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MACROMODELING OF ELECTRICAL GRIDS WITH RENEWABLE ENERGY SOURCES FOR ASSESSING THEIR ENERGY EFFICIENCY

Petro Lezhniuk, Vyacheslav Komar, Serhii Kravchuk
Vinnitsa National Technical University, Vinnitsa, Ukraine
lezhpd@gmail.com, *Kvo1976@ukr.net*, *sv.kravchuk@ukr.net*

Abstract: In the article it is proposed to use macro-modeling of electrical grids for assessing the quality of their operation in the form of an integrated readiness characteristic of electrical grids with RES. It has been done on the basis of the analysis of the problems of providing high-quality electrical supply under conditions of the intensive development of renewable energy sources (RES) and characteristics of electrical grids determined by means of qualimetry that are essential for providing high-quality electricity. This will contribute to the development of generalized solutions and grid development strategies, especially when it comes to RES development. The components of the integral index are determined as the probability of matching the actual mode to the “ideal” one. The “ideal” mode is determined by the principle of least action and corresponds to the circuit diagram of the grid formed by the r-scheme. The basis determined in this way reduces the subjectivity of both evaluations and decisions taken on their basis.

Keywords: electrical grids, renewable energy sources, reliability of electricity supply, losses of electric energy, electricity quality, energy efficiency

1. Introduction

The quality of electricity is characterized by the level of reliability (continuity) of electricity supply, costs of providing services for the transmission, distribution and supply of electric energy, as well as its quality. Today, power distribution grids have practically exhausted the bandwidth reserve, their level of automation is rather low and remote control is limited to the use of obsolete equipment. This situation is complicated by the unregulated development of renewable energy sources (RES), which often negatively affects the quality of electricity supply. Under such conditions, when planning RES development in electrical grids, two options are considered. The first one is the construction of RES with no significant changes in the scheme of the electrical grid and without updating its electrical equipment. Another approach consists in the development of generation in the electrical grids and its simultaneous reconstruction and modernization. Taking into account the current technical condition of grid equipment, the second option is more appropriate. Developing this option, it is possible to increase the set capacity of RES to values corresponding to the potential of solar, hydro and wind resources of the region simultaneously with the improvement of the technical condition of the electrical grid. Considering the first variant, the set capacity of the RES is substantially limited by the transmission capacity of the elements of the electrical grid. For making a decision on the choice of the development option, it is necessary to assess the current status of the functional readiness of the electrical grids in order to ensure the quality of electricity supply.

2. Tasks

An attempt is made to use the classical approaches of qualimetry [1] to assess the quality of operation of electrical grids with renewable energy sources. To do this, the Quality Function Deployment method is used. This method combines several approaches and allows moving from the wishes of potential customers to have a quality product to designing the technological process of obtaining this product. The use of the mathematical instrument of qualimetry allows determining the set of parameters which being influenced can provide the required quality level of electricity supply. However, the result multivector complicates the development of generalized solutions and grid development strategies, especially when it comes to building RES. Therefore, it is expedient to develop an integral indicator of the quality of functioning of electrical grids with RES, which will allow switching from the vector task of evaluating the functional readiness of the required level of quality of electricity supply to the scalar one [2]. This process generalizes the characteristics of the quality of the functioning of the electrical grid and enables the comparison of the variants of grid development with RES in accordance with the enlarged parameters. The quality of the functioning of the power supply system is then divided into several characteristic components, and its essential properties are distinguished, while the influence of other inessential ones is taken into account in the parametric form. That is, the method of macromodeling is used when describing only the external characteristics of the electrical grid, presented as a complex dynamic system with many inputs and outputs in the form of mathematical relations [3, 4].

In works [5, 6], the quality of the functioning of the technical system is determined by the expression:

$$E = \sum_{\forall s} \left(\Phi_s H_s \right), \qquad (1)$$

where H_S is the probability of a state S; Φ_S is the probability that the system operates is in this state.

In such a form, the quality of the system operation consists of the sum of its states characterizing its performance and may differ on the degree of compliance with the state with normal parameters. This approach can be used to assess the quality of the operation of the electrical grid with RES, since the limits of the deviation of the network mode parameters from the nominal ones are set. For example, the voltage on the power bus lines at the consumers' end can vary within ±5 % of the nominal value of U, and the frequency deviation is also possible. Thus, within the permissible range the states of the electrical grid are workable, but they differ in balance and structural reliability, electricity quality and cost-effectiveness.

3. The purpose of the article is to develop the integral indicator of the operation quality of electrical grids in order to select their optimal development according to the criterion of maximum energy efficiency consisting of such components as reliability, minimum of electricity losses and corresponding quality of electricity.

4. Integral indicator of the quality of the electric network operation

The quality of the electrical grid operation is characterized by reliability, quality of electric energy, and electricity losses. It can store in time the values of all parameters that characterize the ability to perform the necessary functions in the specified modes and conditions of operation, maintenance, storage and transportation within the established limits. The process of the electrical grid operation can be described by a plurality of states into which the grid passes depending on the states of its elements. Each of the states is characterized by the probability of successful performance of power functions. Proceeding from this, the graph of states can be considered (see Fig. 1), where the transition from state to state is characterized by a certain intensity of failures λ and restorations μ. In the grid with RES, it also depends on the characteristics of wind and photovoltaic stations (WEP and FES), small hydroelectric power plants (SHPP), cogeneration units (CU) and EES.

The combination of the principles of Markov processes and the theory of similarity allows constructing a mathematical model which combines the probabilistic component in determining the functioning quality of electrical grids and the change of mode parameters in the process of their functioning.

Similar modeling of Markov processes being performed, the principles of criterion modeling can be applied to the system of Kolmogorov-Chapman equations [7, 8]. As a result, a function has been obtained that can assess the quality of the functioning of the electrical grid with renewable energy sources. In the criterion form it will look like [9]:

$$f\left(x_*\right) = \sum_{i=1}^{m} p_i \prod_{j=1}^{n} x_{*j}^{k_{ij}}, \qquad (2)$$

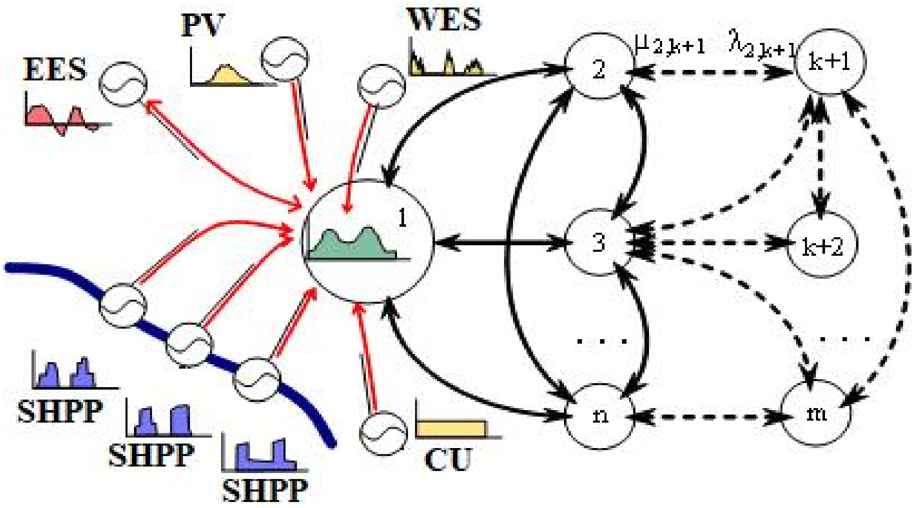

Fig. 1. Graph of the states of the electric network with renewable energy sources

where p_i is a similarity criterion which in this case is the probability of staying in the i-th state; $\prod_{j=1}^{n} x_{*j}^{k_{ij}}$ is a performance index in the i-th state; x_{*j} are independent parameters characterizing the basic properties of the system in the corresponding states; k_{ij} are elements of the matrix of transitions corresponding to the Kolmogorov-Chapman system of equations; m is the number of working conditions; n is the number of system characteristics.

As an example, let us consider a two-line energy transmission line (ETL). Assuming that the intensity of failures and restorations for each circle of transmission lines are the same, equation (2) will take the form:

$$f(x) = p_1 x_1^{-(\lambda_{12}+\lambda_{13})} x_2^{\lambda_{12}} x_3^{\lambda_{13}} + p_2 x_1^{\mu_{21}} x_2^{-(\lambda_{24}+\mu_{21})} x_3^{0} + \\ + p_3 x_1^{\mu_{31}} x_2^{0} x_3^{-(\lambda_{34}+\mu_{31})} = p_1 \left(\frac{x_1}{x_2}\right)^{-\lambda_{12}} \left(\frac{x_1}{x_3}\right)^{-\lambda_{13}} + \\ + p_2 \left(\frac{x_2}{x_1}\right)^{-\mu_{21}} x_2^{-\lambda_{24}} + p_3 \left(\frac{x_3}{x_1}\right)^{-\mu_{31}} x_3^{-\lambda_{34}}.$$

Let us find the logarithm and potential of the components that characterize each of the states:

$$\left.\begin{array}{l} \left(\dfrac{x_1}{x_2}\right)^{-\lambda_{12}} \left(\dfrac{x_1}{x_3}\right)^{-\lambda_{13}} = e^{-\lambda_{12}\cdot(\ln(x_1)-\ln(x_2))} \cdot e^{-\lambda_{13}\cdot(\ln(x_1)-\ln(x_3))}, \\ \left(\dfrac{x_2}{x_1}\right)^{-\mu_{21}} x_2^{-\lambda_{24}} = e^{-\mu_{21}\cdot(\ln(x_2)-\ln(x_1))} \cdot e^{-\lambda_{24}\cdot\ln(x_2)}, \\ \left(\dfrac{x_3}{x_1}\right)^{-\mu_{31}} x_3^{-\lambda_{34}} = e^{-\mu_{31}\cdot(\ln(x_3)-\ln(x_1))} \cdot e^{-\lambda_{34}\cdot\ln(x_3)}. \end{array}\right\} \quad (3)$$

Proceeding from the fact that the natural logarithm can be regarded as time necessary for the variable to achieve a certain value of the equation (3), we can rewrite:

$$\left.\begin{array}{l} e^{-\lambda_{12}\cdot(t_1-t_2)} \cdot e^{-\lambda_{13}\cdot(t_1-t_3)} = P_{11} \cdot P_{12}, \\ e^{-\mu_{21}\cdot(t_2-t_1)} \cdot e^{-\lambda_{24}\cdot t_2} = P_{21} \cdot P_{22}, \\ e^{-\mu_{31}\cdot(t_3-t_1)} \cdot e^{-\lambda_{34}\cdot t_3} = P_{31} \cdot P_{32}, \end{array}\right\} \quad (4)$$

where P is the probability of achieving the corresponding values by the determined parameters of the operation quality of the electrical grid.

Taking into account this mathematical model of the functioning, quality of the electrical grid is defined by the expression:

$$E = p_1 P_{11} P_{12} + p_2 P_{21} P_{22} + p_3 P_{31} P_{32} = \\ = \sum_{i=m} \left(p_i \prod_{j=n} P_{ij} \right), \quad (5)$$

which corresponds to expression (1), where $p_i = H_s$ is the probability of a state, $\prod_{j=n} P_{ij} = \Phi_s$ is the probability that the system being in this state operates successfully (P_{ij} is the probability of providing an appropriate characteristic of the functioning quality).

The integral performance index in the form (5) allows moving from the vector task of evaluating the functioning quality to the scalar one. It includes information about various electrical grid parameters and accepts values from 0 (worst) to 1 (best), depending on their level of functional readiness.

5. Determination of the components of the integral indicator of the operation quality of electrical grids

General requirements to be met by an integral indicator are: reflection of objective reality; evaluation of efficiency, quality and optimality; the possibility of physical and abstract interpretation; the ability to being calculated using a computer; normalization and reflection of the "extreme" states of electrical network (EN) in the light of potentially and really possible states; it must characterize separate subsystems and systems in general in all life cycles; it must break down into partial indicators and be combined into generalized ones.

The main task of the electrical grid is to ensure reliable supply of high-quality electricity to consumers connected to it. Therefore, the main characteristics that should be integrated by the integral performance index are reliability, quality of electric energy and the efficiency of EN operation.

The efficiency of the electrical grid during the operation is largely determined by the loss of electricity in it. With the use of RES, the current distribution in the electrical grid can be achieved, which corresponds to an efficient mode [10], that is, the mode at which electrical power losses in the grid are minimum. Taking into account, that the processes associated with the current distribution in such an electrical grid undergo the principle of least action [11], then such a mode is considered as "ideal", that is, corresponding to the minimum level of electrical energy losses.

In order to compare the energy efficiency of different development variants of electrical grids, we assume that their electricity losses should be "ideal". That is, the coefficients of current distribution in them are determined by the expression [12]:

$$\mathbf{C}_r = \mathbf{R}^{-1}\mathbf{M}^T \left(\mathbf{M}\mathbf{R}^{-1}\mathbf{M}^T\right)^{-1}, \quad (6)$$

where $\mathbf{R}$ is a diagonal matrix of active resistances of grid transmission lines; $\mathbf{M}$ is the first matrix of compounds which is formed from a complete matrix $\mathbf{M}_\Sigma$ by removing the nodes corresponding to the power supply; T is the symbol of the transposed matrix.

When RES are developed in distribution electrical grids, it is necessary to assess balance reliability, that is, to determine the probability of non-compliance of consumption schedules with RES electricity generation occurring due to the instability of such sources. Using statistical data and applying the mathematical apparatus of the Gaussian mixtures [13], it is possible to estimate the probability of conformity of generation and consumption for a certain time of a day:

$$p_i\left(\sum_{k=1}^{m} P_{RES_{i,k}} = \sum_{j=1}^{n} P_{i,j}\right), \qquad (7)$$

where p_i is probability of fulfilling the condition $\sum_{k=1}^{m} P_{RES_{i,k}} = \sum_{j=1}^{n} P_{i,j}$; $P_{RES_{i,k}}$ is the power of a renewable energy source; $P_{i,j}$ is load capacity; m is the number of generated nodes; n is the number of nodes consumption; i is the number of a time interval.

Obviously, the analysis consists in comparing the total generation of the RES feeder with its total load. If an hourly schedule is considered, the expression for determining the probability of providing a balance takes the following form:

$$P_{\text{б}} = \frac{1}{24}\sum_{i=1}^{24} p_i\left(\sum_{k=1}^{m} P_{RES_{i,k}} = \sum_{j=1}^{n} P_{i,j}\right). \qquad (8)$$

Evaluating the efficiency of the electricity grid operation with renewable energy sources is based on the assessment of the conformity of the actual mode with the basic one, conducting the analysis of statistical data to fulfill the condition $P_{RES\ i,k} = \sum_{j=1}^{n}\left(C_{r\,k,j} \cdot P_{i,j}\right)$ for each hour of the day and determine the probability according to the analysis performed.

The probability of providing the basic mode as “ideal” is determined by the expression:

$$P_{\Delta P} = \\ = \frac{1}{24}\sum_{i=1}^{24}\left[\prod_{k=1}^{m} p_{i,k}\left(P_{RES_{i,k}} = \sum_{j=1}^{n}\left(C_{r\,k,j} \cdot P_{i,j}\right)\right)\right], \qquad (9)$$

where $p_{i,k}$ is the probability of fulfilling the condition $P_{RES_{i,k}} = \sum_{j=1}^{n}\left(C_{r\,k,j} \cdot P_{i,j}\right)$; $C_{r\,k,j}$ are the coefficients of current distribution according to the r-scheme for the k-th source and the j-th consumer. During the evaluation of the quality assurance component of the electric power, the main attention was paid to ensuring the standard deviations of the voltage in the nodes and the distortion of the voltage curve, since these indicators are the most characteristic for RES. To estimate the voltage deviation in the nodes of consumption, we take an approach that is based on the concept of “ideal” mode, which is taken as the base one. In the “ideal” mode, voltage drops and, consequently, voltage deviations in grid nodes are smaller.

To determine the voltage drop in the base mode, use the expression:

$$\Delta\mathbf{U} = \sqrt{3} \cdot \mathbf{Z} \cdot \mathbf{C}_r \cdot \mathbf{J}_H\,, \qquad (10)$$

where $\mathbf{Z}$ is a diagonal matrix of the resistance of electrical grid elements; $\mathbf{C}_r$ is a matrix of coefficients of current distribution according to the r-scheme; $\mathbf{J}_H$ is a matrix of currents in the load point.

By the expression of the relationship between the voltage drop in a branch and the voltage deviation in the node relative to the base node

$$\Delta\mathbf{U} = \mathbf{M}^T\left(\mathbf{U} - \mathbf{n} \cdot U_b\right), \qquad (11)$$

and with the use of (10) the voltage deviation in the node relative to the base can be determined:

$$\mathbf{U}_\Delta = \sqrt{3} \cdot \mathbf{C}^T \cdot \mathbf{Z} \cdot \mathbf{C}_r \cdot \mathbf{J}_H\,. \qquad (12)$$

By expression (12) a dependence $U_\Delta = f\left(J_i\right)$ for basic mode can be created. With this dependence it is possible to obtain the range of changes of load currents in relation to the currents of RES generation by constructing a plurality of curves for a particular electrical network (see Fig. 2). This area will correspond to the standard deviation of the voltage in the load nodes. Statistics being analyzed, the probability of a condition $J_{RES\ min\ i,k} \le \sum_{j=1}^{n}\left(C_{r\ j,k} \cdot J_{i,j}\right) \le J_{RES\ max\ i,k}$ for each hour of the day can be determined. The component of the voltage quality in the integral index is determined by the expression:

$$P_U = \frac{1}{24}\sum_{i=1}^{24}\left[\prod_{k=1}^{m} p_{i,k} \\ \left(J_{RES\min i,k} \le \sum_{j=1}^{n}\left(C_{r\ j,k} \cdot J_{i,j}\right) \le J_{RES\max i,k}\right)\right], \qquad (13)$$

where $p_{i,k}$ is the probability of fulfilling the condition

$$J_{RES\ min\ i,k} \le \sum_{j=1}^{n}\left(C_{r\ j,k} \cdot J_{i,j}\right) \le J_{RES\ max\ i,k}\,.$$

$J_{RES\ min\ i,k}$, $J_{RES\ max\ i,k}$ are the minimum and maximum values of the current in the point of RES attachment respectively, which correspond to the area of permissible deviations in the load node $J_{i,j}$.

Therefore, in accordance with the obtained dependencies (see Fig.2), the limits of permissible RES generation are determined, and the analysis of the correspondence of voltage deviations in the nodes of consumption is reduced only to the analysis of the ratio of generation currents and consumption. Approaches used during the development of the method of analysis of voltage deviations in the nodes of the electrical grid, allow us to develop a method for evaluating the quality component of electrical energy in the integral index which takes into account non-standard deviations of the non-sinusoidal voltage.

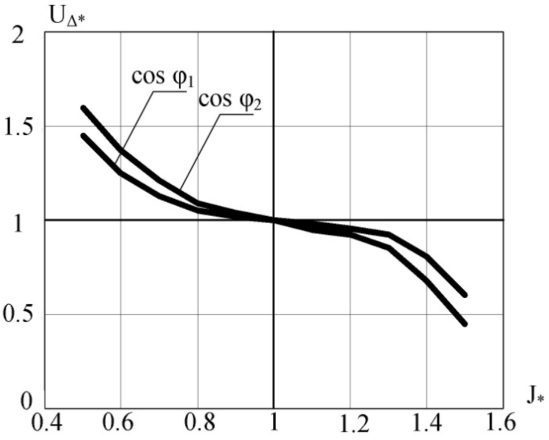

Fig. 2. Curves $U_{*\Delta} = f\left(J_{*i}\right)$ *for a particular network.*

In [14], the coefficient of distortion is proposed which is defined by the expression:

$$K_C^y = \sqrt{A_V K_{2U}^2 + B_V \sum_{n=2}^{\infty} \left(K_{U(n)}^2 \big/ n\sqrt{n}\right)} \le 1\% \,, \qquad (14)$$

where A_V i B_V are coefficients depending on the voltage class.

By this factor, the level of permissible distortion for each of the nodes depending on the characteristics of consumers can be determined. Taking into account, that the bulk of distortions in distribution electrical grids of 10 kV and above are non-sinusoidal currents and voltages, specifically they are to be discussed here. Let us apply the approach that was used to determine the voltage deviations in the nodes. To do this, the expression (12) is transformed to the form:

$$\mathbf{U}_{\Delta v} = \sqrt{3} \cdot \mathbf{C}^T \cdot \mathbf{Z}_v \cdot \mathbf{C}_v \cdot \mathbf{J}_{Hv} \,, \qquad (15)$$

where $\mathbf{Z}_\nu$ is a diagonal matrix of resistance elements of the electrical grid for the *v*-th harmonic; $\mathbf{C}_\nu$ is a matrix of the coefficients of current distribution which is defined by an expression $\mathbf{C}_\nu = \mathbf{Z}_\nu^{-1}\mathbf{M}^T\left(\mathbf{M}\mathbf{Z}_\nu^{-1}\mathbf{M}^T\right)^{-1}$;

$\mathbf{J}_{H\nu}$ is a current distortion matrix on ν-th harmonic in the load point.

By the value of the allowable voltage distortion obtained by the coefficient (14) and by the current distortion (15) the permissible injection of distortion voltage from the source of these distortions can be obtained:

$$U_{sc\_\nu} = U_{b\_\nu} - \left(\Delta U_{\nu\Sigma} + U_{\Delta\nu}\right),$$

where U_{b_ν} is the distortion in the base node; $\Delta U_{\nu\Sigma}$ is the value of voltage drop on the path to the source of distortion.

Taking into account the obtained results, the probability of ensuring the quality of electric energy for the non-sinusoidal voltage can be determined by the expression:

$$P_{K_U} = \\ = \frac{1}{24}\sum_{i=1}^{24}\left[\prod_{\nu=1}^{40}\left(\prod_{k=1}^{m} p_{i,\nu,k}\left(U_{sc\ i,\nu,k} \le U_{sc\_ad\ i,\nu,k}\right)\right)\right], \qquad (16)$$

where $p_{i,\nu,k}$ is the probability of fulfilling a condition $U_{sc\ i,\nu,k} \le U_{sc\_ad\ i,\nu,k}$; $U_{sc\ i,\nu,k}$ is the injection of voltage distortion from a source k according to the *v*-th harmonic; $U_{sc\_ad\ i,\nu,k}$ is the allowable injection of voltage distortions from the source k in the *v*-th harmonic.

6. Data provision

The proposed method for assessing the quality of operation is based on the analysis of currents and capacities in the generation and consumption nodes. This somehow simplifies the technical support of this task, since it is possible to use data from automated system of control and metering of energy resources (ASCME) or intelligent counters. However, not all consumption nodes are equipped with ASCME and the operation of measuring devices is not synchronized in time. Therefore, it is necessary to consider possible sources of obtaining the source output data. The most common sources of output data in power distribution networks are:

1. electricity supply meters installed on the main sections of electrical grids of 10 kV, whose design or features allow obtaining only the values of total release of electricity during the calculation period. At consumers' substations, only passport parameters of transformers are known;
2. on the main sections of electrical grids of 10 kV similar instruments of accounting are installed, and, for

consumers' substations, additional information on consolidated electricity output during the calculation period is provided for determining the coefficients of the load of their transformers;

3. on the main sections of electrical grids of 10 kV devices allowing the record of total release of electricity, as well as the schedule of its flow during the reporting period are installed; for consumers' substations, besides the power supply, typical load and generation schedules are additionally provided which allow simulating the probable modes of the electrical grid operation with an interval of 30 minutes;
4. for main sections of electrical grids of 10 kV and for consumers' substations, data provision is similar to the previous case; weather posts have been installed at some substations, where changes in the temperature of the environment during the reporting period can be recorded. This allows taking into account the temperature dependence of the resistance of transmission lines when determining the component of the integral value of the functioning quality of the power grids.

The best option is to perform mode simulation according to load and generation schedules. Substantial deviation of the results in other variants of obtaining the initial data can be explained by the fact that some modes whose appearance has a negligible probability are not taken into account, though they differ significantly from the "ideal" ones.

Therefore, the transition to simulating load schedules and generation increases the result of assessing the efficiency of the power grid in comparison with other options of obtaining the source data, and can be used to assess the quality of operation of power grids during the transition to Smart Grid technologies.

It is possible and expedient to use additional data concerning the dynamics of the electrical grid (change of the topology, position of switching devices, etc.), schedules of electricity consumption, and also the generation of electricity by means of distributed generation, in order to clarify and realize the calculated model of the electrical grid in real conditions with using the RES.

7. Conclusions

New economic conditions in the electric power sector increase the requirements for ensuring the quality of electricity supply. Since the main factor in ensuring the necessary level of electricity quality is the functional availability of electrical grids, i.e. their operation quality, the task is to develop a strategy for the development of both electrical grids and sources of electrical energy in them.

Functional readiness of electrical grids can be estimated by the indicator of operation quality which depends on the reliability, efficiency and quality of electric energy. For the unambiguous solution of the task of evaluating the operation quality, which is a vector, the method of determination of the integral index is proposed which can transform the task of assessing the operation quality of electrical grids with renewable energy sources to a one parameter task. To do this, the theory of the Markov processes and the theory of similarity are combined.

The estimation of the integral index of the operation quality of the electrical grid is carried out by comparing the actual modes with the "ideal" ones. This approach allows comparing different variants of transmission and distribution systems without specifying their technical and economic indicators. Using the "ideal" mode which corresponds to the efficient current distribution in the electrical grid by r-scheme as the basic one enables obtaining a unified methodological basis for determining the components of the integral operation quality index and avoiding subjectivity while comparing different configurations and sets of capacities of local electrical systems.

The proposed integral indicator of the operation quality of electrical grids with renewable energy sources meets the general requirements related to the following indicators: reflects objective reality; allows evaluating efficiency, quality and optimality; provides the possibility of physical and abstract interpretation; reflects the "extreme" states of the system, taking into account potentially possible ones; can be easily decomposed into partial indicators and so on. In addition, the proposed approach allows the evaluation to be carried out by analyzing the currents and voltages in the nodes of the grid which allows the use of ASECA information at the stage of creating Smart Grid.

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МАКРОМОДЕЛЮВАННЯ ЕЛЕКТРИЧНИХ МЕРЕЖ З ВІДНОВЛЮВАНИМИ ДЖЕРЕЛАМИ ЕНЕРГІЇ ДЛЯ ОЦІНЮВАННЯ ЇХНЬОЇ ЕНЕРГОЕФЕКТИВНОСТІ

Петро Лежнюк, В’ячеслав Комар, Сергій Кравчук

В роботі на основі аналізу проблем забезпечення якісного електропостачання в умовах інтенсивної розбудови відновлюваних джерел енергії (ВДЕ) та визначених засобами кваліметрії характеристик електричних мереж, які є істотними для забезпечення якісного електропостачання, запропоновано застосовувати макромоделювання електричних мереж для оцінювання якості їх функціонування у вигляді інтегральної характеристики готовності електричної мережі з ВДЕ. Це сприятиме розробленню узагальнених рішень та стратегії розвитку мереж, особливо коли йдеться про розбудову ВДЕ. Складові інтегрального показника визначаються як імовірність відповідності фактичного режиму “ідеальному”. “Ідеальний” режим визначається, виходячи з принципу найменшої дії і відповідає заступній схемі мережі, сформованій за r-схемою. Визначений таким чином базис дає змогу знизити суб’єктивність і оцінки, і прийнятих на основі неї рішень.

Petro Lezhniuk – Dr. Sc., Professor, Head of the Department of Power Plants and Systems of Vinnitsa National Technical University. Scientific interest – optimal control of power system modes based on criterion method. He is engaged in the development of methods and means of automation of optimal control of modes of power systems; development of models, methods and algorithms of estimation of mutual influence of main and distribution electric networks; research into the conditions of efficient use of renewable energy sources in electric grids.. His research results have been published in more than 120 scientific papers including 17 patents, 11 monographs.

Vyacheslav Komar – Dr. Sc., Assosiate Professor, the Department of Power Plants and Systems of Vinnitsa National Technical University. Scientific interests – mathematical modeling of the normal modes of power systems and the operation quality under condition of development of dispersed generation; solving the problems of optimal control of modes of power systems. His research results were published in more than 81 scientific papers including 4 patents, 4 monographs.

Serhii Kravchuk – Ph. D., Assosiate Professor, the Department of Power Plants and Systems of Vinnitsa National Technical University. Scientific direction: automation of optimal control of normal modes of power systems. Investigates parametric similarity in problems of optimal control of electrical systems. His research results were published in more than 16 scientific papers including 4 patents, 3 monographs.