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Dynamic energy management system with real time component control to increase the efficiency of local polygeneration microgrid

***Abstract**. The paper is devoted to approaches to creating in energy management system with dynamic control of components based on modern information technologies. It is proposed to implement the energy management strategy of local objects by coordinating supply and demand in real time. The balance between own generation and consumption in micro-energy systems with several sources should be ensured by the maximum share in their energy balance of renewable sources. It has been established that the structural-algorithmic synthesis of the dynamic management system of the polygeneration microgrid means ensuring its functional integrity based on the selected structure of sources and the coordination of the power balance of the local facility in real time, taking into account the stochastic generation of electricity from renewable sources. The conditions for creation of energy information connections are investigated. The technical platforms for the realisation of the basic principles of the dynamic energy management system using modern IT infrastructure and the possibility of remote monitoring and control of final current collectors based on the current cost of electricity is proposed.*

***Streszczenie.** Artykuł poświęcony jest podejściu do tworzenia w systemie zarządzania energią dynamicznego sterowania elementami w oparciu o nowoczesne technologie informatyczne. Proponuje się realizację strategii zarządzania energią lokalnych obiektów poprzez koordynację podaży i popytu w czasie rzeczywistym. Równowaga między wytwarzaniem a zużyciem własnym w mikrosystemach wieloźródłowych powinna być zapewniona poprzez maksymalny udział w ich bilansie energetycznym źródeł odnawialnych. Ustalono, że synteza strukturalno-algorytmiczna dynamicznego systemu zarządzania mikrosiecią poligeneracyjną polega na zapewnieniu jej integralności funkcjonalnej w oparciu o wybraną strukturę źródeł oraz koordynację bilansu mocy lokalnego obiektu w czasie rzeczywistym z uwzględnieniem stochastyczne wytwarzanie energii elektrycznej ze źródeł odnawialnych. Badane są warunki tworzenia powiązań informacji o energii. Zaproponowano techniczne platformy realizacji podstawowych zasad dynamicznego systemu zarządzania energią z wykorzystaniem nowoczesnej infrastruktury informatycznej oraz możliwości zdalnego monitorowania i sterowania końcowymi odbiornikami prądu w oparciu o aktualny koszt energii elektrycznej.* **(Dynamiczny system zarządzania energią ze sterowaniem komponentami w czasie rzeczywistym w celu zwiększenia wydajności lokalnej mikrosieci poligeneracyjnej**)

Keywords: energy management, real time control, efficiency, local object, polygeneration microgrid.
Słowa kluczowe: zarządzanie energią, sterowanie w czasie rzeczywistym, efektywność, obiekt lokalny, mikrosieć poligeneracyjna..

Introduction

The European experience of energy security in the context of the global "green" energy transition and decentralization of energy supply systems shows a return to object management of resource assets related to own energy production, mostly distributed renewable energy sources (RES). Existing results of research and practical implementation of combined energy systems (CES) allow to substantiate new technical, technological and economic solutions for energy needs of local objects with the lowest cost [1].

The level of technical support for intelligent monitoring, accounting and management of technological processes in electrical grid is sufficient for the introduction market cost mechanisms in the energy sector. Form one side, It will get a possibility to optimize the operation energy system in real time, reducing peak loads. From another – it will allow to involve users (electricity consumers) to format the management decisions at the system level through the introduction of dynamic energy management based on the current price of electricity. Using a reduction in peak electricity demand can significantly reduce the system costs of generating electricity.

Modern CES is prospectively to consider as energy information complexes, Where the increasing level of energy efficiency is achieved through the new organization of management of their functioning. It is assumed that the solution of this problem will be the basis for ensuring the reliability of power supply, guaranteed energy quality, the possibility of its accumulation, segmentation and hierarchy of power energy and information flows, making optimal management decisions, as current as prospective [2,3].

Further development of «Smart» grid will allow solving new problems of optimal management of the functioning combined-type electric power systems with a significant share of renewable sources. The level of use of information technologies for technical support of monitoring, accounting and management of technological processes in electrical grid is sufficient to introduce new mechanisms for managing energy efficiency networks and electricity pricing at the level of end consumers [4]. The main at this step is not only optimization the power systems operation according for the cost criteria, and also formation of technical and economic prerequisites for the implementation new principles microgrid management with the participation of users by monitoring the parameters power consumption in real time [5,6].

Literature survey

Well-known methods of electricity consumption control in energy management system based on identification of loads of switching devices, in which electricity metering is carried out, determine the components of the system of local equipment for data fee and processing, create automated databases parameters of electricity consumption modes [7].

The dynamic control components of energy management system with real time for generating reports and distributing them to specific users are justified. As a part- the function of measuring connected capacities of current-pickers at the selected time interval by means of primary accounting and through the communication channel with the channel-forming equipment [8]. Administrative models in energy management systems [9] passed power information to a data processing device, where they are compared with defectively defined daily levels of power consumption and through a separate communication channel transmit a signal to turn on/off the corresponding switching device, while automated control of switching devices is carried out on the basis of built-in additional devices with remote access [10].

Further development of such approaches is seen in the intellectual management of energy resources to cover demand with the necessary reliability of power supply and ensuring the environmental component. The method can be the basis for the creation of energy management systems using artificial neural networks and evolutionary algorithms for predicting energy balances and efficient use of energy. The target of dynamic management is not only the optimization of electrical supply and accumulation electrical energy, but also adaptive load adjustment.

So, the substantiation of technical and technological solutions monitoring system and cost of management for electrical supply of local objects (LO) by forming the structure and specifics of CES realisation with polygeneration, coordinating electricity consumption schedules with the volumes of electricity of its own generation, Also, its current cost, the forecast of generation by renewable sources, requires the development control components for the dynamic energy management system.

Local objects with dynamic management of electrical costs have possibility potential to improve energy efficiency electricity consumption through the use of combined power supply systems with renewable sources and changing the role of the user. The creation control components for managing electricity consumption as the principles of dynamic energy management are based on the Technology Internet of Things (Io).

The research is devoted to a comprehensive solution of the issue real-time management of electricity costs by coordinating generation processes in the formation in energy balance CES and electricity consumption management with the participation of user with modern information technologies

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Materials and methods

Cost management systems for electricity supply has significant potential for improving energy efficiency. It is required the use of combined electrical supply systems with RES and changed the role of users [11].

Dynamic energy management includes traditional principles at all levels of energy distribution, combines them into an integrated structure for simultaneous optimal regulation of demand. First of all, it is to reduce electricity consumption in peak periods at the highest cost of electricity. It is achieved by improving the energy management system based on the use of intelligent end devices and algorithms for managing distributed energy resources with highly developed communication tools. These are able to ensure optimal functioning of the system in real time. System components are interacted with each other, creating an integrated automated management structure able to learn.

The creation dynamic control of components electricity consumption management system laid down the principles of energy management in real time using modern information technologies [12]. This approach is the subject of an overall energy management strategy for individual objects., Since at the same time, the strategy of electricity consumption should be implemented by coordinating supply and demand in real time. The balance between own generation and consumption within microenergy systems must be ensured by the implementation of certain rules. Ensuring the maximum share of renewable sources in the energy balance of CES is the main.

The structural and algorithmic synthesis of dynamic management system and organization of functioning CES means ordering its integrity with clearly defined characteristics. The structure is logical and with possibility technical ways of implementation in real time using technology Internet of Things [13.14]. The target of developing a dynamic energy management system (DEMS) CES local object with polygeneration is based on the application of methodological approaches. They are reduced to the representation of this system in the locations of states and moments of time, where behaviour is predefined for the functional requirements of the local object.

Dynamic control of components energy management system takes place by generating real-time information:

- on the agreement the structure and the condition of sources in the formation energy balance CES, reliable provision electrical consumption schedule LO at the lowest cost [15];
- technical support for automatic determination of the current cost electricity CES with discreteness of calculating conditional dynamic tariff 0,5 hour [16];
- dynamic monitoring of the current cost of electricity with realization of computational procedures and a user interface on the choice electrical consumption management scenario based on Technology Io [17].

Generalized Functional model structure DEMS (fig.1) allows remote real-time monitoring conditions of sources (DER_1, DER_2…DER_n) and electrical consumption end current users CES_n with a dedicating wireless communication channel.

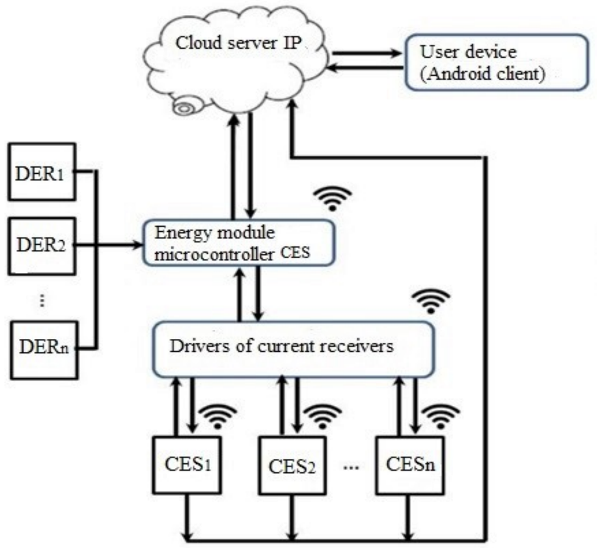

Fig.1. Generalized structure of functional model the dynamic energy management system of a local objects з CES.

The development of a functional model DEMS LO are based on dependence of current energy consumption levels in the half-hour time interval on operational factors. They are affected the formation of energy balance and the current cost of electricity CES (levels of own generation sources, refusal sources, sudden reject schedule electricity consumption). Let is x_1, x_2, x_3 - electricity consumption levels, which characterize, respectively, the number residents in the hostel, temperature external environment and additional numerical parameter to account the features of the schedule educational process. Let is ε some random quantity, which characterizes the variability of the model and caused by irregular stochastic events. In general, the model can be represented as follows [18]:

(1) $$y = f(\beta, x_1, x_2, x_3, \varepsilon),$$

where f – is some function, β –is addiction vector parameter.

From the point of view of dynamic management, It is important to set a functional dependence f for its realization in the model (1) and design an appropriate software interface with automatic export of data on the state of sources, own generation level, profiles electrical consumption of final current users for realizing control algorithms.

As mathematical model electrical consumption, LO was chosen linear regression model of the form:

(2) $$y = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + \varepsilon,$$

and its generalizations:

(3) $$y = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + \beta_3 x_3 + \varepsilon$$

where y – the average electrical consumption at the selected time interval, $\beta_0, \beta_1, \beta_2, \beta_3$ — coefficients, to be determined. In the future, equality (2) i (3) we will conditionally call abbreviated and extended models, respectively.

For processing and available statistical data, a computer program was developed in software Delphi. The specified program converts the source data into a plan matrix for building models (2), (3) and calculates the coefficients of the model. Research probabilistic properties of the resulting model and the analysis of its relevance to real data was carried out using the developed program in software Delphi and statistical package *STATISTICA*.

If it will be input additional variables to the model and distribution of the obtained models to objects of other purposes, designed software makes it possible to implement more advanced type dependencies (2) i (3) with identification of parameters of linear models [19]. The differentiate scalar and vector-matrix quantities is achieved using bold for the latter.

A generalized linear model will be considered as a dependence of the form:

(4) $$Y = X\beta + \varepsilon,$$

where *Y* – is the vector of observations of the dependent variable, *X* - matrix observations of independent variables, called as regression matrix or matrix of experiment or plan, β - vector (unknown) coefficients, ε - error vector with zero average. Dimension *dim*(.) data values designated accordingly are:

$$dim(Y) = dim(\varepsilon) = n, dim(\beta) = p, dim(X) = n \cdot p,$$

therefore, it is possible to write:

$$Y = \begin{pmatrix} y_1 \\ y_2 \\ \cdots \\ y_n \end{pmatrix}, \ \beta = \begin{pmatrix} \beta_0 \\ \beta_1 \\ \cdots \\ \beta_{p-1} \end{pmatrix},$$

$$X = \begin{pmatrix} x_{10} & x_{11} & \cdots & x_{1,p-1} \\ x_{20} & x_{21} & \cdots & x_{2,p-1} \\ \cdots & \cdots & \cdots & \cdots \\ x_{n0} & x_{n1} & \cdots & x_{n,p-1} \end{pmatrix}, \varepsilon = \begin{pmatrix} \varepsilon_1 \\ \varepsilon_2 \\ \cdots \\ \varepsilon_n \end{pmatrix}.$$

In the future we accept, that $n > p$. The transition notation from scalar expression (2) i (3) to vector-matrix (4) has a standard procedure: postulated as real addictive variable *y* with accuracy to random addictive fault ε can be represented as a linear combination (independent) real variable, regressors $x_0, x_1 \ldots, x_{p-1}$:

(5) $$y = \beta_0 x_0 + \ldots + \beta_{p-1} x_{p-1} + \varepsilon,$$

as well as the presence of an appropriate sample volume *n*. In this case, the function, $f(x) = \beta' x = \beta_0 x_0 + \ldots + \beta_{p-1} x_{p-1}$ that is, the right side without a random component is a linear function of regression, where $\beta_0 \ldots \beta_{p-1}$, - are regression coefficients.

The representative is totality an *n,* which obtained experimentally by separation:

(6) $$(x_{ij}, \ldots x_{i,p-1,} y_i), i = 1,2, \ldots, n \ ,$$

where x_{ij} — is significance *j* - regressor (*j* - independent variable) at *i* - observation, y_i — proper dependent variable. So, it is denoted ε ε_i fault value ε at *i*-th observation and sequentially selective values (5) in equality (4), obsessed *n* equalities:

(7) $$y_i = \beta_0 x_{i0} + \ldots + \beta_{p-1} x_{i\,p-1} + \varepsilon_i, i = 1,2, \ldots, n,$$

which are conveniently represented as a single vector-matrix equality (4).

To evaluate the vector coefficients β used known least squares method. So, vector $b = (b_0, \ldots, b_{p-1})'$ is the solution of the minimization target:

(8) $$\|Y - X\beta\|^2 \xrightarrow[\beta \in R^p]{} min$$

where R^p- *p*- measurable Euclidean space, minimum is $\beta \in R^p$, and the norm $\|z\|$ vector $z = (z_1, \ldots, z_n) \in R^n$ is as $(z_1^2 + \cdots + z_n^2)^{1/2}$.

Its shown in [18,19], the decision (8) is like as a solution ***b*** systems of so-called normal equations:

(9) $$X' X\beta = X' Y$$

Under any conditions of the system (9) is compatible, while, matrix *X* has full rank. Its solution, and the solution (8) the only one and has the form:

(10) $$b = (X' X)^{-1} X' Y$$

where $^{-1}$ — sign matrix rotation.

Evaluation *b* of vector β is carried out by applying the least squares method. So, the function $\hat{y} = b' x = b_0 x_0 + + b_1 x_1 + \cdots + b_{p-1} x_{p-1}$ is an evaluation of the regression function $\beta' x$.

The construction of a regression model of form (4) as values dependent variable are taken actual, at the beginning of a discrete time reference, electrical consumption levels with projection for the appropriate energy management scenario, taking into account the profile of the load schedule. At the equality (4) for «acronym» model (2) three variables are taken as independent: x_0, x_1, x_2, and for the extended model another variable was introduced x_3 (as *p* = 3 in the first case and *p* = 4 in the second). So, x_0 and x_3 – are the so-called fictitious variables, and x_0 always equal to 1 (its role is to introduce a constant component into the model), and x_3 is 1 or 0. Its depended, on which management scenario the user has chosen, x_1 – installed power current primers, which are included to the simple scenario, x_2 – levels of generation of own sources.

Program realization of calculations has done by using software Delphi. The functional algorithm of which involves the construction of an experiment matrix *X* are based on statistical observations and researched regression data with determination coefficients in accordance with (10), construction of balance graphs for the resulting model.

Results and discussion

Implementation of distributed energy management local object as a component DEMS involves the use of a single energy module (EM) and web services with technology IoT. The use of such a distributed architecture requires careful coordination of both the structure and controlled processes (fig.2).

The user profile (UP) as the central module of the system is due to coordinate actual levels electrical consumption with possible scenarios of user behavior.

Information on the status and levels of generation CES sources directs to the resource and consumption controller (CRPS) with further calculation of the current cost electricity at the selected time interval and subsequent dynamic formation of management orders in automatic and automated modes.

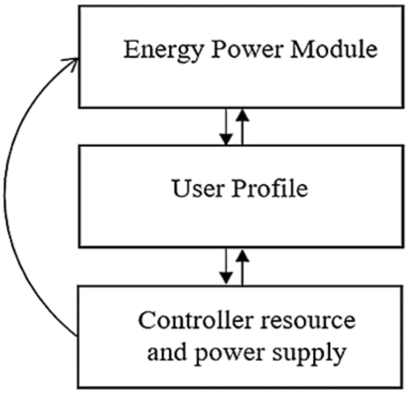

Fig. 2. Architecture of adaptive energy management system of local objects

The computing module CRPS is configured for autonomous control and maintenance of processes of regulation / control of electrical consumption in power module of the LO with several sources. Its characterized such as:

formation and processing of primary data using a local platform IoT for distributed management of energy flows with the ability to interface with the user. Based on IoT information about actual state of electrical consumption of LO is transferred to the PC module. The information on the current cost of electricity is up to CRPS;

predictive state of assessment CES by calculating the conditional dynamic tariff [11] identifies factors, that affect the achievement of a predetermined goal (for example, exceeding the budget for electricity supply), including the directivity selected user scenarios.

The realization of dynamic control components in distance monitoring and management energy consumption of local objects with electricity sources is proposed to do with several independent blocks. They are doing several operations in automatic and automated control modes. Generalized structure of the technical platform DEMS shown in fig. 3. based on channel-forming equipment wireless connections Wi-Fi Direct, nRF24L01+, Zigbee and LoRa.

Block of analysis, forecasting, information processing and management of electric consumers (MKPM) maintains constant communication with the Internet to form a database on the state of the system in real time with the ability to manually control remotely and receive predictive information. MKPM is polled universal blocks of primary keeping, information processing and management (KPM), It uses wireless channels and analyzes in real time data on RES generation and an actual electricity consumption according for a given algorithm.

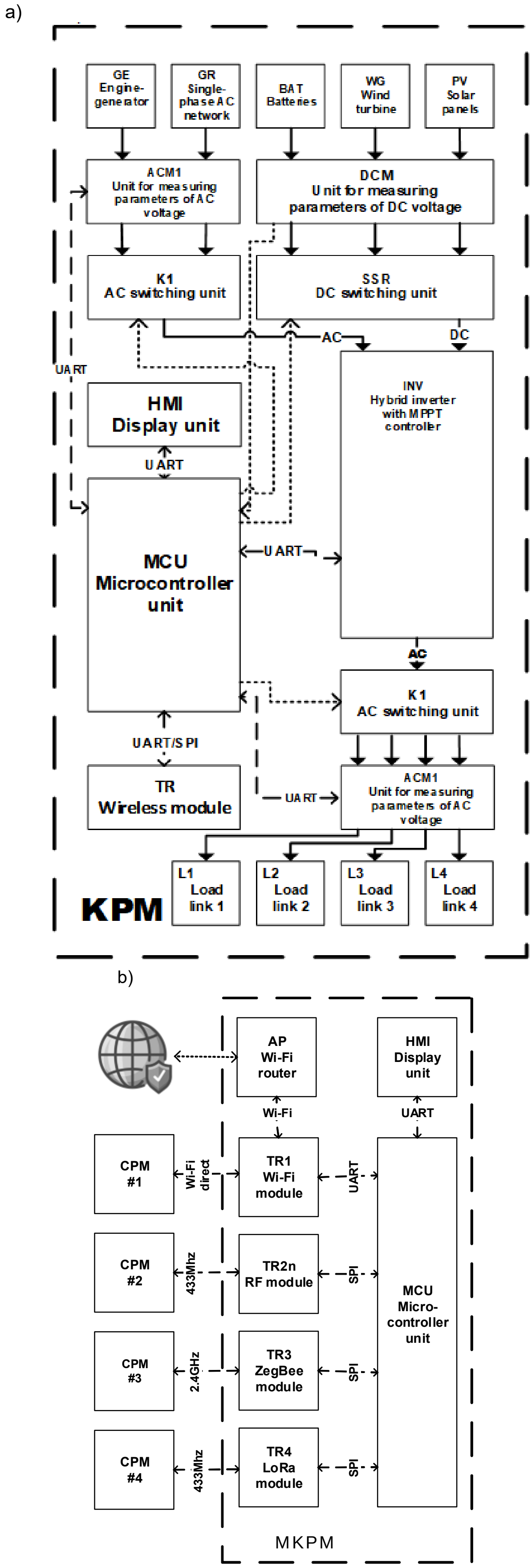

Fig. 3. Generalized structure of technical platform DEMS using Technology IoT: a) block of primary keeping, information processing and management (KPM); b) block of analysis, forecasting, information processing and management of electric consumers (MKPM).

Also, it generates through the server and the Internet the sending of control signals to adjust the consumption schedule (through KPM blocks, if necessary). The components of the MKPM unit include a microcontroller (MCU), touch screen display (HMI) and several wireless modules (TR).

MCPM operates on the board RobotDyn, which combines a microcontroller ATmega2560 (MCU) and Wi-Fi module ESP8266. Both controllers can work simultaneously and independently of each other. MCU has a sufficient number of digital channels input/output to connect peripherals. It has built-in support for standard external device connection protocols SPI, I^2C, UART. It's enough for program code of scenarios, which taking into account the volume of permanent, operational and non-volatile memory. Program code of the block MKPM uses common software libraries for the functioning of connected devices (Open Source). It does not require licensing support.

Display module Nextion, which is part of the block. and provides a human-machine interface (HMI)/ It combines a built-in processor and touch display with software Nextion Editor. HMI panel Nextion Enhanced NX8048K070-011 7.0" TFT with touchscreen, controlled by a sequential asynchronous bus UART. Powerful 32 bit processor allows show complex pictures and animations. Convenient editor is almost full-fledged SCADA system, with which it is possible in the mode WYSIWYG create graphical shells (acronym «What You See Is What You Get»).

Block MCPM through wireless modules TR is connected with blocks CPM, using wireless communication channels, depending on the features of spatial distribution final current receivers within the LO.

When creating a laboratory layout for modeling the functionality of dynamic control, four types of wireless communication were selected. They are used unlicensed carrier frequency ranges with different spectrum: *Wi-Fi Direct,* radio modules *nRF24L01+, Zigbee* and *LoRa*.
Each of the selected types of communication has its advantages and disadvantages.

Wi-Fi Direct does on the module ESP8266, on the board RobotDyn. Wi-Fi Direct uses the same basic technology, frequency as traditional Wi-Fi and provides similar bandwidth and speed. Wi-Fi Direct –is technology, which allows many devices with support Wi-Fi easily connect to each other and exchange data without the need to organize traffic and transfer data packets through a central router. The protocol is easy to use. If you want to connect two devices together, you must only activate Wi-Fi Direct on both. wait a while for the two devices to find each other and then start the automatic pairing process. Wi-Fi Direct more than a hundred times faster, then Bluetooth, however, it consumes much more electricity. The distance at which the module can operate does not exceed one hundred meters.

To organize data exchange between two or more microcontrollers, sometimes the most convenient option is wireless communication using radio modules *nRF24L01+*, They have a low price, low power consumption, easy setup and high flexibility when building networks of various topologies. The distance at which the module can operate depends on a number of factors: the presence of an antenna, the possibility of propagating a signal in the line of sight, etc. For equipment with an external amplifier, the signal propagation range is hundreds of meters.

ZigBee is a short-range network technology. The technology is based on the radio standard IEEE 802.15.4 and is designed to standardize communication between low-power devices from different manufacturers M2M (Machine-to-Machine). A feature of the network is high resistance to failures, long service life of end devices from a single battery charge, support for a large number of connections and joint operation of devices from different manufacturers. ZigBee provides for the transfer of information within a radius of 5 to 75 (in open areas up to 200) meters with a maximum speed 250 кBit/s. Of the latest versions supports direct connection, Zigbee allows end devices from different manufacturers to work directly without the participation of an additional router, flexibly configure device behavior scenarios and increase the data transfer rate.

LoRa technology provides long-distance communication with low power consumption. LoRa can be used for two-way transmission of information for a long time using remote sensors and their power supply on a single charge of a small capacity battery. LoRa signals under certain conditions can propagate over a distance of 15-20 km. With LoRa technology is possible to provide stable communication over long distances, avoiding the disadvantages of cellular communication, Wi-Fi and BLE (Bluetooth with low power consumption). For communication of the microcontroller and communication modules, SPI, UART protocols are used.

Blocks of primary collection, information processing and management CPM installed directly near the connection points of the current collectors and transmit the collected data for further analysis and control through wireless networks to the MCPM block and receive control directives. If necessary, it is possible to switch to manual control. The components of CPM include systems for measuring electrical parameters and actuators of end switching devices.

The development of an adaptive control energy information system for a LO with several architectural levels involves the implementation of several functional modules to form an energy balance with the participation of heterogeneous sources with a single power bus in the secondary circle, built the information on the current cost of electricity using IoT. The principle of control of local electrical consumption with polygeneration is shown (fig. 4). At the same time, the user profile allows to take into account the structure and specifics of the power consumption system, also to create protocols for feedback on electricity demand, and its current cost and forecasting of renewable generation volumes.

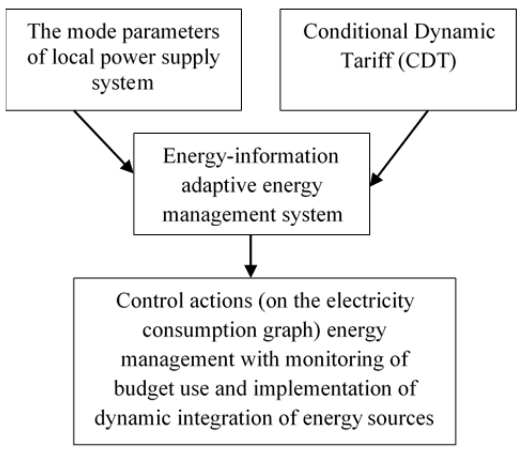

Fig. 4. Energy-information principles management of local electricity consumption with polygeneration

Dynamic control of components in energy management system is implemented on a single platform with automatic and automated modes of control of independent blocks (fig. 5, 6): analysis, forecasting, processing of primary information; primary collection, information processing and management with wireless communication channels different standards depending on the displacement of current collectors;

block for obtaining predictive information, informing users about the state of the system in real time and the ability to control in an automated (with the participation of the user) remotely.

Functional interaction between system components (sources, energy module, user profile and controller of resources and power consumption) consists in the formation of DEMS algorithms based on available management decisions while ensuring the continuity of a given power supply schedule.

That is why, the design DEMS is necessary integrate technical tools and implemented mathematical models to solve problems in the presence of stochastic components, the distribution of the network architecture with multiparametric relationships between functional elements, which in real time can change the degree of mutual influence.

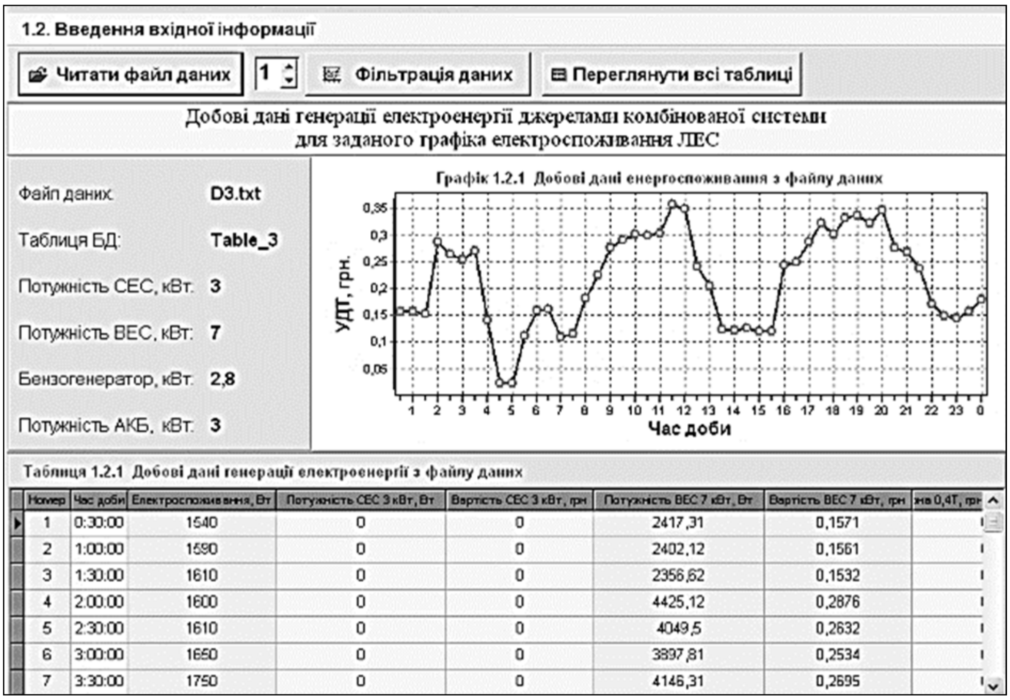

Fig. 5. Interface for entering the output data of the software module of dynamic energy management CES with a wind-solar system, gasoline power station and static power supply.

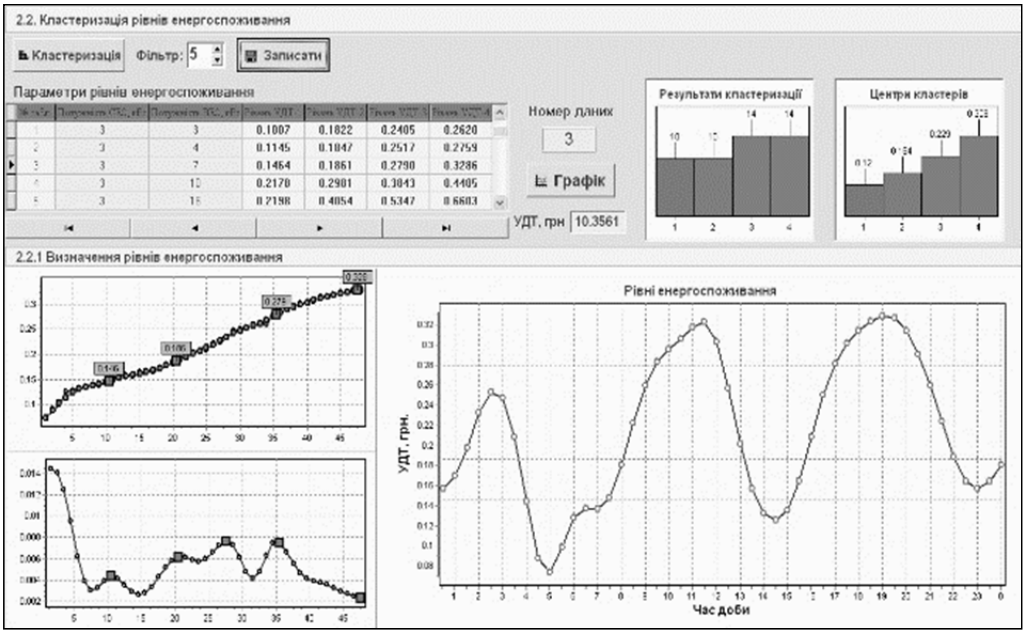

Fig. 6. Screen window for estimating daily power consumption levels in the time interval 0,5 hour dynamic energy management software module CES with a wind-solar system, gasoline power station and static power supply.

The missing external centralized management (dispatching), planning and control of electrical consumption of LO such kind, distributed decision-making system imposes certain corrections at the local level, based on user scenarios. Important is coordination functioning of system components to direct for pleasure of user requirements within accepted DEMS scenarios.

Conclusions

The obtained research results showed ways to further improve the ways to manage electricity costs in real time. The proposed approaches allow the use of scalability and capability increasing control channels to form the necessary structure, introduce modular dynamic energy management systems in the form of functionally completed components. They have the access to the standard interface by combining cloud technologies, communication and computing resources, using standard wireless interfaces with communicate between system components and the user.

This will increase the energy efficiency of microgrids of this class and opens up opportunities for users to participate in the electrical supply of their facilities at the lowest cost.

Further development of microenergy systems with polygeneration will certainly be associated with the processing of large amounts of data on the state of their dispersed elements in real time. Therefore, the use of IoT technologies is the most promising for this.

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