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Modeling and method for assessing the efficiency of the power system

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ABSTRACT

The work is dedicated to addressing the issues related to assessing the efficiency of modern electrical power systems, especially as an increasing number of consumers desire to actively influence the electricity supply schedule, providing conditions to electricity producers. The research can be divided into two main segments: the development of a model for assessing the efficiency of electrical power system operation and the development of a method for analyzing the performance of the energy system, which is based on a model of changes in the quality indicators of the energy system. The proposed model takes into account properties of the energy system such as the probability of uninterrupted network operation, normalized frequency of electrical power, the volume of consumed electrical energy, and the electrical energy supplied by the transmission organization. It is expected that this model will help provide a more accurate assessment of the efficiency of energy system operation under normal operating conditions. Furthermore, a method for analyzing the efficiency of energy system operation has been developed, which is based on a model of changes in the quality indicators of the energy system. A unique feature of this method is the introduction of a new comprehensive indicator of energy system efficiency, which is determined using a convolution method of partial indicators, namely: the volume of electrical energy supply, the quality of electrical energy supply, and the efficiency of electrical energy supply. The reliability of the model was confirmed through the calculation of the daily electric supply and load schedule.

Keywords: Modeling; electrical power system; efficiency assessment; effective operation of the energy system; electrical power supply indicators; daily load schedule; automatic control system; energy production cost; consumer management

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INTRODUCTION

In the modern world, increasing energy demand, rapid changes in climate conditions, and the scarcity of traditional resources create the need for new approaches to energy systems. Addressing these challenges depends on our ability to efficiently manage energy to ensure a sustainable and stable future for the global community.

Efficiency assessment of the energy system becomes a crucial tool in achieving ambitious energy goals. It enables a scientific approach to analyzing energy complexes, identifying effective and ineffective solutions, and developing strategies aimed at reducing energy consumption, optimizing resource utilization, and minimizing negative impacts on the environment.

Knowledge of methods for assessing the efficiency of energy systems is highly relevant for energy industry professionals, researchers, as well as government and commercial entities involved in the development of energy policy strategies.

By conducting an analysis and comparison of different methods, we can identify optimal solutions for creating a more resilient, efficient, and environmentally friendly energy system for the future.

LITERATURE REVIEW

Assessing the efficiency of an energy system involves various methods and tools that systematically study, analyze, and measure different aspects of the energy system and its components.

These methods help determine the level of system efficiency, identify potential issues, conduct comparative analyses of different operational modes, and develop strategies to optimize all elements of the energy complex.

The implementation of energy storage systems is one of the most future-oriented directions for enhancing the efficiency of an energy system.
Additionally, such an initiative allows addressing other important tasks related to providing ancillary services, such as voltage and frequency regulation in the electrical power system [1, 2], [3].

The article [4] proposes an innovative approach to assessing the capabilities of energy supply in distribution systems. In this approach, the power output of the power source is considered as the target parameter, while various user requirements for reliability are treated as primary constraints. Modeling demonstrates that the proposed approach can contribute to increasing the economic efficiency of distribution systems while simultaneously increasing the power supply capacity. It has also been observed that relaxing reliability constraints can significantly enhance the operational capabilities of the power source. Furthermore, the impact of increasing the capacity of distributed generation on improving reliability becomes more apparent when the system load increases [5].

In the articles [6, 7], an algorithm has been proposed to assess the efficiency of the energy system after the installation of distributed energy resources (DER), which corresponds to the reductions in technological energy costs.

$$\delta W = \Delta W - \Delta W(P_{DRG}), \quad (1)$$

where ΔW is technological electricity consumption in the absence of DER; $\Delta W(P_{DRG})$ is technological electricity consumption in the electric network with the presence of DER P_{DRG}.

In the article [8], a model has been proposed for assessing the effectiveness of the power supply system, which involves analyzing the power system graph (PSG) and evaluating each element of the power supply system based on selected indicators.

As an integral indicator of the performance efficiency of any existing power supply system, it is proposed to use the profitability of electricity processing, which can be determined by the ratio of net income from electricity processing to the expenses for its processing, as referenced in [9].

$$P = \frac{\Delta EPV}{E}, \quad (2)$$

where ΔEPV is net income from electricity processing; E is company's expenses on electricity processing.

In articles [10, 11], a new model has been developed that allows for the evaluation of performance efficiency and budget surplus indicators for systems with multiple states in the presence of interaction between damage and maintenance processes.

In this model, the impact of changes in the performance of multi-state systems on their performance efficiency is investigated [12].

In the articles [13, 14], it is comparatively easy to implement the potential for improving energy efficiency offered by early energy assessments that take into account local regulations and specific conditions, instead of providing a one-size-fits-all solution, which is often directly transferred from a completely different context and developed according to different parameters.

The technology of production and the quality of life are based on the development and efficient use of energy, as well as the indicator of energy consumption per capita [15]. In the face of the imbalance between energy demand and generation, as well as increasing environmental pressures, an integrated energy system has become a necessary cornerstone for meeting the growing demand for energy [16]. An integrated energy system can be seen as a comprehensive system of energy production, supply, and distribution created through organic coordination and optimization of energy production, transmission, conversion, storage, and consumption in the planning, construction, and operation processes [17]. Integrated energy systems are of paramount importance for increasing energy efficiency, reducing carbon emissions, and ensuring the production of clean energy [18].

In [19, 20], a performance indicator for evaluating the efficiency of power plants was proposed, which is based on the properties of productivity indicators obtained from the analysis of feasibility and thermodynamic efficiency. The efficiency indicator for the operation of a power plant within an energy system was developed using the properties of constraints and the possibility of combining different types of energy, taking into account their distinct impacts, borrowed from thermodynamics analysis. [21] Additionally, the properties of sequence and balance of the considered options were drawn from the feasibility analysis. This indicator was adopted as the basis for formulating the optimization task for generating the power plant's output.

In [22] a method for analyzing efficiency is described, which enables the effective allocation of maneuverability characteristics among power plants. When there is an imbalance between the system demand and the capacity generated by power generation facilities, the concept of marginal energy cost is used to balance the system demand for appropriate analysis [23].

The implementation of an inadequate and inefficient energy strategy can lead to negative consequences, such as energy crises, rising energy costs, environmental pollution, and dependence on external energy supplies.

Therefore, ensuring the efficient use of energy and improving energy efficiency becomes an important strategic goal for society and the country's economy.

In modern conditions of the development of the electricity market, an increasing number of consumers express a desire to actively influence the electricity supply schedule by providing conditions to electricity producers.

This process, known as demand-side management, includes shifting electricity consumption hours, setting peak tariffs, agreements on load restrictions or increases during specific periods, and so on.

Typically, such conditions are established through special contracts or additional agreements between consumers and electricity producers. These contracts help ensure the necessary volume of electricity to meet the consumers' needs and maintain the stability of the electrical supply.

Assessing the efficiency of energy system operation using existing methods, taking into account consumer management and contracts, is impossible; therefore, there is a need to adapt the methods to different system configurations and operating modes.

THE PURPOSE OF THE ARTICLE

The goal of the article is to enhance the efficiency of the electrical power system by improving the method for evaluating the operation efficiency of the electrical power system under normal operating conditions, taking into account disturbances that occur depending on the volume, quality, and effectiveness of electricity supply.

To achieve the objective, the following tasks need to be addressed:

– to develop models that determine the performance indicators of the energy system to assess the volume, quality, and efficiency of electricity supply.

– to develop a method for analyzing the efficiency of energy system operation based on a convolution model of energy system operation indicators.

MAIN PART
MODEL FOR ASSESSING THE EFFICIENCY OF THE POWER SYSTEM

To determine the efficiency indicator of energy system operation, the following assumptions need to be made. Due to the predominance of thermal power plants in the Ukrainian energy system, the influence of the self-regulation coefficient from hydroelectric power stations is insignificant, so it can be considered negligible and set to 0. The value of the load regulating coefficient at full capacity, k_n, can vary significantly during the day due to changes in the load profile and depending on voltage-frequency characteristics. The complexity in calculating the value of k_n, even with a known load profile, lies in determining the relationships $\frac{\partial U}{\partial \omega}$. Therefore, significant attention is given to the experimental determination of k_n. For a small power system up to 100 MW, the value of k_n is assumed to be 2 [24].

A model that determines the efficiency of electricity supply calculates a generalized indicator formed by the convolution of partial indicators, including:

– the volume of electricity supply (C_p);

– the quality of electricity supply (C_f);

– the efficiency of electricity supply (C_{ef}).

The individual indicators of the model $C_п$, C_f, $C_{еф}$ are grouped together as they all express the efficiency of electricity supply. Therefore, these indicators are aggregated into a comprehensive indicator C_r using the ideal point method. The ideal point method is commonly used in multi-criteria optimization problems and doesn't rely on auxiliary information regarding preferences among the set of indicators.

The fundamental idea of this method is based on the assumption that there exists an ideal point at which all indicators reach their extremes for the problem's solution. However, in practice, finding such an ideal point is usually not feasible. Therefore, it becomes important to determine a point close to the ideal point that belongs to the set of feasible solutions [25].

To solve a multi-objective optimization problem using the ideal point method, you first determine the coordinates of the ideal point and its metric to calculate the distance to the optimal point. Finding the coordinates of the ideal point involves solving individual single-objective optimization problems for each of the optimization criteria. When the ideal point belongs to the set of feasible solutions, the problem is considered solved.

The proposal to address the issue of electricity shortages by borrowing it at interest from another energy transmission organization is similar to a banking system's principle. This approach suggests that when there's a shortage of electricity in one area, it can be borrowed or transferred from another organization that has excess capacity. It's a concept similar to financial borrowing but applied to the energy sector to ensure a more reliable and stable electricity supply.

The indicator of electricity supply volume is calculated using the following formula

$$C_p = \frac{P_m \cdot V_{c.e}}{V_{p.e}}, \quad (3)$$

where P_m is probability of failure-free network operation; $V_{c.e}$ is consumed electricity volume, MVA·h; $V_{p.e}$ is supplied electricity volume, MVA·h.

The indicator of electricity supply quality is determined as

$$C_f = \frac{\omega_f}{\omega_n}, \quad (4)$$

where ω_n is normalized frequency value of electricity, Hz; ω_f is actual frequency value, Hz.

The actual frequency value can be calculated as follows

$$\omega_f = \frac{\Delta S}{\frac{S_g}{S_{sp}}(-m_g + k_n)}, \quad (5)$$

where m_g is the coefficient of frequency self-regulation at full power in the power system; k_n is the coefficient of load regulating effect at full power; S_p is the magnitude of the total power consumed by the load in the power system, MVA; S_g is the magnitude of the total power generated and transported by the power system, MVA.

The regulating effect of load at full capacity is determined as

$$\frac{\partial S_{sp}(\omega, U)}{\partial \omega} = \frac{\partial S_{sp}}{\partial \omega} + \frac{\partial S_{sp}}{\partial U}\frac{\partial U}{\partial \omega}. \quad (6)$$

The values of $\frac{\partial S_{sp}}{\partial \omega}$ and $\frac{\partial S_{sp}}{\partial U}$ are determined by the properties of consumers, while the coefficient $\frac{\partial U}{\partial \omega}$ depends on the characteristics of generators, the electrical network, and automatic frequency regulators.

The coefficient of load regulating effect at full power is determined as the derivative of the expression in formula (7) with respect to frequency at the point $\omega = \omega_0$.

$$k_n = \frac{\partial S_n}{\partial \omega}\frac{\omega_0}{S_{n0}}\bigg|_{\omega=\omega_0} = \frac{S_1 + 2S_2 + ... + nS_n}{S + S_1 + S_2 + ... + S_n}. \quad (7)$$

To assess the efficiency of electricity supply and consumption, an **efficiency coefficient** is introduced and determined by the formula

$$C_{ef} = \frac{V_{c.e}}{V_{p.e} + V_b + (V_b \cdot C)}, \quad (8)$$

where $V_{c.e}$ is the volume of consumed electrical energy within the selected time interval, MVA·h; $V_{p.e}$ is the volume of electrical energy supplied by the electric utility company, MVA·h; V_b is the volume of electrical energy borrowed from another electric transmission organization through the banking system, MVA·h; C is the percentage introduced for electricity usage.

The overall model indicator, an indicator of electricity supply efficiency, is derived based on the partial indicators C_p, C_f, C_{ef} the ideal point method and is defined as follows:

$$C_r = \sqrt{\sum_{i=1}^{n}(C_i - C_{id.i})^2}, i = \overline{1, n}, \quad (9)$$

where C_i is the values of the partial indicators; C_{id} is the values of the partial indicators at the ideal point – a fictitious point in an n-dimensional space where the values of the partial indicators reach their extremum.

METHOD OF POWER SYSTEM EFFICIENCY ANALYSIS

To determine the partial indicators mentioned in formulas (3, 4, 8), let's consider an example of a daily schedule of total electricity supply and consumption, as shown in Fig. 1.

The daily schedule of total electricity supply and consumption is divided into three time intervals, namely:

– interval I from 7:00 AM to 11:00 AM;
– interval II from 11:00 AM to 13:00 PM;
– interval III from 13:00 AM to 18:00 PM.

To calculate the partial indicators for interval I

According to the graph in Fig. 1 (interval I), the volume of consumed electrical energy exceeds the supplied volume, indicating a shortage of electricity for the consumer, which indicates inefficient electricity supply.

1) The indicator of electricity supply volume is determined by formula (3).

The volume of supplied electricity is determined by the formula

$$V_{p.e}^{I} = S_{p.e}^{I}(t_{11} - t_7), \text{ MVA} \cdot \text{h}. \quad (10)$$

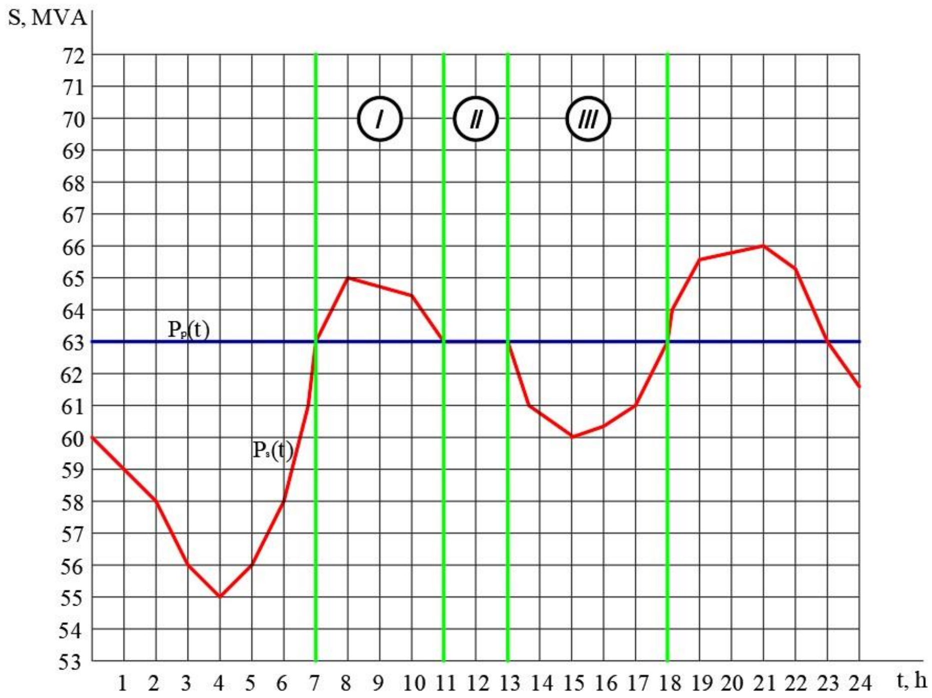

Fig. 1. **Daily schedule of full electrical energy supply and consumption**
Source: **compiled by the authors**

The volume of consumed electricity is calculated using the formula

$$V_{c.e}^{I} = \sum_{i=7}^{11} \left(\frac{S_{c.e.i}^{I} + S_{c.e.i+1}^{I}}{2} (t_{i+1} - t_i) \right), \text{ MVA} \cdot \text{h}. \quad (11)$$

2) The indicator of electricity supply quality is calculated using formula (4), which involves finding the ratio of the actual frequency value to the normalized value.

3) The indicator of electricity supply efficiency is determined by formula (7).

The volume of supplied electricity is calculated using formula (10).

The volume of consumed electricity is calculated using formula (11).

The volume of borrowed electricity is determined as follows:

$$V_{b}^{I} = V_{c.e}^{I} - V_{p.e}^{I}, \text{ MVA} \cdot \text{h}. \quad (12)$$

The percentage (C) introduced for borrowing electricity is based on the tariffs of the electricity transmission organization, which lends a certain volume of electricity in debt.

Calculation of partial indicators for interval II

On interval II, the volume of supplied electricity equals the volume of consumed electricity.

This case is considered ideal in terms of electricity supply efficiency.

1) The electricity supply volume indicator is calculated using formula (3).

The volumes of electricity supplied and consumed are determined using the formula

$$V_{p.e}^{II} = V_{c.e}^{II} = S_{p.e}^{II}(t_{13} - t_{11}), \text{ MVA} \cdot \text{h}. \quad (13)$$

2) The power quality index is calculated using formula (4), which finds the ratio of the actual frequency value to the normalized one.

3) The efficiency index of electricity supply volume is determined by formula (7).

The volumes of electricity supplied and consumed are calculated using formula (13).

Since on interval II, the volume of electricity consumed is equal to the volume of electricity that can be transmitted by the electricity transmission organization, there is no need to take electricity in debt.

Calculation of partial indicators for interval III

According to the graph in Figure 1 (interval III), the volume of supplied electricity exceeds the volume of electricity consumed.

Since the consumer does not fully utilize the supplied volume of electricity, there is an excess, which characterizes inefficient supply.

1) The electricity supply volume indicator is calculated using formula (3).

The volumes of electricity supplied and consumed are determined using the formula

$$V_{p.e}^{III} = S_{p.e}^{III}(t_{18} - t_{13}), \text{ MVA} \cdot \text{h}. \quad (14)$$

The volume of consumed electricity is calculated using the formula

$$V_{c.e}^{III} = \sum_{i=13}^{18} \left(\frac{S_{c.e.i}^{III} + S_{c.e.i+1}^{III}}{2} (t_{i+1} - t_i) \right), \text{ MVA} \cdot \text{h}. \quad (15)$$

2) The indicator of power supply quality is calculated according to formula (4), which involves finding the ratio of the actual frequency value to the normalized frequency.

3) The indicator of electricity supply volume efficiency is determined by formula (7).

The supplied electricity volume is found using formula (14).

The consumed electricity volume is calculated using formula (15).

As on interval III, the volume of electricity consumed equals the volume of electricity that the electricity transmission organization can transmit, there is no need to borrow electricity through the banking system.

Fig. 2 shows the hourly variation graph of the aggregated indicator C_r.

RESEARCH RESULTS

The efficiency of electricity supply is assessed by the aggregated indicator of power supply efficiency (C_r).

To determine it, partial indicators (C_p, C_f, C_{ef}) are calculated, based on which aggregation is performed in C_r.

According to the graph in Fig. 1, the total power supplied by the power transmission organization over the course of a day is S_p = 63 MVA.

For interval I, the volume of electricity supplied $V^{I}_{p.e}$ amounts to 252 MVA·h.

The volume of electricity consumed $V^{I}_{c.e}$ amounts to 257.162 MVA·h.

The probability of the node in the power system operating without failure $P_{м}$ amounts to 0.496.

Then, according to formula (3), the electricity supply volume indicator is calculated as C_p = 0.506.

To calculate the electricity supply quality indicator (C_f) you calculate the actual frequency value using formula (5), which results in ω_f = 48.968 Hz.

The electricity supply quality indicator (Cf) calculated using formula (4) is equal C_f = 0.979.

The electricity supply efficiency indicator C_{ef} calculated with a 10% banking interest and the amount of borrowed electricity, which is 5,162 MVA·h, according to formula (7), is 0.978.

The overall electricity supply efficiency indicator for interval I, calculated using formula (8), is C_r = 0.537.

The results of calculations for the overall electricity supply efficiency indicator on intervals I - III are presented in Table 1.

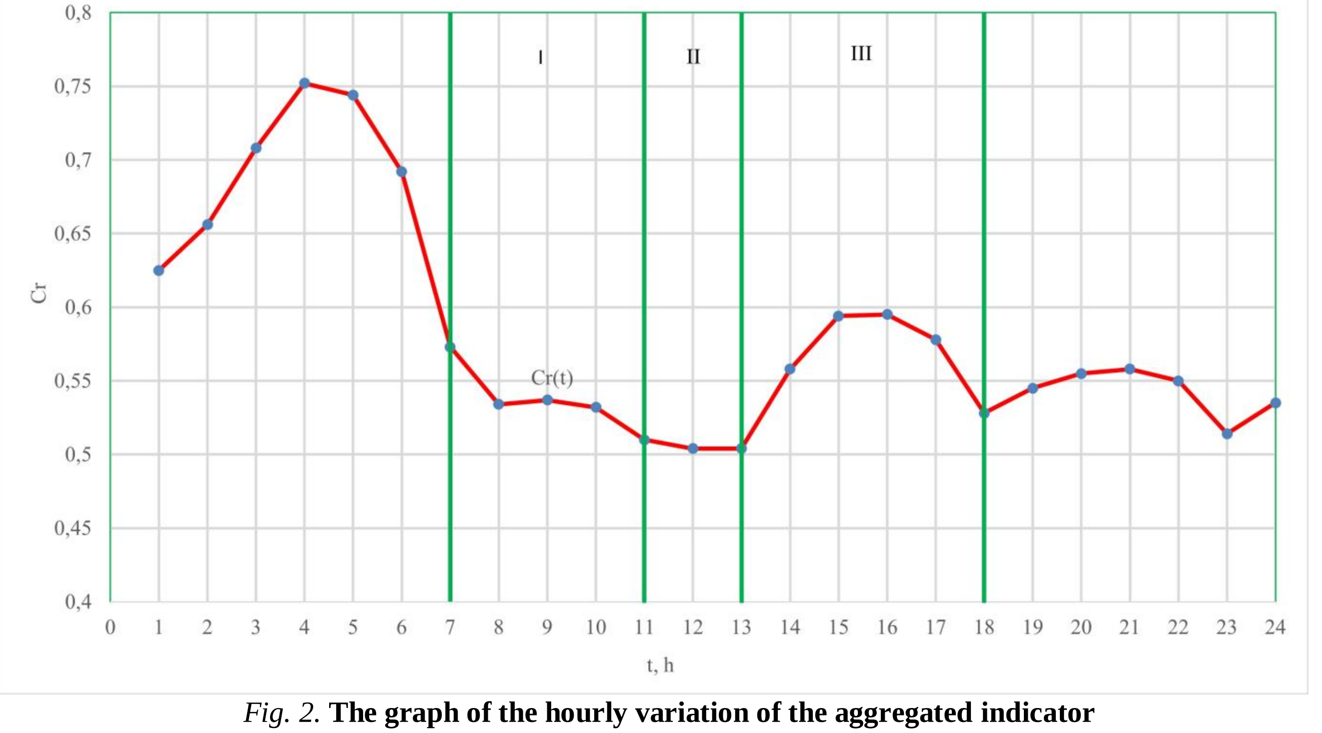

Fig. 2. **The graph of the hourly variation of the aggregated indicator**
Source: **compiled by the authors**

On interval I, the electricity supply volume indicator is C_p = 0.537, $V_{p.e}$ < $V_{c.e}$, which means that the volume of electricity consumed exceeds the volume of electricity supplied. This indicates inefficient electricity supply.

The electricity supply quality indicator Cf is 0.979, indicating a deviation of the frequency from the normalized value (50 Hz) by 2.1 %.

The efficiency indicator for electricity supply and consumption, which is 0.978, indicates inefficiency in supply since $V_{p.e}$<$V_{c.e}$, which means there is a need to borrow electricity from another electricity transmission organization through the banking system with interest. The shortage of electrical energy is equal to V_b = 5.162 MVA·h.

On interval II, an ideal scenario of electricity supply and consumption is considered, as $V_{p.e} = V_{c.e}$, resulting in a partial indicator of electricity supply volume $C_п$ of 0.496.

The quality indicator of electricity supply is equal to 1, which means $\omega_ф = \omega_н$ = 50 Hz. This indicates that there are no voltage deviations, and electricity is supplied and consumed at the same frequency.

The efficiency indicator for electricity supply and consumption is equal to 1, indicating that the supply and consumption of electricity are highly efficient.

On interval III, the electricity supply volume indicator C_p = 0.48 and with $V_{p.e} > V_{c.e}$, this indicates inefficient electricity supply.

The quality of electricity supply indicator, which is 1.029, indicates a deviation of frequency from the normalized value (50 Hz) by 2.9 %.

The efficiency indicator of electricity supply and consumption C_{ef} = 0.967 indicates that the supply and consumption of electricity are inefficient, as there is an excess of electricity that is not being consumed, amounting to 10.412 MVA.

as there is an excess of electricity that is not being consumed, amounting to 10.412 MVA.

CONCLUSIONS

1. A method and model for assessing the efficiency of electricity supply and consumption have been developed, allowing the evaluation of the operational efficiency of the electrical power system under normal operating conditions using a single indicator. This indicator is based on the aggregation of various indicators of different origins into one overall indicator.

The following individual indicators for the supply and consumption of electrical energy have been proposed: the indicator of the supplied and consumed electrical energy volume, the indicator of the quality of supplied and consumed electrical energy, and the indicator of the efficiency of supplied and consumed electrical energy.

2. Comparing the traditional method of assessing the efficiency of electrical energy supply with the method proposed in the paper, it can be concluded that in some cases, the obtained data are inadequate. For example, on interval I, the efficiency of electrical energy supply using the traditional method is C_{ef} = 1.13 > 1, making it impossible to assess this indicator adequately. However, according to the proposed method, when the required electrical energy is borrowed through the banking system on the same interval, the efficiency is C_{ef} = 0.978, which allows for a more adequate assessment of the results obtained.

Comparing the aggregated indicators C_r obtained when calculating the efficiency of electrical energy supply on intervals I-III, it can be concluded that the ideal aggregated indicator is the value on interval II C_r = 0.504, because $V_{п.е} = V_{с.е}$ = 126 MVA·h та $\omega_ф = \omega_н$ = 50 Hz.

Table 1. **The results of the electricity supply efficiency calculations**

The calculated values	Intervals		
	I	II	III
S_g, MVA	63	63	63
S_{sp}, MVA	65	63	60
$V_{p.e}$, MVA·h	252	126	315
$V_{c.e}$, MVA·h	257.162	126	304.588
ω_f, Hz	48.968	50	51.429
ω_n, Hz	50	50	50
V_b, MVA·h	5.162	0	0
C_p	0.506	0.496	0.48
C_f	0.979	1	1.029
C_{ef}	0.978	1	0.967
C_r	0.537	0.504	0.582

Source: **compiled by the authors**

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Моделювання та метод оцінки ефективності енергосистеми

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АНОТАЦІЯ

Робота присвячена проблемам оцінки ефективності експлуатації сучасних електроенергетичних систем, коли все більше споживачів проявляють бажання активно впливати на графік електропостачання, надаючи умови виробникам електроенергії. Дослідження поділяється на два основні сегменти: розроблення моделі для оцінки ефективності експлуатації електроенергетичної системи та розроблення методу аналізу ефективності енергосистеми, в основу якого покладено модель зміни показників якості енергосистеми. Запропонована модель враховує такі властивості енергосистеми, як ймовірність безвідмовної роботи мережі, нормоване значення частоти електроенергії, об'єм споживаної електроенергії та електроенергії, що постачається електропередавальною організацією. Очікується, що ця модель допоможе більш точно оцінити ефективність експлуатації енергосистеми при нормальному режимі роботи. Крім того, був розроблений метод аналізу ефективності експлуатації енергосистеми, в основу якого покладено модель зміни показників якості енергосистеми. Унікальною особливістю цього метода є те, що вводиться новий узагальнений показник ефективності енергосистеми, який визначається за методом згортки частинних показників, а саме: об'єм поставки електроенергії, якість поставки електроенергії та ефективність поставки електроенергії. Достовірність моделі була підтверджена шляхом розрахунку добового електричного графіка постачання та навантаження.

Ключові слова: моделювання; система електропостачання; оцінка ефективності; ефективна експлуатація енергосистеми; показники поставки електроенергії; добовий графік навантаження; автоматична система управління; сталість виробництва енергії; споживче управління

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