\left[\underline{Y}_{\Sigma}\right]$.

In this work, two new algorithms are proposed for determining the optimal placement of PMU devices, based on the principle of dividing the nodal admittance matrix into submatrices (algorithms A1 and A2). The differences consist in the fact that the A1 algorithm assumes that the PMU device provides the measurement of only the voltage phasor in the network node, and the A2 algorithm implies the use of both voltage phasor and current phasor measurements in all branches incident to the nodes where the PMU devices are installed. In order to determine the nodal voltages in the nodes where the PMU installation is not planned, the telemeasurements of the power flows from the SCADA system are used in combination with the measured phasors,.

According to the A1 algorithm, the nodes of the studied electrical network are divided into two subsets *P* and *Q*, while the matrix of nodal admittances is divided into four submatrices, one of which is a band-shaped matrix of maximum rank, under the assumption that PMU devices located in the nodes of the subset *P* ensure full observability of the power grid. To divide the nodal admittance matrix into four submatrices, the following steps must be taken:

1. The ranks of all nodes of the electrical network are determined, i.e. the number of branches incident to each node.

2. The maximum rank node with branches incident to this node are excluded from the circuit. If there are several nodes of maximum rank, a node is selected according to the numbering

order of the nodes in the circuit, the exclusion of which will not result in the partitioning of the circuit into subcircuits. The inclusion of a node of maximum rank *q* in a subset *P* leads to the unlooping of *g* circuits in the analyzed single-line diagram of the electrical network. In other words, the number *g* of open circuits at each step is equal to the number of branches incident to the node that was excluded at this step.

3. After removing a node, the ranks of all remaining nodes in the single-line diagram of the electrical network are recalculated.

4. It is checked whether there are any closed circuits left in the studied network. If there are any left, steps 2 and 3 are repeated until all closed loops are removed from the single-line diagram of the electrical network.

5. The nodes of the subset *P* are numbered in random order; one node in each tree is necessarily included in the subset *P*.

6. The nodes of the trees are numbered sequentially starting with the nodes adjacent to those that were included in the subset *P*.

7. Isolated nodes are numbered in the last turn arbitrarily.

8. In the subset *Q* there are included the nodes of the trees that were not included in the subset *P* as well as the isolated nodes.

According to the A2 algorithm, the information from the PMU installed in node *i* about the complex values of currents and voltages ensures the calculation of mode parameters not only at the installation site, but also for the opposite end of the branch *i-j* based on the passive parameters of the equivalent scheme in the given branch. The nodes for which the voltage is calculated based on the equivalent circuit parameters are called pseudo-PMU nodes, they become part of the *PP* subset. Thus, according to this algorithm, three subsets *P*, *PP* and *Q* are formed. In order to divide the nodes of the analyzed system into three subsets, the following steps must be taken:

1. The ranks of all nodes of the electrical network are determined, i.e. the number of branches incident to each node.

2. The maximum rank node with branches incident to this node are excluded from the circuit. If there are several nodes of maximum rank, the first node is selected in the order of numbering of the nodes in the network. The excluded node is included in the subset *P*.

3. After excluding any node, the ranks of the remaining nodes in the circuit are determined again. Nodes whose ranks have decreased are indicated as pseudo-PMUs (they are included in the *PP* subset).

4. Steps 2 and 3 are repeated until all nodes with rank $R \geq 3$ have PMUs or pseudo-PMUs placed.

5. If the rank of a node at any step is 1 or 2, then the node is included in the subset Q and the complex value of the voltage at this node will be determined linearly by the balance of currents.

6. The nodes of each subset are numbered in random order, but sequentially: first, the nodes of the subset P, where PMUs are installed, then the nodes of the subset PP, which have information about pseudo-measurements, and finally - the nodes of the subset Q, i.e. nodes of rank $R \leq 2$, not included in the first two subsets.

The optimal placement of PMU devices using algorithms A1 and A2 is illustrated using the IEEE-14 test scheme with 14 nodes. In this scope, IEEE-14 single-line diagram is presented with the initial numbering of the nodes, as well as the numbering performed according to the A1 and A2 algorithms. The concept of a dot diagram is also introduced. The term of dot diagram means a conventional presentation of the nodal admittance matrix, in which all non-zero elements are replaced by points.

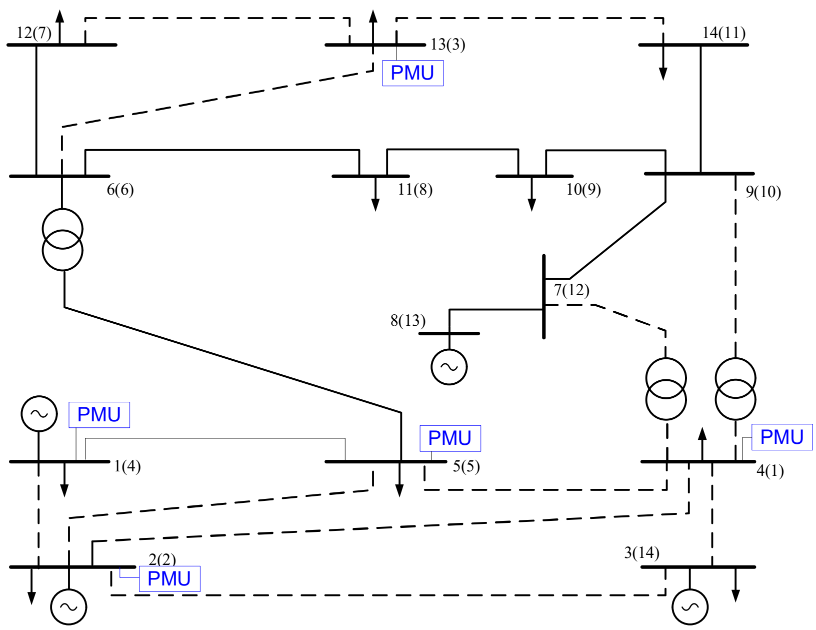

Fig. 4. Single-line diagram of the IEEE-14 test scheme with initial numbering, as well as numbering performed according to the A1 algorithm (in brackets)

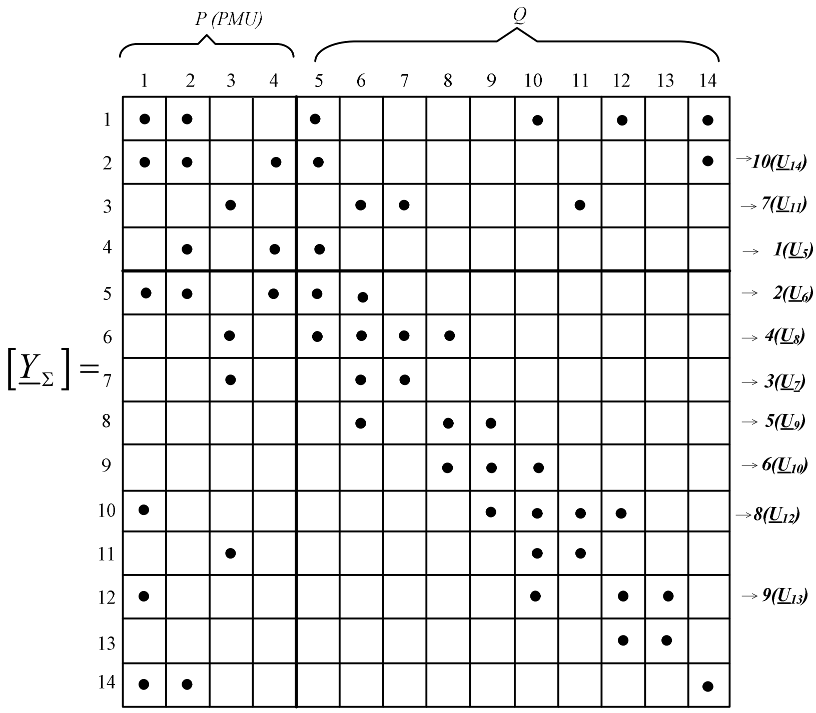

Fig. 5. Point diagram of the nodal admittance matrix for the IEEE-14 test scheme, where the submatrix $[\underline{Y}_{qq}]$ is reduced to the band form (according to algorithm A1)

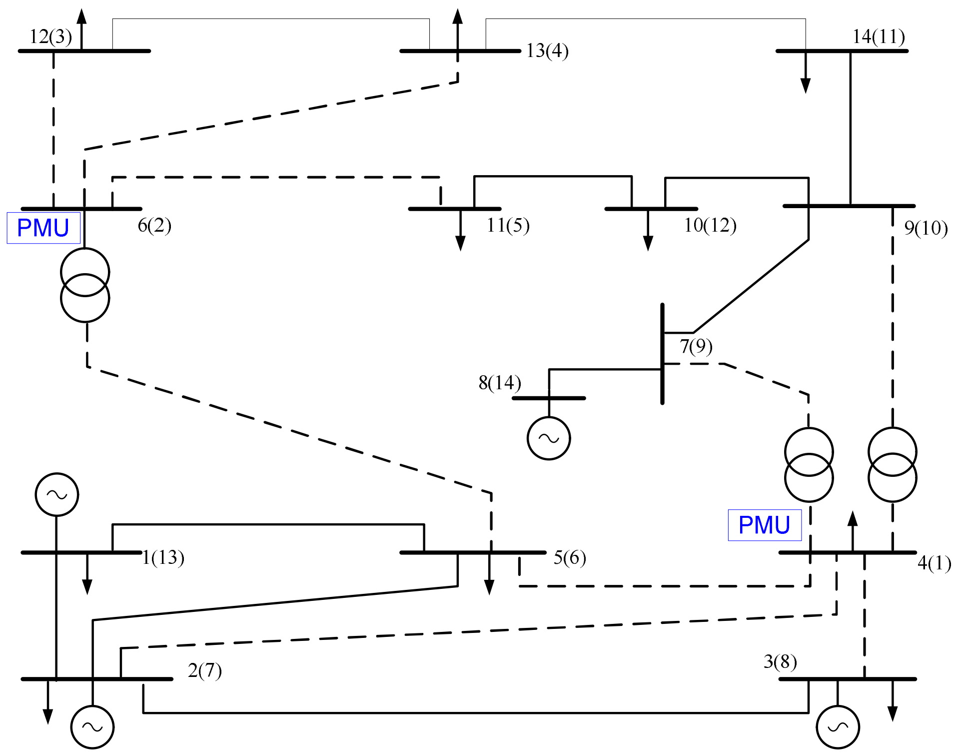

Fig. 6. Single-line diagram of the IEEE-14 test scheme with initial numbering, as well as numbering performed according to the A2 algorithm (in brackets)

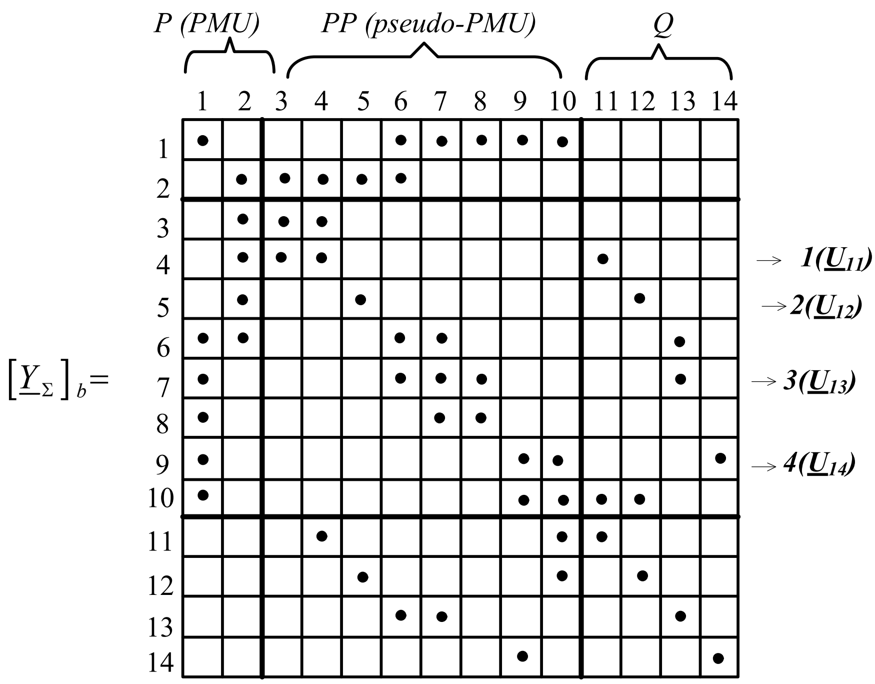

Fig. 7. Dot diagram of the nodal admittance matrix for the IEEE-14 test scheme, shown in fig. 6 (according to algorithm A2)

Obviously, the advantage of the A2 algorithm over A1 is the reduction of the number of PMUs required to ensure network observability.

Table 5 shows the results of the optimal placement of PMU devices in the IEEE-14, IEEE-24, IEEE-30, IEEE-57 test schemes, made using the A1 and A2 algorithms, as well as taken from other sources to compare the results.

Table 5. Comparison of the results obtained according to PMU optimal placement algorithms for IEEE test schemes

Algorithms	**IEEE test scheme name**			
	IEEE-14	**IEEE-24**	**IEEE-30**	**IEEE-57**
Algorithm A1	4 PMU	7 PMU	8 PMU	10 PMU
Algorithm A2	2 PMU	5 PMU	5 PMU	9 PMU
Algorithm A3 [13]	5 PMU	6 PMU	----	10 PMU
Algorithm A4 [14]	4 PMU	7 PMU	10 PMU	17 PMU
Algorithm A5 [15]	4 PMU	7 PMU	10 PMU	17 PMU
Algorithm A6 [16]	4 PMU	----	10 PMU	17 PMU
Algorithm A7 [17]	4 PMU	----	10 PMU	16 PMU

A comparative analysis of the presented results demonstrates the advantages of the algorithms A1 and A2 proposed in this research, since solutions with a similar or smaller number of PMU devices were found for all the studied test schemes.

Chapter IV shows that the proposed algorithms for the optimal placement of PMUs (A1 and A2) have an important advantage: they provide an accelerated and ultra-accelerated method for calculating the steady state mode. Traditionally, the calculation of the steady state mode and the process of static state estimation of the EPS is performed using telemetry data obtained from SCADA systems. To calculate the regime of these networks, programs that implement the nodal voltage method are used. The initial data for the calculation are the mathematical model of the EPS, the loads in the nodes in the form of active and reactive power and the voltage in one of the nodes, which is called the balance node. There is formed a system of equations, which are nonlinear with a large number of variables and restrictions in the form of inequalities. To solve such systems of equations, iterative algorithms with successive approximation of the desired result are used. The placement of PMU devices in the nodes of the electrical network using the A1 and A2 algorithms ensures the simplification and acceleration of the steady state calculation. The minimization of the time required for the calculation of the permanent regime is achieved by using the method of determining values and the transformation of the block matrix of the system of linear equations.

The column-matrix of nodal voltages $[\underline{U}_\Sigma]$ is divided into two submatrices $[\underline{U}_p]$ and $[\underline{U}_q]$, respectively. The first submatrix includes the determining nodal voltages, i.e. the independent quantities, and the second submatrix includes the dependent variables. The submatrix $[\underline{U}_q]$ is determined as a function of $[\underline{U}_p]$. This way of dividing the column matrix $[\underline{U}_\Sigma]$ is the basis of all the fast methods for calculating the steady state mode of the EPS [10]. After dividing the matrix $[\underline{U}_\Sigma]$ into sub-matrices, the system of nodal equations describing the operation mode of the SEE can be written in the form [10]:

$$\begin{cases} [\underline{Y}_{pp}]\cdot[\underline{U}_P]+[\underline{Y}_{pq}]\cdot[\underline{U}_q]=[\underline{J}_p]; \\ [\underline{Y}_{qp}]\cdot[\underline{U}_P]+[\underline{Y}_{qq}]\cdot[\underline{U}_q]=[\underline{J}_q]. \end{cases} \tag{19}$$

If the elements of the submatrix $[\underline{U}_p]$ are known (these are the determining nodal voltages), then they can be considered independent variables, thus the dependent variables of the subset $[\underline{U}_q]$ are calculated from the second equation of the system (19) using the expression:

$$[\underline{Y}_{qq}]\cdot[\underline{U}_q]=[\underline{J}_q]-[\underline{Y}_{qp}]\cdot[\underline{U}_P], \tag{20}$$

where matrix $[\underline{Y}_{qq}]$ is reduced to a lower triangular or band structure, because according to algorithms A1 and A2, in this case, the number of PMU devices located in the network nodes will be minimal.

To illustrate the accelerated algorithms of operation mode calculation, the IEEE-14 test scheme was chosen. The steady state mode was calculated using the RastrWIN program, and the calculation results are compared with the voltages determined using accelerated methods based on algorithms for the optimal placement of PMUs (A1 and A2).

If the first placement algorithm A1 is applied for the IEEE-14 test scheme, then taking into account the installation of PMUs in nodes 1, 2, 3 and 4 (Fig. 4, nodes are indicated in brackets), as well as using traditional measurements of power flows in the nodes, the accelerated method can be used to obtain the values of the nodal voltages in all dependent nodes. The sequence of determining the nodal voltages is indicated to the right of the dot diagram of the nodal admittances (Fig. 5).

It should be noted that if the voltage of node i is determined from the expression for the current balance of node j, then it is necessary to solve a linear equation as a function of $\underline{U}_i$. If the voltage of node i is determined from the expression for for the current balance of the same node i, the voltage of that node is determined by solving a nonlinear equation using the iterative method.

The calculation of the steady state using the A2 algorithm contains two stages. In the first stage, by determining the voltage drop in the branches incident to the installation node of the PMU, the nodal voltages of the nodes adjacent to the PMU location are calculated (pseudo-measurements), and then, based on the PMU data, pseudo-measurements and traditional SCADA data , the voltage values in the dependent nodes are determined from the current balance equations. In this case, it is important that, as in algorithm A1, the voltage value for node i is determined from the expression for the current balance of node j, then it will be necessary to solve a linear equation as a function of $\underline{U}_i$. In fig. 7, to the right of the dot diagram of the nodal admittances, the sequence of determining the unknown voltages in dependent nodes is indicated.

The differences between the results obtained using the A1 and A2 algorithms and those obtained using the RastrWIN program are not greater than 0.1%, which indicates the high accuracy of the results obtained using the accelerated algorithms for calculating the steady state mode. Such calculation methods make it possible to significantly simplify the solution procedure, because predominantly systems of linear equations are solved, which has a positive effect on the speed of calculation and the accuracy of the obtained results.

Also in the **Chapter IV**, a PMU placement algorithm is presented to perform static state estimation, when the state vector of the EPS is determined by solving a system of linear equations. Static state estimation allows to get the most probable state of the system (as a control section) at a given moment of time according to measurements and parameters of the mathematical model of the electrical network. Both joint use of SCADA and PMU data (hybrid estimation algorithms [17-20]) and exclusive use of PMU measurements are used to make simplier static state estimation algorithms. In this research, a static state estimation algorithm is proposed which is based on the exclusive use of PMUs; the electrical network becomes fully observable with the help of PMUs installed in the nodes of the system, and the state estimation problem is reduced to solving a system of linear equations, since the static state model takes a linear form. The advantage of this algorithm for EPS state estimation is that it uses a system of linear equations.

GENERALCONCLUSIONS AND RECOMMENDATIONS

Based on the theoretical and practical results of the research, the following **conclusions** are formulated:

1. Based on the analysis of the literature in the field and own researches, a classification of identification methods [22] of equivalent circuit parameters for power lines and power transformers based on the use of synchronized phasor measurement technology was developed (Chapter 2, subchapter 2.1).

2. There are developed methods for determining the passive parameters of electric lines, power transformers with two and three windings [22, 23] based on the balance of currents and balance of powers methods, as well as based on the quadrupole method using measurements made in one and two operating modes of the studied object (Chapter 2, subsection 2.2, 2.3).

3. Analytical relations were obtained [23] for determining the passive parameters of the Γ-, Π- and T-shaped equivalent scheme of a two-winding transformer by using the fundamental parameters of the quadrupole (Chapter 2, subchapter 2.3).

4. Algorithms for the placement of PMU devices have been developed; they are based on transformations of the nodal admittance matrix using the method of determining values [24, 25]. The developed algorithms were tested on test schemes with a number of nodes from 9 to 57. A comparative analysis of the obtained results shows that the proposed algorithms ensure a smaller or similar number of PMU devices required for installation compared to the other known algorithms. In this case, any node in the electrical network that meets the requirements of the applied algorithm can be selected as the PMU installation point (Chapter 3, subchapter 3.5).

5. The algorithms for the optimal placement of the PMUs developed in this thesis ensure the performance of the steady stare calculation using accelerated and ultra-accelerated processes [25, 26], due to the use of the method of determining values and the transformation of the system of nodal equations (Chapter 4, subchapter 4.1, 4.2). The static state estimation of the EPS is greatly simplified, in the case of the exclusive use of PMUs, because to determine the state vector it is necessary to solve a system of linear equations (Chapter 4, subchapter 4.3).

Recommendations: due to the fact that the parameters of equivalent schemes of EPS elements change during operation, it is recommended to use the identification methods based on the SPM technology proposed in this thesis to update the parameters of equivalent schemes of existing mathematical models for EPS. The data for performing the calculations can be obtained from the PMUs located at the nodes of the network according to the optimal location algorithms proposed in this research, which ensure both the minimization of the costs of implementation and operation of this technology, as well as the full observability of the studied electrical network. The updated parameters of the mathematical models can later be used for static state estimation and steady state calculation using the algorithms developed in this study.

Further research directions and objectives: it is proposed to direct further studies on this research topic to the creation of software for determining the passive parameters of equivalent schemes based on SPM data (real-time as well as from historical measurements). This software is of practical interest from the point of view of creating active-adaptive models of EPS, as well as for preventive diagnostics of equipment condition.

Another important area is the creation of software for algorithms for the optimal placement of PMU devices, in order to be able to determine the minimum number and optimal locations to install PMU' complexes for power networks containing a large number of nodes. Of great importance in this context will be the results of the use of algorithms developed for determining the optimal locations for the placement of PMUs in the nodes of the national transmission electric power system for voltage classes of 35-110 kV, as well as for distribution networks.

Taking into account the growing interest in the Republic of Moldova towards renewable sources of energy, the extension of distribution networks, the development of EPS with distributed generation, a promising and currently little studied direction for the application of SPM technology is the static state estimation in distribution networks. This approach implies the use of synchronized measurements from electricity meters or other intelligent electronic devices to compile power balances and to identify areas of the grid with significant technical and commercial losses

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1. **MURDID, E**., STRATAN, I. Parameter Identification of Transformers and Transmission Lines Based on Synchronized Measurements. Annals of the University of Craiova, Electrical Engineering series, No. 43, Issue 1; pp. 114-121, 2019. ISSN: 1842-4805, 0.49 c.t.

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1**. MURDID, E.**, STRATAN I. Estimarea parametrilor reţelelor electrice utilizând măsurări fazoriale sincronizate. Conferința Tehnico-Științifică a Colaboratorilor, Doctoranzilor și Studenților, Universitatea Tehnică a Moldovei, 15-17 noiembrie, 2012. Chișinău, 2013, vol. 1, pp. 413-416. ISBN 978-9975-45-249-6. ISBN 978-9975-45-250-2 (Vol.1), 0.33 c.t.

ADNOTARE

Autor - *MURDID Ecaterina*. **Titlul -** *Elaborarea modelelor matematice ale elementelor sistemelor elelctroenergetice bazate pe tehnologia măsurărilor fazoriale sincronizate*. Teză de doctor în vederea conferirii titlului științific de doctor în științe tehnice la specialitatea 221.01. *Sisteme şi tehnologii energetice*, Chișinău, 2023.

Structura tezei: Lucrarea conține o introducere, patru capitole, concluzii generale și recomandări, bibliografie din 101 titluri și include 5 anexe, 129 pagini, 41 figuri, 17 tabele. Rezultatele obținute sunt publicate în 8 lucrări științifice.

Cuvinte cheie: măsurări fazoriale sincronizate (MFS), modele matematice, parametrii schemelor echivalente, linie electrică, transformator de putere, observabilitatea rețelei electrice, calcul regimului permanent, estimarea stării statice a rețelei electrice.

Domeniul de studiu: științe inginerești.

Scopul tezei: dezvoltarea metodelor și algoritmilor de modelare matematică a elementelor SEE bazate pe tehnologia MFS.

Obiectivele tezei sunt determinarea factorilor care au cel mai semnificativ impact asupra modificărilor valorilor reale ale parametrilor pasivi ai schemelor echivalente ai liniilor electrice și transformatoarelor de putere; analiza cercetărilor științifice privind posibilitatea utilizării măsurătorilor sincronizate pentru rezolvarea problemelor practice din domeniul electroenergetic; dezvoltarea și cercetarea metodelor de identificare a parametrilor pasivi ai liniilor electrice și ai transformatoarelor de putere pe baza utilizării tehnologiei MFS; dezvoltarea algoritmilor pentru amplasarea optimă a dispozitivelor PMU, ținând cont de asigurarea observabilității SEE și minimizarea costurilor economice; studiul algoritmilor propuși privind amplasamentul optim al PMU pentru simplificarea algoritmilor de calcul al regimurilor permanente, precum și pentru simplificărea procesului de estimare a stării statice a SEE.

Noutatea și originalitatea științifică a tezei: se demonstrează că în condițiile utilizării măsurărilor fazoriale sincronizate devine posibilă utilizarea metodei tensiunilor nodale determinante, metodei balanței curenților și puterilor la noduri, metoda cuadripolului pentru a introduce noi abordări privind determinarea parametrilor schemelor echivalente ale elementelor componente ale SEE și , respectiv, calculul regimului permanent de funcționare.

Rezultatele obținute care contribuie la soluționarea problemei științifice importante, demonstrează că în condițiile utilizării complexe a tehnologiei MFS este simplificat semnificativ procesului de identificare a parametrilor pasivi ai schemelor echivalente ale elementelor SEE pe parcursul funcționării acestora, precum și algoritmii dezvoltați pentru amplasarea optimă a dispozitivelor MFS, pe lângă determinarea numărului minim de PMU-urile pentru instalarea în nodurile rețelei electrice asigură, de asemenea, o simpplificare atât a calculului regimului permanent, cât și a estimării stării statice a SEE.

Semnificație teoretică: Teza aduce contribuții științifice la calculul și analiza regimurilor SEE, la metodologia de determinare a parametrilor schemelor echivalente fără efectuarea testelor de teren, la dezvoltarea modelelor de amplasare optimă a dispozitivelor de măsurări fazoriale sincronizate.

Valoarea aplicativă a lucrării și implementarea rezultatelor: Rezultatele lucrării pot fi utilizate de operatorii de rețea pentru a crea modelele SEE activ-adaptive, pentru a crea metodologii pentru diagnosticarea echipamentului pe parcursul funcționării, pentru a determina numărul minim de PMU instalate în rețelele de diverse clase de tensiune, cu condiția că este asigurată observabilitatea completă a SEE, pentru implementarea calculelor accelerate ale regimurilor de funcționare și evaluarea stării sistemului cu utilizarea numai a măsurărilor MFS precum și cu utilizarea simultană a măsurărilor MFS și SCADA.

АННОТАЦИЯ

Автор - *МУРДИД Екатерина***. Название -** *Разработка математических моделей для элементов электроэнергетических систем на основе технологии синхронизированных векторных измерений***,** диссертация на соискание ученой степени кандидата технических наук, *специальность 221.01. Энергетические системы и технологии*. Кишинэу, 2023

Структура работы: Работа состоит из введения, четырех глав, заключения, библиографии со 101 источником, 5 приложений, содержит 129 страниц, 41 рисунков и 17 таблиц. На тему исследования опубликовано восемь научных статей.

Ключевые слова: синхронизированные векторные измерения (СВИ), математические модели, параметры схем замещения, линия электропередач, силовой трансформатор, наблюдаемость электрической сети, расчет установившегося режима, оценивание состояния.

Область исследования: инженерные науки.

Цель диссертации заключается в разработке методов и алгоритмов математического моделирования элементов ЭЭС на основе технологии СВИ.

Задачи диссертации: определение факторов, оказывающих наиболее существенное влияние на изменения реальных диапазонов значений пассивных параметров линий электропередач и силовых трансформаторов; анализ научных исследований на возможность использования измерений PMU для решения практических задач в области электроэнергетики; разработка и исследование методов определения пассивных параметров схем замещения линий электропередач и силовых трансформаторов на основе применения технологии СВИ; разработка алгоритмов оптимального размещения устройств СВИ с учетом обеспечения наблюдаемости ЭЭС и минимизации экономических затрат; исследование предлагаемых алгоритмов расстановки СВИ на возможность увеличения надежности и упрощения как расчетов установившихся режимов, так и оценивания состояния ЭЭС.

Научная новизна и оригинальность работы: демонстрируется, что в условиях использования синхронизированных векторных измерений появляется возможность использовать метод определяющих узловых напряжений, метод баланса токов и мощности в узлах, метод четырехполюсника для внедрения новых подходов в определении параметров схем замещения элементов ЭЭС и в расчетах установившихся режимов.

Полученные результаты, способствующие решению важных научных задач доказывают, что при комплексном применении технологии СВИ существенно упрощается процесс идентификации пассивных параметров схем замещения элементов ЭЭС в процессе их эксплуатации, а разработанные алгоритмы оптимальной расстановки устройств СВИ, помимо определения минимального количества устройств для размещения в узлах сети, обеспечивают упрощение расчета установившегося режима и оценивания состояния ЭЭС.

Теоретическое значение: Данное исследование вносит научный вклад в расчет и анализ установившихся режимов ЭЭС, в методологию по определению параметров схем замещения без проведения натурных испытаний, в развитие математических моделей оптимального размещения устройств СВИ.

Практическая ценность работы и внедрение результатов: Результаты исследования могут использоваться сетевыми операторами для создания активно-адаптивных моделей ЭЭС, для создания методологий по диагностике оборудования в процессе эксплуатации, для определения минимального количества PMU, устанавливаемых в сетях различных классов напряжения при условии обеспечения полноценной наблюдаемости ЭЭС, для осуществления ускоренных расчетов установившихся режимов и оценивания состояния системы при исключительном использовании данных СВИ, а также при совместном использовании измерений СВИ и SCADA.

ABSTRACT

Author - *MURDID Ecaterina*. **Title -** *Development of mathematical models for elements of electric power systems based on the technology of synchronized phasor measurements***.** Doctoral thesis in technical sciences specialty 221.01. *Energy systems and technologies*, Chisinau, 2023

Thesis structure: The paper comprises an introduction, four chapters, general conclusions and recommendations, 101 bibliography titles, and includes 5 Annexes, 129 pages, 41 figures, 17 tables. The research results are published in 8 scientific papers.

Keywords: synchronized phasor measurement (SPM), phasor measurement unit (PMU), mathematical models, equivalent circuit passive parameters, power line, power transformer, electric network observability, steady state calculation, state estimation.

Field of study: engineering sciences.

The purpose of the thesis consists in the development of methods and algorithms for mathematical modeling of EPS (electric power system) elements based on SPM technology.

Objectives are determination of the factors that have the most significant impact on changes in the real values of the passive parameters of power lines and power transformers; analysis of scientific researches on the possibility of using PMU measurements to solve practical problems in the field of electric power engineering; development and analyses of the methods for determining the passive parameters of equivalent schemes of power lines and power transformers based on the use of SPM technology; development of algorithms for the optimal placement of PMU devices, taking into account ensuring the observability of the EPS and minimizing economic costs; study of the proposed algorithms for arranging the PMU in scope of increasing reliability and speed of the algorithms for calculating steady state modes, as well as for the possibility of simplifying the process of state estimation of the EPS.

Scientific novelty and originality of the work: it is demonstrated that under the conditions of using synchronized phasor measurements, it becomes possible to use the method of determining nodal voltages the method of balance of currents and power flows in nodes, the quadrupole method in order to introduce new approaches in determining the passive parameters of equivalent schemes of EPS elements and in steady state calculations.

The results obtained, which contribute to the solution of important scientific problems, prove that with the integrated use of SPM technology, the process of identifying passive parameters of equivalent schemes of EPS elements during their operation is significantly simplified, and the developed algorithms for the optimal PMU placement, in addition to determining the minimum number of PMUs for placement in network nodes, also provide a simplification for steady state calculation and static state estimation of EPS.

The theoretical value. This study makes a scientific contribution to the calculation and analysis of steady state EPS modes, to the methodology for determining the parameters of equivalent circuits without field tests, to the development of mathematical models of optimal PMU placement.

The practical value of the work and the implementation of research results. The results of the work can be used by network operators to create active-adaptive EPS models, to create methodologies for diagnosing equipment during operation, to determine the minimum number of PMUs installed in networks of various voltage classes, ensuring full EPS observability, to carry out accelerated calculations of steady state modes and assessing the system state estimation while using only SPM measurements as well as simultaneously using SPM and SCADA measurements.

MURDID ECATERINA

DEVELOPMENT OF MATHEMATICAL MODELS OF ELEMENTS OF ELECTRICAL POWER SYSTEMS BASED ON THE TECHNOLOGY OF SYNCHRONIZED PHASOR MEASUREMENTS

221.01. ENERGY SYSTEMS AND TECHNOLOGIES

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