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Forecasting the electricity pricing of energy islands with renewable sources

Abstract. The strategy for the development of local low-power systems involves the use of several sources. The efficiency of functioning such systems depends on the purposeful reliability management and it is based on the rational hierarchical connections of their structural components. Coordination of the structure of diversified sources and their participation in the formation of energy balance of micro-energy systems in the conditions of dynamic development of renewable energy is an actual research task. The purpose of research was to develop a method of reliability-cost optimization of structure of micro-energy systems with dissimilar sources, which is based on the use of reliability indicators and cost of electricity. The studies conducted are based on the modern methods of applied statistical analysis, the theory of reliability, the synthesis of complex multi-aggregate systems. Through the implementation of the Markov model and simulation modeling of the functioning of sources, it has been obtained the conditions for optimal formation of the energy balance of micro-energy system with the lowest cost of electricity, considering the reliability indicators. Computational experiments made it possible to obtain the regularities of cost evolution of electricity and to show its dependence on the structure and algorithms of the sources' functioning. Using a probabilistic modeling method, it has been proved for the first time that the cost of electricity is sensitive to the ratio availability of renewable sources of primary energy. The practical application of results lies in the increase in efficiency of energy islands through the structural and algorithmic optimization of diversified sources (traditional and renewable) based on determining the cost of electricity

Keywords: diversified sources of electricity; reliability-cost analysis; the Markov model; simulation modeling; efficiency of microgrids

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INTRODUCTION

Future low capacity energy systems depend on the development of systems with distributed generation capacity using multiple energy sources, primarily, the renewable ones.

The study is devoted to the substantiation of need to use the renewable sources of electricity in energy islands with renewable sources (EIRS) with traditional sources, as

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well as considering the probabilistic nature of access to the primary natural factors (power of solar insolation, wind speed, etc.) for traditional and renewable sources. This approaching is due the expected economic effect, namely, a reduction in the primary fuel costs for internal combustion engines. At the same time, the instability of operation of the renewable sources (RES) over time (caused by seasonality, natural factors, geographical location, etc.), the problem of substantiating the installed capacity of sources (traditional and renewable) is a rather difficult research issue. Provided that the uninterrupted power supply in the EIRS is ensured.

The study is devoted to the development of power systems with small volumes of electricity consumption, having an installed capacity of electricity consumers of up to 15 kVA. The island or autonomous operating mode of such a micro-energy system is typical for the local facilities with limited access to main grid (centralized power system). The use of combined power supply with several dissimilar sources is a feasible solution for such systems.

Forecasting the electricity prices of EIRS is the important component for developing low capacity systems and designing the hybrid systems combining multiple sources. It is important to consider that the management of EIRS efficiency is a relevant problem and it depends on the structures and algorithms of analyzing the prime electricity cost of such systems.

In the study of complex multicomponent energy systems with a stochastic nature of the behavior of its elements, the mathematical modeling involves the description of random processes that develop depending on a number of random factors. Most models of discrete systems with a stochastic nature of functioning are built on the basis of queuing models, the processes of which are random, and in many cases, the Markov ones. Therefore, to solve such problems, it is expedient to use the mathematical apparatus of the theory of the Markov processes. Mathematical description of the Markov processes is usually represented as systems of differential (in the case of non-stationary mode) or algebraic (for stationary mode) equations, the solutions of which, in general, cannot be obtained explicitly. This necessitates the application of numerical methods for solving systems of differential or algebraic equations. In the power systems with multiple sources, it is possible to apply the processes of data transmission to the information network of dispatching systems of the corresponding levels, the performance of tasks and data exchange with external devices in the computer system, etc. for the analysis of reliability and efficiency of the use of generating capacities.

Low-power supply systems with several sources are created for the modernization of existing networks and they require technical and economical justifications to choose the composition of generating capacities [1; 2]. The hybrid micro-energy systems usually include solar and wind generators to reduce the use of hydrocarbons as primary fuel from traditional sources [3]. The research of hybrid power system recently requires new approaches to intelligent management of this kind of local power supply and forms a separate conceptual direction of microgrid development as a lower-level smart grid system. This is the feature of operation of such microgrids: the coordination of their modes with the load and possibility of parallel operation with the main network [4]. The autonomy class of such systems is primarily due to the insufficient reliability of the main network. The creation of micro-energy systems of energy island is both a solution of the problem of power supply reliability and the creation of prerequisites for the introduction of RES [5]. Management of the efficiency of the combined power supply system can be solved on the basis of optimal distribution of share in the energy balance between traditional and renewable sources according to the specific cost criterion for electricity. The introduction of renewable sources creates certain restrictions for the needs of autonomous power supply systems of industrial, residential or other objects. The combined use of heterogeneous sources allows both managing the reliability of power supply, and considering the stochastic supply of natural resources to coordinate the current load or using energy storage [6; 7]. Based on the well-known publications [2; 3; 6], it is possible to generalize the composition of local micro-energy systems (Fig. 1), which are built on the basis of the use of several heterogeneous sources.

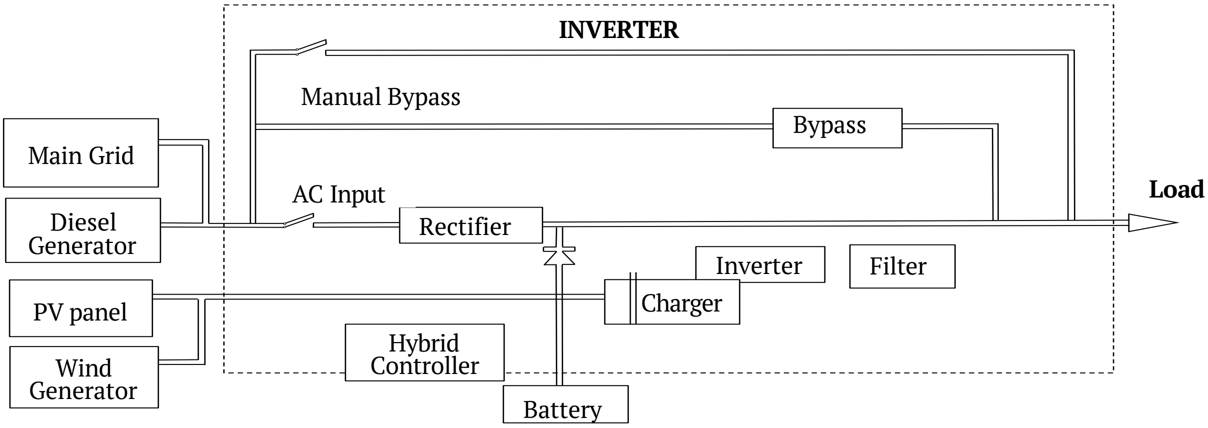

Figure 1. The principles of energy islands with renewable sources design

Publications [8-10] are devoted to the development of models for the search for optimal structures of autonomous power supply systems, as well as to the study of pricing of electricity in the energy islands with renewable sources.

The purpose of research was to increase the efficiency of island microgrid systems by means of structural optimization of traditional and renewable sources through the indicators of reliability and probability of supply of wind and solar energy with an assessment of the cost of electricity.

MATERIALS AND METHODS

For the analysis of EIRS, it is used the graph theory, which is one of the most convenient mathematical modeling tools to determine the reliability of complex systems. There are two sets of graph: (a) set of vertices and (b) set of edges [11].

The theories of the Markov processes is an effective tool for the analysis of reliability characteristics. It is used for estimating the probabilistic indicators of complex multicomponent systems [12-14]. The peculiarity of construction of the Markov models lies in the consideration of microgrid in different states such as operational and refusal ones. Each state is characterized by different operational efficiency and resources ensuring reliability. Transitions between system states occur at the times of refusal or restoration of one or another element of the system. It is described the process according to the models of discrete states for the selected time of system operation. A random process is called the Markov process, considering the following factors: if the probability of system transition during the time $t>t_0$ t for any moment t_0 depends only on the state at the moment $t=t_0$, and does not depend on the fact how the system entered this state. There are several conditions. Since the transitions statistically independent, the intensity of failures and the intensity of recovery are constant in time and different from state to state. The time intervals between the adjacent transitions are distributed according to the exponential law. Thus, for the Markov process, the probabilities of transitions from the *i*-th to the *j*-th state during the time Δt will be determined by the intensity of failure λ_{ij} as:

$$P_{ij}(\Delta t)=1-exp(-\lambda_{ij}\Delta t). \tag{1}$$

For short time intervals Δt:

$$P_{ij}(\Delta t)\approx 1\lambda_{ij}\Delta t. \tag{2}$$

A circle with the identification number can be represented for reliability graph of each EIRS state (vertex) of the system. The transition from one state to another will be depicted as the the lines (edges) connecting the states. For the numerical analysis of the EIRS reliability, the mathematical theory of graphs can be used [12; 15].

It is possible to perform the reliability analysis of EIRS with graphs. Random failures of system elements can be modeling with random graphs. The reliability characteristics of individual elements (blocks) are used to quantify the reliability of EIRS. It is assumed that the failures of elements are statistically independent.

The theories of the Markov and semi-Markov processes are also used. In this case, the Markov chains with states are considered, which can be represented in the form of matrix of transition probabilities [13; 14]:

$$P=\begin{bmatrix} p_{11} & p_{12} & \cdots & p_{1n} \\ p_{21} & p_{22} & \cdots & p_{2n} \\ p_{n1} & p_{n2} & \cdots & p_{nn} \end{bmatrix}. \tag{3}$$

The elements of transition matrix p_{ij} represents probability of the system transition to the state j from the state i in one step. The diagonal element pij represents the probability that the system will be constant.

The transition from one state to another is described according to the cumulative distribution function e_{EIRS}, for each state *k* for random variables. In case of the Markov processes, all distributions $F_{k(t)}$ are exponential ones. Knowing the transition probabilities such as: p_{ij}, parameters, λ_{ij} and distributions $F_{k(t)}$ of the time during which the process remains in state i , the weight of each edge is $\lambda_{ij}=p_{ij}\lambda_i$ The semi-Markov process is determined by the transition probabilities of the embedded Markov chain p_{ij} and conditional distribution $F_{k(t)}$ of the time duration; the system remains in state i provided that the system moves into the pre-defined state *j*.

Thus, the graph representing the semi-Markov process has to describe each edge transition probability p_{ij} and conditional distribution $F_{k(t)}$ of time, so that the process remains in the state corresponding to the state in transition of this edge.

Thus, one unreserved element can exist in three states: s_1 – the element is in order, s_2 – the element is out of order, it is not required the need to supply disconnection, and – s_0 the element is out of order (state of failure) (Fig. 2a). If the failure stream has intensity λ and restoration intensity μ, the system transits from state to state and back after a certain time [16]. The graph of state-to-state transitions of the time *d*tλ and μ characteristics is shown in the Figure 2b.

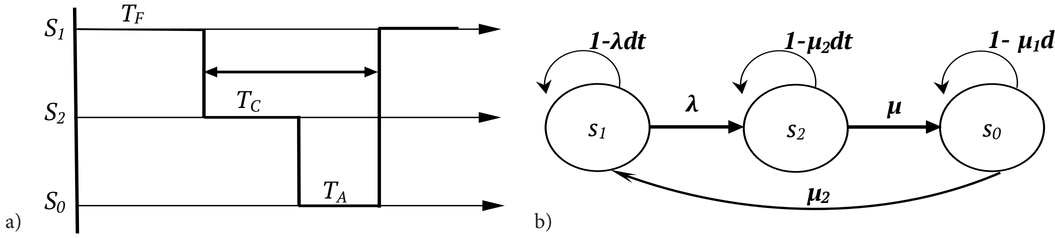

Figure 2. The time diagram of a single element transitions: from one state to another (a) and the graph of states (b)
Source: developed by the authors based on [16]

The graph of transitions of the Markov process allows system of differential equations of states [14]:

$$\frac{dp}{dt} = \sum_{j\in G} \lambda_{ij} p_j(t) - p_i(t) \sum_{j\in G} \lambda_{ij}, \qquad (4)$$

where G_i is the subset of states of the Markov process which allows transition into state i, and G_i is the subset of states that may be achieved from state i, and λ_{ij} is intensity of the transitions.

The system (4) is linearly dependent, and therefore, it is required to add another equation (normality equation) to make the solution unique:

$$\sum_{i=n}^{n} p_i = 1. \qquad (5)$$

Let's consider the structure of EIRS that combines three sources of electric power: R_1 is the supply from the network; R_2 is a set with electric energy consisting of static converters with accumulative features and a set with renewable primary energy.

R_3 is a set with combustion engines (gas/diesel, gas/petrol, diesel, biofuels, etc.). Automatization is a specific feature of these sources, enabling the required activation time (namely, the time from transition of unloaded/cold reserve to the operating mode).

Probably, the changing restoration process is a source, represented by two independent one-by-one variables. These variables are performed identically and are free as a set.

The research of EIRS reliability indicators should be reduced to structural optimization of sources [17]. There are two approaches to solving the optimization task. It is based on achieving the maximum reliability indicators. It will be adhere to the directivity of established resource costs, or it will minimize the average specific losses in the system according to the established limit indicators of reliability. Solving the optimization task will be guided to minimize the cost function by a set of variables corresponding to the selected constraints [18; 19]. The choice of the structure of EIIR sources has a significant impact on the reliability indicators of microgrid system, primarily on the current specific resource costs and system efficiency. It is obvious that in case of using the renewable energy sources, their share in the energy balance should be maximal, provided that the reliability (continuity) of power supply is ensured. This is exactly for achieving the maximum reduction in the specific cost of electricity [20]. In terms of reliability, the process of EIRS functioning is a stochastic recovery process (Fig. 3) [13]: The quantities are random, independent and have the same distribution.

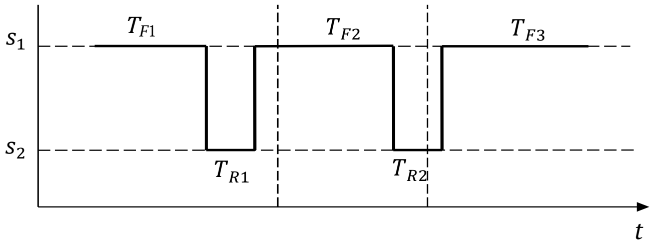

Figure 3. The alternating restoration process of EIRS operation

Source: developed by the authors based on [13]

If one source fails, another source out of the set ones is available and can operate. In general, the sequence of activation sources (if the source fails) is presented by the general EIRS algorithm. Sources of the set are operating in unloaded reserve with time delay and they are required for activation.

GPSS World (General Purpose Simulating System) simulation system [8] was used to build a simulation model of the studied system. The choice of this software environment is based on the availability of a specialized and object-oriented language with the ability to display dynamic processes in real systems, generate arbitrary laws of distribution of stochastic values, diagnose errors during the execution of a simulation program, etc.

RESULTS AND DISCUSSION

It is supposed that the time of failure, the time of system elements restoration (sources D_1, D_2, D_3, as well as the connection expiration time are distributed by an exponential law with parameters λ_1, λ_2, λ_3, μ_1, μ_2, μ_3, and λ_4, respectively. In fact, these parameters depend on the choice of a "candidate" among the selected sources from the sets $D_2^1,\dots, D_2^{n1}$ and $D_3^1,,\dots ,D_3^{n1}$ respectively.

That is $\lambda_i=\lambda_i(x_i)$, $i=\overline{1,4}$; $\mu i=\mu_i(x_i)$, $i=\overline{1,3}$, where x_i, $i=\overline{1,3}$ is the integer value characterizing the selected model of the source Di; and x_4 is the selected expiration time value to activate the source D_3.

Considering that all random variables of the model are distributed according to the exponential laws, the mathematical model of the process of EIRS operation with heterogeneous sources is presented as *a* semi-Markov process with *a* set of system states. The system states are represented by a vector with three components $d=(d_1, d_2, d_3)$, where

$$d_1 = \begin{cases} 1, \text{when } D_1 \text{ works} \\ 0, \text{when } D_1 \text{ is restored} \end{cases} \qquad (6a)$$

$$d_2 = \begin{cases} 1, \text{when } D_1 \text{ works} \\ 0, \text{when } D_1 \text{ is restored} \end{cases} \qquad (6b)$$

$$d_3 \begin{cases} 0, \text{when } D_3 \text{ is restored,} \\ 1, \text{when } D_3 \text{ operational and in unloaded mode,} \\ 2, \text{when } D_3 \text{ operational and is in standby mode,} \\ 3, \text{when } D_3 \text{ works.} \end{cases} \qquad (6c)$$

This is a set of possible states of system *D*:

$D=\{(d_1, d_2, d_3)\}=\{(0,0,0); (0,0,2); (0,0,3); (0,1,0);(0,1,2); (0,1,3); (1,0,0); (1,0,1); (1,1,0); (1,1,1)\}.$

After analyzing the peculiarities of the system functioning, it is proved that:

- the state (0,0,1) of the system is impossible as the restoration of sources D_1, D_2 and D_3 must be in the state (2), in operating state (3), or in restoration state (0);
- the state (0,1,1) of the system is impossible during the restoration of source D_1 the source D_2 is in operating state, and the source D_3 cannot be in unloaded mode (1): the source D_3 must be prepared for activation (2), work (3), or restoration (0);
- the states (1,0,2) and (1,0,3) of the system cannot be considered when the source D_1 is in operating state and the source D_2 is in restoration state (0), the source D_3 cannot be prepared for activation (2) or work (3);
- system states (1,1,2), (1,1,3) are impossible, when the sources D_1 and D_2 are operating, that is, they are in state (1), the source D_3 cannot be prepared for activation (2) or work (3).

The graph of the system transitions from one state to another is represented in the Figure 4.

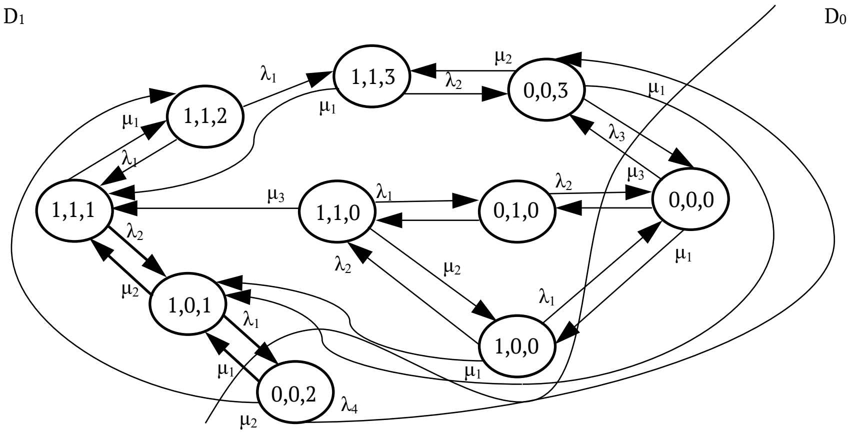

Figure 4. The graph of the system transitions from one state to another in one step

Continuing the analysis of the system functioning, it can be stated that some transitions from one state to another are simply impossible. For instance, only one source may fail at one point of time (therefore the transition is forbidden); the source D_3 may fail if it is activated (therefore the transition is forbidden), etc.

In terms of system efficiency, the set of states of the system D can be divided into two subsets D_1 and D_0,

$$D=D_1\cdot\cup\cdot D_0,\ D_1\cdot\cap\cdot\mathrm{D\_0}=\varnothing, \tag{7}$$

where:

$D_1=\{(1,1,1);(0,1,2);(1,0,1);(0,1,3);(1,1,0);(0,0,3);(0,1,0);(1,0,0)\}$

is the set of the system operating states;

$$D_0=\{(0,0,2);(0,0,0)\}$$

is the set of the system disabling states.

To calculate EIRS reliability indices (availability factor, average failure rate, average recovery time), it is necessary to determine:

- average time of the semi-Markov process in all possible states of the system;
- probabilities of transition from a state to the embedded Markov chain;

The average system time in states is as follows:

$$m(1,1,1)\frac{1}{\lambda_1+\lambda_2}, m(0,1,2)=\frac{1}{\lambda_4+\mu_1} \tag{8}$$

$$m(0,0,3)=\frac{1}{\lambda_3+\mu_1+\mu_2}, m(0,1,0)=\frac{1}{\lambda_2+\mu_1+\mu_3}.$$

The matrix of probabilities of transitions in one step of the embedded Markov chain is as follows:

$$P=\|P((d_1, d_2, d_3); (k_1, k, k_3))\|$$

To conclude, it is necessary to choose a source of electricity among a number of possible "candidates" in the structure of EIRS model. However, the types of sources must be selected by the system structure. Generally, one of the two approaches is considered in the formulation of optimization problem (although the others are possible): the first task is to maximize the reliability index; the second task is to minimize the average specific losses of the system operation.

The problem in such definition is considered below.

The problem of optimization is to find the minimum prime cost with a few variables with several constraints. The prime cost of electricity is the most important criterion for evaluation EIRS effectiveness (which was generated by it).

This is the calculation of electricity generation cost:

$$e_{EIRS}=\frac{Z_\Sigma}{W_{EIRS}}=\frac{(w_1B_{11}+w_2B_{22}+w_3B_{33}+\ldots+w_iB_{im})+{}^{E}/_{q}}{W_{EIRS}}=\frac{qB+E}{W_{EIRS}} \tag{9}$$

where: Z_Σ is the total discounted expenses; W_{EIRS} is the average amount of electricity generated by *EIRS*; $B=w_1B_{11}+w_2B_{22}+w_3B_{33}+\ldots+w_iB_{im}$ is a total cost of electricity generation from the sources of the first year of project implementation; *E* is total operational expenses; *q* is a rate of return on capital investments; *E/q* – the operational expenses given by the first year for n years.

The stationary distribution of the embedded Markov chain is found from the system of equations (10).

$$\begin{gathered}
p(0,0,0)=\frac{\lambda_3}{\lambda_3+\mu_1+\mu_2},\, p(0,0,3)=\frac{\lambda_2}{\lambda_2+\mu_1+\mu_2},p(0,1,0)+\frac{\lambda_1}{\lambda_1+\mu_1+\mu_2}\rho(1,0,0);\\
p(0,0,2)=\frac{\lambda_1}{\lambda_1+\mu_2}\rho(1,0,1);\\
p(0,0,3)=\frac{\mu_3}{\mu_1+\mu_2+\mu_3}\rho(0,0,0)+\frac{\lambda_4}{\lambda_4+\mu_1+\mu_2}\rho(0,0,2)+\frac{\lambda_2}{\lambda_2+\lambda_3+\mu_1}\rho(0,1,3);\\
p(0,1,0)=\frac{\mu_2}{\mu_1+\mu_2+\mu_3}\rho(0,0,0)+\frac{\lambda_3}{\lambda_2+\mu_3+\mu_1}\rho(0,1,3)+\frac{\lambda_1}{\lambda_1+\lambda_2+\mu_3}\rho(1,1,0);\\
p(0,1,2)=\frac{\mu_2}{\lambda_4+\mu_1+\mu_2}\rho(0,0,2)+\frac{\lambda_1}{\lambda_1+\lambda_2}\cdot p(1,1,1)\\
p(0,1,3)=\frac{\mu_2}{\lambda_3+\mu_1+\mu_2}\rho(0,0,3)+\frac{\mu_3}{\lambda_2+\mu_1+\mu_3}\rho(0,1,0)+\frac{\lambda_4}{\lambda_4+\mu_1}\rho(0,1,2);\\
p(1,0,0)=\frac{\mu_1}{\mu_1+\mu_2+\mu_3}\rho(0,0,0)+\frac{\lambda_2}{\lambda_1+\lambda_2+\mu_3}\rho(1,1,0)\\
p(1,0,1)=\frac{\mu_1}{\lambda_4+\mu_1+\mu_3}\rho(0,0,2)+\frac{\mu_1}{\lambda_3+\mu_1+\mu_2}\rho(0,0,3)+\frac{\mu_3}{\lambda_1+\mu_2+\mu_3}\rho(1,0,0)\frac{\lambda_2}{\lambda_1+\mu_2}\rho(1,1,1);\\
p(1,1,0)=\frac{\mu_1}{\lambda_2+\mu_1+\mu_3}\rho(0,1,0)+\frac{\mu_2}{\lambda_1+\mu_2+\mu_3}\rho(1,0,0)\\
p(1,1,1)=\frac{\mu_1}{\lambda_4+\mu_1}\rho(0,1,2)+\frac{\mu_1}{\lambda_3+\lambda_3+\mu_1}\rho(0,1,3)+\frac{\mu_2}{\lambda_1+\mu_2}\rho(1,0,1)+\frac{\mu_3}{\lambda_1+\lambda_2+\mu_3}\rho(1,1,0).
\end{gathered} \tag{10}$$

Considering the above mentioned facts, it is important to solve two simulation optimization problems [20]:

1. To find the structures and algorithms of EIRS allowing the average specific costs of the EIRS electricity generation with the failure source R_1 attaining a minimum *C→min*, under constraints imposed on system reliability. Herewith, the availability factor K_A (operative availability K_{OA}) should not be less than a normalized value $K_A (K_A > K)$.

2. To find such structures and algorithms of EIRS, allowing the availability factor of the system to achieve the maximum K_A→*max* by limiting the average specific costs of the EIRS for electricity generation. It should not be more than the preset value.

3. Further research will focus on the study of structures and algorithms of EIRS with RES (Fig. 5).

The software algorithm consists of three stages, the procedure and the content represented graphically in the Figure 5.

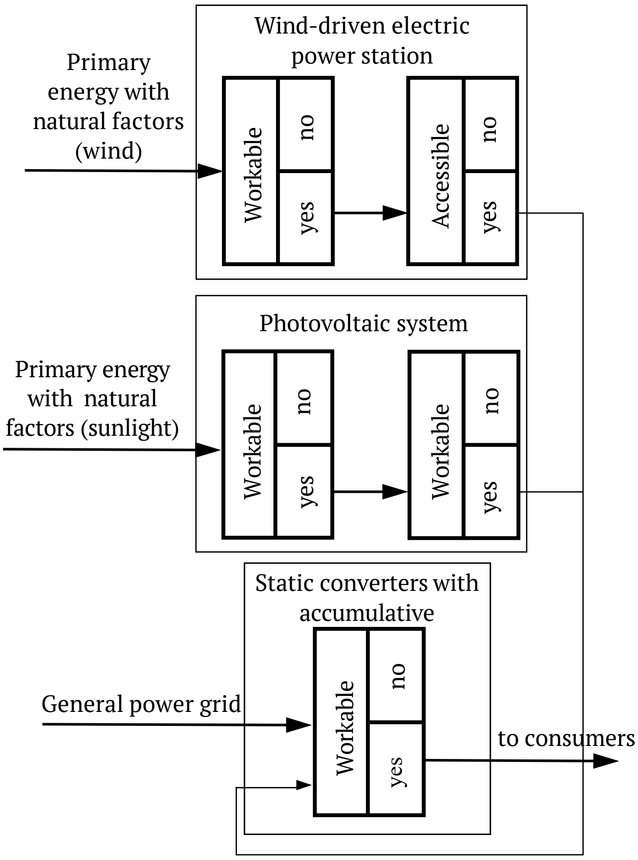

Figure 5. The structure and algorithms of EIRS operation

In the Figure 6, it is shown the algorithm of EIRS functioning through the simulation modeling with GPSS [18]. The study was performed within the following stages:

- development of a conceptual model;
- design and implementation of a simulation model software;
- checking the model adequacy;
- reliability evaluation of simulation results;
- planning and carrying out the experiment.

The adequacy of mathematical models of real system depends on the reliability of probability of distribution determination of random variables that describe the process of EIRS elements [21].

From a mathematical perspective, two procedures are important: solving the systems of linear algebraic equations and the procedure for generating the random variables (given in advance by the distribution functions of random variables) [12]. The Gaussian method is used to solve the systems of linear algebraic equations after eliminating the linear dependence of the equations [12]. As for the random variable generation procedure, the use of random variables lies in the basis of simulation modeling method. It is necessary to generate random variables with given distribution laws [12]. The inverse function method is used, which is based on the following statement of probability theory [12]. For example, $F(x)$ – a distribution function, and R – a random variable uniformly distributed in the interval [0, 1]. Then the random variable $X=F^{-1}$ – will have a distribution function $F(x)$:

$$P(X\leqslant x)=P(r\leqslant F(x))=\int_0^{F(x)}f(r)dr=F(x). \qquad (11)$$

The sequence of random numbers r_1, r_2, r_3... is converted into a sequence x_1, x_2, x_3..., which has a given law $F(x)$ (distribution density function $f(x)$). The general algorithm for modeling the random continuous variables with a given probability distribution function follows from this: a random number is generated $r_i\in[0\ 1]$; a random number is calculated $x_i=F^{-1}(r_i)$.

$F^{-1}(r_i)$F^(-1) (r_i), it is used a piecewise linear approximation of the corresponding continuous functions [21]. To obtain the function of normal distribution of a random variable X with mathematical expectation $m_x\neq 0$, the square deviation $\sigma_x\neq 1$ calculation is as follows:

$$X=m_x+\sigma_x Z, \qquad (12)$$

Z – a random variable with a standard normal distribution function, for which the function has been approximated $F^{-1}(z)$.

To specify other laws (non-exponential, non-uniform, and non-normal), special programs are used. It is allowed to perform the numerically tabulation of inverse functions, that is, to calculate the necessary values of the points of piecewise linear approximation functions.

This simulation does not impose restrictions on the types of the used probability distributions of random variables.

There is a problem of probabilistic description of the random processes with an incomplete statistical information (there are no reliable data of the energy potential of wind and sun and the principles of their distribution). It leads to significant errors in the simulation.

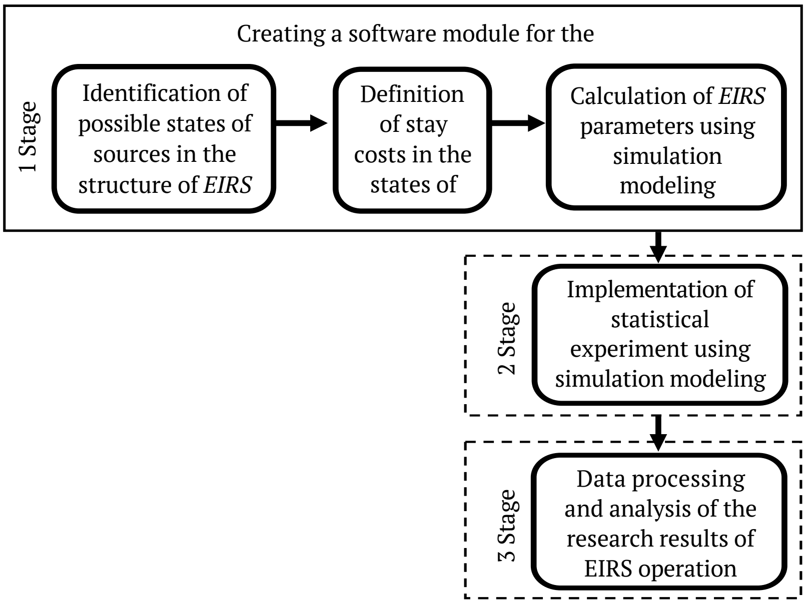

Figure 6. The operating algorithm of the software for researching EIRS using simulation modeling with GPSS

This is a solution to this problem: to determine the probability of a sufficient daily supply of wind or solar energy potential for Wind-driven electric power station (WEPS) and Photovoltaic station (PS), determined for a specific area. In the Table 1, it is shown the results of analytical solution and simulation modeling for some of 75 variants of the EIRS structures.

Table 1. The results of analytical solution and simulation modeling for some of 75 variants of the EIRS structures

Serial number of variant	Serial number of source (model series of source)		Specific cost of EIRS electricity, $		Error (%)
	R_2	R_3	The result of analytical solution	The result of simulation	
1	1	1	4.3084	4.2528	1.29
…	…	…	…	…	…
16	2	1	3.4453	3.5126	1.95
…	…	…	…	…	…
46	4	1	2.1530	2.2074	2.52
…	…	…	…	…	…
61	5	1	1.4255	1.4569	2.20
…	…	…	…	…	…
75	5	15	1.4149	1.4256	0.76

The research result of this work is the development of a method for the reliability management and functional analysis of systems of this class at the stage of preliminary design for solving the optimization problem, considering the specific cost of electricity. Moreover, this approach allows developing control algorithms for such systems, considering the power consumption levels of a local object.

Thus, the description of these sources as a scheme of reliability and functioning can be represented as a series of connections of two hypothetical elements (the EIRS structure with a set of sources is shown in the Figure 5). Using simulation results, it is shown that the system components are characterized by the period between failures, restoration time, cost of unit of electricity generation, specific losses due to power failure. The probabilities of availability of energy natural factors are added for WEPS and PS (throughout the year, the source ones are supplemented with delay time for activation). Every time, the parameters are described by the distribution of random variables.

EIRS, as a stochastic system, cannot be described by analytical mathematical models. In the further research, it is suggested to apply the method of simulation modeling. The simulation model and algorithms of functioning of autonomous systems with renewable energy sources are developed. The proposed approach provides for the use of probabilistic model of availability for renewable sources, which allows evaluating the reliability and efficiency of the system, given that it is impossible to obtain them analytically.

Based on the analysis of simulation results of 75 investigated variants of the system structure (Table 1), it has been found that the use of renweable sourse leads to a reduction in the cost of electricity. At the same time, the formation of energy balance by increasing the share of renweable sourse leads to an increase in the efficiency of EIRS by more than 13%.

Finally, it is important to emphasize that EIRS structures are characterized by a set of possible states of each element of the system, the set of possible states of the system and matrix of transition probabilities (transition graph).

The results obtained can be used to develop a methodology for determining the economic efficiency with implementation of local energy systems. Reliability-cost indicators can be additional indicators of investment efficiency of long-term projects, based on the projected total volume of electricity generation, as shown in the figure [5]. The principles and approaches for evaluating the effectiveness of investments and adapted for transitional market economies are the basis of the development of technical and economic indicators [20-22]. It is proved that the projection of island microgrid systems with renewable sources is possible with two compromise approaches to determining investment efficiency indicators: deterministic levels of power supply reliability and cost of electricity. The first approach is based on the calculation of present value of EIRS implementation, which includes all costs for n years of project implementation; the second one – on obtaining a specific indicator – the reduced cost of electricity at the beginning of investment project, based on the projected total volume of electricity generation and analysis of structural implementation in terms of its economic efficiency – comparing NPV (Net Present Value) with possible losses (loss of profits) in the interruptions in energy supply during the project.

CONCLUSIONS

On the basis of Markov model and simulation model of EIRS functioning with two dissimilar sources through the computational experiments, the evolution of the prime cost of electricity was developed and its dependence on the structural composition and algorithms for sources operation was proved. To obtain these results, the probabilistic method was used for modeling the availability energy potential of renewable sources. It is obvious that the prime cost of electricity is sensitive to the availability factor, which depends on the structure of EIRS. EIRS availability indexes (in particular availability factor) can vary in all structural variants of EIRS.

The prime cost of electricity varies widely from $1.42 to $4.31 per kWh throughout the simulation interval, and it is particularly sensitive to the reliability of the main source. The analysis of simulation results shows that the structural-algorithmic implementation of the EIRS using RES allows (at the pre-design stage) ensuring the given (directive-defined) levels of power supply reliability with restrictions on capital costs, and reaching the economically advantageous levels of cost of electricity, which will allow reducing the payback period of such systems by 18-20 months.

Further research related to the justification of choice of the model series, first of all, the installed generating capacities of traditional and renewable sources in the structure of EIRS and the improvement of analytical model of the reliability-cost analysis of microgrid system with the possibility of forecasting the generation levels of renewable sources in real time.

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REFERENCES

[1] Valenciaga, F., & Puleston, P.F. (2005). Supervisor control for a stand-alone hybrid generation system using wind and photovoltaic energy. *IEEE Transactions on Energy Conversion*, 20(2), 398-405.

[2] Mao, M., Jin, P., Hatziargyriou, N.D., & Chang, L. (2014). Multiagent-based hybrid energy management system for microgrids. *IEEE Transactions on Energy Conversion*, 5(3), 938-946.

[3] Kaplun, V., & Osypenko, V. (2019). About using electricity pricing for smart grid dynamic management with renewable sources. *IEEE International Conference on Energy Smart Systems (ESS)*, 2019, 256-261.

[4] Reddey, J.B., & Reddy, D.N. (2008). Probablistic performance assessment of a roof top wind, solar photo voltaic hybrid energy system. *Engineering Science & Education Journal*, 2(4), 281-298.

[5] Cecati, C., Citro, C., Piccolo, A., & Siano, P. (2011). Smart operation of wind turbines and diesel generators according to economic criteria. *IEEE Transactions on Industrial Electronics*, 58(10), 4514-4525.

[6] Choi, D., Kim, H., Won, D., & Kim, S. (2009). Advanced key management architecture for secure SCADA communications. *IEEE Transactions on Power Delivery*, 24(3), 1154-1163.

[7] Georgilakis, P. (2008). Technical challenges associated with the integration of wind power into power systems. *Renewable and Sustainable Energy Reviews*, 12, 852-863.

[8] Kondoh, J., Ishii, I., Yamaguchi, H., Murata, A., Otani, K., & Sakuta, K. (2000). Electrical energy storage systems for energy networks. *Energy Conversion and Management*, 41, 1863-1874.

[9] Deshmukh, M.K., & Deshmukh, S.S. (2008). Modeling of hybrid renewable energy systems. *Renewable and Sustainable Energy Reviews*, 12, 235-249.

[10] Roozbehani, M., Dahleh, M.A., & Mitter, S.K. (2011). *Volatility of power grids under real-time pricing*. Retrieved from https://arxiv.org/pdf/1106.1401.pdf.

[11] Osypenko V., & Kaplun V. (2017). About the intelligent decision making system for dynamic electricity pricing on renewable microgrids. In *Proceedings of the 9-th International Workshop on Inductive Modeling* (IWIM-2017) (pp. 348-350). Lviv: Lviv National Polytechnic University.

[12] Gross, J., & Yellen, J. (1999). *Graph theory and its applications*. Boca Raton: Chapman and Hall.

[13] Korolyuk, V.S., Brodi, S.M., & Turbin, A.F. (1975). Semi-Markov processes and their applications. *Journal of Soviet Mathematics*, 4(3), 244-280.

[14] Zbirko, M.D., Kuznetsov, V.N., & Turbin, A.F. (1980). On a semi-Markov model for reliability analysis of a system with restorable protection. *Automation Remote Control*, 41(6), 879-887.

[15] Mohsenian-Rad, A.-H., & Leon-Garcia, A. (2010). Optimal residential load control with price prediction in real-time electricity pricing environments. *IEEE Transactions on Smart Grid*, 1(2), 120-133.

[16] Ivakhnenko, G. (1971). Polynomial theory of complex system. *IEEE Transaction on Systems, Man and Cybernetics*, 1(4), 364-378.

[17] Holland, J., & Arbor, A. (1975). *Adaptation in natural and artificial systems*. Ann Arbor: The University of Michigan Press.

[18] Farlow, S.J. (1984). *Self-organizing methods in modeling: GMDH type algorithms*. Basel: Marcel Decker Inc.

[19] Zhao, Z., Lee, W.C., Shin, Y., Member, S., & Song, K. (2013). An optimal power scheduling method for demand response in home energy management system. *IEEE Transactions on Smart Grid*, 4(3), 1391-1400. doi: 10.1109/TSG.2013.2251018.

[20] Feroldi, D., & Zumoffen, D. (2014). Sizing methodology for hybrid systems based on multiple renewable power sources integrated to the energy management strategy. *International Journal of Hydrogen Energy*, 39(16), 8609-8620.

[21] Haddadian H., & Noroozian R. (2017). Multi-microgrids approach for design and operation of future distribution networks based on novel technical indices. *Applied Energy*, 185(1), 650-663.

[22] Ostanin, V. (2022). Effects of repulsion and attraction between rotating cylinders in fluids. *Scientific Herald of Uzhhorod University. Series "Physics"*, 51, 39-47.

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Прогнозування ціноутворення на електроенергію енергетичних островів з відновлюваними джерелами

Анотація. Стратегія розвитку локальних енергосистем малої потужності передбачає використання декількох джерел. Ефективність функціонування таких систем залежить від цілеспрямованого управління надійністю і базується на раціональних ієрархічних взаємозв'язках їх структурних складових. Узгодження структури різнорідних джерел та їх участі у формуванні енергетичного балансу мікроенергетичних систем в умовах динамічного розвитку відновлюваної енергетики є актуальним науковим завданням. Метою дослідження було розроблення методу надійнісно-вартісної оптимізації структур мікроенергосистем з різнорідними джерелами, в основу якого покладено використання показників надійності та собівартості електроенергії. Проведені дослідження ґрунтуються на сучасних методах прикладного статистичного аналізу, теорії надійності, синтезу комплексних багатоагрегатних систем. Шляхом реалізації марковської моделі та імітаційного моделювання функціонування джерел одержані умови оптимального формування енергетичного балансу мікроенергосистеми з найменшою вартістю електроенергії та урахуванням показників надійності. Обчислювальні експерименти дозволили одержати закономірності еволюції вартості електроенергії та показати її залежність від структури та алгоритмів функціонування джерел. Шляхом використання ймовірнісного методу моделювання вперше доведено, що собівартість електроенергії чутлива до коефіцієнта доступності відновлюваних джерел до первинної енергії. Практичне застосування результатів полягає в підвищення ефективності енергетичних островів шляхом структурно-алгоритмічної оптимізації різнорідних джерел (традиційних та відновлюваних) на основі визначення собівартості електроенергії

Ключові слова: різнорідні джерела електроенергії; надійнісно-вартісний аналіз; марківська модель; імітаційне моделювання; ефективність мікронергосистем