Evaluation of Functioning Quality of Local Electrical Systems by the Criterion Method Based on Markov Processes

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Abstract— **The article proposes to use of a combination of the criterion method and Markov processes to evaluate the quality of functioning of renewable energy sources (RES) in the form of integrated readiness characteristic of the electricity network with RES or a local electrical system (LES). This is possible through the analysis of the problems of ensuring the quality of electricity supply in the conditions of intensive development of RES and defined by the qualimetric characteristics of the electricity networks, which are important for the provision of quality electricity. This contribute the development of generalized solutions and network development strategies, especially when it comes to building RES. The components of the integral index are determined as the probability of matching the actual regime to the "ideal". The "ideal" mode is determined on the basis of the principle of least action and corresponds to the circuit diagram of the network formed by the r-scheme. The basis thus determined in this way reduces the subjectivity of both evaluations and decisions taken on the basis of it.**

Keywords— power distribution networks, renewable energy sources, reliability of electricity supply, losses of electric energy, electricity quality, energy efficiency.

I. Introduction

The quality of electricity is characterized by the level of reliability (continuity) of electricity supply, the cost of providing services for the transmission, distribution and supply of electric energy, as well as the quality of electrical energy. Today, power distribution networks have practically exhausted the bandwidth reserve, have a low level of automation, and remote control is limited to the use of obsolete equipment. This situation is complicated by the disorderly development of renewable energy sources (RES), which often negatively affects the quality of electricity supply. In these conditions, when planning RES development in electric networks, two options are considered. The first is the construction of RES with no significant changes in the scheme of the electric network and without updating its electrical equipment, the other - the development of generation in the electrical network with its simultaneous reconstruction and modernization. Taking into account the current technical condition of network equipment, the second option is more appropriate. By developing this option, simultaneously with the improvement of the technical state of the electric network, it is possible to increase the installed capacity of RES to values that correspond to the solar potential, hydro and wind resources of the region. Whereas, in the first variant, the installed capacity of the RES is substantially limiting the throughput of the elements of the electrical network. In order to make a decision on the choice of the development option, it is necessary to assess the current status of the functional readiness of the electricity networks in order to ensure the quality of electricity supply.

II. Tasks

The use of the mathematical instrument of qualimetry [1] allows to determine the set of parameters, the influence on which can provide the required level of quality of electricity supply. However, the multivector of the result complicates the development of generalized solutions and network development strategies, especially when it comes to building RES. Therefore, it is expedient to develop an integral indicator of the quality of functioning of electric networks with RES, which will allow to switch from the vector task of evaluating the functional readiness of the required level of quality of electricity supply to the scalar [2]. This generalizes the characteristics of the quality of the functioning of the electrical network and allows you to compare the variants of network 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 nonessential ones is taken into account in the parametric form.

In works [3, 4], the quality of the functioning of the technical system is determined by the expression:

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

where H_s – probability of a state S ; $\varPhi_s$ – the probability that the system is in this state of operation.

In this form, the quality of the system's operation consists of the sum of its states, which characterize its performance and may differ in the degree of compliance of the state, normal to the parameters. This approach can be used to assess the quality of the operation of the electrical grid with RES, since for the network mode parameters, the limits of their deviation from the nominal ones are set. For example, the voltage on the tires of the consumers can vary within ± 5% of the nominal value of U, and the frequency deviation is also allowed. Thus, within the permissible state of the electrical network are working, but they differ in balance and structural reliability, electricity quality and cost-effectiveness.

The purpose of the article is to develop an integral indicator of the quality of operation of electric networks in order to select optimal their development on the criterion of maximum energy efficiency as components of reliability, a minimum of electricity losses and the corresponding quality of electricity.

III. Integral indicator of the quality of functioning of the electric network

The quality of the functioning of the electricity network is characterized by reliability, quality of electric energy, and electricity losses. It is its property to store in time within the established limits 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. The process of functioning of the electrical network can be described by a plurality of states in which the network 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, one can speak of the graph of states, the transition from state to state is characterized by a certain intensity of failures λ and restorations μ. In a network with RES, this 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 the theory of Markov processes and the theory of similarity allows us to construct a mathematical model that combines the probabilistic component in determining the quality of functioning of electrical networks and the change of regime parameters in the process of their functioning A similar modeling of Markov processes allows us to apply the principles of criterion modeling to the system of Kolmogorov-Chapman equations [5, 6]. As a result, a function has been received that can assess the quality of the functioning of the electricity grid with renewable energy sources. In the criteral form it will look like [7]:

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

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

As an example, consider a two-line power 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:

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

Perform the logarithm and potentiation of the components that characterize each of the states:

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

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

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

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

Taking into account this mathematical model of the quality of functioning of the electric network 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 $p_i = H_s$ – probability of a state, $\prod_{j=n} P_{ij} = \Phi_s$ – the probability that the system is in this state successfully operates (P_{ij} – the probability of providing an appropriate characteristic of the quality of functioning).

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

IV. Determination of the Components of the Integral Indicator of the Quality of Operation of Electrical Networks

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

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

The economical operation of the electrical network in the process of operation is largely determined by the loss of electricity in it. With RES, you can achieve the current distribution in the electrical network, which corresponds to the economic regime [8]. That is, a mode that meets the minimum level of electrical power losses in the network. Given that the processes associated with the distribution of current in such an electrical network are subject to the principle of least action [9], then such a regime is considered as "ideal", which corresponds to the minimum level of electrical energy losses.

In order to compare the energy efficiency of different variants of the development of electric networks, we consider that their losses of electricity should be "perfect". That is, the coefficients of current distribution in them are determined by the expression [10]:

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

where $\mathbf{R}$ – diagonal matrix of active resistances of transmission lines of the network; M – 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 – symbol of the transposed matrix.

In conditions of development of RES in distribution electrical networks it is necessary to assess the balance reliability, that is, the determination of the probability of non-compliance of consumption schedules and generation of RES, due to the instability of such sources. According to statistical data, using the mathematical apparatus of Gaussian mixtures [11], it is possible to estimate the probability of conformity of generation and consumption for a certain time of day.

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

in (7) p_i – probability of fulfilling the condition $\sum_{k=1}^{m} P_{RES_{i,k}} = \sum_{j=1}^{n} P_{i,j}$; $P_{RES_{i,k}}$ – the power of a renewable energy source; $P_{i,j}$ – load capacity; m – number of nodes generated; n – number of nodes consumption; i – number of time interval.

Obviously, the analysis consists of comparing the total generation of the AVE feeder with its total load. If an hourly schedule is considered, then the expression to determine the probability of providing a balance takes the form:

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

Evaluating the efficiency of the operation of an electricity grid with renewable energy sources is based on the assessment of the conformity of the actual regime with the basic 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 and every hour of the day and determine the probability of the analysis performed.

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

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

where $p_{i,k}$ – probability of fulfilling the condition; $C_{r\ k,j}$ – current distribution coefficients for r-scheme for k-th source and 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 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.

By dependence $U_\Delta = f\left(J_i\right)$ it is possible to obtain the region of change of load currents in relation to the currents of generation of RES by constructing a plurality of curves for a particular electrical network. This area will correspond to the standard deviation of the voltage at the load nodes. By analyzing statistics, you can determine 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 and every hour of the day. The component of the voltage quality in the integral index is determined by the expression:

$$P_U = \frac{1}{24}\sum_{i=1}^{24}\left[\prod_{k=1}^{m} p_{i,k}\begin{pmatrix} J_{RES\ min\ i,k} \le \\ \le \sum_{j=1}^{n}\left(C_{r\ j,k}\cdot J_{i,j}\right) \le \\ \le J_{RES\ max\ i,k}\end{pmatrix}\right], \qquad (10)$$

where $p_{i,k}$ – probability of fulfilling; $J_{RES\ min\ i,k}$, $J_{RES\ max\ i,k}$ – respectively, the minimum and maximum value of the current at the point of attachment of the RES, which corresponds to the area of permissible deviations in the load node $J_{i,j}$.

That is, in accordance with the obtained dependencies, the limits of permissible generation of RES 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 network, 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.

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:

$$P_{K_U} = \frac{1}{24}\sum_{i=1}^{24}\left[\prod_{\nu=1}^{40}\left(\prod_{k=1}^{m} p_{i,\nu,k}\left(U_{sc\ i,\nu,k} \le U_{sc\_ad\ i,\nu,k}\right)\right)\right] \qquad (11)$$

where $p_{i,\nu,k}$ – probability of execution $U_{sc\ i,\nu,k} \le U_{sc\_ad\ i,\nu,k}$; $U_{sc\ i,\nu,k}$ – Injection of distortion by voltage from source k according to harmonic ν; $U_{sc\_ad\ i,\nu,k}$ – allowable injection of distortions by voltage from source k in harmony ν.

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 quality of electricity is the functional availability of electrical networks, ie their quality of operation, the task is to develop a strategy for the development of both electric networks and sources of electrical energy in them.

Functional readiness of electric networks can be estimated by the indicator of the quality of functioning, which depends on the reliability, efficiency and quality of electric energy. For the unambiguous solution of the task of evaluating the quality of functioning, which is a vector, the method of determination of the integral index is proposed, which allows to reduce the task of assessing the quality of functioning of electric networks with renewable energy sources to one-parameter. To do this, a combination of the theory of Markov processes and the theory of similarity is performed.

An estimation of the integral index of the quality of the operation of the electrical network is carried out by comparing the actual modes with the "ideal". This approach allows comparing different variants of transmission and distribution systems without specifying their technical and economic indicators.

In addition, the proposed approach allows the evaluation to be carried out by analyzing the currents and voltages in the nodes of the network, which at the stage of creating Smart Grid allows the use of ASECA information.

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