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MATHEMATICAL MODEL AND ALGORITHM FOR THE DETERMINATION OF THE ORIGIN OF ELECTRICITY FROM RENEWABLE ENERGY SOURCES IN THE ELECTRIC POWER SYSTEM

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Abstract. *The article deals with the development of a method and algorithm for calculation of individual compo-nents of electricity flows in the branches of an electric power grid circuit caused by generation and con-sumption in its nodes. In particular, it is about estimating the share of renewable energy sources (RES) in the electricity consumption of a given consumer. The method is based on methods and algorithms for the calculation of steady-state modes of power grids, integrating a mathematical model for determining the components of current flows in the branches of the power system circuit. The model employs distribution coefficients of currents in the circuit branches from RES nodes and node voltages to form a matrix of cur-rent distribution coefficients for RES across the power grid branches. Since RES in electric power systems (EPS) use general power grids to transmit the electricity they generate, accurate determination of their power share within overall flows enables the impact of RES on the EPS mode parameters to be considered. The peculiarity of the algorithm for estimating the share of RES in the electricity consumption of a given consumer is its consideration of physical processes in the power system. The input data for the calculation are the power system parameters, the node loads (specified by capacity or schedules), as well as arrays of RES generation and centralized power supply nodes and consumers with a controlled value of the Guar-anteed Origin of electricity from RES. The voltages during the formation of the matrix of power distribu-tion coefficients at nodes along the branches of the power grid are determined by the calculation results of the power grid steady-state modes or by experimental measurement data. The method's efficacy and the accuracy of estimating the RES share in the power consumption of a given consumer are verified and demonstrated through a practical example. Determination of the share of the consumer's electricity con-sumption, which origin from renewable sources can be guaranteed, creates an enabling environment that would foster producers and consumers to increase the use of renewable energy sources and promotes the development of the green energy market. Ref. 18. Fig.3.*

Key words: *renewable energy sources, power grids, matrix of power distribution coefficients of nodes by branches of the power grid, share of consumer electricity from RES.*

МАТЕМАТИЧНА МОДЕЛЬ ТА АЛГОРИТМ ВИЗНАЧЕННЯ ПОХОДЖЕННЯ ЕЛЕКТРОЕНЕРГІЇ СПОЖИВАЧА ВІД ВІДНОВЛЮВАНИХ ДЖЕРЕЛ ЕНЕРГІЇ В ЕЛЕКТРОЕНЕРГЕТИЧНІЙ СИСТЕМІ

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Стаття присвячена розробленню методу та алгоритму розрахунку окремих складових перетікань електроенергії у вітках схеми електричної мережі, що зумовлені генеруванням та споживанням у вузлах. Зокрема йдеться про оцінювання частки електроспоживання певного споживача електроенергії, що забезпечується з відновлюваних джерел енергії (ВДЕ).

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Метод ґрунтується на методах та алгоритмах розра хунку усталених режимів електричних мереж. В основу методу покладено математичну модель для визначення складових перетікань електроенергії у вітках схеми електричної мережі, в якій використовуються коефіцієнти розподілу струмів у вітках схеми від вузлів з ВДЕ та вузлові напруги. В результаті формується матриця коефіцієнтів розподілу потужності ВДЕ у вітках електричної мережі. Оскільки ВДЕ в електроенергетичних системах (ЕЕС) для передачі генерованої ними електроенергії використовують електричні мережі загального призначення, то визначення їх частки потужності в перетоках дозволяє враховувати вплив ВДЕ на параметри режиму ЕЕС. Особливістю алгоритму оцінювання частки електроспоживання заданого споживача, яка забезпечується з ВДЕ, є врахування фізичних процесів у електричній мережі. Вхідними даними для розрахунку є параметри електричної мережі, навантаження вузлів, заданих потужністю або графіками, а також масиви вузлів генерування ВДЕ і централізованого живлення та споживачів з контрольованим значенням гарантованого походження електроенергії від ВДЕ. Напруги під час формування матриці коефіцієнтів розподілу потужності вузлів по вітках електричної мережі визначаються за результатами розрахунку усталених режимів електричної мережі або за експериментальними даними вимірювання. На прикладі перевірена працездатність розробленого методу та адекватність результатів оцінювання частки електроспоживання заданого споживача, яка забезпечується з відновлюваних джерел енергії. Визначення частки електроенергії споживачів, яку вони гарантовано отримують від ВДЕ, формує умови для стимулювання генерувальних компаній і споживачів збільшувати використання відновлювальної енергії та сприяти розвитку ринку «зеленої» енергетики. Біб. 18. Рис. 3.

Ключові слова: *відновлювані джерела енергії, електричні мережі, матриця коефіцієнтів розподілу потужності вузлів по вітках електричної мережі, частка електроенергії споживача від ВДЕ.*

Використані скорочення

List of Abbreviations and Symbols

EPS – electric power system

GO – Guarantees of Origin

PL – power line

PVPP – photovoltaic power plants

RES – renewable energy sources

WPP – wind power plant

Introduction and task statement. Renewable energy sources, in particular wind and photovoltaic power plants (WPP and PVPP), typically use general purpose power grids to transmit the generated electricity to consumers. Therefore, it is important to know how they affect the technical and economic parameters of power grids. This applies to voltage levels, load and capacity of power lines (PL) and transformers, short-circuit currents and their conformance with switching device values [1-4]. In addition, the development and increase of the share of renewable energy in power supply systems give rise to a number of issues not directly related to the impact on grid parameters. First and foremost, using renewable energy helps to reduce emissions of harmful substances such as carbon dioxide and other pollutants that adversely affect human health and the environment. It is necessary to know the real origin of electricity from renewable energy sources in order to objectively assess the impact of renewable energy generation on the technical and economic parameters of power grids and the process of decarbonization, i. e. the replacement of traditional fossil fuel sources in the electricity balance. This problem is currently referred to in the energy community as "Guaranteeing the Origin of Electricity" [5, 6]. Guarantees of Origin (GO) for renewable energy allow generation companies and consumers to increase the use of renewable energy and promote the development of the green energy market. Guarantees of origin of electricity from renewable energy sources make it possible to: stimulate renewable energy producers to expand their capacities and invest in new technologies; increase consumer responsibility and awareness of their contribution to the reduction of greenhouse gas emissions and climate change; and improve energy security by creating conditions for the decentralization of energy supply and the formation of local electric power systems based on renewable energy sources.

Since it is not yet feasible or practical to fully replace electricity consumption with renewable energy, differentiating between the degrees of "greenness" is essential for both renewable energy producers and industrial consumers seeking to reduce CO_2 emissions [7]. This is especially applicable to power systems where nuclear and thermal power plants, as well as renewable energy sources, are involved in balancing the mode of the electric power system (EPS).

In addition to the environmental aspect, this is mainly due to the need for auditable reporting [8], as shareholders expect companies to disclose the amount of CO_2 emitted [9]. As a result, manufacturers are increasingly demanding auditable environmental products in order to position themselves favorably among competitors by having a smaller carbon footprint, and to meet their customers' desire for carbon-friendly products [10]. The latter is also reflected in the growing demand for green energy from residential consumers.

The peculiarities of the physical processes of electricity transmission make it impossible to separate the flow of "green" energy from RES to the consumer without certain assumptions [11]. Therefore, in order to ensure that a given consumer receives green energy, a number of European countries use an artificial approach to separating the physical processes from the commercial ones, which consists of using "Certificates of Origin" to label each unit of renewable energy. Interested parties can trade these certificates separately from the physical energy. Once the electricity is consumed, the certificates are cancelled [12].

In the engineering practices of different countries, a number of methods are used to calculate power flows from each individual generator or entity of the power association, both with unambiguously specified information and with probabilistic and statistical estimation of losses (regression analysis) [13-15]. All available methods for the distribution of transmission losses can be divided into groups of methods based on proportional distribution [13], specific increases in power losses [14] and share distribution [15], depending on the assumptions and approximations made.

Existing approaches to organizing the work of national electronic registers of Guarantees of Origin do not take into account the topology of the grid and the place of electricity generation. The registers are organized on the principles of separating physical processes from commercial ones. Therefore, it is relevant to supplement the existing structure of the organization of the Guarantees of Origin by taking into account physical processes in the electricity transmission and distribution systems, which requires the development of an appropriate mathematical apparatus. **The goal** of the article is to develop a method for estimating the share of electricity in the consumption of a given consumer that is provided by renewable energy sources.

Determining the origin of electricity in the branches of the power grid. The idea of the method for determining the share of power flows in power grids from a set of RES to certain load nodes is to first determine the value of the total power at the beginning and at the end of each branch of the circuit, which is determined by the formula [16]:

$$\dot{\mathbf{S}}_b = \sqrt{3}\,\dot{\mathbf{U}}_d\,\mathbf{M}_\Sigma\,\widehat{\mathbf{I}}_d \;, \tag{1}$$

where $\dot{\mathbf{S}}_b$ is a power matrix where the columns represent the power at the beginning and the end of the power grid branches. $\dot{\mathbf{U}}_d$ is the diagonal matrix of voltages in the nodes, including the balancing nodes; $\mathbf{M}_\Sigma$ matrix of branch connections in nodes, including balancing nodes; $\widehat{\mathbf{I}}_d$ diagonal matrix of currents in the branches of the circuit (hereinafter, the sign $\frown$ means that the matrix or vector is conjugated).

In order to obtain the part of power that is transferred from RES to a particular consumer, we first write down the values of the beginning and end power in the i-th branch of the power grid from (1):

$$\dot{\mathrm{S}}_{bi} = \sqrt{3}(\dot{\mathbf{U}}_d\mathbf{M}_{\Sigma i})\widehat{\mathrm{I}}_i \,, \tag{2}$$

where $\mathbf{M}_{\Sigma\mathrm{i}}$ is a vector-column of the matrix of branch connections in nodes $\mathbf{M}_\Sigma$; $\widehat{\mathrm{I}}_i$ is the current in the i-th branch.

To convert from currents in branches and nodes to power, we can rewrite equation (2) accordingly. To accomplish this, the currents in the branches $\widehat{\mathrm{I}}_i$ are defined by the currents in the nodes.

$$\dot{\mathrm{I}}_i = \mathbf{C}_i\dot{\mathbf{J}} \;, \tag{3}$$

where $\dot{\mathbf{C}}_i$ is the i-th vector-row of the matrix of distribution of specified currents in the nodes $\dot{\mathbf{J}}$ along the branches of the circuit.

The current distribution matrix is calculated by the method of single currents or by the formula [16]:

$$\mathbf{C} = \mathbf{z}_b^{-1}\mathbf{M}_{\Sigma t}(\mathbf{M}_\Sigma\mathbf{z}_b^{-1}\mathbf{M}_{\Sigma t})^{-1} \,, \tag{4}$$

where $\mathbf{z}_b$ is the diagonal matrix of complex impedances in the branches of an electrical grid circuit.

If the scheme and parameters of the EPS are relatively permanent, then the method of determining currents in branches using the current distribution matrix **C** is more appropriate.

Taking into account (3) and (4), expression (2) will be rewritten:

$$\dot{\mathrm{S}}_{bi} = \sqrt{3}(\dot{\mathbf{U}}_d\mathbf{M}_{\Sigma i})\widehat{\mathbf{C}}_i\widehat{\mathbf{J}} \,, \tag{5}$$

Given that

$$\widehat{\mathbf{J}} = \frac{1}{\sqrt{3}}\dot{\mathbf{U}}_d^{-1}\dot{\mathbf{S}} \;, \tag{5}$$

takes the form:

$$\dot{\mathrm{S}}_{bi} = (\dot{\mathbf{U}}_d\mathbf{M}_{\Sigma i})\widehat{\mathbf{C}}_i\dot{\mathbf{U}}_d^{-1}\dot{\mathbf{S}} \;, \tag{6}$$

where $\dot{\mathbf{S}}$ is the vector of consumer loads and generation, including RES, at nodes, including balancing nodes.

Let's denote in (6)

$$\dot{\mathbf{D}}_i = (\dot{\mathbf{U}}_d\mathbf{M}_{\Sigma i})\widehat{\mathbf{C}}_i\dot{\mathbf{U}}_d^{-1} \,, \tag{7}$$

where vector-row $\dot{\mathbf{D}}_i$ consists of coefficients that represent the share of the total power of the i-th branch that is caused by the power flowing through it from each node.

Taking into account (7), the formula (6) of the power in the i-th branch will be rewritten:

$$\dot{\mathrm{S}}_{bi} = \dot{\mathbf{D}}_i\,\dot{\mathbf{S}} \,, \tag{8}$$

In general, we can write that

$$\dot{\mathbf{S}}_b = \dot{\mathbf{D}}\dot{\mathbf{S}} \,, \tag{9}$$

where $\dot{\mathbf{D}}$ is a matrix of coefficients of power distribution in the nodes over the branches of the power grid, which is formed from n rows $\dot{\mathbf{D}}_i$, *n* is number of branches in the power grid.

Using formula (9), we can determine the power components in the power grid's branches from the nodes' power. To determine the flows from RES in the branches of the scheme, only RES power should be included in $\dot{\mathbf{S}}$ from formula (9):

$$\dot{\mathbf{S}}_{b\,RES} = \dot{\mathbf{D}}\dot{\mathbf{S}}_{RES}\,, \qquad (10)$$

where $\dot{\mathbf{S}}_{b\,RES}$ is the vector of power flows in the branches of the circuit caused by the power of RES nodes; $\dot{\mathbf{S}}_{RES}$ is a vector of node power corresponding to the nodes of the RES scheme.

To determine the power $\dot{S}_{RES\,j}$, that the consumer receives at the *j*-th node from RES, the corresponding power balance is compiled (see Fig. 1):

$$\dot{S}_{RES\,j} = \dot{S}^{+}_{RES\,j} - \dot{S}^{-}_{RES\,j}\,, \qquad (11)$$

where $\dot{S}^{+}_{RES\,j}$, $\dot{S}^{-}_{RES\,j}$ are the powers that are generated by RES and that enter or leave the *j*-th node, respectively.

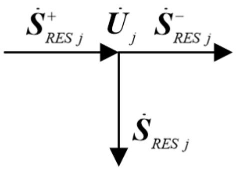

Fig. 1. Consumer's power from RES in the j-th node

The power $\dot{S}^{+}_{RES\,j}$ and $\dot{S}^{-}_{RES\,j}$ are determined by formula (9), in which the first connection matrix $\mathbf{M}_{\Sigma}$, compiled for all nodes of the circuit, is represented as the sum of two matrices:

$$\mathbf{M}_{\Sigma} = \mathbf{M}^{+}_{\Sigma} + \mathbf{M}^{-}_{\Sigma}, \,, \qquad (12)$$

where $\mathbf{M}^{+}_{\Sigma}$ is a matrix consisting of a fragment of the connection matrix, the elements of which are zeros and ones with sign "+"; $\mathbf{M}^{-}_{\Sigma}$ is the same matrix, but its elements are zeros and ones with the sign "-".

It can be seen from (7) and (8) that the coefficients of the distribution of node power $\dot{\mathbf{S}}$ to branch power $\dot{\mathbf{D}}_i$ depend not only on the parameters of the power system, but also on the voltage of the nodes. Therefore, to ensure the adequacy of the mathematical model, the voltage values $\dot{\mathbf{U}}$ of the nodes must correspond to the power values of the nodes $\dot{\mathbf{S}}$ In this case, the EPS mode would be balanced and the nonlinear dependence of electricity losses in power grids on the power of nodes $\dot{\mathbf{S}}$, including $\dot{\mathbf{S}}_{RES}$ [17], would remain.

An algorithm for estimating the share of electricity supplied from renewable energy sources in the consumption of a given consumer. Fig. 2 shows an algorithm for determining the share of electricity generated by RES and transmitted to a given electricity consumer. The approach in the algorithm is such that, using (9), the power flows are determined in the branches of the power grid that are incidental to the nodes with the list of RES electricity consumers specified in it. Directly in the node, we can calculate, from the power balance of a group of different consumers, the power of a specific consumer, which is oriented to the consumption of electricity from a particular RES, taking into account the physical processes in the power system. Thus, it is possible to estimate the degree of load coverage of a given consumer by RES supplying energy to the power system during a controlled time period T. The input data for the calculation are the parameters of the power grid, the load of nodes specified by power or schedules, and the amounts of nodes of RES generation $\boldsymbol{\theta}_{RES}$ and centralized generation $\boldsymbol{\theta}_{CS}$ and consumers with a controlled value of the guaranteed origin of electricity from RES $\dot{\mathbf{S}}_{RES}$.

In order to convert the consumer's power to the electricity consumed, the average or maximum load methods are used. Depending on the chosen method, the average $\dot{S}_{aver}$ or maximum $\dot{S}_{max}$ value of the consumer's power for the period T is given. A more accurate method is when the forecasted hourly consumption schedule for the day ahead is set and the actual consumption data is based on the automated commercial electricity metering system (ACEMS). In the first case, the forecasted amount of electricity planned to be consumed from RES is determined. In the other case, the actual amount of electricity consumed from RES is determined. This data is sent to the register of guarantees of origin, taking into account the amount of guaranteed coverage of the consumer's load with energy from renewable energy sources [6, 18].

Depending on the need and technical capabilities of the metering system, the program is initiated on an hourly or scheduled basis in accordance with the schedules of electricity generation and consumption in the power grid.

The array of node voltages required for the calculations can be obtained in two ways: as a result of steady-state calculations or based on the data from the ACEMS. If the hourly forecasted values of RES generation and consumption are determined, the voltage is determined based on the results of steady-state calculations or, where the accuracy is acceptable, based on average statistical data. If the actual values are determined accordingly, the output data are the results of voltage measurements in the ACEMS.

After forming the array of node voltages, the incident matrix $\mathbf{M}_{\Sigma}$ and the matrix of coefficients of distribution of node-specified currents in the branches of the power grid

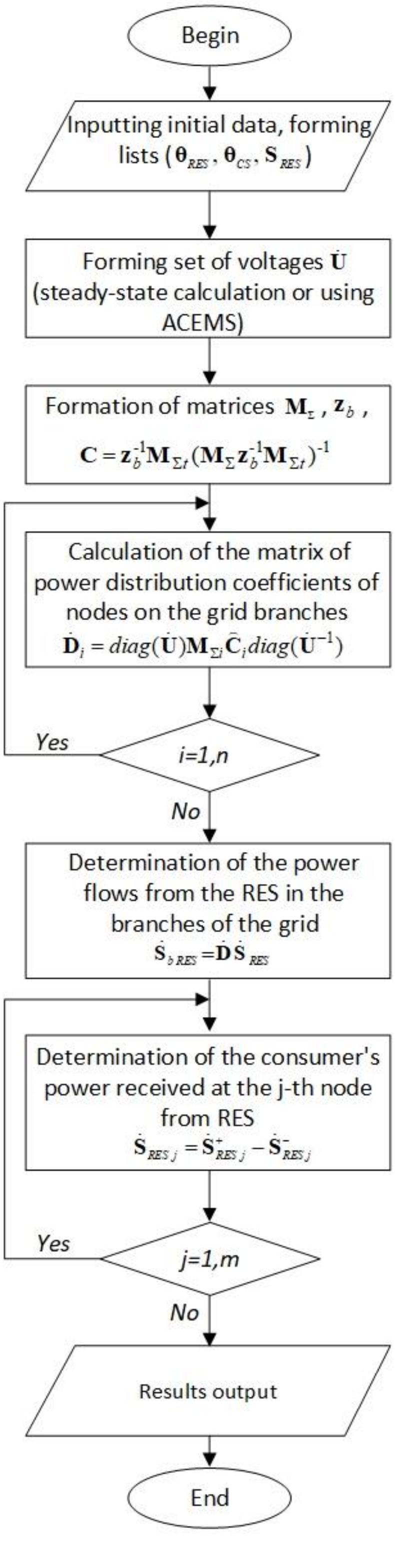

Fig. 2. Algorithm for the determination of the consumer's electricity supply from renewable energy sources

$\dot{\mathbf{C}}$ are formed. Then, the matrix of power distribution coefficients of nodes over the branches of the power grid $\dot{\mathbf{D}}$ is calculated, which consists of the rows $\dot{\mathbf{D}}_i$.

Using the matrix $\dot{\mathbf{D}}$, we identify those parts of the total power $\dot{\mathbf{S}}_{b\,RES}$ in the grid branches that flow from RES. By summing the power $\dot{S}_{b\,RES}$ of the branches incidental to the *j*-th nodes with controlled consumption from RES, their guaranteed value of electricity from RES is determined.

These nodes can be of two types. If a node is a dead-end, i.e. only branch with RES power

$\dot{S}_{RES\,j}$ approaches it, then that power is the RES power for that consumer. If the node is an intermediate node, as shown in Fig. 1, the power $\dot{S}_{RES\,j}$ is determined from the power balance in the *j*-th node. In the "Results output" block, depending on the form of the input data, the power $\dot{S}_{RES\,j}$ is recalculated into consumer electricity originating from RES and is appropriately protocoled [6, 18].

The effectiveness of the developed method for determining the origin of the electricity from renewable energy sources in the electric power system is demonstrated through the example of a 110 kV power grid, the scheme of which is shown in Fig. 3. The resistance of the branches, load and generation are shown in the scheme. The balancing node is node 1 and the RES is located at node 6. The steady-state mode test calculation for the maximum generation of the PV system (at 13:00) was performed using PowerFactory 15.1. Based on the results of the steady-state mode calculation, the node voltages were determined (on Fig.3, the modules and voltage phases are shown in the scheme near the nodes).

Using the values of the calculated node voltages, according to (9), we calculate the matrix of power distribution coefficients of the 6th RES node for the power in the branches (13).

Multiplying the matrix of power distribution coefficients of the nodes by the power of the 6th node, we obtain the power matrix for the branches of the power grid from RES of the 6th node (14).

For example, branches 5 and 6 transmit the power of 5.254+5.292=10.546 MW to node 5. The power losses in these branches are (5.292-5.254)+(5.319-5.292)=0.065 MW. Since the active load power of the 5th node in maximum mode is 25 MW, the remaining power 25-10.546=14.454 MW is transmitted by the balancing node 1.

$$\dot{\mathbf{D}}_6 = \begin{array}{c} \begin{array}{ccccccc} \mathbf{1} & \mathbf{2} & \mathbf{3} & \mathbf{4} & \mathbf{5} & \mathbf{6} & \mathbf{7} \end{array} \\ \left| \begin{array}{ccccccc} 0 & -0.567-j0.001 & 0.567+j0.001 & 0 & 0 & 0 & 0 \\ 0.452-j0.002 & 0 & 0 & -0.091+j0.0 & -0.361+j0.001 & 0 & 0 \\ 0 & 0.562-j0.001 & 0 & 0.090+j0.0 & 0 & 0 & -0.653+j0.001 \\ 0 & 0 & 0 & 0 & 0.349-j0.002 & -0.349+j0.002 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0.355 & 0.645 \end{array} \right| \end{array} \begin{array}{c} \\ \mathbf{2} \\ \mathbf{3} \\ \mathbf{4} \\ \mathbf{5} \\ \mathbf{6} \end{array} \qquad (13)$$

$$\dot{\mathbf{D}}_6\dot{\mathbf{S}}_6 = \begin{array}{c} \begin{array}{ccccccc} \mathbf{1} & \mathbf{2} & \mathbf{3} & \mathbf{4} & \mathbf{5} & \mathbf{6} & \mathbf{7} \end{array} \\ \left|\begin{array}{ccccccc} 0 & 8.223-j0.105 & -8.223+j0.105 & 0 & 0 & 0 & 0 \\ -6.580+j0.074 & 0 & 0 & 1.325-j0.015 & 5.254-j0.059 & 0 & 0 \\ 0 & -8.246+j0.084 & 0 & -1.327-j0.014 & 0 & 0 & 9.573-j0.098 \\ 0 & 0 & 0 & 0 & -5.292+j0.025 & 5.292-j0.025 & 0 \\ 0 & 0 & 0 & 0 & 0 & -5.319 & -9.681 \end{array}\right| \end{array} \begin{array}{c} \\ \mathbf{2} \\ \mathbf{3} \\ \mathbf{4} \\ \mathbf{5} \\ \mathbf{6} \end{array} \qquad (14)$$

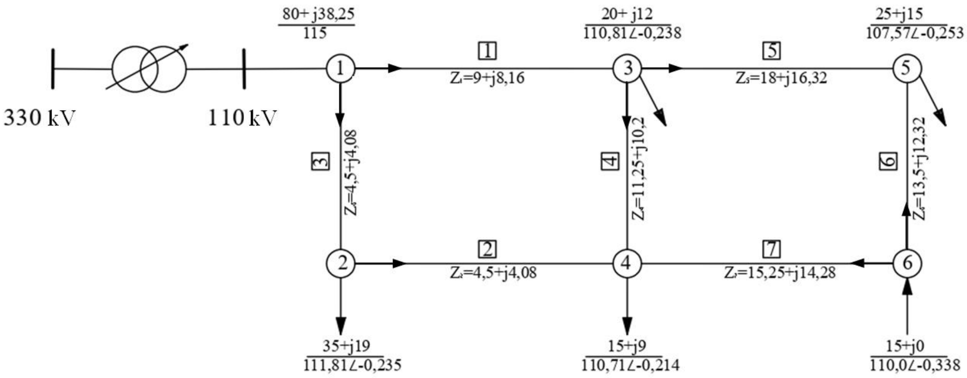

Fig. 3. Scheme of the electrical grid

Conclusions

The method and algorithm for calculating separate components of electricity flows in the branches of the power grid circuit caused by generation and consumption in the nodes are developed. The method determines the share of electricity, supplied by RES facilities connected to the power grid, in the total consumption of a given consumer of electricity. The method is based on a mathematical model for determining the coefficients of RES power distribution in the branches of the power grid. The proposed method can be a tool for confirming the Guarantee of Origin of the energy consumed in the retail market. Since RES use general power grids to transmit the electricity they generate, the determination of their share in the power flows to consumers allows taking into account the impact of RES on the parameters of the power system mode and can be used in the operational planning of the electricity balance.

An algorithm has been developed to determine the amount of guaranteed coverage of the consumer's load with energy from renewable energy sources. This algorithm can be used to perform a qualitative and quantitative assessment of the possibility of providing electricity of Guaranteed Origin for each energy consumer. Such assessments are transparent to end users and take into account physical processes in the electricity grid, which will help to increase consumer confidence in the results of calculations of electricity supply from renewable-energy power plants. Determining the share of consumers' electricity that they are guaranteed to receive from renewable energy sources creates conditions to encourage generating companies to produce and consumers to increase their use of renewable energy and promotes the development of the green energy market.

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