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## Optimizing the control of a transactive energy system with periodically changing architecture based on Internet of energy

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### ABSTRACT

The article proposes a solution to the problem of improving the quality and efficiency of control systems for transactive energy systems, which are characterized by repeated periodic changes to their architecture. Information technologies are expanding the capabilities of microgrids, one such technology being the Internet of Energy (IoE). IoE is a global interconnected network consisting of smart grids interacting with each other via information technologies. IoE facilitates the convergence of cyber-physical and economic indicators of network operation, providing the ability to improve control quality by predicting expected changes in dynamics. The proposed solution for IoE control optimization is based on load change forecasting technology, ensuring efficient power distribution between generators and an optimal generator on/off schedule. The optimization criterion and constraints are formulated mathematically. The proposed load forecasting technology is based on the use of the eigenvalues of the state matrices of the transactive energy system. The results of calculating the eigenvalues calculated by the methods of the first group (the Power method and the Khilenko method) and the second group (the Krylov method and others) are presented. The article considers a transactive system with a variable structure based on the Internet of Energy, which can consist of a different set of generation sources, solving an optimization problem based on technical and economic criteria. The solution of the optimization problem of minimizing the cost of primary fuel for diesel generators to reduce costs and reduce CO<sub>2</sub> emissions using power distribution programs for forecasted load schedules and forecasted RES schedules is demonstrated using examples of two transactive systems.

**Keywords:** transactive energy system; Internet of Energy; microgrid; control optimization; Krylov method; Khilenko method

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### INTRODUCTION

The development of modern energy is moving towards diversification of both generators and consumers of electricity.

At the same time, the introduction of new solutions in various industries leads to the emergence of new consumer groups (autonomous cars, cryptocurrency transactions, etc.) [1], [2], [3], and an increase in the efficiency of electricity generators (increased efficiency of solar panels, wind generators, etc.) [3], [4], [5] creates additional volumes of electricity that can be quickly used in local networks.

Accordingly, transaction energy systems that ensure the interaction of individual clusters of

generators and producers are increasingly becoming a standard solution for meeting the needs and ensuring the efficient functioning of the energy market for all its participants. In general, the further development of the energy market with the expansion of the involvement of distributed energy resources requires the use of the latest advances in information technology to provide the ability to effectively and safely manage complex distributed systems with Big Data processing [6], [7], [8].

An important problem of ensuring the stable operation of the power system is to ensure real-time control, which involves a certain level of control center speed.

Solving this problem in the conditions of growing volumes of information, the number of

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power grid participants, the complexity of the network structure and other factors requires the use of specialized software and algorithmic support.

The interaction between systems with several heterogeneous energy carriers makes it possible to achieve affordable and clean energy, using energy resources in a more expedient way ensuring the stable functioning of the power system requires the use of multi-criteria optimization and smart control methods to determine the optimal system structure at a given time and the optimal distribution of energy received from different sources in order to maximize the efficiency of the entire system as a whole. A solution to this problem can be based on the use of load change forecasts, which is especially important for systems with periodically variable architectures, where generator activation and deactivation as usual performed according to predetermined schedules. An adequate, real-time forecast of expected load increases or decreases will enable the control system to immediately respond and make the necessary adjustments to generator operating modes. Consequently, this control optimization will improve the stability of the power system and ensure efficient generator operation, delivering economic benefits through optimized fuel consumption. (At the same time, this affects the solution of an important problem: the smart control system must to maximize the reduction of emissions into the environment and minimize the costs of energy production.). The load change forecasting technology presented below is based on the estimation of the eigenvalues of the state matrices of a transactive power system. In the current work, without loss of generality, a model comparative analysis is carried out using the example of the operating parameters of two microgrids with different types of renewable energy generators.

In this case, the proposition that a transactive (TE) power system allows interaction in such a way that all levels of energy production and consumption can exchange information with each other and, accordingly, carry out purchase and sale operations is considered valid. This approach offers several advantages over the traditional energy system, such as better use of network assets, increased customer satisfaction, and reduced energy costs [9]. Automation and robotics are the basis of energy systems, requiring the creation of appropriate smart control systems and the solution to the scaling problem.

### THE THEORETICAL BACKGROUNDS

The application of such a concept as transactive energy in combination with Microgrid has created

new paradigms for study in this sector. Theoretical research on this topic is relevant, given the interest of the energy market in systems that integrate renewable energy sources (RES) in the Microgrid network and, accordingly, improve the solution of environmental problems in certain territories. Thus, Microgrids built on the TE ideology are an attractive solution, but the implementation of which is associated with a number of technological problems. The general scheme of the TE system that combines Microgrid clusters based on traditional generators and RES clusters is shown in Fig. 1.

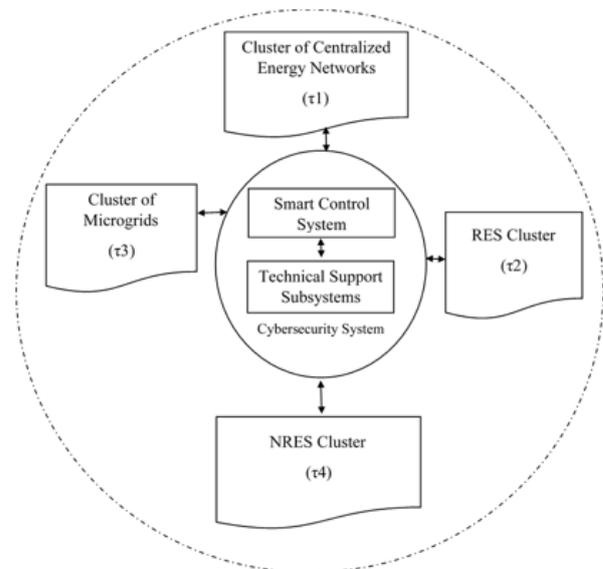


Fig. 1. The general diagram of the transactive system

Source: compiled by the authors

The problem of synchronizing the functioning of individual clusters with different inertia ( $\tau_i$ ) is emphasized by the transition process parameters presented in Fig. 1, which can be significantly different for different clusters.

Internet of Energy IoE is driving the convergence of cyber, physical, and economic performance of the electricity grid [10], [11], [12], [13]:

- most IoE devices will have and/or require connectivity to the Internet.;
- IoE devices must work together to perform various functions in the electricity value chain and its demand;
- new market participants will emerge, such as aggregators, consumer buyers, distributed producers (DERs), and microgrids;
- a large amount of data will be generated, stored, or processed in real time.

Connecting devices to the Internet of Energy poses a cybersecurity challenge for grid operators and all parties involved. This requires investments in

technology to ensure the integrity and security of all devices on the network.

The sheer scale of IoT networks, which can span thousands of devices, poses challenges for scaling security mechanisms. Solutions must maintain performance while protecting the vast number of devices on the network.

Modern technologies, including blockchain, artificial intelligence (AI), edge computing, and quantum-resistant cryptography, are used to ensure the cybersecurity of IoE systems [14].

The authors of the article [15] indicate that blockchain can transform the Smart Grid by moving from a centralized to a decentralized architecture, increasing security against attacks through data immutability and transparency, and optimizing transactions through smart contracts for peer-to-peer energy trading.

The article [16] highlights the low scalability and high energy consumption of traditional blockchains, and concludes that future systems require modern architectures and adapted legal frameworks for local markets.

In addition, thorough verification of interacting devices may be required to prevent data from being disseminated through unauthorized devices or connections. Data sent to the cloud must also be verified to avoid risks to sensitive data.

In a transactive energy market, Microgrid clusters that are part of a transactive system and other participants, with their specific energy production and consumption profiles, can use market signals to exchange energy services in the electricity distribution network. Energy trading can incentivize Microgrids to fully utilize local energy production to provide affordable energy to their consumers. A transactive energy market can facilitate the use of demand response when available energy resources cannot fully meet local loads and imported energy is expensive. The main goal of such a market is to use value-based signals to incentivize market players to provide efficient generation and demand decisions by managing their flexibility, taking into account the technical constraints of the network. It should be recalled that Microgrids originated with the idea of self-sufficiency of their facilities, however, this scenario quickly changed with the realization that transactive methods can be used strategically to gain economic advantages [17]. In this context, demand response and transactive energy programs have become widely discussed in research aimed at balancing consumption and generation in the power system [18]. TE includes characteristics that allow the distribution system to operate with flexibility of

both consumers and producers in the balance between demand and supply.

Traditionally, in a transactive energy system, four main subsystems are distinguished [19], [20], [21]:

- a physical system that includes the production, storage, transmission and distribution of energy together with consumer Smart devices;

- an information system built on the basis of collecting, processing, organizing and transmitting information both in the energy system and in energy markets;

- a transactive system;

- a regulation system.

The combination of Transactive Energy (TE) and the Internet of Energy (IoE) creates a digital ecosystem where energy functions as a dynamic digital asset.

Further, instead of the terms “transactive system” and “regulation system”, we will use the terms “trading platform” and “management system (smart management system)” as more accurately reflecting the functional tasks being solved. In addition, given the level of cyber threats has increased significantly at the current time, the above list of subsystems is supplemented by a cyber protection subsystem, which is allocated as a separate component, and the trading platform, physical and information subsystems will be combined into the block "technical support subsystems" as shown in Fig. 1.

Let us consider the algorithms for controlling the power grid of a distributed power system operating in island mode and requiring guaranteed power sources and including

- generators of guaranteed power, the problem of non-optimal operating modes and inefficient use of fuel.

- renewable energy sources and storage systems.

and compare the functioning of a transactive network with various control strategies using the example of Microgrid systems, the structure of which is shown in Fig. 2.

Uncertainty renewable power source requires forecasting currently there are many forecasting methods based on including using artificial intelligence methods [22].

Multi-objective optimization in transactive systems it is based on various methods a priori post-prior and others [23], [24].

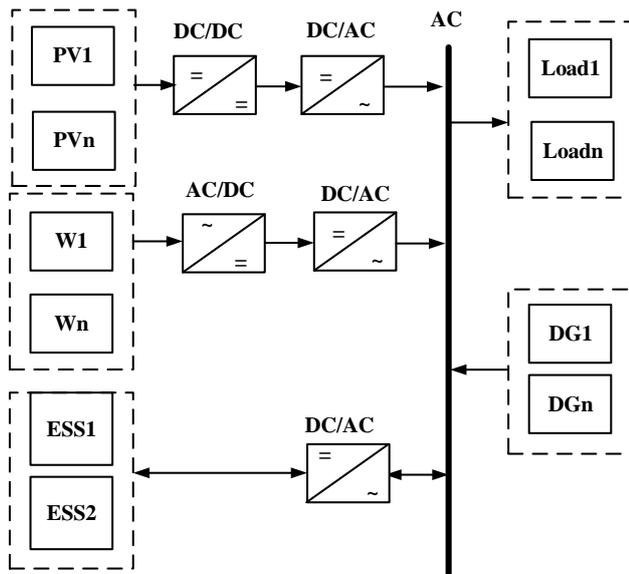


Fig. 2. Microgrid

(DG1, DG2 – guaranteed power sources; PV – solar generator; ESS – energy storage systems; Load – load; DC/DC and DC/AC – converters)

Source: compiled by the authors

## RESEARCH AIM AND OBJECTIVES

The purpose of the article is to consider a transactive system based on the Internet of Energy with a variable structure that can consist of a different set of generation sources, considering sustainability issues and solving an optimization problem based on technical and economic criteria.

The tasks that are solved in the work:

- formulation of the optimization problem of multi-covariate optimization.
- finding the eigenvalues of the matrices of the transactive system under variable regimes to confirm its stability.
- solving the optimization problem of minimizing the costs of primary fuel consumption of diesel generators to reduce
- construction of algorithms and power distribution programs for predicted load schedules.

## RESEARCH METHODS

For research, general methods of electrical engineering are used. For research of stability of a transactive system, methods of Danilevsky, Fadeev, Newton, Power and Khylenko method are used.

When solving problems of multi-objective optimization of Microgrids, the lexicographic method and methods of nonlinear programming are used to find the minimum of individual functions. Algorithms and a program in the Matlab language are developed.

## MATERIALS AND METHODS

The architecture of the electricity grid is increasingly transforming, in particular to one with two-way flows of energy and information. This architecture creates a cyber-physical requirement, where both physical devices and information components must meet this architectural need. As the architectural requirements change, the cyber-physical and economic aspects of the network must be designed in a way that ensures interoperability.

This provides an opportunity for the development of standards to ensure interoperability.

The emergence of new market participants creates the need for more devices, platforms and economic structures, not to mention regulatory changes to manage and control their participation in electricity markets.

A mechanism for storing, managing and protecting data collected in real time is necessary to protect the interests of all stakeholders.

Let us consider the features of building systems taking into account the basic provisions of IoE, the representation of a decentralized (distributed) power system as a set of connected power cells using multi-agent control systems built on the same control principles.

An important element of IoE is, of course, the presence of smart meters or sensors that constantly monitor all processes in this network, helping IoE understand daily schedules and consumers adjust their energy consumption and usage patterns [25].

The monitoring and control system may have some other additional functions according to the size of the microgrid and real-world applications, for example, tariff and market trading management and ancillary services such as frequency regulation, voltage regulation, improvement of electricity quality and reliability, demand response capabilities, change of related operating modes to microgrid monitoring and control systems [25], [26].

We note in advance that both when choosing the system architecture and when changing the architecture, it is important to use multi-criteria optimization and control methods to determine both the system structure and the optimal distribution of energy received from different sources. Solving this generalized problem, taking into account the scaling of the system, requires a separate study and is beyond the scope of the current work.

Microgrid systems, which are presented in this study, are built and operate according to the following basic principles:

- decentralized of the network;

- formation and maintenance of local power balances and independent balancing of the system;
- implementation of bidirectional power flows between participants;
- dynamic change of participant types in the transactive system;
- presence between power equipment not only electrical connections and interaction provided by power networks, but also information connections and interaction;
- possibility of interaction with the centralized power system and its subjects, which ensures the optimal combination of traditional centralized and distributed energy for users.

But for practically all generators and variables  $V = (V_1, V_2, \dots, V_n)^T$  that describe their dynamics, the following relations will be valid [22]:

$$|\dot{v}_m|_{t \geq t_0 + \tau'_{b,i}(m)} = |\dot{v}_m|_{t < t_0 + \tau'_{b,i}(m)}, \quad (1)$$

where  $|\dot{v}_m|$  is the modulus of magnitude,  $\tau'_{b,i}(m)$  is the boundary layer interval for the  $m$ -th variable  $v_m$ ,  $m \in \theta$ ,  $\theta$  is the set of all integers from 1 to  $n$  inclusive. The selection of variables included in the vector  $V$  is carried out in accordance with the tasks of analysis and modeling of the power system, and as a rule include current, voltage, energy storage parameters and other indicators.

The presence of a boundary layer is associated with technological features characteristic of power system equipment, in particular with the presence of transient processes. As is known, the speed of transient processes can differ significantly from the speed of steady-state modes.

In the general case, the description of the mathematical model of the dynamics of TE network will be presented in the form of a system of differential equations

$$\dot{v}_i = f_i(V, t), \quad V_i(t_0) = V_i^0 \quad \left( i = \overline{1, n} \right), \quad (2)$$

where  $V = (V_1, V_2, \dots, V_n)^T$ ,  $t_0$  is the initial moment of integration. In the case of using piecewise-interval linearization, the right-hand side of the equation (2) is rewritten as follows

$$f_i = \mathbf{A}v + \mathbf{B}, \quad (3)$$

where  $\mathbf{A}$  is  $n \times n$  matrix, and the vector  $\mathbf{B}$  takes into account some additional influences.

As the main criterion for the efficiency of the smart grid management system, and, accordingly, the network as a whole, we will consider the cost of

electricity. The value of this criterion will be distinguished using a weighting factor. Accordingly, the objective function is to minimize the specific costs of primary fuel  $F(P)$  for the local power system, which supports the continuity of power supply. We will consider the task of optimizing the operation of the power system as a task of maximizing (minimizing) the complex objective function

$$\begin{aligned} F &\rightarrow \max \\ F &= k_1 f_I + k_2 \phi_I \\ f_I &= \max f(v_i) \\ \phi_I &= \max \phi(v_i) \end{aligned} \quad (4)$$

$f$  and  $\phi$  determine separate indicators (in the simplest case, two main ones) of the operation of Microgrids (in particular, producers' profit, fuel consumption, etc.).

Note that changes in the architecture can be both predictable (related to the natural operating schedules of generators of certain types) and emergency. We will plan that the smart control system should provide control of the power grid in both cases, with the possibility of connecting, if necessary, to external networks or generators. The modeling problem in solving such a problem and the choice of mathematical methods and computational algorithms is an accompanying separate problem and will be considered below.

At the same time, maximizing the efficiency of the entire system, in addition to achieving the best indicator according to the above main criterion, should include:

- maximum reduction of emissions into the environment;
- minimization of energy production costs.

We will consider the application of the indicated approach to the analysis of the state and dynamics of the thermal energy system, the implementation of the corresponding control algorithms, the calculation of control parameters and economic indicators with optimized control and arbitrary control for two specific thermal energy networks.

The systems when solving network management problems, we will assume that.

1. There are no losses in the lines and system elements.
2. Only active power consumption is considered (reactive power and higher harmonics are absent).

In the example of the first model TE system, we will consider a Microgrid, which structurally consists of the following elements (Fig. 2): two

sources of guaranteed power supply DG1, DG2, a solar PV generator, an energy storage system ESS and a load (without W- wind generator).

The multi-objective optimization problem of transactive systems consists of several conflicting objectives: environmental, economic, technical, in contrast to traditional optimization problems that do not correspond to a single solution.

Each solution that does not violate the given constraints can be chosen as optimal. To achieve the given objectives in the multi-objective optimization problem while satisfying the given constraints, it is necessary to determine data for various parameters, including the load and generated power of each generator, the power and charging/discharging time of the ESS.

A number of works ([10], [18], [21]) consider the problem of optimal energy management of several energy nodes, each of which is an energy system with several energy management levels, in order to plan electricity demand profiles and manage their internal energy resources to reduce overall energy costs and CO<sub>2</sub> emissions. An important task of the current study is the selection of mathematical tools and computational algorithms for more accurate forecasting of demand dynamics, taking into account significantly different rates of transient processes in different energy producers-generators.

The optimization problem of a transactive system is described by the function

$$f(x)=[f_1(x), f_2(x), f_3(x)]. \quad (5)$$

The optimization process consists of the corresponding objective functions, each of which is optimized according to its own criteria:

$$- f_1(x) = f_{cost}(P, t) \quad \text{economic (financial)}$$

contour (economic criteria);

$$- f_2(x) = f_{tech}(P, t) \quad \text{technical (energy contour)}$$

(technical criteria);

$$- f_3(x) = f_{ecol}(P, t) \quad \text{ecological and social}$$

contour (optimization according to environmental criteria).

Solving a multi-criteria optimization problem using the lexicographic method consists in performing the ranking of criteria and solving individual optimization problems for given contours.

It should be noted that in the approaches of transactive energy, one of the main criteria of the objective function is the reduction of the cost of electric energy, for transactive systems it is the economic criterion. The next is the technical one. Since the impact of the local network on the environment is usually less than the impact of traditional energy systems, due to the availability of

renewable energy sources, we will set it as the last criterion [27], [28], [29].

This paper considers in detail the optimization according to the technical criterion – minimizing the fuel consumption of diesel generators.

Diesel generators are used as guaranteed power sources at fixed speeds and provide efficient operation on fuel only in a limited range of loads [30]. For most engines, this load range is approximately 70-100 % of the nominal load.

The fuel consumption cost can be accurately approximated by a second- or third-degree polynomial function or cubic spline (cubic spline interpolation accurately models the curve with minimum residuals) of the generated electricity with coefficients obtained from its fuel consumption curve, or a specific fuel consumption curve provided by the manufacturer or actually measured [29], [30], [31]. Accurate fuel consumption modeling is an important issue for optimal planning of diesel generators, with fuel consumption being a function of optimization.

Optimization of the total cost of electricity of a transactive system:

$$\begin{aligned} optC(P, t) = & \sum_{i=1}^k C_i(P_i, t) = \sum_{i=1}^l C_{PVi}(P_i, t) + \\ & + \sum_{i=1}^j C_{Wi}(P_i, t) + \sum_{i=1}^m C_{DGi}(P_i, t) + \sum_{i=1}^n C_{Bi}(P_i, t) \end{aligned} \quad (6)$$

The objective functions are arranged according to the lexicographic order  $f_1(x)$  from the most important to the least important  $f_k(x)$

Let us write the lexicographic problem as

$$\text{Lex minimize } f_1(x), f_2(x), \dots, f_k(x), \quad x \in S \quad (7)$$

When solving the problems, the following restrictions apply:

1. There are no losses in the lines and elements of the system.
2. Only active power consumption is taken into account (reactive power and higher harmonics are absent).

$$\begin{aligned} P_{DER \min} & \leq P_{DER} \leq P_{DER \max} \\ P_{DG \min} & \leq P_{DG} \leq P_{DG \max} \\ P_{ESS \min} & \leq P_{ESS} \leq P_{ESS \max} \end{aligned} \quad (8)$$

The main source of energy is solar generators. During periods of insufficient energy from solar generators, other types of generators are connected to the operation, including subsystems of guaranteed power supply.

In particular, these can be wind generators and diesel generators. It should be noted that the specific fuel consumption of diesel generators nonlinearly depends on the power of the generators.

A combined optimization method is proposed, based on nonlinear programming when solving individual optimization problems and optimization methods based on rules that establish the priority of using renewable energy sources and storage systems.

To solve the optimization problem of a separate circuit, a step-by-step algorithm for power distribution between distributed generation sources has been developed, which optimizes the operation of the microgrid system according to the appropriate criteria.

TES energy management using Internet of Energy technology, which contributes to effective real-time energy management, smart-monitoring and decision-making analysis [32], [33].

### RESEARCH RESULTS

The Microgrid (Fig.2), which is part of the considered transactive system, must be in the energy balance, which means that the sum of the consumed power of the load  $P_{loadi}(t)$  must be equal to, or less than, the power of all distributed sources  $P_{PVi}(t)$ , energy storage systems  $P_{ESSi}(t)$  and the power of guaranteed power sources  $P_{DGi}(t)$

$$\sum_{i=1}^n P_{DGi}(t) + \sum_{i=1}^r P_{PVi}(t) \pm \sum_{i=1}^k P_{ESSi}(t) = \sum_{i=1}^m P_{loadi}(t). \quad (9)$$

Fig. 3 shows a model hourly daily load schedule.

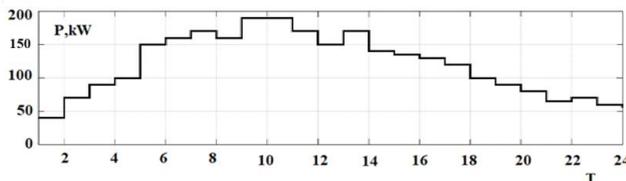


Fig. 3. Daily load schedule  
Source: compiled by the authors

MATLAB is used for simulations and the results show optimization from the system in Fig. 4.

The power distribution by generators and battery is shown in Fig. 4. The power selection program should calculate the optimal power distribution between generators and take into account the forecast indicators of their dynamics. The calculated data is based on LCOE and data on fuel costs and diesel generator parameters [34], [35], [36].

This task is a component of the above-mentioned task of selecting mathematical methods and computational algorithms adequate for obtaining adequate forecasts of the dynamics of the power grid and calculating the values of the control parameters of the Microgrid.

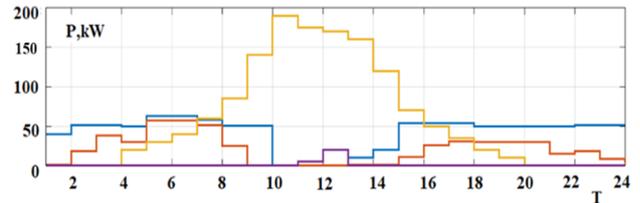


Fig. 4. Power distribution by system elements (red line - DG1 power; blue line - DG2 power; yellow - solar generator; purple - storage system power)  
Source: compiled by the authors

Table 1 presents the calculation results for the following model matrix:

$$\begin{matrix} a(1,1) & 100 & 10 & 50 & 50 \\ 100 & -120 & 50 & 10 & 50 \\ 10 & 50 & -105 & 40 & 10 \\ 50 & 10 & 40 & -95 & 10 \\ 50 & 50 & 10 & 10 & -85 \end{matrix} \quad (10)$$

The elements of the model matrix  $\mathbf{A}$  correspond to the values of individual indicators describing the state of the power grid, the description of which is given in the form of a system of ordinary differential equations (2) with a linearized right-hand side in the form of (3).

Table 1. Determination of the largest eigenvalue at  $a(1,1) = -1200$  with a given range of permissible changes in eigenvalues (-999-+999)

| Power method  | Khilenko method | Laverrier -Newton method |
|---------------|-----------------|--------------------------|
| -1213.11      | -1213.11        | -179.15                  |
| Fadeev method | Krylov method   | Danilevsky method        |
| -179.15       | -179.15         | -179.15                  |

Source: compiled by the authors

Table 1 shows that the computational methods used to determine eigenvalues can be roughly divided into two groups (the first group includes the Power method and the Khilenko method; the second group includes the Krylov method, the Laverrier-Newton method, and others).

The general theoretical importance of calculating matrix eigenvalues, on the one hand, and the increasing importance of using prediction in

modern control systems, on the other, make the development of new methods relevant.

The Khilenko method was developed to address the design of complex, high-dimensional dynamic systems and is focused on predicting their dynamics, as its algorithms are directly linked to mathematical transformations of system models represented as systems of differential equations. Therefore, it was natural to use this method to solve power system control problems. As an alternative, Krylov's method, in its classical description, and, as shown in Table 1, its use generally requires adjusting the computational parameters. Accordingly, this complicates control automation and underlies the advantages of the Khilenko method (as a representative of the first group of methods and focused on working with large models) for use in power grid control systems. The use of the Khilenko method (as well as other methods of the first group, in particular the Power method, does not require the researcher's prior knowledge of the range of eigenvalues of the mathematical model of the power system – see Table 1, and, accordingly, provides a more robotic functioning of the control system, which requires less intervention from a human administrator.

Obviously, in further developments in the control systems of power numbers, the matrix derived from the vicoristic methods of another group can lead to incorrect results and unstable energy management. A detailed comparison of the results of the methods of the first group (power method and Khilenko's method) with the methods of another group (Laverrier-Newton, Fadeev, Krylov, Danilevsky methods) is given in [37], [38].

The correlation of forecast indicators with the varying values of the power numbers allows the matrix to more accurately determine the moments when different generators are turned on and, apparently, to optimize the expenditures of the primary fuel.

To solve the problem of optimized power distribution of several generators operating in parallel, nonlinear programming is used.

The optimization problem is defined by the function  $f_{tech}(P, t)$ , according to the formula

$$\min F_i(P_i), \quad (11)$$

where  $P$  is the generator power,  $F$  specific fuel consumption of guaranteed power sources.

The function is calculated under the following restrictions:

– the sum of the powers by which the generator powers change must be equal to the load change

$$\Delta p_{1i} + \Delta p_{2i} + \dots + \Delta p_{ni} = \Delta P_i, \quad (12)$$

– the change in the power of each generator must lie within the following limits

$$\begin{aligned} -\Delta P_i &\leq \Delta p_{1i} \leq \Delta P_i, \\ -\Delta P_i &\leq \Delta p_{2i} \leq \Delta P_i, \\ -\Delta P_i &\leq \Delta p_{ni} \leq \Delta P_i \end{aligned} \quad (13)$$

– the generator power must not be greater than the maximum power

$$\begin{aligned} (\Delta p_{1i} + P_{1(i-1)}) &\leq P_{1\max}, \\ (\Delta p_{2i} + P_{2(i-1)}) &\leq P_{2\max}, \\ (\Delta p_{ni} + P_{n(i-1)}) &\leq P_{n\max} \end{aligned} \quad (14)$$

The flowchart based on the developed algorithm for optimizing current costs is presented in Fig. 5.

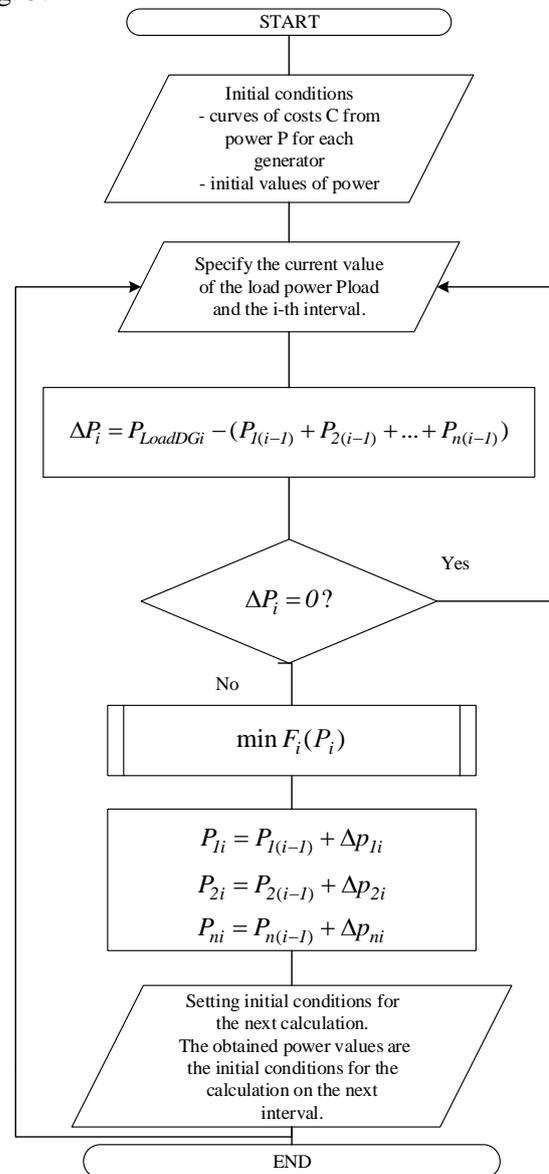
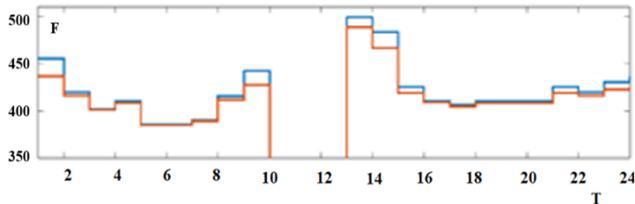


Fig. 5. Flowchart  
Source: compiled by the authors

In MATLAB, the *fmincon* function (constrained nonlinear multivariable minimum function) is used to search for the minimum value of fuel consumption.

In Fig. 6 presents the specific consumption of primary fuel with optimal (quasi-optimal) management with corresponding changes during the day.



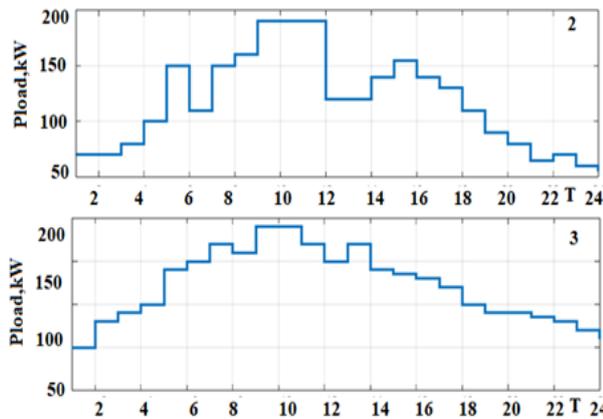
**Fig. 6. Specific consumption of primary fuel for the optimized system (red line) and non-optimized system (blue line)**  
Source: compiled by the authors

The uniform (non-optimized) power distribution across generators (system with non-optimized control) presented in Fig. 6 should be used in the absence of information about individual dependences of fuel consumption on power and it should be calculated using the expression for each interval:

$$F_{unif} \left( \frac{P_{loadDG}}{k} \right) = F_1 \left( \frac{P_{loadDG}}{k} \right) + F_2 \left( \frac{P_{loadDG}}{k} \right) + K + F_k \left( \frac{P_{loadDG}}{k} \right), \quad (15)$$

where *k* is the number of generators, *P<sub>loadDG</sub>* is part of the load that comes to the generation from the diesel generators.

At intervals 10-13 there is no fuel consumption, the generators are turned off, consumption occurs from the solar generator and energy storage system.



At night, consumption occurs exclusively from diesel generators.

Compared to the uniform distribution of load power for a given load schedule across operating sources of guaranteed power, the use of the optimal algorithm in local systems allowed primary fuel consumption to be reduced by 2.1 % due to the redistribution of electricity generation among generators. In addition, fuel delivery costs will also be further reduced.

A study of 5 different load schedules was conducted, 4 of which are presented in Fig. 7. The results are listed in Table 2. Depending on the load schedules, fuel consumption savings vary in the range of 1.5-2.3 %.

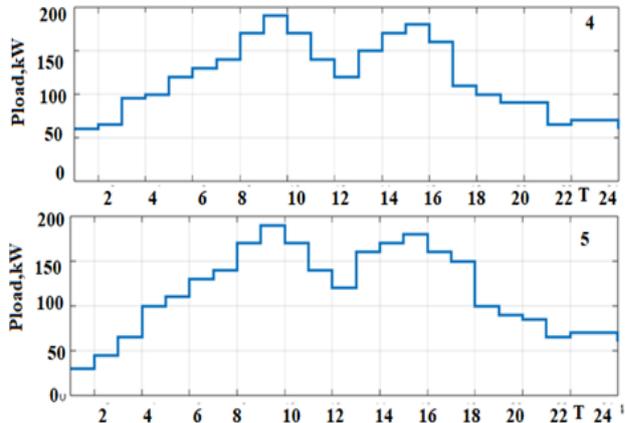
**Table 2. Calculation results in tabular form**

| Power graph | P <sub>mean</sub> , kW | P <sub>min</sub> , kW | P <sub>max</sub> , kW | F <sub>mean</sub> , g/W | F <sub>uniform</sub> , g/W | F %  |
|-------------|------------------------|-----------------------|-----------------------|-------------------------|----------------------------|------|
| 1           | 115                    | 30                    | 190                   | 126                     | 129,2                      | 2,1  |
| 2           | 119                    | 40                    | 190                   | 127,7                   | 130                        | 1,8  |
| 3           | 117                    | 55                    | 190                   | 131                     | 133,4                      | 1,55 |
| 4           | 118                    | 50                    | 190                   | 130                     | 133,2                      | 2,3  |
| 5           | 121                    | 60                    | 190                   | 125,2                   | 128                        | 2,28 |

Source: compiled by the authors

Unlike renewable energy sources, whose energy production capabilities are sometimes limited by the instability of climatic conditions, uninterruptible power supply modules are usually used in microgrid systems to compensate for such types of energy shortages at consumers, as well as in cases of damage and losses in the power system.

In the example of the second model TE system (Fig. 2), we will consider Microgrid system in which a wind generator (W) is introduced, and the battery (ESS) is connected to the AC bus via a bidirectional converter.



**Fig. 7. Daily load schedules**  
Source: compiled by the authors

The presence of a wind generator expands the capabilities of the system. The distribution system works in such a way that the selection of energy power from renewable sources is a priority, depending on the price function, time of day and restrictions.

As indicated earlier, the objective function is to minimize costs, including the specific primary fuel consumption  $F(P)$  for the local power system of the system, which ensures continuity of power supply with maximum use of energy from renewable sources.

The introduction of renewable energy sources into the local system leads to diesel fuel savings, but increases the installed capacity and cost of power equipment of the hybrid system, and also affects the reliability and operating modes of the components of the energy complex.

Energy balance of the system taking into account the wind generator capacities  $P_w$ :

$$\sum_{i=1}^n P_{DG_i}(t) + \sum_{i=1}^r P_{PVi}(t) + \sum_{i=1}^l P_{Wi}(t) \pm \sum_{i=1}^k P_{ESS_i}(t) = \sum_{i=1}^m P_{load_i}(t) \quad (16)$$

Similar calculations were performed for the daily load schedule (Fig. 8) and for the system under consideration.

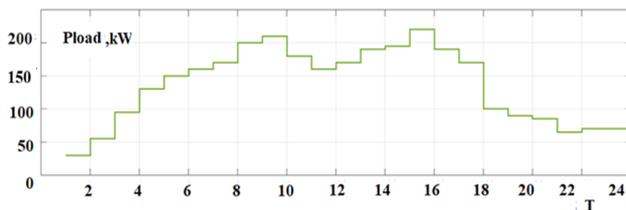


Fig. 8. Load profile  
Source: compiled by the authors

The dependence of the total specific primary fuel consumption for all diesel generators for the optimized system (red line) and the non-optimized system (blue line) on the power is shown in Fig. 9.

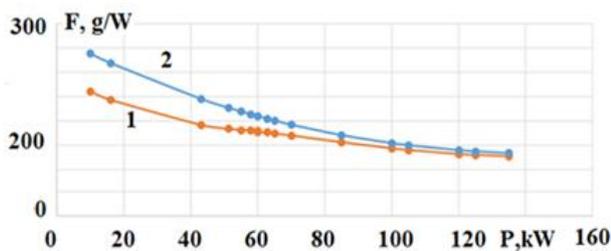


Fig. 9. Dependence of specific fuel consumption on power with optimized and non-optimized control  
Source: compiled by the authors

Analysis of the obtained results shows significant fuel savings at low powers up to 50 kW (specific fuel consumption with optimized distribution is 7.4-11.3 % lower than with non-optimized distribution). At powers close to maximum, the difference is up to 2 %.

When forming optimization functions, it is important to take into account the components of the cost of electricity from a diesel generator. The price per 1 kWh of diesel generator energy  $C_{DG}(t)$  consists of current costs, which are fixed maintenance costs and a percentage of the price for a diesel installation, and variable costs that are associated with the cost of primary fuel and depend nonlinearly on the generated power.

Fuel costs are also affected by transient processes that occur when the load power changes:

$$C_{DG}(t) = kF_{DG}(P_{DG}) + \Delta C + C_{cur}, \quad (17)$$

where  $C_{cur}$  is current consumption,  $kF_{DG}(P_{DG})$  is a function of variable consumption of primary fuel from generated power,  $\Delta C$  is a function of fuel consumption in transient operating modes.

The fuel consumption schedule  $C_{DG}(t)$  has a similar appearance to the primary fuel consumption  $P_{DG}(t)$  because the fuel price is the most influential component of the total cost than the other price components.

The power distribution by generators and storage systems is presented in Fig. 10 (blue line – DG1 and DG2 power, yellow line – solar generator, red line – storage system power, purple line – wind generator) and corresponds to the optimal power distribution by generation sources (wind generator, solar generator, DG generators and storage system).

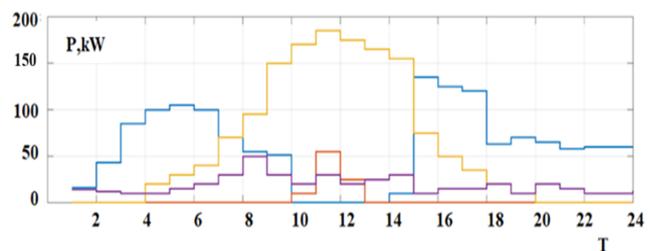


Fig. 10. Power distribution by system elements  
Source: compiled by the authors

## DISCUSSION OF RESULTS

It should be emphasized that for both considered Microgrid systems, the power selection program must calculate the optimal power distribution across generators and take into account the forecast indicators of their dynamics. This task is a component of the above-mentioned task of

selecting mathematical methods and computational algorithms to obtain adequate forecasts of the dynamics of the power grid and calculate the values of the Microgrid control parameters.

In the considered transactive energy systems on based Internet of Energy, when using correct computational procedures, the application of an optimal control algorithm compared to uniform distribution of load power according to specified load modes on operating sources of guaranteed power allowed to reduce the primary fuel consumption by at least 1.5 % due to the redistribution of electricity production between producers. At the same time, an increase in the number of components of the power system led to an increase in the effect of using optimal control.

These calculations show that:

- network scaling and the effect of control optimization are correlated functions;
- the importance of optimal control increases with the growth of the power system dimension and allow us to assume a further increase in the efficiency of using optimal (optimized) control algorithms when scaling TE systems.

Further improvement of the quality of smart control systems in this case, taking into account the different energy content of the power system components, should be based on the use of decomposition models [37, 38], which will reduce the load on the computing unit and speed up calculations. Consideration of this issue goes beyond the scope of this work and requires additional research.

Further development of the work is the use of other optimization algorithms to find the best option, verification of the algorithm using digital twins, study of cyber security problems in Microgrids with Internet of Energy using blockchain technologies and machine learning.

## CONCLUSIONS

When moving to complex transactive energy systems, improving their economic performance requires the use of optimal control algorithms, including the issue of minimizing the time it takes to make a decision on switching modes when changing the architecture of the energy system.

Two transactive system with different power supply sources were considered, which have guaranteed power sources to cover energy in the event of uncertainty in renewable sources. The primary fuel consumption of diesel generators was optimized using the developed algorithm and a program based on it. This allowed reducing fuel transportation costs and reducing CO<sub>2</sub> emissions. The modeling results show a cost reduction of up to 11% depending on the load schedules and system composition.

Arbitrary choice of mathematical support and appropriate algorithms for use in power grid control systems without taking into account the technological features of their elements, in particular different durations of transient processes, etc., can lead to incorrect results and, accordingly, unstable operation of the power grid. Minimizing significant errors in management decision-making requires the use of specialized problem-oriented methods and algorithms that utilize forecast data. The proposed load forecasting technology is based on the use of eigenvalues of the state matrices of a transactive energy system. Information technology is expanding the capabilities of microgrids, one such technology is the Internet of Energy. An important element of IoE is the presence of smart meters or sensors that constantly monitor all processes in this network, helping IoE understand daily schedules and consumers adjust their energy consumption and usage patterns.

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## Оптимізація керування транзактивною енергетичною системою з періодично змінною архітектурою на основі Інтернету енергії

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### ABSTRACT

У статті пропонується вирішення проблеми підвищення якості та ефективності систем керування транзактивними енергетичними системами, які характеризуються періодичними змінами їхньої архітектури. Інформаційні технології

розширюють можливості Мікромереж, однією з таких технологій є Інтернет енергії (ІоЕ). ІоЕ – це глобальна взаємопов'язана мережа, що складається з інтелектуальних мереж, що взаємодіють одна з одною за допомогою інформаційних технологій. ІоЕ сприяє конвергенції кіберфізичних та економічних показників роботи мережі, надаючи можливість покращувати якість керування шляхом прогнозування очікуваних змін у динаміці. Запропоноване рішення для оптимізації керування ІоЕ базується на технології прогнозування зміни навантаження, що забезпечує ефективний розподіл потужності між генераторами та оптимальний графік увімкнення/вимкнення генератора. Критерій оптимізації та обмеження сформульовані математично. Запропонована технологія прогнозування навантаження базується на використанні власних значень матриць станів транзактивної енергетичної системи. Представлено результати розрахунку власних значень матриць, розрахованих методами першої групи (метод потужності та метод Хіленка) та другої групи (метод Крилова та інші). У статті розглядається транзактивна система зі змінною структурою на основі Інтернету енергії, яка може складатися з різного набору джерел генерації, система керування вирішує задачу оптимізації на основі техніко-економічних критеріїв. Робота запропонованої системи керування демонструється на прикладах для двох транзактивних систем при розв'язанні задачі оптимізації мінімізації вартості первинного палива для дизель-генераторів з метою зниження витрат та зменшення викидів CO<sub>2</sub> за допомогою програм розподілу потужності для прогнозованих графіків навантаження та графіків ВДЕ

**Ключові слова:** транзактивна енергетична система; Інтернет енергії; мікромережа; оптимізація керування; метод Крилова; метод Хіленка

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