Comprehensive Management of Electricity Demand Distribution in Time

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Abstract. The paper is aimed to strengthen the controllability of electricity consumption mode at all structural layers of the country's energy system (ES) to establish the optimal load curve in the PS. Following this goal, the energy system was broken down into seven structural layers - from the technological operation to the ES. For each layer, an expert assessment of the effectiveness of six institutional and operational methods of electricity demand-side management (DSM) was done. The integrated application of the suggested methods was tested in two industrial consumers, which proved the effectiveness of this approach for leveling their aggregated load curve. To ensure an appropriate economic impact on the electricity demand, given the influence of individual consumers on the load curve fluctuation in the ES, a particular price function considering the cross-correlation coefficient of the load curves was developed. It was proved that the complex DSM methods application significantly improved the controllability of the electricity consumption mode. To incentivize consumers to adjust their electricity consumption, a special price system functionally related to the cross-correlation coefficient of the consumer and the ES load curves was developed. The marginal price values depending on the cross-correlation coefficient were defined, while the intermediate price values were calculated by the functional transformation of the ES load curve into the price scale. The significance of the research results lies in the fact that ranking the DSM methods by the priority of application for various structural layers of ES and their integrated application almost doubled the DSM effectiveness.
Keywords: structural layers of power system, electricity load curve, regulation of electricity consumption mode, cross-correlation coefficient, price function.

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Controlul distribuirii complexe cererii de energie electrică în timp

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Rezumat. Scopul lucrării este de a consolida controlul modului de consum a energiei la toate nivelurile structurale ale sistemului unificat de energie electrică (UEES) al statului pentru a forma programul optim de încărcare pentru UEES. Pentru atingerea acestui scop s-a realizat structurarea sistemului de energie electrică pe 7 niveluri - de la funcționarea tehnologică până la UEES. Pentru fiecare nivel structural s-a efectuat evaluarea eficacității aplicării principalelor 6 metode instituționale şi instrumentale de gestionare a regimului consumului de energie. Aprobarea utilizării complexe a metodelor de management a fost implementată pe exemplul a doi consumatori industriali, ceea ce a dovedit eficacitatea acestei abordări la nivelarea programului de sarcină electrică totală (LEG). Pentru impactul economic asupra formării cererii de energie electrică, ținând cont de influența consumatorului asupra neuniformității LEG al UOEES, a fost elaborată o funcție de preț din coeficientul de corelație încrucișată al LEG. Cele mai importante rezultate: metodele de control al consumului de energie se diferențiază în principale şi auxiliare în funcție de gradul de impact al acestora asupra LEG al fiecărui nivel structural al UEES. Este dovedit că utilizarea complexă a metodelor a îmbunătățit semnificativ controlabilitatea modului de consum de energie. Semnificația rezultatelor cercetării constă în faptul că diferențierea metodelor de reglare a regimului de consum de energie prin prioritatea de aplicare pentru nivelurile structurale ale sistemului de energie electrică şi utilizarea lor integrată a aproape dublat eficiența controlului modului.
Cuvinte-cheie: nivelurile structurale ale sistemului de energie electrică, programul de sarcină electrică, reglarea modului de consum de energie, coeficientul de corelație încrucișată, funcție de preț.

Комплексное управление распределением спроса на электрическую энергию во времени

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Аннотация. Целью работы является усиление управляемости режима электропотребления на всех структурных уровнях объединенной электроэнергетической системы (ОЭЭС) государства для формирования оптимального графика нагрузки ОЭЭС. Для достижения поставленной цели произведено структурирование электроэнергетической системы на 7 уровней – от технологической операции до ОЭЭС. Для каждого структурного уровня проведено экспертное рейтинговое оценивание эффективности применения основных 6 институциональных и инструментальных методов управления режимом электропотребления. Апробация комплексного использования методов управления реализована на примере двух промышленных потребителей, что доказало эффективность такого подхода при выравнивании их суммарного графика электрической нагрузки (ГЭН). Для экономического воздействия на формирование спроса на электрическую энергию, учитывающего влияние потребителя на неравномерность ГЭН ОЭЭС, разработана ценовая функция от коэффициента взаимной корреляции ГЭН. Наиболее существенные результаты: методы управления электропотреблением дифференцированы на основные и вспомогательные по степени их воздействия на ГЭН каждого структурного уровня ОЭЭС. Доказано, что комплексное использование методов существенно улучшило управляемость режима электропотребления. Для стимулирования потребителей к управлению электропотреблением разработана система цен на электроэнергию, функционально связанных с корреляцией суточных ГЭН потребителя и ОЭЭС. Установлены экстремальные значения ценового диапазона в зависимости от коэффициента корреляции, а промежуточные значения цены вычислены функциональным преобразованием ГЭН ОЭЭС в ценовую шкалу. Значимость результатов исследований заключается в том, что дифференцирование методов регулирования режима электропотребления по приоритетности применения для структурных уровней электроэнергетической системы и комплексное их использование повысило результативность управления режимом практически вдвое. Разработанная ценовая система, основанная на использовании коэффициента корреляции ГЭН, усилила мотивацию потребителей к выравниванию суммарного графика нагрузки ОЭЭС.

***Ключевые слова*:** структурные уровни электроэнергетической системы, график электрической нагрузки, регулирование режима электропотребления, коэффициент взаимной корреляции, ценовая функция.

LIST OF ABBREVIATIONS

UES - unified energy system; ELS - electrical load schedule; IC - industrial consumer; TP - technological process; CRM - correlation-resonance method; TTM - technical-technological method; OM - organizational method; DM - directive methods; EM - economic method; NM - normalization methods; ACM - agitation and communicative methods; DSO - distribution system operator; NPM - network planning and management; CRM - correlation-resonance method.

INTRODUCTION

Trends in the development of distributed generation, taking into account regional features of resource potential [1], the creation of small energy systems, and the implementation of new flexible forms of participation in the energy market, as well as the intergovernmental association of energy systems [2, 3], are the modern

European paradigm for transforming energy in order to decarbonize, enhance energy security and resilience of energy systems [4-7]. In addition, to a key process of such transformation the demand-side management of electricity [8-9]
should be added which, within national and macro-regional energy systems, allows for multiple positive effects: technical, economic, ecological-climatic, and others.

Unified energy systems of Moldova and Ukraine starting since 16.03.22 has been synchronized with the European Union (EU) energy system for parallel operation [2].

The transformation of Ukraine's electricity market into a competitive one, through the implementation of "bilateral contracts" and a "balancing market", highlights the need for mechanisms to maintain a permanent energy balance. The proper quality of electric power and high reliability of power supply are the easiest to ensure with a uniform electric load schedule (ELS). However, the characteristic feature of the daily schedules of electric loads of the Unified Energy System of most countries is the presence of two peaks - morning and evening - as well as a significant decrease in the load during night hours, with fluctuations between maximum and minimum values of consumed power reaching

25...30% [10]. Such a configuration of the electric load schedules is due to the fact that the total demand for most goods and services, exhibited by end consumers throughout the day, is characterized by significant non-uniformity, determined by the biological cycle of humans. Thus, in the morning and evening there is a surge in demand for electricity, gas, water, transport, communication, while these goods and services are hardly in demand at night. This can lead to a deficit or deterioration in quality during peak periods, and to the loss of such goods during the "night gap".

Aligning the load curves of the United Energy System will contribute not only to achieving the balance of the electrical energy [11], but also to saving fuel and energy resources, reducing losses of electrical energy in the electric networks, decreasing the wear and tear of network infrastructure, improving the quality and reliability of energy supply to consumers, as well as the environmental friendliness of the power industry.

Therefore, the UES and electricity producers are striving to align the load of electrical consumption over time, while consumers are primarily interested in saving on electricity bills. To achieve these goals, a range of institutional and instrumental methods are used to manage the regime of electricity consumption, among which economic ones should prevail, although they are not dominant in the energy sector of Ukraine. The time-differentiated pricing system currently functions only for the population and does not take into account the individual technical and economic characteristics of other segments of the electric energy market. At the same time, as experience shows, the use of only pricing levers is insufficient to solve this problem, especially in the short term.

In these conditions, the task of maintaining the balance of consumption with supply (generation) through alignment of the demand curve for electric power over time remains extremely relevant.

I. PROBLEM STATEMENT

Effective operation of the unified energy system is possible only with harmonious balancing of supply and demand in the electric energy market in real time through targeted management of the electricity consumption at all levels of the integrated power system. At the same time, the selectivity and degree of influence of each management method for each structural unit requires investigation.

To intensify the process of aligning the electricity load curve over time to an acceptable level for the European Union, it is necessary to provide an objective rating assessment of the priority of management methods and improve the methodology for calculating differentiated prices that encourage the increase of uniformity in daily electricity demand.

II. ANALYSIS OF RECENT RESEARCH

Studies aimed at aligning daily and annual electricity load curves are primarily focused on a specific industry or an individual management method, and as a result, do not provide tools for comprehensive impact on all segments of the electricity market consumers.

The authors [12] have improved the multi-level approach to managing hourly electricity consumption modes by industrial consumers using the technological process resource. However, the approaches proposed in [12] are complex and can only be applied to a limited range of technological processes.

In [13], administrative regulation of a company's electricity load with multiple levels of management is considered, which is necessary to balance the load and eliminate technical and economic consequences of imbalances. Demand management is limited to forming economic dispatch schedules for switching on and off the electric power consumers.

In the article [14], a mixed nonlinear programming model is developed taking into account electricity consumption and tariffs for managing the electricity load. However, to simultaneously reduce deviations and lower electricity costs, it is necessary to coordinate the load curve in advance.

The contribution [15] to the literature on energy consumption management consists of implementing a three-stage management structure to improve the energy stability of industrial consumers, differentiating them into large, medium and small ones. However, the optimality of energy consumption based on the results of reducing production costs and CO_2 emissions was tested on the example of two completely different industrial consumers - foundry and textile, without considering the specifics of their technological process.

Authors of [16] consider optimization tasks for the electricity consumption, including normalizing electricity consumption, demand management, by load shifting, and correction electricity consumption mode.

In [17], electricity consumption mode management is carried out using technical, organizational, and economic methods to reduce electricity consumption during peak energy system hours, but management is only considered at the level of individual enterprises.

In [18], the effectiveness of energy savings through administrative correction of time measurement is discussed. However, the specifics of electricity consumption distribution across regions of the country are not taken into account in the study.

The optimization task of the power supply mode is solved in [19] based on criteria of minimum losses in networks, as well as taking into account the constraints on the schedules of electrical loads corresponding to the maximum reduction of consumer costs and minimizing changes in operations that make up the technological process.

In [20], a methodology for calculating load losses of electrical energy in consumer networks is described; theoretical expressions for calculating losses are given, taking into account the shape of the consumer's electrical load schedule and the volume of transferred energy.

One organizational method of energy consumption management [21] is aimed at improving the consumer demand profile during peak hours through a compensatory photovoltaic system programmed to operate in parallel with the electrical grid. The methodology includes an analysis of the shape of the electrical load schedule, energy prices, and the profile of photovoltaic generation.

The Smart Energy Grid provides for direct or indirect energy consumption management [22]. Direct control programs include demand shaping, load shifting, peak limiting, filling gaps, strategic load growth, or its preservation. It is claimed that the load shifting is the best among the direct control methods.

Thus, the analysis of researches and publications indicates the relevance of further searching for effective methods for managing the electric load curve and incentives for reducing the unevenness of the daily electricity consumption. The examined methods could have given a much greater effect when used in combination.

Therefore, the aim of this work is to investigate the possibilities of the integrated application of economic, technological, organizational, and other methods of influence to form an optimal electricity consumption mode at all structural levels of the unified energy system, as well as to improve market levers for increasing the evenness of the electrical load schedules.

III. RESEARCH METHOD

The research was conducted using the following methods: expert evaluation of the priority of methods for managing the electricity consumption regime; graph-analytical method using graph theory to regulate the electricity load curve of an industrial consumer using technological resources; complete enumeration method to search for the optimal version of uniformity of the total electricity load curve; methods of mathematical statistics and probability theory to study the electricity load curve and determine the consistency of expert opinions; theory of functions and mathematical modeling in calculating the differentiated price system for electricity.

IV. RESULTS AND DISCUSSION

To maintain a permanent balance between energy production and import with energy consumption and export, let us consider the application of a complex of control measures directed simultaneously at all structural levels of the unified electric energy system (UES) (Fig. 1).

The UES is divided into the following levels:

- The simplest technological operation that sums up the power of the electrical equipment involved during the investigated time interval can be taken as the 1st basic level;
- The entire technological process should be taken as the 2nd level, as it integrates the powers consumed by the set of technological operations used in the considered section of the electrical load schedule;
- The 3rd level consists of consumers with commercial accounting of electrical energy as an autonomous market unit.
- The 4th level is occupied by electricity supply companies, which have a license for independent economic activity in supplying electrical energy to the end consumers of the electricity energy market (in Ukraine, these are suppliers at free prices, universal service providers, and the "last hope" supplier);
- The 5th level consists of regional distribution system operators (DSO), allocated by administrative-territorial features and engaged in the transmission and distribution of electrical energy. DSOs ensure the reliability and quality of power supply;

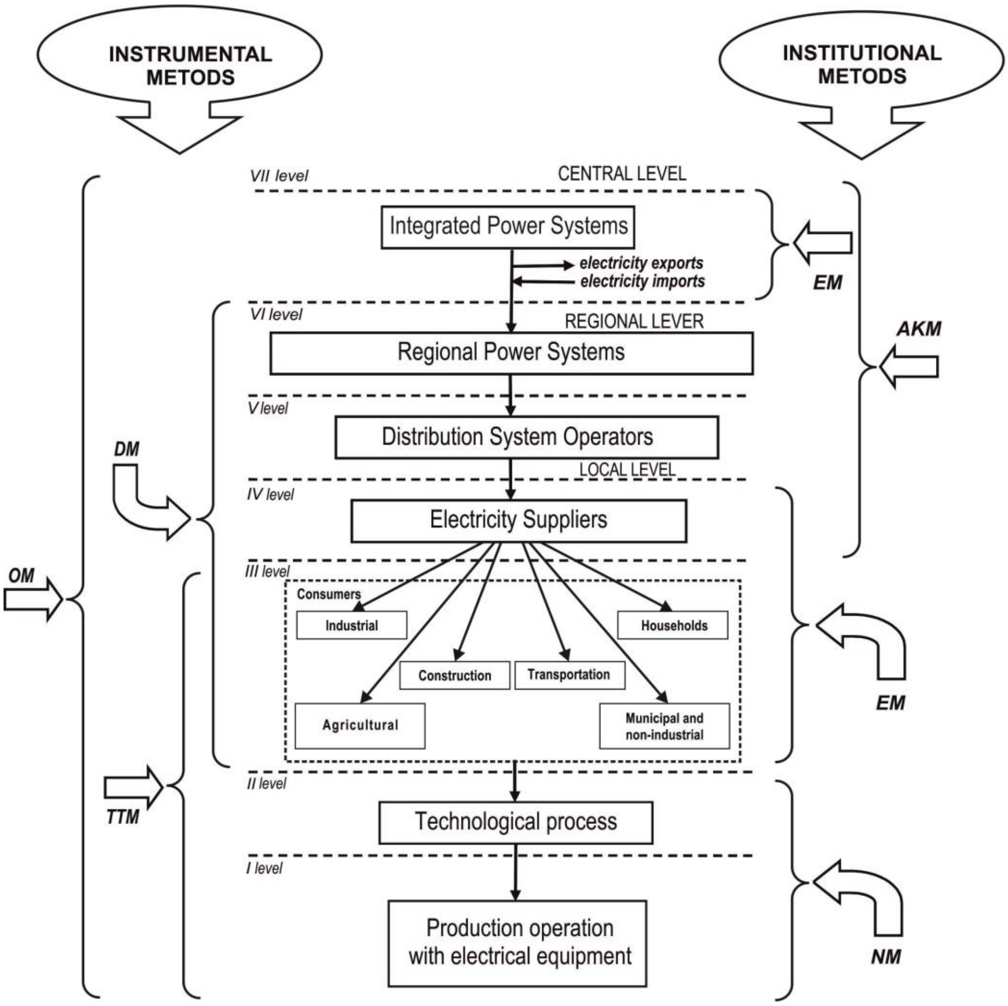


Fig. 1. Application of methods for managing the schedule of electrical load for the structural levels of the UES (EM - economic methods, NM - normalization methods, DM - directive methods, TTM - technical and technological methods, OM - organizational methods, AKM - agitative and communicative methods IC - information campaigns).

- The highest 7th level is formed by the unified energy system of the state - the totality of power plants, power grids, and other elements of the electric power industry under centralized management of a unified technological process of production, transfer and EE distribution.

For each level of the unified energy system, it is necessary to choose the most effective levers of influence and ensure their objective rating assessment for their comprehensive use. Rational management of power consumption mode is achieved through instrumental methods of direct impact (technical and technological, organizational, command-compulsory) and indirect institutional methods that stimulate demand regulation (economic, normative, agitation-communicative) and others.

From Fig 1, it can be seen that according to expert conclusions, technical and technological methods (TTM) that utilize technological resources are most applicable at levels 1-3.

Normalization methods (NM) justify the amount of specific energy costs and implement control over their compliance. NM are effective at levels 1-2; in this case, electricity consumption regulation mainly serves the purposes of energy conservation.

Organizational methods (OM), in particular, load curve alignment as a result of mutual displacement of its components, can be implemented at any structural level of the unified energy system – from 1 to 7, but its application is most accessible at lower levels. At the same time, organizing energy exchanges with other countries, transitioning to distributed power systems with an emphasis on using regional fuel and energy resources, and other similar policies are the prerogative of higher levels.

Agitative and communicative methods (ACM) are aimed at raising consumer awareness of the need to regulate demand with consideration of electricity payment based on the system of differentiated prices, use of individual renewable energy sources, energy labeling of products, etc.

Economic methods (EM) are based on financial and economic instruments that affect the volume and modes of energy consumption, with the price of electricity playing the role of the main regulator.

If market methods of demand regulation are inefficient or act too slowly, it is advisable to use directive methods (DM); for example, at levels 3-6, mandatory disconnection of category II and III consumers, limitation of daily electricity consumption, seasonal time counting correction, and so on.

In order to establish the selective responsiveness of levels of the unified energy system to a specific management method and to rank methods of influence, 12 experts, specialists in electricity consumption management, were surveyed. Experts assessed the priority of applying a particular method at each level of the unified energy system on a 6-point scale, where 1 corresponds to the least impact, and 6 corresponds to the most significant impact.

Statistical processing of the results allowed to calculate the coefficients of concordance W and Pearson's correlation coefficient using the $\chi_R^2 = W \cdot m \cdot (k-1)$, where $m = 12$ - the number of experts, $k = 6$ - the number of methods considered, and the tabular (critical) value $\chi_{KR}^2 =$ 11,07 for a 5% level of significance, the number of degrees of freedom $\gamma = k - 1 = 5$, and also to determine the degree of agreement among the experts (Table 1). The results indicate that differentiating methods into main (1, 2, 3) and auxiliary (4, 5, 6) based on their significant impact on the graph of the electric load at a certain level, and applying them in combination, will facilitate the formation of an optimal energy balance.

The effectiveness of complex management will be tested on two industrial consumers, starting with the implementation of technical and technological methods to balance the graph of the electric load in the most energy-intensive technological processes and workshops, using the identified time reserves in the technological processes and applying the network planning and management method (NPM) [23], and in the next stage, implementing the algorithm of the organizational correlation-resonance method (CRM) [24], by shifting the aligned graphs of the electric load of the industrial consumers relative to each other in time.

Figure 2 shows the initial winter electric load graphs of two machine-building industrial consumers (graph 1 in Fig. 2a and graph 3 in Fig. 2b). To align these graphs, reserves of production time R_t were identified through the analysis of the discrete technological process (TP) [23]. These reserves represented the possible displacement of parallel operations along the TPs and the corresponding movement of electric loads without violating the completion time and quality of the TPs.

The synthesis of new graphs was carried out by the purposeful redistribution of the starts and finishes of TP operations within R_t, using the exhaustive search method and guided by the criterion of reducing the unevenness of the graphs.

After redistributing the loads of most power-intensive operations along the technological process (up to 80% of the controllable power) within the calculated R_t, the configurations of the electrical load graphs of both industrial consumers acquired the shape of curves 2 and 4 on Fig. 2, respectively.

It can be seen that the redistribution of consumed power by operations led to a significant reduction in the unevenness of the electrical load graph, which is evidenced by the comparison of the calculated indicators of graph alignment (Table 2).

The following commonly used indicators were analyzed. The unevenness indicator K_{NR}, which characterizes the range of the electrical load graph, can be determined from the mathematical relationship:

Table 1

Results of ranking management methods by levels of the unified energy system

№	Naming of level of Unified Energy Systems of Ukraine	W	χ_R^2	Alternating management methods in order of their priority
1	Operation with electrical equipment	0,6356	38,14	1. TTM; 2. NM; 3. OM; 4. EM; 5. DM; 6. ACM

2	Technological process	0,4152	24,91	1. TTM; 2. OM; 3. NM; 4. DM; 5. EM; 6. ACM
3	Consumer with commercial metering	0,8025	48,15	1. EM; 2. TTM; 3. DM; 4. OM; 5. NM; 6. ACM
4	Electricity Suppliers	0,6982	41,89	1. EM; 2.ACM; 3. OM; 4. NM; 5.TTM 6. DM
5	Distribution System Operators	0,8154	48,92	1. DM; 2. OM; 3. TTM; 4. NM; 5. EM; 6. ACM
6	Regional Power System	0,9170	55,02	1. OM; 2.ACM; 3. DM; 4. NM; 5. TTM; 6. EM
7	Unified Energy Systems of Ukraine	0,8264	48,59	1. EM; 2. OM; 3. ACM; 4. DM; 5. TTM; 6. NM

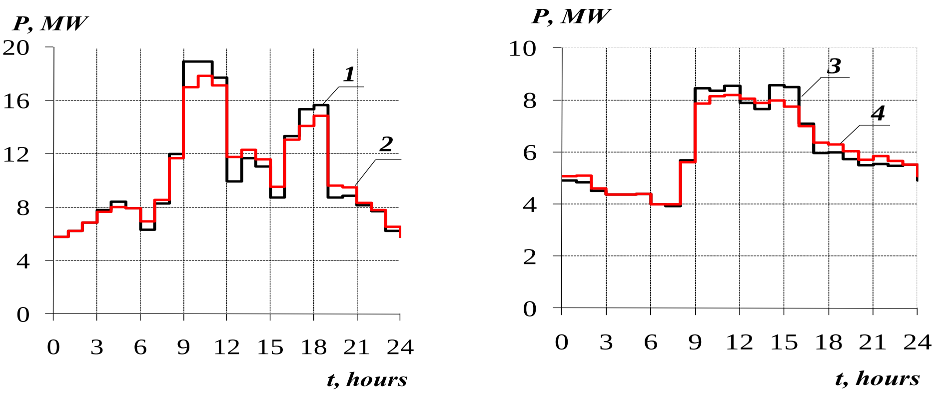
$$K_{NR} = \frac{P_{MIN}}{P_{MAX}} \qquad (1)$$

where P_{MIN}, P_{MAX} are respectively the minimum and maximum power values.

Since the values of P_{MIN}, P_{MAX} can theoretically vary in the interval [0; +∞), the unevenness indicator takes values within the range [0; 1]. When $K_{NR} = 1$, the electrical load graph is perfectly uniform.

To investigate the relationship between the maximum power value P_{MAX} and its mean value P_{SR}, the maximum indicator K_M is used:

$$K_M = \frac{P_{MAX}}{P_{SR}} . \qquad (2)$$



a b

Fig. 2. Electric load graph: a - industrial consumer IC-1 (1 - initial, 2 - after alignment by network planning and management method); b - industrial consumer IC-2 (3 - initial, 4 - after alignment by network planning and management method).

Theoretically, K_M can take values $K_M \geq 1$. An increase in K_M corresponds to an increase in the non-uniformity of the electric load graph.

The graph filling indicator K_{ZG} is inversely proportional to K_M:

$$K_{ZG} = \frac{1}{K_M} = \frac{P_{SR}}{P_{MAX}} . \qquad (3)$$

The limits of K_{ZG} correspond to the interval (0; 1].

From a statistical point of view, the shape indicator K_F provides a more detailed assessment of the shape of the electric load graph than K_{NR}, K_M, and K_{ZG}, because K_F is defined as:

$$K_F = \frac{P_{SRKV}}{P_{SR}}, \quad (4)$$

where P_{SRKV} is the root mean square value of the power:

$$P_{SRKV} = \sqrt{\frac{1}{T}\int_0^T P^2(t)\,dt}, \quad (5)$$

where T is the duration of the selected period for calculations.

The daily electric load curve is usually presented as a histogram with hourly averaged power (Fig. 2), in which case P_{SRKV} is found using the formula:

$$P_{SRKV} = \sqrt{\sum_{i=1}^{n}\left(P_i^2 \cdot t_i\right) \Big/ \sum_{i=1}^{n} t_i}, \quad (6)$$

where P_i is the power on the ***i***-th section with a duration of t_i; n is the number of sections in the electric load curve (for the daily electric load curve $n = 24$).

According to (4), K_F takes on the minimum value of $K_F = 1$ when $P_{SRKV} = P_{SR}$ at $P(t) = const$, which corresponds to the most preferable mode for the unified energy system.

The variance D_P is a measure of the deviation of the current power values P_i from their average value P_{SR}:

$$D_P = P_{SRKV}^2 - P_{SR}^2 = P_{SR}^2\left(K_F^2 - 1\right) \quad (7)$$

The indicators of non-uniformity of the electric load curves for two industrial consumers shown in Fig. 2, calculated from expressions (1)-(7), are presented in Table 2.

Table 2

Indicators of non-uniformity of ELS for two industrial consumers (IC) in Fig. 2.

ELS options of two IC	Indicators of non-uniformity of the ELS of IC				
	K_{ZG}	K_M	K_{NR}	K_F	D_P
ELS of IC-1 before regulation	0,5516	1,8127	0,3044	1,0723	17,027
ELS of IC-1 after regulation by network planning methods	0,5843	1,7114	0,3225	1,0574	13,415
ELS of IC-2 before regulation	0,7078	1,4128	0,4576	1,0335	2,6229
ELS of IC-1 after regulation by network planning methods	0,7418	1,3481	0,4877	1,0272	2,1208

The analysis of the indicators of non-uniformity presented in Table 2 shows that as a result of transforming graph 1 into graph 2, the indicator of the ELS filling K_{ZG} increased by 5.93%, indicating an overall increase in uniformity (for a perfectly uniform ELS $K_{ZG} \to 1$); the non-uniformity indicator K_{NR} increased by 5.95%, i.e., the difference between P_{MIN} and P_{MAX} decreased; the form factor indicator K_F decreased by 1.41% (indicating an approach of P_{SRKV} to P_{SR}); the peak indicator K_M decreased by 5.92%, and the variance D_P decreased by 26.9%.

The non-uniformity indicators also improved as a result of transforming graph 3 into graph 4: K_{ZG} increased by 4.8 %, K_{NR} increased by 6.58 %; K_F decreased by 2.3 %, K_M decreased by 4.8 %, and D_P decreased by 23.7 %.

The achieved alignment of the ELS of industrial consumers contributes to electricity savings due to a reduction in electrical energy losses in power grids; the electricity savings δW_{C1} will be calculated according to [20] as a result of changing the K_F indicator before and after aligning the ELS.

At an average level of losses in the industrial consumer networks of 13.6% of the total consumed electrical energy, for industrial consumer IC-1 δW_{C1} during the day:

$$\delta W_{C1} = \Delta W_N \cdot \left(1 - \frac{K_{F2}^2}{K_{F1}^2}\right) =$$

$$= \frac{13,6\,\% \cdot 250,5}{100\,\%}\left(1 - \frac{1,0574}{1,0723}\right) = 0,47\ MW \cdot h$$

where ΔW_N - the losses of electrical energy in the IC networks before leveling the electrical load graph; K_{F1}, K_{F2} - indicators of the form before and after leveling the ELS, respectively (Table 1).

For industrial consumer IC-2, the savings δW_{C2} = 0.12 MW·h are achieved.

Of course, the achieved leveling of the ELS due to the energy-saving effect will lead to a proportional reduction in the payment for electrical energy.

Since the graph of the aggregated electrical power system load is a superposition of its load graphs, it is rational to apply the correlation-resonance method [25] in the next stage of leveling, which is based on leveling the resulting graph by shifting two electrical load graphs with a step of τ relative to each other. The variant with the minimum value of the cross-correlation function is preferred.

$$k(p_{RS}(\tau)) = \left[\frac{1}{t_C}\left(\begin{aligned}&\int_0^{t_C-\tau} p_R(t)\,p_S(t+\tau)dt\ + \\ &+\int_{t_C-\tau}^{t_C} p_R(t)\,p_S(t-t_C+\tau)dt\end{aligned}\right)\right] - \quad (8)$$
$$-P_R P_S \quad \to \min$$

where $\tau = t_{RS}$ – is the time shift between graphs, hours;

t_C – cycle duration (period), for a daily electrical load graph, $t_C = 24$ hours;

$p_R(t),\ p_S(t)$ - normalized to the maximum power value of the first and second electrical load graphs at time t, respectively, relative units;

$P_R,\ P_S$ – average power of both electrical load graphs, relative unit.

The nature of the change in the cross-correlation function with an hourly shift of the electric load curve within τ = 1…24 hours is shown in Fig. 3: curve "k_1" represents the original ELS 1 relative to the ELS 3, curve "k_2" represents the adjusted load graphs ELS 2 and the ELS 4.

From (8), it can be seen that the cross-correlation function depends on the level of electricity consumption and can take any absolute values (on Fig. 3, $k(p_{RS}(\tau))$ varies from -0.062 to +0.07 relative units).

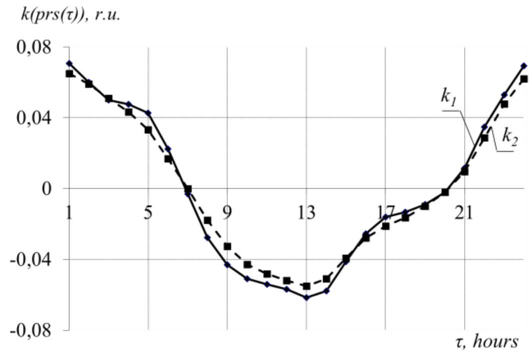


Fig. 3. Cross-correlation function as a function of shift τ: k_1 - for the electric load graph before regulation, k_2 - after applying network planning and management.

After applying network planning and management, the cross-correlation function decreased, and the minimum value of both $k(p_{RS}(\tau))$ corresponds to the optimal shift at $\tau = 13$ hours. However, implementing a shift of $\tau = 13$ hours in practice is extremely problematic. Therefore, it is appropriate to analyze the result of mutual shifting of electric load curves within realistically achievable limits of $\tau_P = \pm|1\ldots2|$ hours, which can be realized, for example, by shifting the start of work by τ_P.

The relationship of the cross-correlation function at four real shift options - 1, 2, 22, and 23 hours - showed (see Fig. 3) that for the load graphs ELS 1 and ELS 3, $k(p_{13}(1)) > k(p_{13}(2)) > k(p_{13}(23)) >> k(p_{13}(22))$ and for the adjusted load graphs ELS 2 and 4, $k(p_{24}(1)) > k(p_{24}(2)) > k(p_{24}(23)) > k(p_{24}(22))$ applies.

Therefore, the best result for aligning the resulting graph from the four options is achieved by shifting the load graph ELS 2 relative to the load graph ELS 4 by $\tau_P = 22$ hours ($\tau_P = -2$ hours).

Figure 4a shows the cumulative ELS of two industrial consumers: graph 5 is obtained by adding the original load graphs of ELS 1 and ELS 3 from Fig. 2; graph 6 - ELS 2 and ELS 4 after regulation by the method of network planning and management. It can be seen that the regulated cumulative ELS 6 is smoother than the original graph ELS 5.

Figure 4b shows the cumulative ELS of the two industrial consumers: graph 7 - with the use of only the correlation-resonance method (by shifting the original ELS 1 relative to the ELS 3 by $\tau_P = -2$ hours); graph 8 - with the use of complex regulation: first with the method of network planning and management, and then with the correlation-resonance method. The best result of the 4 options was obtained using complex regulation (graph 8).

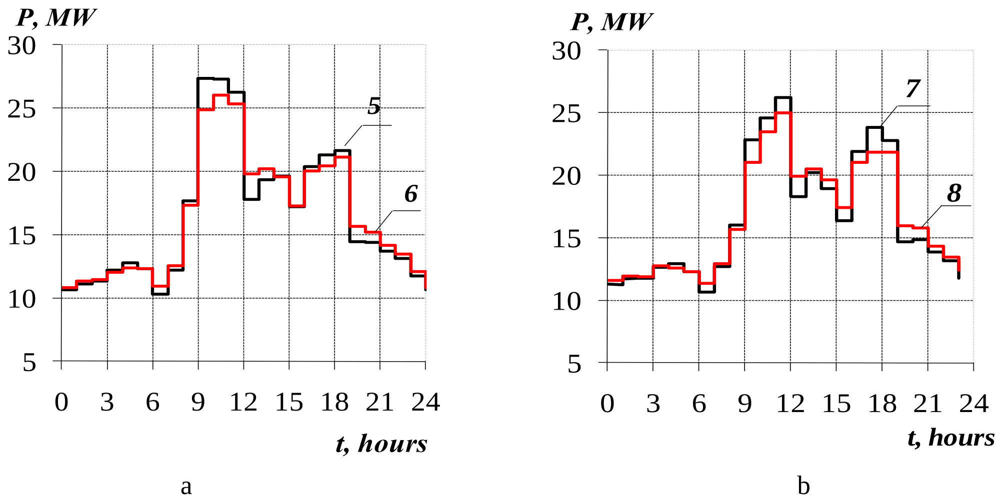


Fig. 4. Cumulative ELS of both industrial consumers under different management approaches: a - curve 5 is the initial cumulative ELS, curve 6 is after management with only NPM; b - curve 7 is after applying only the correlation resonance method (shifted by $\tau_P = -2$ hours), curve 8 is after combined management using both methods - NPM and CRM.

Comparison of the indicators of unevenness of the cumulative load graphs (Table 3) confirms that as a result of complex control, the indicators have significantly improved: thus, after the method of network planning and management, the filling coefficient of the total ELS K_{ZG} increased by 5.47 %, and after the sequential use of NPM and CRM - already by 9.6 %.

Table 3

Indicators of non-uniformity of the cumulative ELS of two industrial consumers

Options for regulating	Indicators of the total ELS				
	K_{ZG}	K_M	K_{NR}	K_F	D_P
Before regulation	0,6031	1,6581	0,3755	1,0495	28,827
After regulation by network planning methods only	0,6347	1,5756	0,4161	1,0411	23,731
After regulation by correlation resonance method only	0,6305	1,586	0,4072	1,0418	24,264
With complex regulation by network planning methods and correlation resonance method	0,6607	1,5134	0,4514	1,0335	19,353

It is noteworthy that there are some peculiarities of the considered indicators: thus, K_{NR}, K_M, K_{ZG} describe the ELS graph only at certain points and depend only on its extremes, which does not allow for an unambiguous assessment of the degree of load unevenness, since different ELS graphs of different configurations can have the same values of the calculated indicators.

Indicator K_F does not always respond to regulation, for example, $K_F = const$ in the case of an additive shift of the ELS graph over time. Moreover, it should be noted that the K_F of two ELS graphs that are different in shape but mirror-symmetric with respect to the vertical axis can have the same values.

The variance $D_P \geq 0$, but its upper limit is not determined, which makes it difficult to compare several different ELS graphs; in particular, the D_P indicator proves to be unsuitable for comparing ELS graphs that differ by orders of consumed power.

It should be noted that the tested methods of managing ELS graphs are quite universal and applicable to most levels of the unified energy system. Further alignment of ELS graphs can be achieved through additional use of other methods of influence.

Based on the fact that the economic method of control is one of the main ones for most structural levels of the unified energy system (Table 1), and the potential for saving on payments for electricity consumption represents a major incentive for electricity consumers, we consider the possibility of improving the system of differentiated prices with the aim of increasing the flexibility of pricing.

Considering that the unevenness of consumers' schedules is not as important as the degree of personal influence of each consumer on the configuration of the resulting energy system schedule ELS UES, we believe that the pricing function should primarily include the coefficient of mutual correlation - the indicator K^{C}_{COR}, which characterizes the degree of coincidence of the forms of two ELS (consumer and UES):

$$K^{C}_{COR} = \frac{\sum_{i=1}^{n} (p_{1i} - P_{SR1}) \cdot (p_{2i} - P_{SR2})}{(n-1) \cdot \sigma_{P1} \cdot \sigma_{P2}},$$

where p_{1i}, p_{2i} – the average hourly power of the 1st and 2nd ELS, respectively;
σ_{P1}, σ_{P2} – the standard deviation of power;
n – the number of ELS steps (for daily schedules $n = 24$);
P_{SR1}, P_{SR2} – the average values of the power of the compared ELS.

For any ELS K^{C}_{COR} varies within the range of [-1; 1], therefore, the coefficient of mutual correlation is more convenient when comparing numerically incomparable ELS, for example, in the case of a joint analysis of the graph of the machine-building industrial consumer and the total graph of the UES.

Most consumers operate in a "hard" technological mode with $K^{C}_{COR} \to 1$ relative to the UES graph, collectively determining its shape. In this case, it is possible to propose a pricing system in which the limiting values of prices C_{MAX} and C_{MIN} are calculated individually for each consumer based on the functional accounting of its K^{C}_{COR}. Since the price of electric energy is deterministic in the range $[C_{MIN}; C_{MAX}]$, it is advisable to choose a classifier for the pricing scale $C \in [C_{MIN}; C_{MAX}]$ when the maximum value of the price rate during peak demand is calculated as:

$$C_{MAX} = \left(1 + K^{C}_{COR}\right) \cdot C_{MID} \quad \text{or} \qquad C^{R}_{MAX} = \left(1 + K^{C}_{COR}\right) \tag{9}$$

and the minimum price C_{MIN} for the night drop in electricity consumption, symmetric to C_{MAX} with respect to C_{MID}, is calculated as:

$$C_{MIN} = \left(1 - K^{C}_{COR}\right) \cdot C_{MID} \quad \text{or} \qquad C^{R}_{MIN} = \left(1 - K^{C}_{COR}\right), \tag{10}$$

where $C_{MID} = const$ - the average price accepted for all industrial consumers at the level of the current single-stage value.

Intermediate price values within the range of $C^{R}_{MIN} \ldots C^{R}_{MAX}$ are calculated by transforming (normalizing) the price scale into an algebraically defined functional dependence on the relative price $C_i^R = C_i / C_{MID}$, based on the deviation of the relative power $\Delta P_i^R = (P_i - P_{MID}) / P_{MID}$ in the power system UES in the *i*-th time zone, for example, linearly [25]:

$$C_i^R = 1 + \alpha \Delta P_i^R \ , \tag{11}$$

where α - is the price coefficient, unitless;
i - is the number of time intervals in a day;
P_i - is the power consumed in the *i*-th interval;
P_{MID} - is the daily average value of the power system's capacity.

Function (11) takes into account the sign of the deviation ΔP_i^R from P_{MID}: on segments with $+\Delta P_i^R$ surcharges are applied, and with negative increments $-\Delta P_i^R$ (during nighttime demand drops) - discounts, the greater $\left|\Delta P_i^R\right|$, the greater the discount.

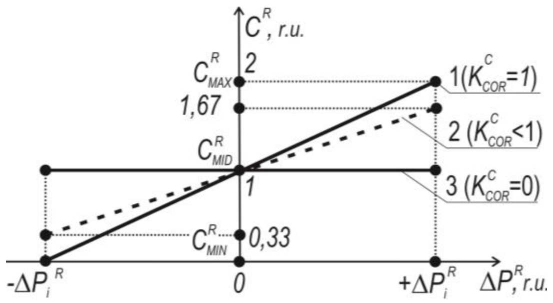


Fig. 5. Price function as a function of power deviation (in relative units).

From Fig. 5, it can be seen that when the demand for electric power is equal to the average daily value $(P_i = P_{MID})$, then $\Delta P_i = 0$ and payment for electric power is made according to C_{MID}. When $P_i > P_{MID}$, the price increases according to (11), and vice versa, when $P_i < P_{MID}$ - the price decreases.

Consumers with $K^C_{COR} \to 1$ (curve 1 in Fig. 5), who form the graph ELS of the energy system, will be most interested in shifting their graph of the power system, seeking to minimize payment for electric energy.

Since the coefficient of mutual correlation can vary within: $-1 \le K^C_{COR} \le 1$, then we focus on the expediency of considering only those graphs of the power system that increase the non-uniformity of the graph of UES, i.e., with a coefficient of mutual correlation within the range of $0 < K^C_{COR} < 1$ (on Fig. 5, the boundary curve 1 corresponds to $K^C_{COR} = 1$, curve 3 - $K^C_{COR} = 0$). In addition, values of C_i^R outside the limits of $0 < C_i^R < 2$ lose their economic meaning, since electric energy cannot be sold at a price of $C_i \le 0$.

Then for the industrial consumer IC-1, which has $K^C_{COR} = 0{,}67$, we obtain from (9) $C^R_{MAX} = 1{,}67$ and from (10) $C^R_{MIN} = 0{,}33$. Curve 2 in Fig. 5 shows the differentiated price system for the industrial consumer IC-1. For industrial consumer IC-1, the price coefficient $\alpha_1 = 4{,}786$, and for industrial consumer IC-2, which has $K^C_{COR} = 0{,}58$, the corresponding $\alpha_2 = 4{,}143$.

The proposed price system has no restrictions on the number of price levels N and responds to any violation of the uniformity of the regime. The flexibility of the price impact on industrial consumers is increased by increasing the daily price levels to $N \ge 24$, which provides a regularity of price distribution adequate to the configuration of the ELS UES. Thus, the price function (11) "tracks" the shape of the ELS UES (Fig. 6a) to encourage industrial consumers to shift their loads to the discount zone.

The daily payment X_E for electric power in relative units with hourly shift of the schedule within $i = 1 \ldots 24$ hours for the industrial consumer was calculated from the expression:

$$X_E = \sum_{i=1}^{N=1;24} C_i^R \cdot W_{E.i} / P_{E.MAX},$$

where $W_{E.i}$ - is the electric power consumed by industrial consumer in the *i*-th hour.

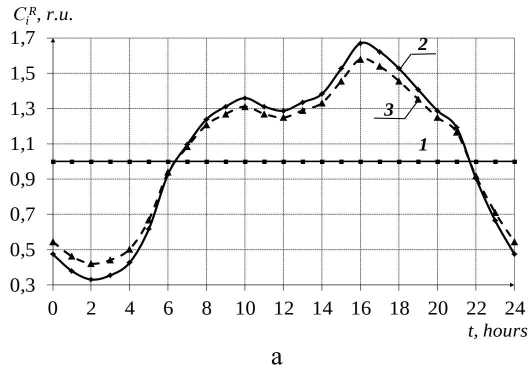
From Fig. 6b, it can be seen that the proposed 24-tariff system provides savings in the payment $\Delta X_E = X_{E.24} - X_{E.1}$ in the case of shifting the load curve of industrial consumer IC-1 by Δt =5.1...14.6 hours and the load curve of industrial consumer IC-2 by Δt =3.1...14.2 hours, where $X_{E.24} < X_{E.1}$. It should be noted that the energy consumption mode with ΔX_E →max is the most attractive for the consumer and the most desirable for the power grid. industrial consumer IC-2 is shifted by Δt =8 hours (Fig. 6b).

The minimum $X_{E.MIN}$ is achieved when the load curve of industrial consumer IC-1 is shifted by Δt =9.5 hours and the load curve of In this case, compared to the payment at the single tariff rate, the achieved savings $\Delta X_E = 200\% \left|X_{E.24} - X_{E.1}\right| / (X_{E.24} + X_{E.1})$ for industrial consumer IC-1 is 9.23% and for industrial consumer IC-2 is 8.7%.

With such a shift, industrial consumers IC-1 and IC-2 become consumer-regulators with a cross-correlation function of $K^C_{\mathrm{COR.1}}$=-0.67 and $K^C_{\mathrm{COR.2}}$=-0.58, respectively.

The criterion for the best option for load curve alignment is the following dynamics of the indicators discussed above:

$$\begin{cases} \left(D_P, K_F, K_M, K^C_{COR}, X_E\right)\downarrow; \\ \left(K_{ZG}, K_{NR}\right)\uparrow. \end{cases}$$



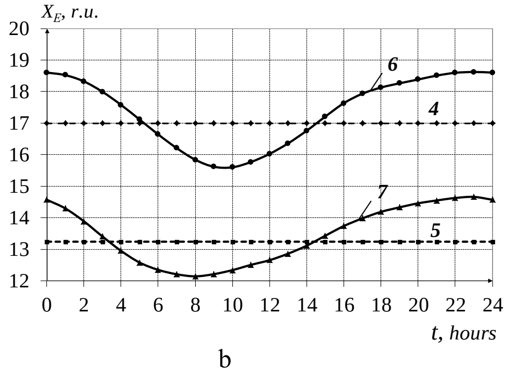


Fig. 6. Distribution graphs over time: a - retail price of electricity (1 - current single-rate price C_{MID}^{R}; 2 - 24-rate price for industrial consumer IC-1, 3 - for industrial consumer IC-2); b - daily payment for electricity with hourly shift of the industrial consumer power schedule (4 – payment $X_{E.1}$ for industrial consumer IC-1 and 5 $X_{E.2}$ - for industrial consumer IC-2 at a single rate; 6 - payment $X_{E.1-24}$ for industrial consumer IC-1 and 7 - $X_{E.2-24}$ for industrial consumer IC-2 at a 24-rate price).

V. CONCLUSIONS

1. Differentiation of the main methods of control by the degree of their influence on the ELS of each structural level of the energy system allowed identifying the main (primary) and auxiliary (secondary) methods, as well as an increase in the effectiveness of forming the energy-efficient power consumption regimes. The complex application of instrumental and institutional methods has increased the controllability of the power consumption regimes almost twofold.

2. For direct economic control of power consumption regimes taking into account the personal influence of the consumer on the unevenness of the ELS UES, it is expedient to include the K_{COR}^{C} indicator in the price function. Calculations of symmetric to C_{MID} maximum and minimum prices depending on K_{COR}^{C} and intermediate values of the price in the functional dependence on the power deviation relative to P_{MID} in the energy system, allowed the development of a flexible pricing system that enhances the motivation of consumers to align the total load curve of the power system.

3. The results of further scientific research in the field of energy complex management with consideration of more complex functional relationships of power consumption regimes with characteristics such as the ability of the consumer to regulate the technological process regime in time, the degree of interest in managing the demand for electricity, the quality of consumed electricity, the reliability of power supply, and others, are of practical interest.

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