Machinery & Energetics
Vol. 15, No. 3. 2024

Journal homepage:
https://technicalscience.com.ua/en

UDC 621.316.11.004
DOI: 10.31548/machinery/3.2024.73

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Features of multi-agent evaluation of microgrid systems efficiency in parallel operation with the power system according to the reliability criterion

Abstract. Ensuring reliable electricity supply to consumers in the face of destruction of critical energy infrastructure and shortage of generating capacities in Ukraine requires the development of distribution systems and their management systems. The purpose of the study was to substantiate the development of models for ensuring the optimal structure of electrical distribution networks under the conditions of connecting micro-networks according to the reliability criterion in conditions of limited investments. The paper uses a method for assessing the structural reliability of complex electrical systems with microgrid structures and forms a rational power distribution of such structures according to the criterion of optimising the reliability indicators of the studied electric power system. A mathematical optimisation model based on a computational system was proposed, designed to solve non-convex problems with minimising integral reliability

Article's History: Received: 15.03.2024; Revised: 30.05.2024; Accepted: 15.08.2024.

Suggested Citation:
Gai, O., Novoseltsev, O., Vorushylo, A., Khomiak, O., & Gai, G. (2024). Features of multi-agent evaluation of of microgrid systems efficiency in parallel operation with the power system according to the reliability criterion. *Machinery & Energetics,* 15(3), 73-83. doi: 10.31548/machinery/3.2024.73.

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indicators, considering financial constraints and the investment efficiency curve. Based on the research, the possibilities of optimisation using the BARON solver available on the NEOS server were examined. The results of the model's performance are demonstrated using examples, considering the parameters of distribution system objects and their limitations on network components. An algorithm and programme for solving the problem of targeting power flows of microgrid structures in multi-node regional power systems are proposed. Algorithms and scenarios for the response of dispatching services are developed, provided that investments are limited, which will ensure the survivability of the power system as a whole. It is established that the development of rational electricity flows of microgrid structures will minimise the under-supply of electric energy by specific load nodes and determine their shares in covering the demand of the energy island in conditions of power shortage. The findings can be used in the operational management of power systems

Keywords: integrated reliability indicators, microgrid structure, power distribution systems, load balancing, microgrid dispatching scenarios

INTRODUCTION

In Ukraine, the structure of electricity generation capacities and power grids is undergoing significant changes, primarily due to the destruction of electricity infrastructure as a result of hostilities, which leads to disruption of existing electricity supply schedules, emergency outages, and significantly increases the integral reliability indicators, which reduces the efficiency of electricity distribution systems. All this determines the need for appropriate restructuring of the network infrastructure based on modern "smart" systems, the introduction of automation systems for controlling electric networks, regulating the operating modes of electric networks and electricity consumption using manoeuvrable capacities, and the introduction of micro-networks. These issues are of considerable scientific and practical interest and are considered by many researchers.

V. Kozyrskyi *et al.* (2020) proved that ensuring the reliability of power grids requires the introduction of partitioning devices and optimised the number and location of these devices. It was pointed out that the proper configuration of partitioning equipment significantly reduces repair costs and increases the reliability of power supply. The mathematical model developed by the authors allows assessing the economic feasibility and stability of the network for end users and is aimed at minimising losses from under-supply of electricity to consumers, but the authors did not consider the presence of microgrid structures in their models.

H. Kruhliak *et al.* (2023) explored dynamic energy component management using state-of-the-art IT technologies. It offers a real-time energy management strategy. The synthesis of a micro-network control system, in particular, its real-time power balance, was investigated. Technical platforms for implementing the principles of energy management and remote control of electric receivers are proposed. From the text of the material, it is not clear how the existing micro-network control systems regulate the reliability of the power supply system.

I. Blinov *et al.* (2022) focused on the problems of regulating the modes of electric distribution networks in Ukraine. Researchers have proposed to implement such regulation through the management of inverters of renewable energy sources, primarily solar power plants connected to this network, according to the "Smart Grid" concept. The researchers did not consider the expediency of complex regulation of modes with a restriction in the form of integral reliability indicators.

The paper by O. Kyrylenko *et al.* (2021) considered options for using electricity storage systems in electric networks. The researchers formalised a general approach to solving the problems of efficient use of electricity storage systems in electric networks as a means of improving the reliability and uninterrupted power supply to consumers. Mathematical models for evaluating the efficiency of their use and determining the optimal configuration are proposed, in particular, for regulating the modes of electrical networks in accordance with the "Smart Grid" concept. The researchers focused on improving consumer reliability, but did not investigate how this affects the reliability of distribution system objects.

H. Bielokha *et al.* (2023) proposed a transition to low-carbon economic development through profound changes in the functioning of energy systems through the use of their hybrid forms, which the researchers consider to be key active agents. However, it is noted that the stochastic nature of renewable energy creates problems that are proposed to be solved based on the mathematical approach of the logic of service dominance. This approach opens up new opportunities, in particular, in interaction with other participants in the energy markets and in preserving the environment. It is indicated that the developed models for optimising the technical and economic indicators of hybrid energy systems helped to reduce costs by 14.7%, but the duration of interruptions in power supply systems was not considered.

E. Bardyk & N.P. Bolotnyi (2023) developed a fuzzy classifier to assess the technical condition of power transformers in case of ambiguity in diagnostic data. The research was based on fuzzy set theory and optimisation methods using the Takagi-Sugeno fuzzy inference system. The results consist in creating a prototype of an expert system for assessing the technical condition of transformers from the standpoint of reliability. This approach formalises expert assessments of the condition of transformers, which allows making objective decisions about their maintenance strategy. It is worth noting that the power transformer is a key element of electrical distribution networks, but the influence of processes occurring in it from the existing microgrid structures that it heals has not been studied.

The optimal composition, location, and coordination of the operation of switching devices and protective equipment in the context of ensuring the reliability of air distribution networks was determined by V. Popov *et al.* (2022). To solve the problem, various reliability indicators were simultaneously optimised and an approach based on a modified greedy optimisation algorithm was proposed, which automatically adjusts the weights of indicators at each iteration to evenly improve all aspects of reliability, but when determining the optimal composition of reliability improvement tools, the presence of microgrid structures in networks was not considered.

H. Bila *et al.* (2022) considered the global optimisation problem using the BARON (n.d.) package – a computing system for solving non-convex optimisation problems to global optimality. It is proposed to use this software to solve purely continuous, integer and mixed-integer nonlinear problems by combining constraints, interval analysis, and duality in the arsenal of reductions with advanced concepts of branches and connections and forming a path through the hills and valleys of complex optimisation problems in search of global solutions, but in this paper a generalised description of the capabilities of the optimisation package was made.

In the study A. Zharkin *et al.* (2022), methods for determining optimal shutdown locations in distribution networks were considered and the use of remote-controlled switching devices was proposed, which is important for cyclic load changes. It is indicated that new technological solutions have made it possible to reduce energy losses and conduct dynamic network management. Strategies and management algorithms based on the economic effect criterion were implemented, but the presence of microgrid structures was not considered.

A method for quickly and accurately determining the best location of a partitioning device in distribution networks with a tree structure has been developed by V. Bezruchko *et al.* (2023). Its application to medium-voltage networks with a vacuum switch was investigated. Systems with automatic load switching and a secondary switch were analysed and the reduction of under-supply of energy to consumers was optimised, but inaccuracy in the development of a mathematical model for determining reliability indicators was made.

The analysis of scientific sources shows that the combination of modern tasks to ensure the reliability and quality of electricity supply to consumers in the conditions of increasing the share of renewable energy sources and the introduction of Smart Grid technologies determines the relevance of creating optimal scenarios for the development of regional micro-networks to improve the reliability indicators of the electric power system to which they are connected, with initially defined means of improving reliability in conditions of limited investment resources. That is why the purpose of the current study was to develop and substantiate approaches aimed at ensuring the managed functioning of regional micro-networks to improve the reliability of electricity supply to consumers. In order to achieve this goal, the task of creating algorithms and scenarios for the development of micro-networks was solved under the condition of limited investment resources and the need to provide electricity to consumers in case of various emergencies in a centralised power supply system.

MATERIALS AND METHODS

To ensure optimal scenarios for the development of electrical distribution networks, including microarrays, the theory and methods of mathematical programming were used. Optimisation problems were formulated as non-linear programming problems. The AMPL modelling language was used to describe them. The problems were solved using the BARON (Branch And Reduce Optimisation Navigator) solver – a computational system for solving non-convex optimisation problems up to global optimality – from the NEOS server (GAMS/BARON, n.d.; NEOS Server..., n.d.). The development of the model and all calculations were carried out with reference to the real economic relationship between the distribution system operator and the supervisory authority – the National Commission for State Regulation of Energy and Public Utilities (NCREPU) (Resolution No. 374, 2018)

The model for improving the reliability of the power supply system, in terms of reducing the resulting SAIDI (System Average Interference Duration Index), is based on the typical scheme shown in Figure 1. It consists of sections of lines between the corresponding nodes of the scheme L_{ij}, loads P_i, and the number of consumers in these loads N_i. Loads, if they are combined by certain conditions, form groups of loads that are indicated by large Latin letters and are accepted by the zones of microgrid formation. The diagram contains heterogeneous means of operational switching: B_1 – input switch, DS_*i* – disconnectors, RR_*i* – reclosers, etc.

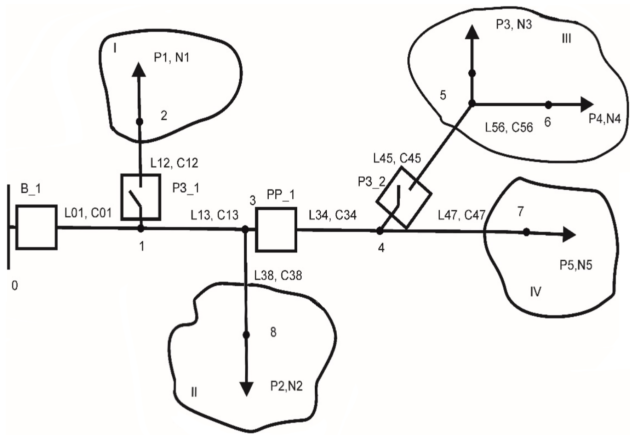

Figure 1. Typical electrical diagram of distribution system facilities.

Note: B_1 – input switch; Lij – section length, Cij – price characteristic of energy transfer by section, DS_i – disconnector, RCR_i – recloser, Pi – power consumption of the load node, Ni – number of load node subscribers

Source: compiled by the authors

The network structure was developed in accordance with the technical requirements of IEC TS 62898-4:2023 (2023). The presence of microgrids in the structure of the electrical distribution network, from the standpoint of power supply reliability, significantly depends on the possibility of microgrids operating in island mode. There are several options for the microgrid operation mode in the absence of a centralised power source:

1) offline operation is not possible;

2) "black" start is possible;

3) autonomous operation of the microgrid system with a certain load limit is possible;

4) full autonomous operation of the microgrid system is possible.

These modes of operation of microgrid structures affect the effectiveness of certain means of improving the reliability of both technical and organisational ones. Accordingly, in the developed mathematical models, to assess the optimal specification of measures and the choice of places and the number of installed elements for improving reliability, zones of development of microgrid structures are considered, in which it is impossible to achieve the reliability targets by available means.

When analysing the resulting reliability of the structure, individual reliability indicators of all consumers connected to this structure were calculated. Based on these values, the resulting assessment of the effectiveness of the structure as a whole was compiled according to method of V. Kozyrskyi *et al.* (2020).

To solve this problem, the classical methods of V. Kozyrskyi & O. Gai (2013) and R. Allan (2013) for developing a series of replacement schemes individually for each consumer were used, indicating the typical time of power supply restoration: a transparent rectangle means that the time of power supply restoration is proportional to the time of emergency restoration, and a shaded rectangle is proportional to the time of fault detection and localisation. The following assumptions were made regarding the possible, from the standpoint of reliability, features of the functioning of microgrids of the structure in accordance with the previously developed operating modes in accordance with the technical requirements of IEC TS 62898-4:2023 (2023), namely:

$$\begin{cases} 1)\ N_i = N_i, \\ 2)\ N_i = N_i \cdot f(t), \\ 3)\ N_i = x_i \cdot N_i, \\ 4)\ N_i = 0, \end{cases} \tag{1}$$

where $f(t)$ – function of changing the time and efficiency of the specified "black" start mode, the value of which lies in the range from 0 to 1 and changes in time in accordance with the capabilities of the means of automatic start of microgrids of the structure in island mode of operation; x_i – indicator that reflects the possible degree of providing power to consumers of the microgrid system in offline mode and takes the value $0 \leq x_i \leq 1$.

RESULTS AND DISCUSSION

As part of the study, the structural reliability for the circuit in Figure 1 was analysed, and a corresponding series of replacement schemes for all P_i consumers was generated, as shown in Figure 2.

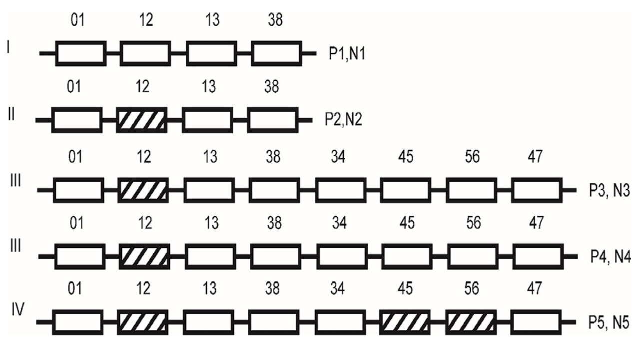

Figure 2. Replacement schemes in terms of reliability for consumers

Notes: Roman numerals I-IV – zones of microgrid structures; 01,..., 56 – equivalent elements of the replacement scheme for the corresponding sections in terms of structural reliability; reliability indicators; P_i – power consumption of the load node, N_i – number of load node subscribers

Source: compiled by the authors

It is worth noting that in the case shown in Figure 2, consumers 3 and 4 are in identical conditions, and therefore, 4 substitution schemes were chosen, which are indicated by Latin numbers, which are possible zones for the development of microgrid structures. It is accepted that consumers are equidistant from the location of the operational field repair team of the distribution system operator, and therefore, the model of finding the recovery time is simplified and taken as a basis:

$$\begin{cases} t_{\text{fast switching}} = 2 \text{ hours}, \\ t_{\text{repair}} = 6 \text{ hours}. \end{cases} \tag{2}$$

Accordingly, the reliability indicators for these structures were calculated using the equation (Kozyrsky & Gai, 2013):

$$\begin{cases} \omega_{\mathrm{Pi}} = \sum_j \omega_j, \\ \tau_{Pi} = \frac{\sum_j \omega_j \cdot \tau_j}{\omega_{\mathrm{Pi}}}, \end{cases} \tag{3}$$

where j – total number of power grids on which the power supply to the i-th consumer depends; w_{pi} – frequency of power supply failures in the Pi-th consumer; τ_{Pi} – time to restore power supply in Pi-th consumer; w_j – failure rate of the j-th section; τ_j – time of restoration of power supply to the j-th section;

Reliability indicators $SAIDI_{practical}$ and $SAIFI_{practical}$ obtained as a result of the operation of a particular distribution system facility are defined by the following expressions:

$$SAIDI_{\text{practical}} = \frac{\sum_i t_{\text{Pi}} \cdot N_{Pi}}{\sum_i N_{Pi}},$$
$$SAIFI_{\text{practical}} = \frac{\sum_i^k n_i}{\sum_i N_{Pi}}, \tag{4}$$

where i – total number of actual emergencies in the electrical network of the distribution system operator under study; $\sum_i^k n_i$ – total number of consumers that are disconnected during long emergency breaks is actually the algebraic sum of the products of the failure rate for each consumer group w_{Pi} by the number of accounting points N_{Pi} in this group; n = $\sum_i N_{Pi}$ – total number of accounting points (in the selected research object, it is assumed that this number is equal to the number of authentic substitution schemes, which are indicated by Roman numerals in Fig. 2, that is n = 4).

For theoretical research, the study moves on from the actual data on outages (t_{Pi}, N_{Pi}), which form a certain sample, up to the mathematical expectation of a certain event, which is characterised by the normal distribution law and the time for restoring power supply τ_{Pi} and failure rate w_{Pi} are determined.

$$SAIDI_{\text{theoretical}} = \frac{\sum_j \tau_{\text{P}j} \cdot \omega_{\text{P}j} \cdot N_{Pj}}{\sum_j N_{Pj}},$$
$$SAIFI_{\text{theoretical}} = \frac{\sum_j^n \omega_{\text{P}j} \cdot N_{Pj}}{\sum_j N_{Pj}}, \tag{5}$$

where j – total number of combined consumer groups (j = I..IV).

Based on a sufficiently large sample of data corresponding to the objects of distribution system operators:

$$SAIDI_{\text{practical}} \cong SAIDI_{\text{theoretical}},$$
$$SAIFI_{\text{practical}} \cong SAIFI_{\text{theoretical}}. \tag{6}$$

It is assumed that the transition from the state of normal operation of groups of electric consumers, when in an emergency situation in the electrical network, groups of consumers are de-energised according to Figure 2 (which corresponds to the state $x_j = 1$), to the state of operation of the system with microgrid structures according to criterion 4 is carried out in accordance with equation (1) (which corresponds to the state $x_j = 0$). In this case:

$$SAIDI_{\text{theoretical}} = \frac{\sum_j \tau_{\text{P}j} \cdot \omega_{\text{P}j} \cdot N_{Pj} \cdot (x_j)}{\sum_j N_{Pj}},$$
$$SAIFI_{\text{theoretical}} = \frac{\sum_j^n \omega_{\text{P}j} \cdot N_{Pj} \cdot (x_j)}{\sum_j N_{Pj}}. \tag{7}$$

To describe the effectiveness of investments ($Eff(x)$) in newly developed microgrids, a logistic or sigmoidal function is used:

$$Eff(x) = 1 - \frac{1}{1+e^{-k(x-x0)}}, \tag{8}$$

where k – parameter that determines the steepness of the transition, and $x0$ – point where the function reaches the value 0.5 (Fig. 3).

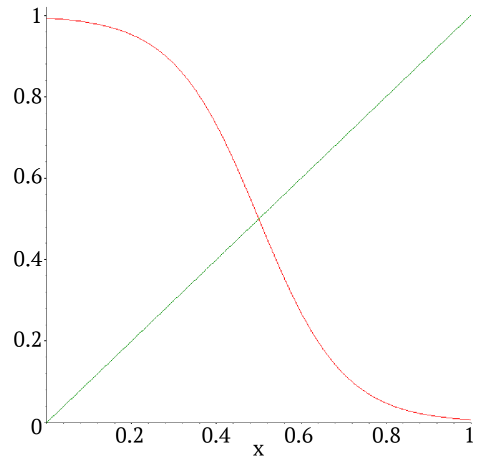

Figure 3. Graph of the dependence of capital investment efficiency in the development of microgrid structures
Source: compiled by the authors

Accordingly, having similar expert assessments for each possible microgrid structure, the investment level was optimised according to the criterion of minimising the SAIDI indicators of the overall structure, provided that the investment fund is limited (C). Thus, two optimisation functions are formed:

$$\begin{cases} SAIDI = \frac{\sum_j \tau_{\text{P}j} \cdot \omega_{\text{P}j} \cdot N_{Pj} \cdot (x_j)}{\sum_j N_{Pj}} \to min, \\ \sum_j c_j \cdot Eff(x_j) \leq C, \\ 0 \leq x_j \leq 1. \end{cases} \tag{9}$$

$$\begin{cases} SAIFI = \frac{\sum_j^n \omega_{\text{P}j} \cdot N_{Pj} \cdot (x_j)}{\sum_j N_{Pj}} \to min, \\ \sum_j c_j \cdot Eff(x_j) \leq C, \\ 0 \leq x_j \leq 1, \end{cases} \tag{10}$$

where j – total number of combined consumer groups (j = I..IV); c_j – amount of capital investment for the full implementation of the development of microgrids of the structure according to the fourth feature based on expression (1); $Eff(x)$ – sign of the efficiency of capital investments during the transition from the first to the fourth features of the functioning of microgrids of the structure according to the reliability criterion based on expression (1).

Thus, the search for the optimal solution with a limited financial resource C leads to the most efficient distribution of the levels of internal electricity supply to consumers for the existing power supply scheme and possible microgrid structures. The results of the mathematical experiment are interpreted and it is indicated that as a result of optimisation, the smaller is x_j, the more efficient is this microgrid structure to be involved in the reliability management of the object of study. Problem (9) and (10) are described using the AMPL code:

```
# parameters and variables
param n := 4; param C_1 := 7;
param p{i in 1..n}; param c{i in 1..n};
param k{i in 1..n}; param x0{i in 1..n};

var x{i in 1..n} ≥ 0 ≤ 1;

# objective and constraints
minimize obj: sum {i in 1..n} p[i]*x[i];
subject to con1: sum {i in 1..n} c[i]*(1.0-1.0/(1.0 + exp(-k[i]*(x[i]-x0[i])))) ≤ C_1;

option baron_options ‘barstats outlev=1 maxtime=120’;
problem NLPa: obj,x,con1;

Accordingly, the input data for the AMPL test case and the BARON solver run are formed as follows:

# prepare the Data
data;
# Data SAIDI
let p[1]:=263.8919308; let p[2]:=149.9870317; let p[3]:=819.2723340; let p[4]:=346.4481268;
# Data SAIFI
#let p[1]:=0.7330331412; let p[2]:=0.5015489914; let p[3]:=2.494776657; let p[4]:=1.199243516;
let c[1]:=5; let c[2]:=5; let c[3]:=9; let c[4]:=6;
let k[1]:=10; let k[2]:=10; let k[3]:=10; let k[4]:=10;
let x0[1]:=0.5; let x0[2]:=0.7; let x0[3]:=0.3; let x0[4]:=0.5;
display p,c,k,x0;
display C_1;

solve NLPa; display obj, _solve_time;
display x;
```

A mathematical experiment was performed for the scheme shown in Figure 1, in accordance with the initial information provided by the distribution system operator regarding the number of accounting points (N_{Pi}), which are part of the scheme for certain groups of consumers Pi (Table 1) and parameters of line lengths of the electric power circuit segment (Table 2). Using expression (5), the reliability indicators of the research object for the implementation of the recommended innovations are calculated and obtained:

$$SAIDI_{\text{theoretical}} = \frac{\sum_j \tau_{Pj} \cdot \omega_{Pj} \cdot N_{Pj}}{\sum_j N_{Pj}} = 1{,}579.6 \text{ min};$$

$$SAIFI_{\text{theoretical}} = \frac{\sum_j^n \omega_{Pj} \cdot N_{Pj}}{\sum_j N_{Pj}} = 4.93 \text{ times}.$$

Table 1. Parameters of combined load groups of the electric power scheme segment

Pi	I	II	III	IV
N_i	323	221	570	274

Notes: Pi – power consumption of the load node, N_i – number of load node subscribers
Source: compiled by the authors

Table 2. Parameters of line lengths of the power circuit segment

Land plot number *ij*	01	12	13	38	34	45	56	47
L_{ij}	2.7	3.2	1.5	5.2	3.6	2.2	1.8	4.1

Notes: L_{ij} – plot length
Source: compiled by the authors

As a result of calculations using the BARON solver from the NEOS server, a result was obtained that shows that the optimal value of the indicator SAIDI = 780.4984666 to find this value, 692 iterations were implemented, which helped to distribute a limited investment resource of 7 units between a possible four microgrid structures (Fig. 1) in the ratio 1 – 0.654453; 2 – 0.930648; 3 – 0.300806; 4 – 0.640115, it is worth noting that the closer the result is to zero, the more investment resources should be spent on this particular facility:

```
═══════════════════════════════════════════════
Iteration Open nodes Time (s) Lower bound Upper bound
1 1 0.06 592.312 780.498
* 138 6 0.32 741.616 780.498
* 531 9 0.70 780.105 780.498
692 0 0.83 780.498 780.498
Calculating duals
*** Normal completion ***
Wall clock time: 0.84
Total CPU time used: 0.83
Total no. of BaR iterations: 692
Best solution found at node: 531
Max. no. of nodes in memory: 13
All done
═══════════════════════════════════════════════
BARON 23.3.11 (2023.03.11): 692 iterations, optimal within tolerances.
Objective 780.4984666
Objective lower bound = 780.497572145, upper bound = 780.498352643
barstatus = 1, modelstatus = 1
max nodes in memory = 13
optimum found at node 531
Baron run time (excluding setup) = 0.83 seconds
obj = 780.498
_solve_time = 0.846831
x [*] :=
1 0.654453
2 0.930648
3 0.300806
4 0.640115
;
sum{i in 1 .. n} c[i]*(1 - 1/(1 + exp(-(k[i]*(x[i] - x0[i]))))) = 7
```

Table 3 summarises the results of calculations and evaluates the effectiveness of capital investments in the development of microgrid structures according to the reliability criterion.

Table 3. Initial information on investment efficiency and modelling results in the NEOS Solver

P_j	I	II	III	IV	$SAIDI_{reop}$	$SAIFI_{reop}$	Δ	Δ, %	Δ, % / C, % C.U.
c_j	5	5	9	6					
x_{0j}	0.5	0.7	0.3	0.5					
$x_{j\ SAIDI}$	0.654	0.931	0.301	0.640	780.498		799.10	50.59	7.23
$x_{j\ SAIFI}$	0.669	0.919	0.309	0.618		2.462	2.468	50.06	7.15

Note: j – total number of combined consumer groups (j = I..IV); c_j – amount of capital investment for the full implementation of the development of microgrid structures according to the 4th feature according to expression (1); $x_{0\ j}$ – point where the function Eff(x_j) reaches a value of 0.5; $x_{j\ SAIDI}$ – solutions of the objective function for certain combined groups of consumers (j = I..IV) when optimising SAIDI; $x_{j\ SAIFI}$ – solutions of the objective function for certain combined groups of consumers (j = I..IV) when optimising SAIFI; Δ, Δ,% – reduction of the reliability indicator in named and conventional units, Δ, % / C – value of capital investment efficiency per conventional unit of resource spent from the investment programme
Source: developed by the authors using NEOS Solver (n.d.)

Table 3 summarises the results of a mathematical experiment that determines the optimal distribution of available limited investment capital, provided that it is directed to increase a certain legally regulated reliability indicator (SAIDI and SAIFI are considered in the model). It is worth noting that the use of limited investment capital in this way partially compensates the owners of microgrid structures for investment in their development and significantly improves the reliability indicators of distribution system operators. For example, in the proposed version, the improvement in reliability indicators will be slightly more than 50%, while % / C – efficiency of capital investments per conventional unit of resource spent from the investment programme is slightly more than 7% per 1 conventional unit of resource spent.

The study by A. Muhtadi *et al.* (2021) focuses on integrating microgrids into electrical distribution systems to improve their reliability. At the same time, the researchers focused more on key aspects of microgrids based on distributed energy resources (DER) and modelled the impact of DER, electric vehicles (EV), and energy storage systems (ESS) on network sustainability. It is worth noting that approaches to ensuring reliability vary: since the current study focuses more on mathematical optimisation and algorithms, while A. Muhtadi *et al.* (2021) analyse the impact of specific technologies and management strategies on the practical aspects of implementing DER, ESS, and EV to improve network reliability and sustainability.

M. Sandelic *et al.* (2021) explores the issue of sustainable electricity supply using microgrids using distributed energy resources, which is consistent with this research. Special attention in the study was paid to improving the methods of reliability assessment through the analysis of wear of power electronics and its impact on the system, this approach is more technical, considering the algorithms and response scenarios of dispatching services under the condition of limited investment, which allows ensuring the survivability of the power system. It is important to note that the study by M. Sandelic et al. (2021) did not analyse the impact of the reliability of microgrids on the development of new procedures for designing and planning future microgrids, which is an important aspect for ensuring the long-term reliability and efficiency of microgrids.

Comparison of the findings of this study with the scientific proposals of V.K. Garg *et al.* (2020), who developed the optimal PV-BESS-based microgrid structure to provide stable electrical energy in the face of load changes and power shortages in rural India, showed that their study did not analyse the possible risks or limitations that may arise when implementing microgrids, in particular, in terms of the reliability of power supply systems.

Comparison of this study with the approaches of C.A. Cortes *et al.* (2017), who proposed an iterative procedure for optimal design of the microgrid topology in active distribution networks, based on graph breakdown, integer programming and performance index for optimal design, however, the researchers did not consider the reliability indicators of microgrids under variable load and equipment failures, which affects the survivability of both microgrids and the distribution system as a whole, and did not form recommendations on the influence of the reliability of microgrid structures on the development of new patterns of design and planning of electrical networks of distribution system operators.

When analysing the results, it is worth referring to the study by S. Peyghami *et al.* (2021), which developed the reliability model of power electronic converters and investigated their impact on the reliability of the power system, but their study does not cover the analysis of the possible impact of reliability on the survivability of the power grid in conditions of failures in the power system itself, and did not conduct mathematical optimisation and did not form algorithms that allow minimising integral reliability indicators, considering financial constraints.

B. Zhang *et al.* (2020) developed a hierarchical structure for evaluating the reliability of an electric power system and considered it from the level of a power electronic converter to the general system. However, it is worth noting that the developed models allow obtaining an estimate of the reliability indicators of microgrid structures considering the system level, but do not form an integral assessment of the reliability of the influence of microgrid structures on the resulting efficiency of distribution systems as a whole.

When comparing the results, it is worth referring to material of X. Guo *et al.* (2024), where the researchers reviewed an integrated index system that takes into account two-level performance and reliability indices, and proposed an agent-based model for modelling physical objects and energy dispatching strategies. The researchers focused on developing indexes, but did not consider exactly how the integrated reliability assessment index system takes into account the interaction between maintenance strategies and limited investment resources.

Comparison of the results obtained with the findings of K. Pang *et al.* (2024), who proposed a new method of long-term planning based on deep learning in the face of various uncertainties, in which the micro-network acts as a backup energy source. They show that in the development of microgrid, it is important to resolve the issue of redistribution and dating of various technical solutions according to the criterion of minimising reliability indicators with a limited investment resource.

In order to compare the conclusions obtained, it is necessary to refer to the study by P.S. Meera *et al.* (2022), which provides an overview of the impact of distributed generation on reliability, considers various methods for evaluating the reliability of the distribution network – analytical, simulation, and hybrid, which affect the optimal placement of switching devices, the use of distributed generation and network reconfiguration, in contrast to this study, where the proposals are evaluated not only from the standpoint of the facility owner, but also consider aspects of improving the efficiency of the distribution system operator as a whole.

It is advisable to compare the findings with the developments of A. Nargeszar *et al.* (2022), which assessed the impact on the reliability of microgrids of changes in the energy characteristics of renewable resources, such as wind speed, tidal flows, and solar radiation, based on the developed equations, but these researchers, unlike the present study, did not interpret the proposed models on the level of centralised power supply and did not assess the possible impact of the reliability of microgrid structures on the efficiency of the system as a whole.

When formulating and approving the investment policy of a distribution system operator in terms of ensuring the planned performance in terms of reliability, it takes a long time to develop adequate responses and scenarios. This introduces significant restrictions on the development of timely management decisions and assessments of effective areas for the development of investment policy to optimise comprehensive indicators of the reliability of the distribution system operator.

As a result of the current study, a mechanism for partial compensation of the cost of forming microgrid structures through the rational allocation of funds from the investment programme of the distribution system operator, the purpose of which is to increase the efficiency of electricity supply to consumers in modern conditions, has been proposed. A method for finding the optimal values of reliability indicators has been developed based on the distribution of the "depth" of microgrid structures at the facilities of distribution system operators, which is formed by the distribution system operator. It is indicated that this approach can be used as an additional tool for the decision-making system in the operational dispatching management of regional energy systems and the assessment of effective areas for the development of investment policy, the purpose of which is to optimise the integral reliability indicators of the distribution system operator.

CONCLUSIONS

As a result of the research, the main goal was achieved – to substantiate the creation of models for ensuring the optimal structure of electrical distribution networks under the conditions of connecting microgrids, considering the criterion of reliability and limited investment. A method for assessing the structural reliability of complex electrical systems with microgrid structures was developed, which helped to develop a rational power distribution of such structures, optimising the reliability indicators of the electric power system under study. The proposed mathematical optimisation model based on a computational system proved to be effective for solving non-convex problems with minimising integral reliability indicators, taking into account financial constraints and the investment efficiency curve. The use of the BARON solver available on the NEOS server confirmed the possibility of optimisation, demonstrating the results using examples, considering the parameters of distribution system objects and their restrictions on network components. Using the basic example, the efficiency of the proposed solutions was demonstrated in the form of slightly more than 50% improved integral reliability indicators and the relative coefficient of investment efficiency per conventional unit of resource spent from the investment programme was determined, which was slightly more than 7% per 1 conventional unit of resource spent. An algorithm and programme for solving the problem of targeting power flows of microgrid structures in multi-node regional power systems was developed, which allows ensuring the survivability of the power system under the condition of limited investments. The results of the study showed that the development of rational electricity flows of microgrid structures minimises the under-supply of electric energy by specific load nodes and determines their recommended shares in covering demand in conditions of power shortage. The results obtained are recommended for use in operational and strategic management of energy systems, which would help to increase their reliability and efficiency of using a limited investment resource.

An important area for further research is to combine methods and models for optimising the number and types of reliability enhancement equipment with the introduction of microgrid structures to increase the investment attractiveness of such technical solutions. It is also advisable to conduct additional research on the efficiency of investments in each specific microgrid structure and to form integral dependencies of the technical and economic efficiency of island modes and the development of a solution based on a multi-criteria Pareto-optimal for a certain group of reliability indicators, since the developed model showed that the optimal solution is slightly different for different reliability indicators.

ACKNOWLEDGEMENTS

The publication was prepared as part of the scientific work "Models and means of preventing deterioration of the quality of power supply to industrial consumers (Monitor-4)" (KPKVK 6541030). The fourth author expresses gratitude to the Volkswagen Foundation (grant No. 97775).

CONFLICT OF INTEREST

The authors declare no conflict of interest.

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Особливості мультиагентної оцінки ефективності роботи систем мікрогрід при паралельній роботі з енергосистемою за критерієм надійності

Анотація. Забезпечення надійного електропостачання споживачів за умов руйнування критичної енергетичної інфраструктури та дефіциту генерувальних потужностей в Україні потребує розвитку систем розподілу та систем керування ними. Метою дослідження було обґрунтування створення моделей забезпечення оптимальної структури розподільних електричних мереж за умов приєднання мікромереж за критерієм надійності в умовах обмежених інвестиційних вкладень. В роботі застосовано метод оцінювання структурної надійності складних електричних систем з мікрогрід структурами та сформовано раціональний розподіл потужності таких структур за критерієм оптимізації показників надійності досліджуваної електроенергетичної системи. Було запропоновано математичну модель оптимізації на основі обчислювальної системи, призначену для розв'язання неопуклих задач з мінімізацією інтегральних показників надійності, враховуючи фінансові обмеження та криву ефективності капіталовкладень. На основі досліджень розглянуті можливості оптимізації з використанням солвера BARON, доступного на NEOS сервері. Результати ефективності моделі демонструються на прикладах, враховуючи параметри об'єктів систем розподілу та їх обмеження на компоненти мережі. Запропоновано алгоритм і програму для розв'язування задачі адресності потоків потужності мікрогрід структур у багатовузлових регіональних енергосистемах. Сформовано алгоритми та сценарії реагування диспетчерських служб за умови обмеженості інвестиційних вкладень, що дозволить забезпечити живучість енергосистеми в цілому. Встановлено, що формування раціональних потоків електроенергії мікрогрід структур дозволить мінімізувати недовідпуск електричної енергії конкретними вузлами навантаження і визначати їх частки у покритті попиту енергоострова за умов дефіциту потужності. Результати дослідження можна використати в операційному управлінні енергосистемами

Ключові слова: інтегральні показники надійності; мікрогрід структури; систем розподілу електроенергії; балансування навантаження; сценарії диспетчеризації мікрогрід