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Integrated Assessment of the Quality of Functioning of Local Electric Energy Systems

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Abstract: This research demonstrates the possibility and expediency of forming local electric energy systems (LEESs) based on renewable sources of energy (RSE) as balancing groups in the electric power system (EPS), which can maintain efficiency and provide power supply to consumers in an autonomous mode. The LEES is a part of the EPS of thermal and nuclear power plants and is considered as a separate balancing group. LEESs are designed in such a way that they can operate autonomously in both normal and extreme conditions in the EPS. The sources of electricity in LEESs are small hydroelectric power plants (SHPPs), photovoltaic power plants (PVPPs), and wind power plants (WPPs), whose electricity generation is unstable due to dependence on natural conditions. Therefore, the structure of a LEES with RSE includes an energy storage system with reserves sufficient to compensate for the unstable generation and balancing of the mode. LEESs can differ significantly in terms of key technical and economic indicators (power supply reliability, power losses, and power quality), and therefore, it is necessary to choose the optimal one. It is not advisable to optimize the quality of power supply in a LEES by individual indicators, as improvement of one indicator may lead to deterioration of another. The functional readiness of a LEES should be assessed by the quality of operation, which depends on reliability, power losses, and power quality. To simplify the task of assessing the quality of operation, which is a vector optimization problem, a method for determining the integral indicator as a number that characterizes the LEES and reflects the compromise between the values of reliability, power losses, and power quality has been developed. The integral indicator of the functioning of complex systems is based on a combination of the theory of Markov processes and the criterion method of similarity theory. The value of the integral indicator of the quality of operation of the LEES allows for comparing different variants of power transmission and distribution systems without determining individual components of technical and economic indicators—reliability, power losses, and power quality. The offered integral indicator of the quality of functioning of a LEES with RSE corresponds to the general requirements for such indicators. It reflects the actual operating conditions; allows for assessing the efficiency, quality, and optimality of power supply systems; and can be easily decomposed into partial indicators.

Keywords: microgrid; local electric energy system; autonomous mode; renewable sources of energy; quality of functioning; optimization; Markov processes; similarity theory

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1. Introduction

With the development of renewable sources of energy (RSE) in the electric power grids of the power system and decentralization of generation, it became possible and expedient to allocate separate microgrids in them. A microgrid is a group of interconnected loads and distributed generation, mainly RSE, with electric grids that can form a regional or local electric energy system (LEES). A LEES, therefore, is considered as a separate controlled object that is able to operate with the energy power system (EPS) in parallel or in isolation to the mode of power, frequency, and voltage control based on a multi-agent system (MAS) [1–3]. During operation, a LEES can operate in parallel with the EPS as a separate balancing group, consuming or generating electricity in the system. Under certain conditions, based on economic interests or due to an extreme condition in the EPS, a LEES can operate autonomously as an isolated intelligent system.

In a multi-microgrid, as in the LEES and in the EPS, the same problems and tasks arise: balancing the mode, regulating frequency and voltage, reducing power losses and improving its quality, increasing the reliability of the power supply, and reducing SAIFI and SAIDI. Therefore, it is logical to extend to them the requirements, techniques, and methods for solving such problems as in a large EPS with thermal, nuclear, and hydroelectric power plants, but with certain assumptions. Modern microgrids are formed on the basis of renewable sources, the vast majority of which are photovoltaic and wind power plants (PVPPs and WPPs). Since the generation of electricity by PVPPs and WPPs depends on weather conditions, microgrids are forced to use energy storage systems to compensate for their unstable generation. In one way or another, all of these factors affect their operating modes and the quality of electricity supply to consumers. To ensure the appropriate quality of power supply systems, the structure of a microgrid may vary depending on the composition of consumers, generation sources, and auxiliary infrastructure. The task of optimizing the composition of microgrids that form the LEES arises. The goal of this task is to choose the structure of the LEES with its elements that would ensure a stable power supply in different operating conditions.

The quality of functioning of the LEES is characterized by several criteria. The main ones are the quality of electricity, reliability of the electricity supply, cost-effectiveness, sustainability and robustness of systems, ability to adapt to changing conditions, and reduction of negative impacts on the environment. The process of operation reflects the behaviour of a local electric energy system in time and can be represented as a sequential change in its states and as Markov processes [4].

Assessment of the state of a specific LEES and comparison of its functional readiness is necessary when analyzing the quality of operation and supporting decision making on the development of the distribution of electric grids in the context of RSE development. The activities in this area are carried out in accordance with requirements in the field of energy efficiency to improve the quality of the electricity supply, create a transparent management system to increase investment attractiveness, and refine the intelligence of electric power grids based on SMART grid technologies.

To assess the quality of the electricity supply, it is necessary to analyze a significant number of different indicators: four for reliability of the electricity supply; eleven for electricity quality; and eight for the quality of service [4]. It is not possible to single out the most important indicators from such a large number of indicators, and they depend on the characteristics of consumers. That is, the level of quality of the electricity supply can be assessed only by the result for the system as a whole. The solution to this problem in relation to modern LEESs is possible only on the basis of system analysis. System analysis involves considering the object under study as a whole. An example is the use of a systemic or integral indicator of the quality of functioning of a complex system of automated production processes [5,6]. Such a numerical indicator allows us to unambiguously assess the quality of the system's functioning in its various states.

It is possible to apply such an integral quality indicator to a LEES only with due regard for the peculiarities of consumer power supply systems. The concept of the quality of operation refers to systems for which it is impossible to formulate an "all-or-nothing" failure criterion. The electric power system belongs to such systems. Due to its redundancy, the failure of some (or even many) elements leads to only partial degradation of the functionality of the LEES. The indicator of the quality of operation characterizes the ability of a local electric energy system to perform its basic functions with some deterioration in the reliability of power supply, an increase in technological losses of electricity, and a deterioration in its quality. The process of transition from one state to another is characterized, as in the Markov model, by failure indicators and recovery time. When macro modelling power supply systems, there is a tendency to use only the main or defining characteristics. These include the fractal characteristics of the load graphs of power supply systems with similarity properties [7]. To simplify the modelling of possible states of a LEES, it is proposed to use the criterion method of similarity theory, which requires a minimum amount of information [8–11].

The goal of this research is to develop a method and corresponding mathematical models for determining the integral indicator of the quality of functioning of a local electric energy system using Markov processes and methods of similarity theory.

2. Modelling the Operation of Power Grids Using Similarity Theory and Markov Processes

Methods based on the theory of Markov processes make it possible to obtain simple mathematical models. This is achieved due to the basic assumption that a process is Markovian if, for each moment in time, the probability of any state of the system in the future depends only on the state in which the system is now and does not depend on how the system got to that state [4]. The assumptions made when building models do not lead to significant errors and therefore are acceptable for solving practical problems in such dynamic systems as the electric power industry. Using the methods of the theory of Markov processes, it is possible to model only the period of normal operation of the elements of the electric power grid (Section 2 of Figure 1) [4].

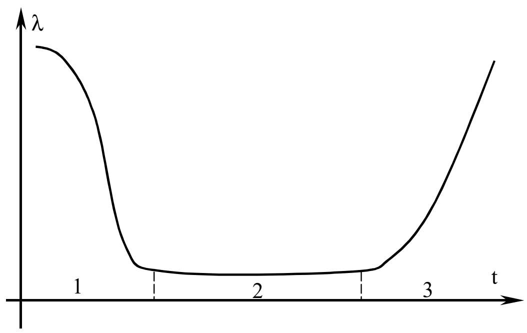

Figure 1. Dependence of the intensity of failures on the operating time.

The period of normal power grid operation can be divided into separate states. These states are operational, but the system parameters can deteriorate from state to state, approaching complete failure. Stepwise recovery also moves the control system from state to state, but in the opposite direction. Assuming that the change in states follows an exponential distribution law, the main principle of Markovian interest theory is fulfilled—the change in states occurs without an aftereffect. Modern diagnostic systems provide information for determining such states. Determination of intermediate states makes it possible to assess the readiness of power grid elements at any time in its operation. This makes it possible to determine the level of reliability of the power grid and provide recommendations to the maintenance staff to build a strategy for the recovery stages.

Thus, for dynamic systems similar to the electrical system, it is possible to use the theory of Markov processes if we accept the following assumptions: no aftereffect and the choice of states in which the exponential law of distribution of a random variable is fulfilled; failures of system elements are independent; the restored system has the same characteristics as the new one; and the intensity of failures and the intensity of restoration are constant [6]. The combination of the principles of Markov process theory and similarity theory allow us to build mathematical models that combine a probabilistic approach to determining the quality of power grid operation and changes in characteristics during their operation.

To describe the process of distribution grid operation, we used the theory of Markov processes. The fundamental assumption made in the modelling is an exponential distribution law for the occurrence of events related to failures and restoration of power supply system elements. There is research evidence [6,7] that indicates a more complex character of the distribution law of the time of occurrence of failures and recovery time than the exponential one, but using the exponential distribution when calculating the probability of failure of these elements is considered generally accepted. This can be explained by the following:

- There is no consensus on the actual law of distribution of failure and recovery times;
- The use of the exponential law of distribution of time between failures leads to errors in the direction of a certain underestimation of the estimated probability of failure-free operation compared to the actual one, i.e., it cannot be the reason for creating an unreliable system;
- There are publications, for example [8], which consider systems with elements whose failure and recovery times are a combination of exponential, Weibull, and normal-logarithmic distributions and which show that for a sufficiently long period of time, these systems behave as if all their elements had an exponential distribution of failure and recovery times.

The process of functioning can be shown in the form of a graph (Figure 2), which can be used to draw up a system of Kolmogorov differential equations [5,9]. Taking into account the assumption that the dynamics of transients between individual states is not taken into account $\left(\frac{dp_i}{dt} = 0\right)$, the system of differential equations has the form:

$$\left.\begin{array}{l} \sum\limits_{i=1}^{m+1} \nu_{ji} p_i = 0, \quad j = \overline{2,n} \\ \sum\limits_{i=1}^{m+1} p_i = 1, \end{array}\right\}, \tag{1}$$

where p_i is the vector of probabilities of states of the system under study; ν_{ji} are elements of the matrix $\boldsymbol{\nu}$, which is the matrix of intensities of transitions from one state to another; $m+1$ is the number of possible states of the system under study; m is the number of operating states; and n is the number of changes in the states starting from operating state 1 (see Figure 2).

To determine the probabilities of the operating states and assess the quality of the system under study, it is necessary to solve the algebraic system in Equation (1), which is written in a more general form as

$$\boldsymbol{\nu} \cdot \mathbf{p} = \mathbf{b}. \tag{2}$$

In criterion programming, the system of orthogonality and normalization equations can be written as follows [8]:

$$\boldsymbol{\alpha} \cdot \boldsymbol{\pi} = \mathbf{b}, \tag{3}$$

where $\boldsymbol{\alpha}$ is the matrix of degree indicators; $\boldsymbol{\pi}$ is the vector of similarity criteria; and $\mathbf{b}$ is the vector of right-hand sides.

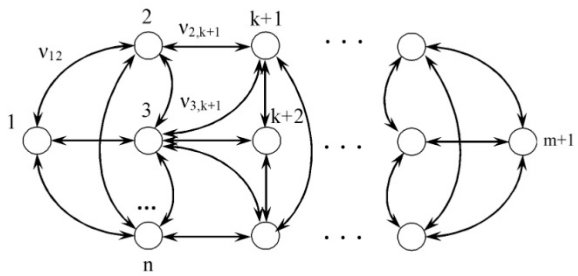

Figure 2. Graph of changes in system states.

If we use an interpolation polynomial [11], then the matrix $\boldsymbol{\alpha}$ of the system of orthogonality in Equation (2) of the criterion programming and the transition matrix $\mathbf{v}$ of the system in Equation (3) can be reduced to a matrix polynomial. We use the exponential function $f(z) = e^{zt}$ for this purpose. If the minimal polynomial (in this case, a characteristic polynomial $\Delta(z)$) consists only of linear factors $(z - z_k)$, then it is enough to define the function $(z - z_k)$ at the characteristic points $z_1, z_2, \ldots, z_{m+1}$. In this case, the system of equations for the coefficients of the interpolation polynomial is as follows:

$$f(z_k) = a_0 + a_1 z_k + \ldots + a_m z_k^m \text{ in matrix form } \begin{bmatrix} f(z_1) \\ f(z_2) \\ \ldots \\ f(z_{m+1}) \end{bmatrix} = \begin{bmatrix} 1 & z_1 & z_1^2 & \ldots & z_1^m \\ 1 & z_2 & z_2^2 & \ldots & z_2^m \\ \ldots & \ldots & \ldots & \ldots & \ldots \\ 1 & z_{m+1} & z_{m+1}^2 & \ldots & z_{m+1}^m \end{bmatrix} \cdot \begin{bmatrix} a_0 \\ a_1 \\ \ldots \\ a_m \end{bmatrix} \tag{4}$$

Solving this system relative to $a_0, a_1, \ldots, a_m$, we obtain

$$f(A) = \sum_{i=0}^{m} a_i A^i.$$

So, in general, the matrix $\boldsymbol{\alpha}$ has a polynomial of the form:

$$f(\boldsymbol{\alpha}) = \sum_{i=0}^{m} a_i \boldsymbol{\alpha}^i. \tag{5}$$

And the matrix $\mathbf{v}$:

$$f(\mathbf{v}) = \sum_{i=0}^{m} a_i \mathbf{v}^i. \tag{6}$$

By performing this transformation, one can use all the properties of scalar polynomials, including the results of the theorems of similarity theory.

It is known [12] that to establish the similarity between the original and the model, instead of the conditions

$$\pi_i = \frac{a \prod_{j=1}^{n} u_j^{\alpha_{ji}}}{f} = idem, \tag{7}$$

equivalent expressions can be used:

$$\mu_i = \frac{\mu_{a_i} \prod_{j=1}^{n} \mu_{u_j}^{a_{ji}}}{\mu_f} = 1, \tag{8}$$

where π_i is the similarity criteria determined by the method of integral analogues; a_i, α_{ji} are constant coefficients of the function f that characterizes the system; u_j is the argument of the function f; and μ_i is the similarity indicator, which is determined by the scale of the relevant coefficients and parameters of the model.

Using these conditions, we can prove the similarity of matrix polynomials and their corresponding matrices. For matrix polynomials (5) and (6), condition (8) can be written as follows:

$$\frac{\mu_{a_1}}{\mu_f} = 1; \ \frac{\mu_{a_2}\mu_{a/\nu}}{\mu_f} = 1; \ \frac{\mu_{a_3}\mu_{a/\nu}}{\mu_f} = 1 \text{ etc.,}$$

$$\text{where } \mu_{a_i} = \frac{a_{ia}}{a_{i\nu}}\mu_{a/\nu} = a \cdot \nu^{-1}\mu_f = \frac{e^{|a|t}}{e^{|\nu|t}}.$$

According to matrix transformations [12], the equivalent transformation can be viewed as transitions to new coordinate bases for the vectors **x** and **y**, i.e., $\mathbf{x}' = \mathbf{Q^{-1}x}$ and $\mathbf{y}' = \mathbf{Py}$. That is, the transformation $\widetilde{\mathbf{A}} = \mathbf{PAQ}$ corresponds to independent coordinate transformations defined by the matrices $\mathbf{Q^{-1}}$ and **P** (non-particular square matrices).

If the vectors **x** and **y** are transformed to the same coordinate basis, then we can write $\mathbf{P} = \mathbf{Q^{-1}}$. That is, we proceed to the similarity transformation $\widetilde{\mathbf{A}} = \mathbf{Q}^{-1}\mathbf{AQ}$. An important property of the similarity transformation is that the determinant of the matrix is invariant with respect to this transformation:

$$det\widetilde{\mathbf{A}} = det\mathbf{A}.$$

Thus, this transformation does not change the eigenvalues of the matrix, so we can write

$$det\left[\mathbf{zE} - \widetilde{\mathbf{A}}\right] = det[\mathbf{zE} - \mathbf{A}].$$

The result of solving the system of equations for matrices $\widetilde{\mathbf{A}}$ and **A** is the same.

The role **Q** of the transformation matrix is played by the modal matrix **H**, i.e., **H**. It can be defined as a set of columns $\mathbf{h}^{(i)}$, which are solutions to homogeneous equations:

$$(\mathbf{zE} - \mathbf{A})\mathbf{h}^{(i)} = 0 \quad i = \overline{1, n}, \tag{9}$$

where n is the matrix rank **A**.

By constructing the matrices $\boldsymbol{\alpha}$ and $\boldsymbol{\nu}$, we can find matrix **H** to satisfy the homogeneous system of Equation (9). Thus, $\mu_{a_i} = \frac{a_{ia}}{a_{i\nu}}$; $\mu_{a/\nu} = a \cdot \nu^{-1}$; $\mu_f = \frac{e^{|a|t}}{e^{|\nu|t}}$, and therefore, condition (8) is fulfilled, which confirm the similarity of the orthogonality matrices of the criterion programming and the transitions of the Kolmogorov equations.

The similarity of modelling Markov processes and criterion modelling allows us to apply the principles of criterion programming to the system in Equation (2) [8]. As a result, we can obtain a function that is a direct criterion programming task [7], which can be used to assess the quality of the distribution grid's functioning. In the criterion form, it has the form [7,13]:

$$f(x_*) = \sum_{i=1}^{m} p_i \prod_{j=1}^{n} x_{*j}^{\nu_{ij}}. \tag{10}$$

where p_i is the similarity criterion, which in this case is the probability of the system being in the state i; $\prod_{j=1}^{n} x_{*j}^{\nu_{ij}}$ is an indicator of the quality of the mill's functioning i; and x_{*j} is an independent parameter that characterizes the basic properties of the system in the corresponding states.

The quality of functioning of an "ideal" power grid, which provides an absolutely reliable power supply with maximum power quality and efficiency, is taken as the baseline value. The materials described above make it possible to expand the application of the results of previous research [8] for use in assessing the quality of functioning of power grids. For example, let us consider the case of a two-circuit power line (PL). Figure 3a shows a graph of its possible states. States 1–3 are operating states, and state 4 is a complete failure. States 2 and 3 are characterized by a reduced level of functional availability due to the failure of PL1 and PL2, respectively (see Figure 3b).

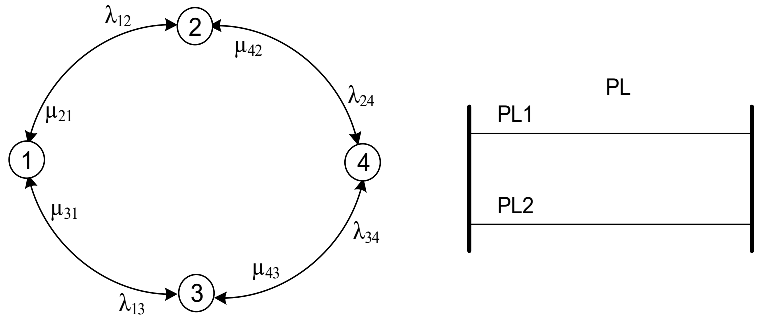

Figure 3. (**a**) State graph. (**b**) Two-circuit power line.

According to the state graph shown in Figure 3, the matrix of transition intensities will have the form:

$$\mathbf{v} = \begin{array}{c} \\ \end{array}\begin{array}{cccc|c} 1 & 2 & 3 & 4 & \\ -(\lambda_{12}+\lambda_{13}) & \mu_{21} & \mu_{31} & 0 & 1 \\ \lambda_{12} & (\lambda_{24}+\mu_{21}) & 0 & \mu_{42} & 2 \\ \lambda_{13} & 0 & (\lambda_{34}+\mu_{31}) & \mu_{43} & 3 \\ 0 & \lambda_{24} & \lambda_{34} & (\mu_{42}+\mu_{43}) & 4 \end{array}.$$

The numbering of matrix **v** elements does not correspond to the indices of failure and recovery intensities since their indexing depends on the path from state to state (see Figure 3).

According to the system in Equation (1) formed for this matrix, it is possible to find the vector of state probabilities **p**. In this case, the criterion model (10) will have the form [14]:

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

Performing logarithmization and potentiation of the components characterizes each state:

$$\begin{cases} \left(\frac{x_1}{x_2}\right)^{-\lambda_{12}} \left(\frac{x_1}{x_2}\right)^{-\lambda_{12}} = e^{-\lambda_{12}\cdot(ln(x_1)-ln(x_2))} \cdot e^{-\lambda_{12}\cdot(ln(x_1)-ln(x_2))} \\ \left(\frac{x_2}{x_1}\right)^{-\mu_{12}} x_2{}^{-\lambda_{24}} = e^{-\mu_{21}\cdot(ln(x_2)-ln(x_1))} \cdot e^{-\lambda_{24}\cdot ln(x_2)} \\ \left(\frac{x_2}{x_1}\right)^{-\mu_{12}} x_3{}^{-\lambda_{24}} = e^{-\mu_{21}\cdot(ln(x_2)-ln(x_1))} \cdot e^{-\lambda_{24}\cdot ln(x_2)} \end{cases}. \quad (11)$$

Based on the fact that the natural logarithm can be regarded as the time required for a variable to reach a certain value [15], Equation (11) can be rewritten as:

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

where P is the probability of achieving the corresponding values of certain parameters of the quality of power grid functioning.

Taking this into account, the mathematical model of the quality of power grid functioning can be determined by the expression:

$$E = p_1P_{11}P_{12} + p_2P_{21}P_{22} + p_3P_{31}P_{32}. \quad (13)$$

where p_i is the probability of the operating condition and P_{ij} is the probability of ensuring the normative value of the parameter j in state i.

The development of RSE in electric power grids further complicates the task of assessing the quality of functioning and, in particular, the reliability component. Therefore, it is advisable to use Markov models, the main advantage of which is the ability to decompose the problem of assessing the impact of RSE on the reliability of the electricity supply [16]. It is possible to consider the process of functioning of the electric power grid as a set of states determined by its structural features. Accordingly, in each state, it is possible to assess the indicators of balance reliability influenced by the individual RSE.

Using this approach, it is possible to decompose the problem of assessing the reliability of an electric power grid with renewable sources of energy. At the first stage, based on the analysis of the structural reliability of the power grid, it is necessary to build a graph of possible states (see Figure 4) in which the power grid can be located depending on the state of its elements (working/failed). At this stage, the influence of RSE is not taken into account.

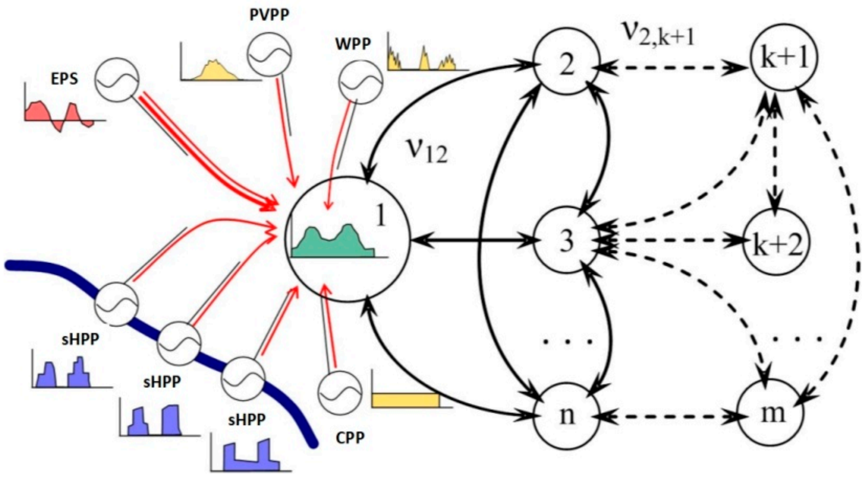

Figure 4. Graphical interpretation of the assessment of the complex indicator of the quality of functioning of the distribution power grid with distributed generation.

The next step is to analyze the balance reliability and other quality components for each operating state. According to the analysis, the quality indicator of grid functioning in a certain state is determined for each operational state i.

3. Assessment of the Quality of Functioning Components

Efficiency. Level of active power losses. The normal scheme of operation of distribution power grids is an open circuit. However, with the development of RSE, power lines with two-way power supplies appear in power grids. At the same time, under certain modes of RSE generation, it is possible to achieve a current distribution close to the closed circuit of the grid [17,18]. Such a mode can be considered "ideal", which corresponds to a minimum level of electricity losses.

The transition from an open circuit to a closed circuit leads to the current distribution, which depends on the parameters of the electrical grid elements and its configuration. Given that the processes associated with the distribution of current in such an electrical grid are subject to the principle of least action [19,20], we can speak of the optimal mode according to the criterion of minimum losses.

In a grid with several power sources, the minimum active power losses for the case when no limits are imposed on the values of nodal currents occur when both the active and reactive components of the currents are distributed in the electrical grid depending only on the active resistances, i.e., according to the substitutional r-grid scheme. This result is consistent with the known conclusions made in [21].

Determining whether the actual mode corresponding to the "ideal" mode can be done by analyzing the statistical data on the condition $P_{RSEi,k}=\sum_{j=1}^{n}(C_{rk,j}\cdot P_{i,j})$ for each i hour of the day and determining the probability based on the analysis.

The probability of ensuring an "ideal" mode is determined by the expression:

$$P_{\Delta P}=\frac{1}{24}\sum_{i=1}^{24}\left[\Pi_{k=1}^{m}p_{i,k}\left(P_{RSEi,k}=\sum_{j=1}^{n}(C_{rk,j}\cdot P_{i,j})\right)\right]. \quad (14)$$

Expression (14) allows us to assess the correspondence of the actual mode at a certain point in time to the "ideal" one, which corresponds to the distribution of power in the power grid according to its r-scheme. Given that standard losses are set for each electricity supply company, expression (14) can be used to estimate the probability of ensuring standard losses $\sum_{j=1}^{n}(C_{rk,j}\cdot P_{i,j}) \geq P_{RSEi,k}$ (where $C_{rk,j}$ is determined in accordance with the grid configuration and the set value of standard losses) [22]. However, obviously, with such a definition of the efficiency component, it is not possible to compare different power grids.

Ensuring the quality of electricity. Voltage deviations. To determine whether the values of power quality indicators (PQI) meet the requirements of [9], they are measured and statistically processed. For all normalized power quality indicators, the minimum calculation period is 24 h. The recommended total duration of continuous measurements is 7 days. Assessment of non-normalized PQI (voltage drops, overvoltages, impulses) is based on the results of long-term observations and their registration using specialized measuring instruments.

The statistical processing of the measurement results of normalized PQI consists of the construction of PQI distribution functions. Based on the measurement results, it is possible to determine the frequency of PQI values falling into a certain interval over the entire range of possible values [16].

To estimate the voltage deviation at the consumption nodes, we use an approach based on the concept of the "ideal" mode. In the "ideal" mode, voltage drops and, as a result, voltage deviations in the grid nodes are smaller. This is confirmed by the modelling results shown in Figure 5, where curve 1 is an arbitrary mode, and curve 2 is the "ideal" mode.

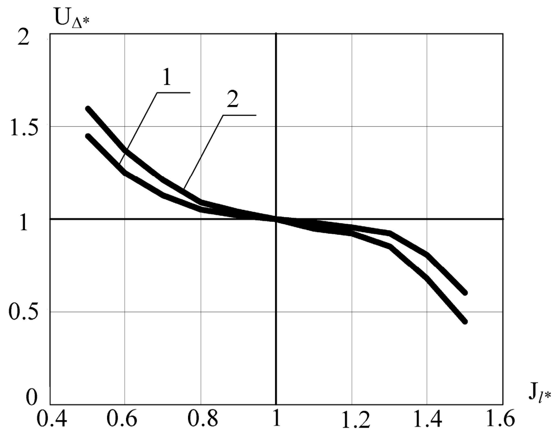

Figure 5. Curves $U_{\Delta *} = f(J_{l*})$ for a certain grid.

By analysis of statistical data, it is possible to determine the probability of fulfilling the condition $J_{RSEmini,k} \leq \sum_{j=1}^{n} (C_{rk,j} \cdot P_{i,j}) \leq J_{RSEmaxi,k}$ for each hour of the day i. The voltage quality component in the integral indicator is determined by the expression:

$$P_U = \frac{1}{24} \sum_{i=1}^{24} \left[\Pi_{k=1}^{m} p_{i,k} \left(J_{RSEmini,k} \leq \sum_{j=1}^{n} (C_{rk,j} \cdot P_{i,j}) \leq J_{RSEmaxi,k} \right) \right]. \tag{15}$$

In accordance with the obtained dependencies (see Figure 5), the limits of permissible RSE generation J_{l*} is determined, and the analysis of the correspondence of voltage deviations $U_{\Delta *}$ at consumption nodes is reduced to analyzing the ratio of generation and consumption currents.

Ensuring balance reliability. The electricity generation schedule of RSE depends on the natural features of the region in which it is located. This feature of RSE introduces certain difficulties to solving the problem of ensuring a reliable and high-quality electricity supply to consumers [23,24].

Developing a method for assessing the component of the mode efficiency and ensuring the quality of electricity is not possible without analyzing the coverage of a given consumption schedule by the potential generation of a solar power plant. To do this, it is necessary to determine the main probabilistic characteristics of the processes of RSE generation and electricity consumption.

Figure 6, as an example, shows the results of the analysis of statistical data on the daily power generation capacity of a PVPP and the load power for a 110/10 kV substation. The analysis was performed in the STATISTICA 10 software environment. The processing of statistical data during the year on the values of the generated power of the PVPP and the electric load makes it possible to determine the law of distribution of these values.

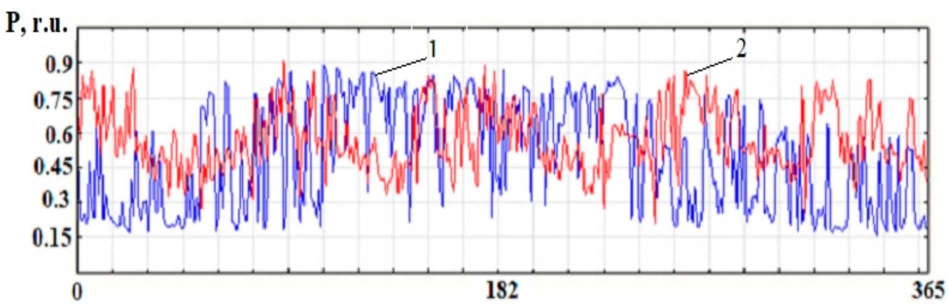

Figure 6. Changes in PVPP generation power (1) and load (2) during the year at a given time of day.

The discrepancy between the schedules of consumption and generation of RSE caused periods when the load power was not provided with the corresponding generation capacity (see Figure 7) [22,25–27].

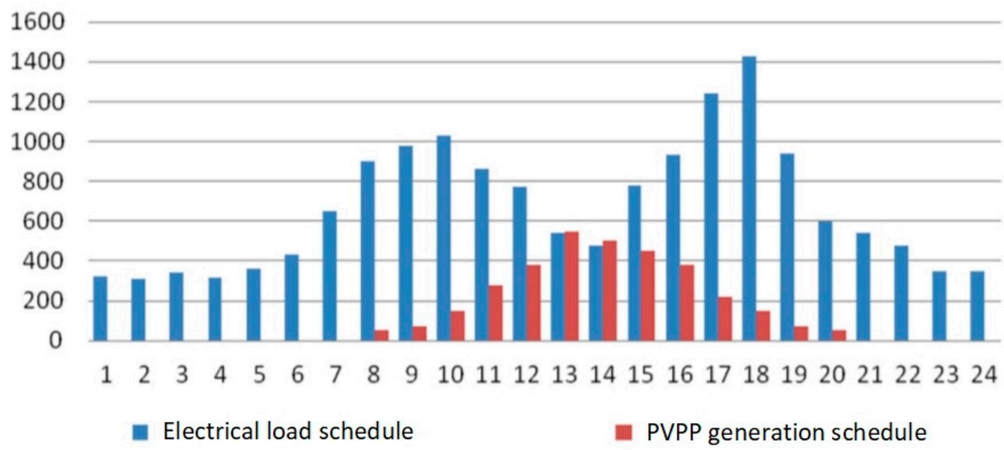

Figure 7. Daily schedules of electric load of the electric grid and generation of PV power plants.

According to the statistical data (Figure 8), using the mathematical apparatus of Gaussian mixtures, it is possible to estimate the probability of matching generation and consumption $p_i = (\sum_{k=1}^{m} P_{RSE\,i,k} = \sum_{j=1}^{n} P_{i,j})$ for a certain time of day. Obviously, the analysis consists of comparing the total RSE generation of a feeder with its total load. Since an hourly schedule is considered, the expression for determining the probability of balance takes the form:

$$P_b = \frac{1}{24}\sum_{i=1}^{24} p_i\left(\sum_{k=1}^{m} P_{RSE\,i,k} = \sum_{j=1}^{n} P_{i,j}\right). \quad (16)$$

where m, n are the number of sources and consumption nodes, respectively.

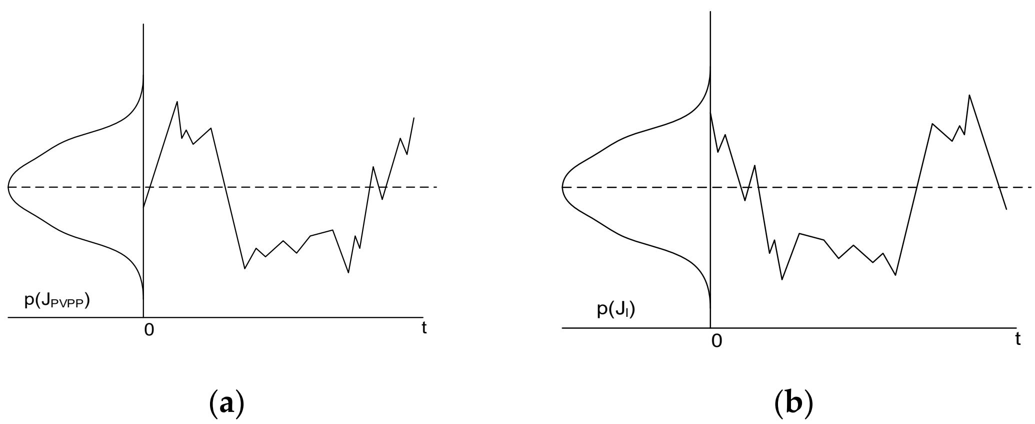

Figure 8. Graphical representation of a set of statistics on generation (**a**) and consumption (**b**).

4. Example: The Impact of Measures on the Value of the Integral Indicator of the Quality of Functioning of Power Grids

This research analyzes a number of measures to assess the impact on the integral indicator of the quality of functioning of one regional electric grid [25,28,29]. The studied electric grid is a complex closed circuit with a voltage of 110/35/10 kV. The design model has 884 nodes and 1740 branches. In the maximum load mode, 36.64 MW of electricity is supplied centralized from the EPS, PVPP, SHPP, and gas-piston cogeneration units. For this grid, using an integral indicator of the quality of functioning, an optimal structure was selected that balances the requirements of reliability, power losses, and power quality. The following grid states were calculated: closed ring circuit, sectioned under reliability conditions (open), sectioned taking into account real technical capabilities, using PVPP, with coordination of PVPP generation and consumption schedules, and using PVPP and electrochemical batteries. Figure 9 shows the results of calculations of the integrated quality indicator E.

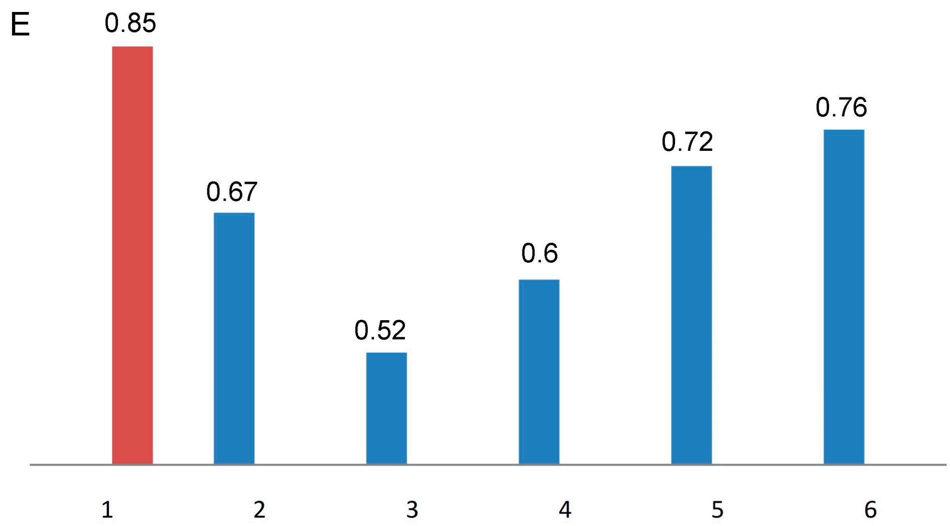

Figure 9. Values of the integral indicator of the quality of functioning for various measures considered in this research.

When determining the optimal sectioning of the power grid, the first stage was to analyze the ring configuration of power distribution companies. For this option, the value of the integral indicator of the quality of functioning was determined to be 0.85 (see Figure 9). Such a grid configuration is considered "ideal" but cannot exist under current technical conditions (case 1).

The calculation of the grid circuit scheme allowed us to determine the optimal points for its disconnection. For this configuration, the quality of functioning is 0.67 (case 2). Such a significant decrease is explained by the inconsistency in generation and consumption schedules and a significant discrepancy in power flows compared to the circuit. Since it was not possible to implement the scheme for case 2 due to the lack of switching devices at the relevant points, the best option was determined by the criterion of the quality of functioning from those possible in terms of technical capabilities (case 3).

The use of PVPP as a means of influencing reactive power flows and replacing the most loaded sections of the grid improved grid efficiency and the quality of electricity. As a result, the integral indicator reached a value of 0.6 (case 4). The coordination of generation and consumption schedules by the method proposed in this research (case 5) and the use of accumulation at PVPP (case 6) allowed us to increase the values of the quality of functioning coefficient to 0.72 and 0.76, respectively.

Thus, according to the integral quality indicator, taking into account real conditions, the best option for the studied grid is the one that uses sectioning, PVPP, and schedules of consumption and generation (case 6 in Figure 9).

5. Conclusions

Due to the development of renewable sources in electric power systems, in particular in distribution grids, it has become possible to create microgrid power supply systems for consumers. Apart from the fact that this provides certain advantages in terms of energy efficiency of the electricity supply, it is possible to form LEESs as part of a single electric power system as balancing groups. Under such conditions, a LEES as a separate controlled object that can operate in parallel with the EPS, consuming or generating electricity in the system, or in isolation with autonomous control of power, frequency, and voltage. For this reason, the structure of the LEES should be formed accordingly.

Since LEES structures can differ significantly in terms of key technical and economic indicators (power supply reliability, power losses, and power quality), it is necessary to choose the optimal one. It is not advisable to optimize the quality of the power supply in a LEES by individual indicators, as improvement to one indicator may lead to deterioration of another. The functional readiness of the LEES should be assessed by the quality of functioning, which depends on the reliability, efficiency, and quality of electricity. Since such a problem is a vector optimization problem, we propose an integral indicator in the form of a number that characterizes the LEES and provides a compromise for the values of reliability, power losses, and power quality.

The offered integral indicator of the quality of functioning of a LEES with RSE is based on the use of the theory of Markov processes and the theory of similarity. Under certain assumptions, the similarity of mathematical models of Markov processes of a dynamic electric power system and the criterion method of similarity theory is shown. On this basis, a mathematical model was developed that allows for comparing the states of individual power LEES structures. As a number, the integral indicator allows us to unambiguously compare possible variants in the LEES structure with different configurations of power grids and different sources of electricity. The advantage of this indicator over other approaches is that there is no need to determine the values of individual components of the optimality criterion.

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