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doi:10.15199/48.2023.09.10

Electrical power and energy balance in the local electrical system by using reconciliation of the generation and consumption schedules

***Abstract**. The paper considers the problem of balancing power and electricity in a local electric power system (LES), in which electricity consumption and its generation by renewable energy sources (RES) are proportional to each other. In the LES, the principle is implemented - what is generated is consumed by its own consumers. The LES is considered as part of an electric power system (EPS) with large power plants, but which can operate in an autonomous mode. The sources of electricity in the LES are small hydroelectric power plants (SHPP), photovoltaic and wind power plants (PV, WPP), the production of which is unstable due to dependence on natural conditions. That is why the LES provides for reserve existing maneuvering capacity, electrochemical storage, hydrogen technologies and biogas plants in the UES. To assess the possibility and effectiveness of methods and means of reserving the instability of RES electricity production, the criterion method of the similarity theory was used. From the analysis of the proportionality and sensitivity of the relative costs of RES reserve capabilities and means, it is shown that the best are hydrogen technologies and the coordination of electricity generation and consumption schedules in the RES. First of all, we recommend to use the possibility of using electricity generation and consumption schedules in the LES. For the amount of electricity that remained unbalanced after such reconciliation, it is advisable to use the hydrogen produced in the LES for full balancing. Coordination of generation and consumption schedules in the LES for balancing electricity in it is carried out using a morphometric apparatus, which is based on the transition from the Cartesian to the polar coordinate system. It is shown that the use of a morphometric apparatus for analyzing the unevenness of graphs has a number of advantages and allows for a comprehensive and detailed assessment of the graphs shape. Conditions are created for monitoring the dynamics of changes in consumption and generation schedules in the LES and assessing the impact on the technological processes of electricity consumers.*

***Streszczenie.** W artykule rozpatruje się problem balansowania mocy i energii elektrycznej w lokalnym systemie elektroenergetycznym (LSE), w którym zużycie energii elektrycznej i jej generowanie przez odnawiane źródła energii (OZE) są dostosowane do siebie. W LSE realizuje się zasadę: to, co zostało wyprodukowane, jest spożywane przez jej własnych użytkowników. LSE jest rozpatrywana jako część składowa systemu elektroenergetycznego (SEE) z dużymi elektrowniami, ale posiadająca możliwość pracy autonomicznej. Żródłami energii elektrycznej w LSE są małe hydroeletrownie (MHE), fotoelektrownie I elektownie wiatrowe (FE, EW), produkowanie energii elektrycznej przez które nie jest stabilne ze względu na zależność od warunków pogodowych. Przeto w LSE są przewidziane rezerwowe moce manewrowe, zbiorniki elektrochemiczne, technologie wodorowe i urządzenia biogazowe. Dla oceny możliwości i skuteczności sposobów i metod rezerwowania niestabilności generowania energii elektrycznej OZE wykorzystano metodę kryterialną teorii podobieństwa. Analiza proporcjonalności i wrażliwości kosztów względnych do ewentualnych sposobów i srodków rezerwowania OZE pokazała, że najlepsze są technologie wodorowe i uzgodnienie wykresów generowania i zużycia energii elektrycznej w LSE. W pierwszej kolejności zaleca się wykorzystanie możliwości uzgadniania w LSE wykresów generowania I zużycia energii elektrycznej. Do ilości energii elektrycznej, która nie jest balansowanie po takim uzgodnieniu, dla pełnego wyrównania zalecane jest wykorzystanie wyprodukowanego w LSE wodoru. Uzgodnienie wykresów generowania i zużycia w LSE w celu wyrównania w nim energii elektrycznej jest realizowane przy użyciu aparatu morfometrycznego, zasadą którego jest przejście od kartezjańskiego do biegunowego układu współrzędnych. Zademonstrowano, że wykorzystanie aparatu morfometrycznego w celu analizy nierównomierności wykresów ma szereg przewag i pozwala na przeprowadzenie wszechstronnego i szczegółowego oceniania formy wykresów. Stwarza się warunki dla śledzenia dynamiki zmian wykresów zużycia i generowania w LSE i oceniania wpływu na procesy technologiczne konsumentów energii elektrycznej. (**Bilans mocy i energii elektrycznej w lokalnym systemie elektroenergetycznym za pomocą uzgadniania harmonogramów wytwarzania i zużycia**)*

Keywords: local electric power system, renewable energy sources, instability of generation, redundancy, reconciliation of generation and consumption schedules, similarity theory, criterion method.
Słowa kluczowe: lokalny system elektroenergetyczny, odnawiane źródła energii, niestabilność generowania, rezerwowanie, uzgodnienie wykresów generowania i zużycia, teoria podobieństwa, metoda kryterialna.

Introduction

Renewable energy sources (RES), in particular photovoltaic and wind power plants (PV, VES), are currently not guaranteed sources of electricity for electric power systems (EPS). Since RES electricity production depends on weather conditions, a capacity reserve is necessary to coordinate their operation with the technological requirements of the UES. [1–3]. To ensure the efficient operation of RES in the UES and reliable electricity supply to consumers, it is necessary to have backup sources of energy that could compensate for the natural instability of RES generation. Today, there may be various options that differ in technical and economic characteristics [4– 6]. In the UES, due to the shortage of maneuverable power, various methods and means of electricity storage are used. First of all, we are talking about the accumulation of electricity produced by RES. Among the most efficient accumulators: electrochemical accumulators, hydrogen and biogas technologies [6, 7]. The UES can also take an active part in the process of mode balancing by coordinating RES generation schedules with load schedules of electricity consumers [8, 9]. Especially when we mean local electric power systems (LES), which are formed as part of existing distribution electric networks, where renewable energy sources are developed and which acquire all the characteristics of systems with a certain autonomy [10].

In the UES, in order to facilitate the passing of the maximum load, incentives are used for electricity consumers to shift their largest load to hours when the system observes a mode with a minimum load [11, 12]. The participation of "active consumers" in the regulation of the electricity balance in the UES can improve the regulation of the frequency and voltage in it [2, 13]. This can be done by setting different tariffs for electricity at different hours of the day in agreement with the distribution system operator. In the UES, it became difficult to maintain the balance of power and electricity when the share of renewable energy sources (RES) in it increased significantly. In particular, with the development of photovoltaic and wind power plants (PV and WPP), which, due to their natural dependence on weather conditions, are not a guaranteed supplier of electricity.

During the balancing of the EES mode, it is necessary to take into account the fact that there may be different regulatory conditions regarding the generation of RES. They can change in such a way that RES generate electricity in the UES without any restrictions (restrictions are allowed only due to possible violations of the stability of the UES), generate electricity in the UES on a forecasted short-term (most often for the next day) hourly schedule, or generate electricity by participating in the RES auction according to the established rules [14].

Let's consider the case when renewable energy sources produce electricity according to the predicted hourly generation schedule for the next day. RES work as part of a balancing group, the total capacity of which can reach from tens to hundreds of MW. The load power of electricity consumers in the LES is proportional to the power of RES. Such a balancing group is by all accounts a local electric power system as part of the UES. It contains energy sources that are connected by electrical networks of various voltage classes, and consumers of electricity, and is also connected to the power system by power transmission lines through which it can give or receive electricity. It is technically and economically possible and expedient to consider such a LES as a separate balancing group. To do this, it is necessary to decide on methods and means of reducing the instability of RES generation in the LES. Among them are systems related to the storage and conversion of electricity, and systems for managing electricity generation and consumption schedules. They differ in cost, and therefore it is advisable to use the last ones first, namely the coordination of RES generation and electricity consumption schedules. The implementation of the method of harmonizing electricity generation and consumption schedules in the first place can also reduce the required capacity of energy storage devices, which will allow to reduce their cost. However, before developing a system of technical implementation and economic motivation of the active behavior of electricity consumers in the LES, it is necessary to investigate the effectiveness of reconciliation schedules of RES generation and electricity consumption as a measure of balancing the LES mode. The purpose of the research is to show the possibility and expediency of reconciliation the schedules of RES generation and electricity consumption in the local electric power system as a way of balancing power and electricity in it.

Electrical power and energy balance in the local electrical system as a balancing group

Fig. 1 shows the composition of the LES, which is a separate balancing group. It includes sources of electricity, accumulators of electricity and consumers of electricity. Sources of electricity are PV, WPP, small hydroelectric power plants (SHPP) and also sources of centralized power from EPS (nuclear power plants (NPP), thermal power plants (TPP), hydroelectric power plants (HPP), hydroelectric storage power plants (HESPP)). As accumulators and converters of electricity into other types of energy and vice versa are used electrochemical accumulators (ECA), hydrogen and biogas plants (BGP). Hydrogen technologies are designed to produce hydrogen through electrolysis, which can be used to generate electricity to maintain the electricity balance in the LES, and the rest of it is used in other industries and in transport. BGUs can be used as a source of thermal and electrical energy (cogeneration plants). Consumers of electricity in the LES are industrial and communal household loads, as well as hydrogen technologies and ECA in charge mode. The energy balance in the LES, as in the balancing group, will be recorded:

$$\begin{aligned} &P_{PV}(t)+P_{WPP}(t)+P_{SHPP}(t)+P_{BGP}(t)\pm \\ &\pm P_{EPS}(t)\pm P_{H}(t)\pm P_{ECA}(t)-P_{cons}(t)-\Delta P(t)=0 \end{aligned}, \quad (1)$$

where $P_{PV}(t)$ – electrical power PV; $P_{WPP}(t)$ – electrical power WPP; $P_{SHPP}(t)$ – electrical power small hydroelectric power plants; $P_{BGP}(t)$ – electrical power cogeneration plants; $P_{EPS}(t)$ – electrical power EPS; $P_{H}(t)$ – electrical power hydrogen plants; $P_{ECA}(t)$ – electrical power electrochemical accumulators; $P_{cons}(t)$ – electrical power electricity consumers, including "active"; $\Delta P(t)$ – technological costs in electrical networks.

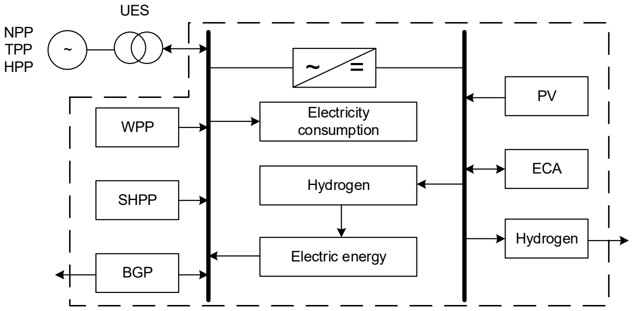


Fig. 1. Energy balancing in the balancing group (local power system)

In the LES as a balancing group, the principle is implemented: all the generated electricity is consumed in the LES, and the excess is transferred to the UES. To ensure the stability of LES in periods of maximum (minimum) consumption or limited capacity of the centralized power supply system, when variations in local generation parameters can lead to violation of restrictions on the parameters of the UES mode, the optimization of RES modes in order to minimize deviations from the centrally set schedule of aggregate generation of RES is relevant under the given restrictions on primary energy resources and RES characteristics [15]:

$$\int_{t_0}^{t_k} \frac{1}{2}\left(P_{RES}(t)-\sum_{i=1}^{n} P_i(t)\right)^2 dt \to \min, \quad (2)$$

where $P_{RES}(t)$ – the total predicted capacity of RES in LES, which is provided to the operator of the balancing group in the form of a generation schedule for the next day; $P_i(t)$ – the current value of RES electrical power for the time interval $t_0 - t_k$, on which the generated electricity in the LES is monitored.

At the same time, the predicted information on meteorological parameters is taken into account, which is provided by the corresponding subsystem of the automated control system (ACS) [16] and allows to sufficiently adequately reproduce the state of RES for a period of up to several days, and then with a refinement for a day in advance with an intraday correction. Due to this, unstable energy sources such as wind turbines and solar power plants in the objective functions and constraints of optimal control tasks can be represented by the mathematical expectation of time dependences of generation $M_{\mathrm{WPP}}\{P(t)\}$, $M_{\mathrm{PV}}\{P(t)\}$, $t \in [t_0; t_k]$.

Despite the fact that the generation of solar power plants and wind turbines can be predicted quite accurately, taking into account the intraday adjustment, but due to the fact that they produce electricity, they are unstable, so a power reserve is necessary in the solar power plant. Such a reserve (see Fig. 1) is electrochemical storage, hydrogen and biogas technologies or system reserve of the UES. It is also possible to compensate for the instability of RES generation by harmonizing their generation schedules and load schedules of electricity consumers. The problem arises, by what methods and means and in what form it is expedient to reserve the instability of RES electricity production and ensure in practice the problem (2).

If the criterion of optimality is to take the total cost of B_{res} for power reservation $P_{res}(t)$ in (2) of unsustainable RES generation, then taking into account the currently possible reservation methods, the problem of minimizing B_{res} will be written:

$$\begin{aligned} B_{res} &= B_{ECA}\left(P_{ECA}\right) + B_{H}(P_{H}) + B_{BGP}(P_{BGP}) + \\ &+ B_{TPP}(P_{TPP}) + B_{cap}\left(P_{cap}\right) + B_{impl}(P_{impl}) \to \min \end{aligned}, \tag{3}$$

where $B_{ECA}(P_{ECA})$ – costs for reservation with electrochemical accumulators; $B_H(P_H)$ – costs of hydrogen technologies; $B_{BGP}(P_{BGP})$ – costs related to the use of biogas technologies as a reserve; $B_{TPP}(P_{TPP})$ – the costs of using the system reserve, which is actually be compensation for maintaining the reserve on TPP power units; $B_{cap}(P_{cap})$ – costs for capacity reserves of power transmission lines, which is necessary for the transportation of electricity from/to the place of connection of reserve power to the UES; $B_{impl}(P_{impl})$ – costs for the implementation of the coordination of electricity generation and consumption schedules in the UES; P_{ECA}, P_H, P_{BGP}, P_{TPP}, P_{cap}, P_{impl} – respectively, optimal capacity values determined from each of the reservation methods.

It is shown in [17] that to optimize the costs of RES reservation with unstable generation and to select appropriate methods and means for this purpose, it is possible to use the criterial method of the theory of similarity [18]. The advantages of the criterion method are that with its help, with a minimum of information, it is possible to obtain a relative assessment of each of the methods and means of RES reservation. The peculiarity of the criterion method is that the solution of the optimization problem is obtained by it in relative units. In our case, this means that using the criterion method, we can give a relative assessment for comparing individual RES reservation methods and get their rating according to the chosen criterion of optimality. In the theory of optimization, it is called -. commensurability proportionality [20]. This is especially important at the stage of created of LES, when only their general technical and economic characteristics are known and there is no accurate data on price indicators.

In accordance with the possibility of the method, a mathematical model is formed. The formation of a criterion model requires certain assumptions. Electrochemical accumulators, installations for obtaining "green" hydrogen and converting it into electricity, as well as cogeneration biogas installations are placed centrally in the LES. Choosing a place for their installation is a separate task [21]. The centralized placement of ECA, hydrogen technologies, and biogas plants is associated with electricity losses in electrical networks, and they are taken into account in the optimization model.

Characterizing the reservation methods, the following should also be noted. The cost of electrochemical type accumulators, the production of which is sufficiently mastered in world practice, is constantly decreasing, and therefore their capacity in power systems is increasing. Hydrogen and biogas technologies as means of reserving unsustainable RES generation are at the stage of development. Their cost does not have a clear tendency to decrease and depends on the use of hydrogen and biogas in other industries. As for the system reserve, within the permissible limits of its use to balance unstable RES generation, its value in market conditions is determined by the state of the UES (deficit or surplus electricity balance). If there is still interest in the development of RES in the UES, then the cost $B_{TPP}(P_{TPP})$ should decrease accordingly.

Taking into account what has been said, the mathematical model for optimizing the specific costs per 1 kW of reserve power for the balancing of RES generation, which takes into account the peculiarities of the UES modes, can be presented in the following form:

$$\begin{aligned} B_{res} &= C_1 P_{ECA}^{-1} + C_2 P_H + C_3 P_{BGP} + \\ &+ C_4 P_{TPP}^{-1} + C_5 P_{impl} + C_6 P_{ECA}^{2} P_{TPP}^{2} P_{H}^{-1} P_{BGP}^{-1} P_{impl}^{-1} \to \min \end{aligned}, \tag{4}$$

on condition that $P_{TPP} \le G_{TPP}$ or $g_{TPP} P_{TPP} \le 1$,

where $C_1, C_2, C_3, C_4, C_5, C_6$ – generalized constants containing the output data of the problem (primarily these are price indicators); G_{TPP} – the maximum capacity of the system reserve that can be used to balance RES generation ($g_{TPP} = 1/G_{TPP}$).

The objective function (4) is formed under certain assumptions. Equation (4) does not take into account some components of the reservation methods of the B_{res} minimization problem from (3). In particular, these are costs for increasing the capacity of power transmission lines, which is considered sufficient at the initial stage. The first component of equation (4) takes into account the specific costs of electrochemical storage devices. Their cost is decreasing, therefore, in the UES, their volume is increasing and the capacity is increasing. The second component takes into account specific costs for the implementation of redundancy using a system for obtaining and using hydrogen as an energy store. Taking into account the fact that part of the hydrogen is used in other industries, the cost of generating electricity in the balancing group will be inversely proportional to P_H. The cost of using biogas to increase reserve capacity has a linear relationship. Provided the system reserve is available and its cost is reduced, it will be used more and P_{TPP} will increase. The last term of the objective function (4) reflects the costs of covering electricity losses in the elements of the electric network, which are associated with the implementation of reservation measures.

To analyze the optimal composition of RES reservation methods and means for proportionality and sensitivity, let's rewrite (4) in criterion form. We will take the parameters of the optimal option as the basic values. Then the cost expression (4) will be written in the criterion form:

$$\begin{aligned} B_{res*} &= \pi_{1o} P_{ECA*}^{-1} + \pi_{2o} P_{H*} + \pi_{3o} P_{BGP*} + \\ &+ \pi_{4o} P_{TPP*}^{-1} + \pi_{5o} P_{impl*} + \pi_{6o} P_{ECA*}^{2} P_{TPP*}^{2} P_{H*}^{-1} P_{BGP*}^{-1} P_{impl*}^{-1} \end{aligned}, \tag{5}$$

where $B_{res*} = B_{res} / B_{res\,\min}$; $P_{ECA*} = P_{ECA} / P_{ECA\,o}$, $P_{H*} = P_H / P_{H\,o}$, $P_{BGP} = P_{BGP} / P_{BGP\,o}$, $P_{TPP*} = P_{TPP} / P_{TPP\,o}$, $P_{impl*} = P_{impl} / P_{impl\,o}$, where $P_{ECA}, P_H, P_{BGP}, P_{TPP}, P_{impl}$ – the current and optimal power values of the reservation methods, respectively, $\pi_{i\,o} = C_i / B_{res\,\min}$ – the optimal values of the similarity criteria.

If for the optimization and analysis of methods and means of reservation of RES generation and determination $\pi_{i\,o}$ use the methods of the theory of similarity, in particular the criterion method, then accordingly the system of orthogonal and normalized (orthonormalized) equations for (4) will be written [18, 19]:

$$\begin{cases} -\pi_1 + 2\pi_6 = 0; \\ \pi_2 - 2\pi_6 = 0; \\ \pi_3 - \pi_6 = 0; \\ -\pi_4 + 2\pi_6 + \pi_7 = 0; \\ \pi_5 - \pi_6 = 0; \\ \pi_1 + \pi_2 + \pi_3 + \pi_4 + \pi_5 + \pi_6 = 1; \end{cases} \Rightarrow$$

(6)
$$\begin{bmatrix} -1 & 0 & 0 & 0 & 0 & 2 & 0 \\ 0 & 1 & 0 & 0 & 0 & -2 & 0 \\ 0 & 0 & 1 & 0 & 0 & -1 & 0 \\ 0 & 0 & 0 & -1 & 0 & 2 & 1 \\ 0 & 0 & 0 & 0 & 1 & -1 & 0 \\ 1 & 1 & 1 & 1 & 1 & 1 & 0 \end{bmatrix} \times \begin{bmatrix} \pi_1 \\ \pi_2 \\ \pi_3 \\ \pi_4 \\ \pi_5 \\ \pi_6 \\ \pi_7 \end{bmatrix} = \begin{bmatrix} 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 1 \end{bmatrix}.$$

Problem (6) does not meet the condition of canonicality, when the measure of its complexity iss=*m–n–1=0,* where m – is the number of members of the objective function, n is the number of variables P_i. In our case, s=7–5–1=1. If in this system of equations all parameters are valid and have certain admissible setting limits, then such Diophantine equations have a valid set of solutions with respect to one (since s=1) with parameters. A set of solutions can be constructed by taking any of the reservation components in (3) as the base. In our case, it is expedient for the base composition to accept the expenses for the organization of coordination of electricity generation and consumption schedules in the LES, which are the most easily implemented and with which the rest of the compositions can be compared. If we accept the costs of using the system reserve to cover the imbalance in the LES, then the basic change will be π_7 , it is enough that from the system level (6) the similarity criterion is applied:

(7)
$$\begin{aligned} &\pi_{1o} = 0{,}2405 - 0{,}2405\pi_7; \quad \pi_{2o} = 0{,}1582 - 0{,}1582\pi_7; \\ &\pi_{3o} = 0{,}1684 - 0{,}8418\pi_7; \quad \pi_{4o} = 0{,}2164 + 1{,}1207\pi_7; \\ &\pi_{5o} = 0{,}1082 + 0{,}0601\pi_7; \quad \pi_{6o} = 0{,}1082 + 0{,}0601\pi_7. \end{aligned}$$

Taking into account the values of the similarity criteria, (5) will be rewritten:

(8)
$$\begin{aligned} &B_{res*} = (0{,}2405 - 0{,}2405\pi_7)P_{ECA*}^{-1} + \\ &+(0{,}1582 - 0{,}1582\pi_7)P_{H*} + (0{,}1684 - 0{,}8418\pi_7)P_{BGP*} + \\ &+(0{,}2164 + 1{,}1202\pi_7)P_{TPP*}^{-1} + (0{,}1082 + 0{,}0601\pi_7)P_{impl*} + \\ &+(0{,}1082 + 0{,}0601\pi_7)P_{ECA*}^{2}P_{TPP*}^{2}P_{H*}^{-1}P_{BGP*}^{-1}P_{impl*}^{-1} \end{aligned}.$$

The relative amount of costs for the reservation of RES generation has two components. The first component is determined by the optimal values of costs for reserve measures and their ratios, the other depends on the capacity of the system reserve G_{TPP}:

(9)
$$\begin{aligned} &B_{res*} = (0{,}2405P_{ECA*}^{-1} + 0{,}1582P_{H*} + 0{,}1684P_{BGP*} + \\ &+0{,}2164P_{TPP*}^{-1} + 0{,}1082P_{cap*} + 0{,}1082P_{ECA*}^{2}P_{TPP*}^{2}P_{H*}^{-1}P_{BGP*}^{-1}P_{impl*}^{-1}) + \\ &+(-0{,}2405P_{ECA*}^{-1} - 0{,}1582P_{H*} - 0{,}8418P_{BGP*} + \\ &+1{,}1202P_{TPP*}^{-1} + 0{,}0601P_{cap*} + 0{,}0601P_{ECA*}^{2}P_{TPP*}^{2}P_{H*}^{-1}P_{BGP*}^{-1}P_{impl*}^{-1})\pi_7. \end{aligned}$$

If the system reserve is not used, then B_{res*} is determined only by the first component:

(10)
$$\begin{aligned} &B_{res*} = (0{,}2405P_{ECA*}^{-1} + 0{,}1582P_{H*} + 0{,}1684P_{BGP*} + \\ &+0{,}2164P_{TPP*}^{-1} + 0{,}1082P_{impl*} + 0{,}1082P_{ECA*}^{2}P_{TPP*}^{2}P_{H*}^{-1}P_{BGP*}^{-1}P_{impl*}^{-1}). \end{aligned}$$

It can be seen from (10) that if the power values of the reservation measures are optimal, that is, in relative units, all $P_{i*} = 1$, then also $B_{res*} = 1$. This means that the expression (10) allows the analysis of RES generation reservation measures for commensurate proportionality and sensitivity B_{res*} to power deviation P_{i*} from their optimal values.

According to the adopted model (4), the appropriate costs for balancing the RES generation schedule and its modified model (10), the optimal costs for backup means are in a certain ratio. The total costs will be economically feasible if they are distributed in the following proportions: costs for electrochemical storage devices for the same capacity are one and a half times higher than for hydrogen technologies, costs for measures to coordinate generation schedules and electricity consumption in LES are the lowest among other means of RES reservation.

Such results were obtained based on the fact that the values of the optimal similarity criteria do not depend on the parameters C_1,…, C_5. As for the generalized indicators C_1 , …, C_5, then their influence on economically feasible power values $P_{ECA*}, P_{H*}, P_{BGP*}, P_{TPP*}, P_{impl*}$ and on costs B_{res*} can be estimated by determining their values from the system of equations written according to the method of integral analogs from (4) taking into account (7) [18] :

(11)
$$\begin{cases} (0{,}2405 - 0{,}2405\pi_7) = C_1 / B_{res}P_{ECA}; \\ (0{,}1582 - 0{,}1582\pi_7) = C_2P_H / B_{res}; \\ (0{,}1684 - 0{,}8418\pi_7) = C_3P_{BGP} / B_{res}; \\ (0{,}2164 + 1{,}1202\pi_7) = C_4 / B_{res}P_{TPP}; \\ (0{,}1082 + 0{,}0601\pi_7) = C_5P_{impl} / B_{res}; \\ (0{,}1082 + 0{,}0601\pi_7) = C_6P_{ECA}^2P_{TPP}^2 / B_{res}P_HP_{BGP}P_{impl}. \end{cases}$$

From the obtained expressions, it is possible to estimate the impact of a change, for example C_1 , on the economically feasible values of all variables. Expressions (11) show that the economically feasible values of capacities, which are determined from each of the reservation methods and the costs of their implementation, depend on the accepted scenario of reservation implementation. Therefore, economically feasible are methods of redundancy and their capacity, and also the implementation parameters of each method are chosen taking into account their mutual influence in the system. For example, if C_1 relative to the basic one will increase by 20% with unchanged C_2, C_3, C_4, C_5 , then the total costs of B_{res} for balancing the RES generation schedule through reservation will increase by 40%.

Criterion equation (10) allows you to evaluate the impact of the initial data on the economically feasible values of costs and capacity, which are determined from each of the reservation methods, that is, to investigate the sensitivity of costs to changes in capacity. With using (10) it is possible to determine changes in specific costs when changing one or another capacity being optimized, that is, to investigate the $B_{рез}$ costs to changes in the power of electrochemical type accumulators and to changes in the power of hydrogen technologies is given. From fig. 2, it can be seen that when the power of electrochemical type P_{ECA} accumulators is increased by 50%, the cost value will increase by 5.5%, and if it is doubled, then the cost value will increase by 20.4%. If P_H is increased by 50%, then the value of costs will increase by 4.3%, which is less than the costs of electrochemical type accumulators. And if it is doubled, then the cost value will increase by 10.4%. The change in costs for coordinating electricity generation and consumption schedules in the LES will be 1.8% and 5.4%, respectively/ Therefore, it is confirmed that the costs of 1 kW of reserve power for RES in order to compensate for their generation instability differ in sensitivity. If measures to compensate for the instability of RES electricity production are implemented in stages, it is advisable to start with the most effective and least expensive ones. From the analysis, it can be seen that such are the coordination of electricity generation and consumption schedules in LES and hydrogen technologies. Since the UES already has the experience of using "active consumers", it is worth investigating the possibilities and efficiency of coordinating electricity generation and consumption schedules for balancing power and electricity in the LES.

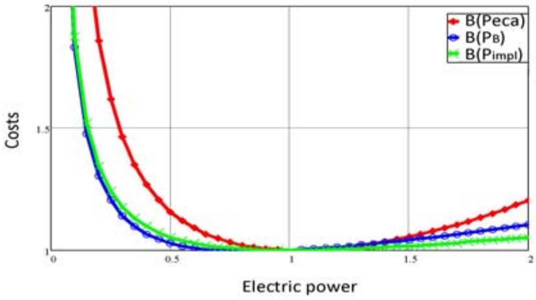
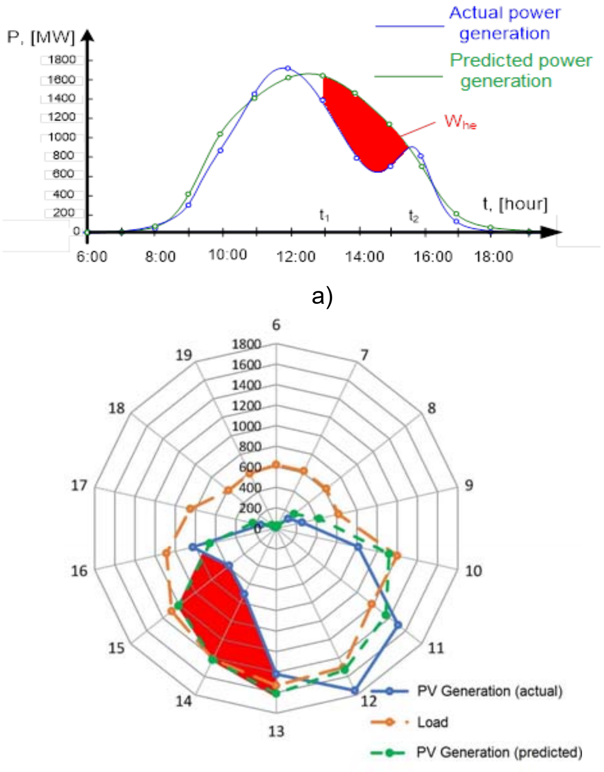


Fig. 2. Sensitivity of the changes to costs in the capacity of electrochemical accumulators (red curve), to changes in the capacity of hydrogen technologies (blue curve) and to coordination of electricity generation and consumption schedules (green curve)

Therefore, it is confirmed that the costs of 1 kW of reserve power for RES in order to compensate for their generation instability differ in sensitivity. If measures to compensate for the instability of RES electricity production are implemented in stages, it is advisable to start with the most effective and least expensive ones. From the analysis, it can be seen that such are the coordination of electricity generation and consumption schedules in LES and hydrogen technologies. Since the UES already has the experience of using "active consumers", it is worth investigating the possibilities and efficiency of coordinating electricity generation and consumption schedules for balancing power and electricity in the LES.

Reconciliation of generation and consumption schedules in the LES for balancing electricity in it

The impact on load schedules is a complex process that requires changes in the technological process of electricity consumers. Therefore, a change in the schedule of electrical loads (SEL) must be substantiated in detail. To do this, it is necessary to choose a convenient method of analysis and comparison of the parameters of the load and electricity generation schedules in the LES. It was shown in [22] that the use of a morphometric apparatus for analyzing the unevenness of graphs has a number of advantages and allows for a comprehensive and detailed assessment of the shape of the SEL. The basis of the application of morphometric analysis is the transition from the Cartesian (Fig. 3a) to the polar coordinate system (Fig. 3b). Thus, the research is designed to formalize the unevenness of the SEL using morphometric analysis, which makes it possible to more reasonably characterize the unevenness of the SEL , in contrast to the classical indicators that describe the nature of the unevenness of the SEL (dispersion, shape coefficients, filling coefficients, coefficients of GEN unevenness). A detailed analysis of the SEL makes it possible to improve the operation of RES in the tasks of filling a given loading schedule within the limits of the balance ownership of users and, as a result, to reduce the unevenness of the SEL network.



a)

b)

Fig. 3. Graph of electric loads and generation of PV: a) in the Cartesian coordinate system, b) in the polar coordinate system

In order to develop a method for coordinating the schedules of RES generation and the load of the LES, it is necessary to assess the influence of the RES generation on the unevenness of the daily schedule of electrical loads. For the analysis and assessment of RES on the total load schedule of the electric network, we will use the integral morphometric indicators of the unevenness of the SEL [22]. As an example, let's consider a typical case when the peak of FES generation falls on a daily dip in the load schedule (see Fig. 3). There is a need to motivate consumers to shift their daily schedule of electric loads to the hours of peak generation of the PV.

The main motivating measure is the zonal tariff for electricity, according to which the cost of electricity is differentiated for the time periods of receipt. The consumer can reduce the electricity bill without reducing the amount of consumption. At the same time, the unevenness of the SEL decreases. If the electricity consumer is in the balancing group, then an additional motivating motive is also the reduction of the difference (2) between the predicted and actual generation schedules in the LES.

In order to estimate the cost of displacement of consumption power, it is necessary to develop an indicator that would take into account the change in the tariff coefficient of the cost of electricity according to the zone tariff. The cost of compensation payments to the consumer for shifting the electricity consumption schedule and the cost of power losses due to the equalization of the total daily SEL are determined:

$$B_{ij} = P_{transf} \cdot C_t \left(K_{tj} - K_{ti} \right) + \beta \pm \delta P \cdot C_t \, , \tag{12}$$

where P_{transf} – the power that the consumer must shift to equalize the load schedule of the LES; C_t – electricity tariff according to the energy supply company; K_{tj} – coefficient of the cost of electricity according to the zonal tariff of the stage of the schedule from which the capacity is planned to be transferred; K_{ti} – coefficient of the cost of electricity according to the zonal tariff of the stage of the schedule to which the power is planned to be transferred; β – the cost of the technological transferred in production, which must be compensated by the LES; δP – change in power losses of the LES network due to adjustment of the consumer's load schedule.

In order to reduce the unevenness of the total daily SEL LES and minimize power losses, it is proposed to adjust the load schedule of transformer substations (TS) in turn according to their load factors. Obviously, the values of the relative values of B_{ij} for each node will differ. In accordance with the given task, we will write the objective function:

$$\sum_{i=1}^{m}\sum_{j=1}^{n} B_{ij}\cdot P_{ij} \rightarrow \min \tag{13}$$

where P_{ij} – the power that needs to be transferred from the j-th step of the load schedule to the i-th; m – hours in which actual consumption of TP is greater than the generation of PV; n – hours in which PV generation will prevail over TS consumption.

The first group of restrictions indicates that the power at any SEL stage should be equal to the total power consumption of this SEL stage. The second group of restrictions indicates that the total shift in consumption by a certain level of SEL should fully compensate for the generation at this level. There is also a restriction on the impossibility of shifting negative values of power consumption.

To solve this problem, we will use the method of the transport problem [20]. An appropriate algorithm and program have been developed. To determine the power that a consumer can maneuver, the technological minimum is determined for each consumer. Based on this, the power that can be transferred by the consumer will be equal to the difference between the actual $P_{l\,i}$ consumption power and technological minimum $P_{tm\,i}$ and for a certain load hour. Consumers are ranked according to their TS load factor.

The hours in which the actual consumption of the TP is less than the generation capacity of the PV are conditionally referred to as "generation" hours. That is, the hours for which consumption capacity will need to be shifted. Hours when the load exceeds the generation capacity and the condition is met $P_{l\,i}(t)-P_{tm\,i}(t)>0$, refer to hours from which power can be transferred. It is this difference that determines the amount of excess power $P_{ex\,i}(t)$, which can be transferred with a certain value and $P_{def\,i}(t)$ – power that is not enough at a certain hour of the day to adjust the daily schedule. Taking into account the identified deficit and surplus capacities, a transport matrix of capacity transfer from hours of surplus to hours of deficit is formed to adjust the daily load schedule. In the event that the total generation power will exceed the power that can be shifted to adjust the electrical load schedule, an additional fictitious source of load generation (virtual power plant [10]) is introduced to obtain a balanced transport problem $P_{vir\,i}(t)=\sum_{i\in\theta} P_i(t)-P_{ex\,i}(t)$ (θ – a number of electric power sources in LES). In the case when the own generation of the PV is not enough to meet the electricity needs of consumers, a conditional source of centralized power is introduced $P_{EPS\,i}(t)=\sum_{i\in\theta} P_i(t)-P_{ex\,i}(t)$.

The solution to the transport problem is recommendations for changing the schedule of electrical loads of consumers, which have the greatest impact on the unevenness of the total load schedule of the LES. Adjustment of the daily schedule of electrical loads is carried out as long as there is a need to fulfill condition (2). After completion, a graphical display of the morphometric model of the electrical load schedule is displayed without taking into account the PV generation, taking into account the adjusted electrical load schedule of the LES (Fig. 4) and the corresponding morphometric indicators for the listed schedules. An example of such a window of the program for coordinating generation and consumption schedules in the LES for balancing electricity in it is shown in Fig. 4.

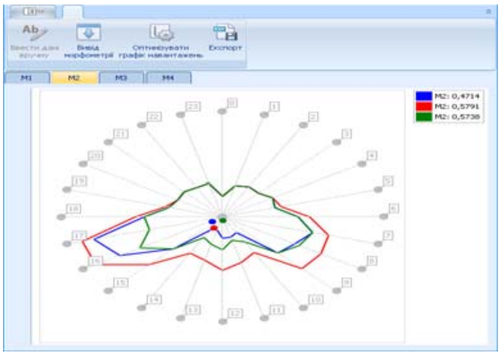


Fig. 4. The output window of the morphometric form of the electric load graph without (red color), with (blue color) taking into account the generation of PV and the optimized electric load graph (green color)

Example

In [4], an example of reducing the difference between forecast and actual electricity generation by a balancing group by means of hydrogen technologies is considered. It is shown that in the case considered in fig. 3, to maintain the balance of electricity in the balancing group with the specified accuracy, 1417 kWh is needed. If this amount of electricity is produced at a TPP using a mixture of 25% hydrogen and 75% gas, then 19,560 kg of hydrogen must be consumed. If this amount of hydrogen is used to refuel cars at a price of 19 USD per kilogram of hydrogen, it will cost 371.6 USD. If you substitute 1417 kWh at the base rate of 0.05 USD/kWh, it will be 59.5 USD. Thus, it is more profitable to shift the load schedule to hours when the actual electricity production is less than the forecast. In the example shown in fig. 3, it is expedient to purchase 1,417 kWh from the UES at the basic tariff from 1:00 p.m. to 3:55 p.m. and increase the consumption of the balancing group for this time. So that the total consumption of electricity does not change, it is necessary to reduce its consumption by the same amount of electricity in the remaining hours of the day. Obviously, such a calculation is not accurate. More precisely, the calculation is carried out by software according to (12) taking into account (13) and the features of the technological process. If necessary, for further analysis and study of dynamics, a list of morphometric parameters of load and electricity generation schedules in LES is issued [22].

Conclusions

Under certain technical and economic conditions, local electric energy systems are formed in the UES, in which power and electricity are balanced according to the principle that what is generated is consumed. According to the implementation of this principle, the UES is a reserve of renewable energy sources in the LES. Under such conditions, the LES faces the task of compensating for the natural instability of RES generation, in particular photovoltaic and wind power plants. It is solved by various methods and means of accumulating electricity produced by RES. One of the methods is proposed, which is not directly related to the accumulation of electricity. It is about agreeing the electricity generation and consumption schedules in the LES. It is also proposed because power supply systems have accumulated experience in leveling load schedules by using zonal metering of electricity at different tariffs.

To assess the possibility and efficiency using the criterion method, a relative comparison of the methods and means of reserving electricity generation from renewable energy sources: electrochemical storage, hydrogen and biogas technologies, maneuverable capacity of UES and coordination of electricity generation and consumption schedules in the LES was performed. It is shown that from the analysis of proportionality and sensitivity of relative costs for possible ways and means of RES reservation, hydrogen technologies and coordination of electricity generation and consumption schedules in the LES are the best. First of all, it is recommended to use the possibility of harmonizing electricity generation and consumption schedules in the LES. It is advisable to use the hydrogen produced in the LES for the amount of electricity that remained insufficient after such coordination for full balancing.

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