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CHAPTER 4

INTELLIGENTIZATION OF CONTROL SYSTEMS FOR LOCAL ELECTRIC POWER SYSTEMS

Abstract

With the increase in the power of renewable energy sources (RES) in power grids and the introduction of methods and means to compensate for the dependence of their generation on natural conditions, their role and significance in electrical power systems (EPS) is changing. RES are a real opportunity to decentralize electricity generation and provide power supply systems with a reliable source of energy. It has been shown that it is advisable to do this in the form of local electrical systems (LES), which operate in normal modes in parallel with the EPS as balancing groups, and in extreme cases are capable of operating in isolation in autonomous mode. To ensure the reliability and quality of electricity supply to consumers in LES, it is proposed to integrate RES and energy storage systems (ESS) in the form of separate microgrids (MG). To ensure the technical and economic efficiency of MGs, they are combined into an intelligent control system based on the principles of SMART Grid. This allows for more rational use of MG resources, effective interaction with the distribution network, and the use of ESS capabilities as a renewable energy reserve in the process of balancing the LES mode. The paper proposes a hierarchical structure of the intelligent LES system as one consisting of separate agents designed to respond to changing current LES states and form collective actions to ensure reliable power supply to consumers. Autonomous agents make management decisions and form a multi-agent system. Structured in this way, LES with smart grids can, during centralized power supply restrictions, not lose RES, but fully utilize their advantages together with energy accumulation and storage systems for reliable power supply to consumers.

KEYWORDS

Local electrical systems, autonomous mode, renewable energy sources, intelligent control system.

With the RES development in the electrical networks of power systems and the decentralization of generation, it has become possible, and to some extent necessary, to organize local electrical systems based on RES. LES can operate in parallel with the EES as a separate balancing group, consuming or generating electricity into the system. Under certain conditions, LES, based on economic interests or due to extreme conditions in the EES, can operate autonomously as an isolated intelligent system. In the Law of Ukraine on the electricity market, LES at the level of electricity generation and distribution is considered as a set of microgrids, which are a group of interconnected loads and distributed generation facilities, including mainly renewable energy sources.

Similar problems and tasks arise in local electrical system s as in the EES: balancing the mode, regulating frequency and voltage, reducing power losses and improving its quality, increasing the reliability of power supply, reducing SAIFI and SAIDI. Modern LES are based on renewable energy sources, the majority of which are photovoltaic and wind power plants (PVPP and WPP). Since the generation of electricity by PV and WPP depends on weather conditions, energy storage systems are necessarily used in RES to reduce the imbalance that their variable generation can cause. One way or another, all of the above factors affect the operating modes of RES and the quality of electricity supply to consumers.

The increase in electricity generated by RES in the EPS leads to more frequent and significant power fluctuations in the system and increases its operational risks. Operational dispatching has little chance of coping with the instability of generation. Often, depending on the state of the power system — whether there is a surplus or deficit of electricity — the operator's actions boil down to limiting RES electricity generation or reducing consumer load. This problem is solved in the interests of the electricity producer and consumer if the RES is equipped with means of direct and reverse conversion of electricity. Surplus electricity after balancing can, for example, be stored in the form of electrochemical accumulators or hydrogen obtained as a result of electrolysis. The reverse process of returning electricity to the RES is carried out as necessary, usually during morning and evening peak load modes or during emergency situations. It is impossible for a distribution system operator (DSO) to effectively cope with such a complex process of electricity generation, transmission, distribution, and conversion in order to balance the system mode reliably and without losses. Today, technologies developed on the principles of SMART Grid successfully cope with this problem. The concept of an intelligent system provides greater opportunities for monitoring and controlling the components of the power system, as well as increasing the reliability, quality, and efficiency of electricity supply to consumers. A key feature of an intelligent system is optimal control of system modes in normal mode and self-recovery, which is defined as the ability to automatically recover after failures.

In order to successfully ensure a reliable and economical power supply to consumers, LES faces the task of intellectualizing its mode control system. The aim of this work is to consider: the process of balancing power and electricity in the LES as a necessary condition for ensuring its normal functioning; methods for reducing imbalances between the predicted and actual generation of renewable energy sources in the LES; the formation of an intelligent control system for the LES mode as part of a multi-microgrid; examples of improving the efficiency of electrical networks through their intellectualization.

4.1 CONDITIONS FOR BALANCING POWER AND ELECTRICITY IN THE LES

RES in particular photovoltaic and wind power plants (PVPP, WPP), are not currently guaranteed sources of electricity for EPS. Since RES electricity generation depends on weather conditions, it is necessary to have reserve capacity in order to coordinate their operation with the technological requirements of the EPS [1–3]. To ensure the effective operation of RES in the EPS and a reliable electricity supply to consumers, it is necessary to have reserve energy sources that could compensate for the natural instability of RES generation. Currently, there are various options available, which differ in their technical and economic characteristics [4–6]. Due to the lack of maneuverable capacity, various methods and means of electricity storage are used in the power system. First and foremost, this involves the storage of electricity generated by RES. Among the most effective storage devices are electrochemical storage devices, hydrogen and biogas technologies [6, 7]. The coordination of RES generation schedules with electricity consumer load schedules can also play an active role in balancing the power system [8, 9]. This is especially true for local electricity systems, which are formed as part of existing distribution networks where RES are being developed and which are acquiring all the characteristics of systems with a certain degree of autonomy [10].

In order to facilitate peak load management, the EES encourages electricity consumers to shift their peak load to hours when the system is operating at minimum load [11, 12]. The participation of "active consumers" in regulating the electricity balance in the EPS can improve frequency and voltage regulation [2, 13]. This is done by setting different electricity tariffs at different times of the day in agreement with the distribution system operator. It has become more difficult to maintain the balance of power and electricity in the EPS when the share of renewable energy sources has grown significantly. In particular, with the development of photovoltaic and wind power plants, which, due to their natural dependence on weather conditions, are not a guaranteed supplier of electricity.

When balancing the EPS regime, it is necessary to take into account the fact that there may be different regulatory conditions for RES generation. They may change in such a way that RES generate electricity in the EPS without any restrictions (restrictions are allowed only due to possible violations of the stability of the EPS), generate electricity in the power system according to a forecast short-term (usually for the next day) hourly schedule or by participating in an auction, or generate electricity according to established rules [14].

Let's consider a case where RES generate electricity according to a forecast hourly generation schedule for the next day. RES operate as part of a balancing group, which total capacity can range from tens to hundreds of MW. The load capacity of electricity consumers in the LES is proportional to the RES capacity. Such a balancing group is, by all accounts, a local electrical system within the IPS. It contains energy sources connected by electrical networks of various voltage classes and electricity consumers, and is connected to the power system by power lines through which it can supply or receive electricity. It is technically and economically feasible and advisable to consider such a LES as a separate balancing group. To do this, it is necessary to determine the methods and means of reducing the instability of RES generation in the LES. These include 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 latter first, namely the coordination of RES generation and electricity consumption schedules. Implementing a method for coordinating electricity generation and consumption schedules can also reduce the required capacity of energy storage devices, which will lower their cost. However, before developing a system for technical implementation and economic motivation of active behavior of electricity consumers in the LES, it is necessary to investigate the effectiveness of coordinating RES generation schedules and electricity consumption as a measure to balance the LES mode. Thus, it is possible to demonstrate the possibility and feasibility of coordinating RES generation and electricity consumption schedules in the local electrical system as a way to balance power and electricity in it.

Fig. 4.1 shows the composition of the LES, which is a separate balancing group. It includes power sources, power storage facilities, and power consumers. The sources of electricity are solar power plants, wind power plants, small hydroelectric power plants (SHP), as well as centralized power sources from the power grid (nuclear power plants (NPP), thermal power plants (TPP), hydroelectric power plants (HPP), pumped storage power plants (PSPP)). Electrochemical storage devices (ESD), hydrogen and biogas plants (BGP) are used as storage devices and converters of electricity into other types of energy and vice versa. Hydrogen technologies are designed to produce hydrogen through electrolysis, which can be used to generate electricity to maintain the electricity balance in the LES, with the remainder being used in other industries and transportation. BGU can be used as a source of thermal and electrical energy (cogeneration plants). Electricity consumers in RES are industrial and municipal loads, as well as hydrogen technologies and ESD in charging mode.

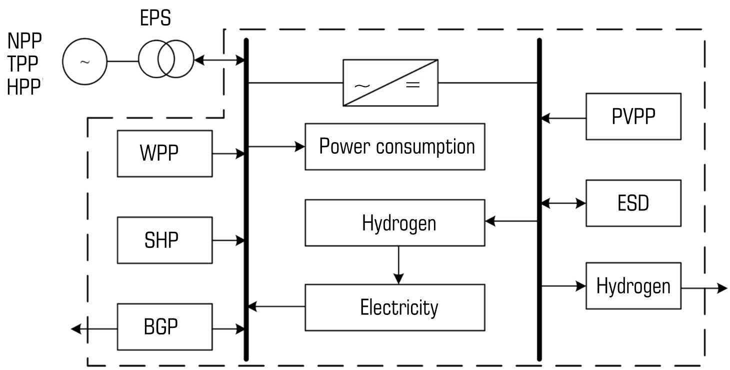

Fig. 4.1 Electricity balancing in a balancing group (local electrical system)

The electricity balance in the LES, as in a balancing group, is recorded as follows:

$$P_{PVPP}(t)+P_{WPP}(t)+P_{SHP}(t)+P_{BGP}(t)\pm P_{EPS}(t)\pm P_{h}(t)\pm P_{ch}(t)-P_{cons}(t)-\Delta P(t)=0 \quad (4.1)$$

where $P_{PVPP}(t)$ – solar power capacity; $P_{WPP}(t)$ – wind power capacity; $P_{SHP}(t)$ – small hydroelectric power capacity; $P_{BGP}(t)$ – electrical capacity of cogeneration plants; $P_{EPS}(t)$ – EPS capacity; $P_{h}(t)$ – hydrogen plant capacity; $P_{ch}(t)$ – electrochemical storage capacity; $P_{cons}(t)$ – power of electricity consumers, including "active" ones; $\Delta P(t)$ – technological losses in electrical networks.

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

$$\int_{t_0}^{t_k} \frac{1}{2}\left(P_{RES}(t) - \sum_{i=1}^{n} P_i(t)\right)^2 dt \to \min \qquad (4.2)$$

taking into account the balance sheet restriction:

$$P_{sc(t)} + \sum_{i=1}^{n} P_i(t) - P_{LOAD}(t) - \Delta P(t) = 0,$$

where $P_{RES}(t)$ – total projected RES capacity of the RES, which is provided to the balancing group operator in the form of a generation schedule for the next day; $P_i(t)$ – current value of RES capacity for the time interval t_0–t_k, during which the electricity generated in the RES is monitored; $P_{SC}(t)$ – centralized power supply from TPPs, NPPs, HPPs; $P_{LOAD}(t)$ – total load of electricity consumers; $\Delta P(t)$ – power losses in electrical networks.

Task (4.2) is usually applied to the entire power system. Another option is to allocate several balancing groups in the power system for simpler and more accurate control of PV and wind power generation. In each balancing group, an Automated Commercial Electricity Accounting System (ACEAS) is established for each RES, and an hourly electricity generation schedule for the next day is forecast. That is, for each *i*-th PVPP and WPP, the values of actual and forecast electricity generation for a given period of time are known. Therefore, in accordance with task (2.2), for each *i*-th RES, the task of achieving a certain accuracy between the forecast and actual electricity generation for a certain period of time, for example, one hour, is formulated:

$$\delta_i = \frac{w_i^P - w_i^A}{w_i^S} \le \delta_{PER} \qquad (4.3)$$

where w_i^P, w_i^A – predicted and actual values of electricity generation by the *i*-th wind farm per unit of time; δ_i, δ_{PER} – current and permissible error values (the permissible error is set at 0.05 for PVPP and 0.1 for wind power plants).

To control the error value, it is necessary to model two graphs: the predicted and actual generation of the PVPP. The error, as the difference between these graphs, must be within the acceptable range or close to it. The following implementations of this task are possible:

1) the actual graph remains unchanged, and the forecast graph is adjusted every hour or every 15–20 minutes;

2) the forecast graph remains unchanged, and the actual graph is adjusted to the forecast graph, or more precisely, brought into the acceptable range.

However, in the latter case, electricity generation and, accordingly, profits are reduced. It is decided which is better: to lose on electricity generation or to reduce penalties for deviations from the acceptable range?

A third option is also possible, when the forecast schedule is adjusted and the actual generation is changed to bring it into or closer to the acceptable range. In other words, when developing a natural simulation model for researching short-term forecasting processes and operational management of RES generation in the EPS mode balancing system using Smart Grid technologies, it is necessary to consider all options.

To build an effective algorithm for forecasting the electricity output of photovoltaic power plants (**Fig. 4.2**) and successfully automate it, it is necessary to have an appropriate array of source data and software. The first step is to create a mathematical model of the PV plant itself. To do this, it is necessary information about the characteristics of the photovoltaic modules, which are specified in the passport data.

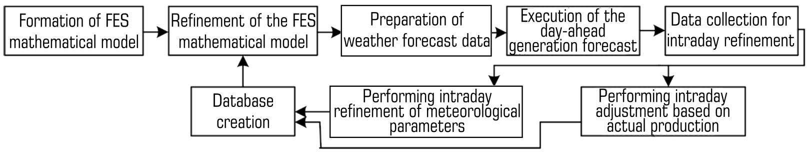

Fig. 4.2 Structural diagram of the automation of the forecasting process for wind power plants as part of a balancing group

Since the operating conditions of wind power plants are constantly changing, their mathematical model is constantly being refined. To automate the process of refining the wind power plant generation forecasting model, a database of parameters is created.

Since the operating conditions of RES are constantly changing, their mathematical model is constantly being refined. To automate the process of refining the RES generation forecasting model, a database (DB) of parameters is created. MySQL is usually used, but it slows down when it is significantly filled. The necessary meteorological parameters from various services are collected in the DB. There are quite a few such services on the market, all of which allow to organize API communication, which automates the data collection process. In addition, there are a significant number of libraries in C#, Python, etc., that implement such communication.

After making a forecast for the next day, no company providing such services can guarantee sufficient accuracy, so it is necessary to use the possibility of intraday adjustment. In different countries, the market accepts the results of this adjustment with varying degrees of discretion. As a rule, this time ranges from 15 minutes to 2 hours. Obviously, the shorter this interval, the better the results. Intra-day adjustments can be made in two ways: by recalculating the generation schedule based on refined meteorological parameters or based on the results of monitoring the current production of electricity from renewable energy sources. The first algorithm requires the use of weather services that adjust their forecasts during the current day.

The second requires the use of telemetry, which can provide polling almost every minute, or ACEAS, which usually works with greater discretion.

After adjustment, the results are sent to the balancing group operator. All data on meteorological parameters, production forecasts, and actual energy production values are also entered into the database for further adjustment of the RES mathematical model. Such adjustments are made during the first month of the forecasting service and then as needed to account for seasonal changes and equipment degradation processes.

The process of automating the forecasting of RES generation schedules and their ongoing adjustment in accordance with changes in operating conditions, primarily weather conditions, is an important element of successful balancing of the power system. As in all dynamic processes related to power systems, in the case under consideration, a special feature is the impossibility of studying them in different modes directly at the facility. Therefore, testing the performance and configuration of the automatic renewable energy generation forecasting system (AREGFS) in order to evaluate its functioning and effectiveness in balancing the state of the power system is only possible through modeling.

Based on the nature of the AREGFS process, it is advisable to use simulation modeling. Since the actual generation value is constantly monitored during balancing using AREGFS, it is possible to use these values during modeling. Such a model can be classified as a physical simulation model. The physical simulation modeling method is considered an experimental research method in which the object itself is not disturbed and studied, but rather a simulation model of the object implemented on a computer.

Fig. 4.3 shows the structure of a full-scale simulation model (FSM) for testing and tuning the AREGFS PVPP. It includes a functional model of the object (FMO), which, together with the AREGFS PVPP, forms a closed system. This allows, with sufficiently accurate modeling of the control object, to achieve maximum reliability of testing the AREGFS PVPP, since in the test system it is possible to reproduce any mode of the object within the permissible range of existence. Along with the advantages, it is necessary to note a certain complexity in the implementation of the structure, which is reflected primarily in the need for not only informational but also physical compatibility between the model and the AREGFS. The correct functioning of the AREGFS in this structure is assessed by comparing the AREGFS outputs with the control data of the real object.

The key link in the organization of the test system's FSM is the construction of a simulator, which is part of the FMO. The simulator is designed to reproduce a specific set of object modes. The PVPP mode is a permissible set of its states and processes of their change. During the transition from one state to another, the current mode indicators (mode parameters) change under the influence of external disturbances (load changes) or control signals to change the actual generation of the PVPP.

When creating and testing a control system based on modeling, the continuous operation of the wind farm is replaced by a set of characteristic modes. Correct implementation of this principle ensures the necessary reliability of the control means verification process. In this case, correctness means the appropriate selection of modes and their number, a set of parameters, and the accuracy of their measurement by the automatic commercial electricity metering system. When signals simulating the parameters of PVPP modes are fed into the control system, the limitations of the transmission system operator (TSO) of the power system are taken into account. First and foremost, this is the state of the EPS in terms of a deficit or surplus in the electricity balance.

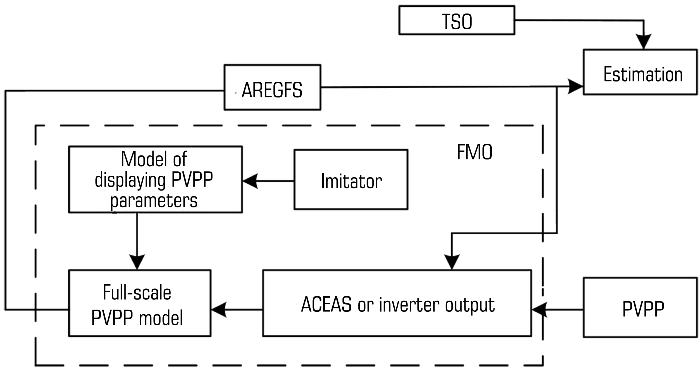

Fig. 4.3 Structure of the AREGFS full-scale simulation test system

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

Despite the fact that the generation of solar and wind power can be predicted fairly accurately, taking into account intraday adjustments, they are unstable in terms of actual electricity production, so a power reserve is necessary in the power system. Such reserves (**Fig. 4.1**) include electrochemical storage devices, hydrogen and biogas technologies, as well as the EPS system reserve. It is also possible to compensate for the instability of RES generation by coordinating their generation schedules with the load schedules of electricity consumers. The question arises as to what methods and means should be used and in what form it is advisable to reserve for the instability of RES electricity generation and to ensure the practical implementation of task (4.2).

In [17], a method was developed for relative comparison of possible ways of reserving renewable energy sources with unstable generation in the power system and assessing the sensitivity of their costs to changes in capacity. To analyze the technical and economic efficiency of various means of reservation, mathematical models were developed based on similarity theory and the criterion method. The criterion method, with minimally available initial information, makes it possible to compare different methods of reserving RES generation and determine the optimal ones. The method allows assessing their comparability and determining the sensitivity of costs to the capacity of the methods of reserving. Criterion models have been developed that allow the construction of dependencies of the costs of means of reserving unstable RES generation on the capacity of the means of reserving. Such dependencies make it possible to choose certain methods of reserving more reasonably in accordance with the characteristics and requirements of the EPS.

4.2 REDUCING IMBALANCES BETWEEN PREDICTED AND ACTUAL RES GENERATION THROUGH A COMBINATION OF METHODS

In electric power systems, the amount of electricity generated and consumed is planned and continuously monitored in order to balance their operation and ensure the required reliability and quality of electricity. Under such conditions, both traditional and renewable energy sources must operate. While modern automated commercial electricity metering systems (ACEMS) make it relatively easy to account for the electricity generated by RES, planning is not so simple. Since the amount of electricity generated by RES depends on the weather forecast, planning turns into forecasting the amount of electricity generated by RES. To date, many methods, algorithms, and programs have been developed for forecasting the generation of electricity from RES, especially solar and wind power plants. Unfortunately, none of them can provide the necessary accuracy, as this is linked to the impossibility of accurately forecasting weather conditions. Therefore, as a solution, it is permissible to adjust the forecast of the hourly schedule for electricity generation by solar and wind power plants for the next day.

Fig. 4.4 illustrates an example of the combined application of methods to reduce the difference between the predicted and actual electricity generation by the balancing group of wind power plants. When the actual value exceeds the forecast for a certain period of time (**Fig. 4.4**, point t_1), it is advisable to reduce this imbalance by storing energy, for example, in the form of hydrogen. Hydrogen can be produced directly at the wind farm, if such a facility is available, or the required amount of hydrogen must be purchased as a service from another producer. The hydrogen option is advisable because, when using, for example, electrochemical storage devices, it is limited by the need to convert the stored energy back into electricity. Whereas in the case of hydrogen, there are more options: use in other industries or in transport, conversion into electricity. When the forecast for a certain time interval is greater than the actual value (**Fig. 4.4**, point t_3), then, after running the forecast refinement program, the predicted generation of the wind power plant is adjusted to the permissible value according to the condition.

For the case shown in **Fig. 4.4**, it is possible to determine the difference between the forecast and actual electricity generation of the wind power plant, which must be compensated for in the task of balancing the power system mode. The amount of electricity generated in excess of the required balance and which can be used for hydrogen production is determined as the area bounded by curves ABC and AC. This is 250.5 MWh.

To calculate the potential volume of green hydrogen production using electrolysis, it is possible to assume that 1 m^3 of hydrogen requires 4.5 kWh of electricity, or 50.56 kWh per 1 kg of hydrogen [18]. For hydrogen production, 250.5 MWh can be consumed, i.e., M = 250.5/50.56 = 4.954 kg of hydrogen per day. If the power system has a deficit in electricity generation, this hydrogen can be used to generate electricity and improve the balance of the power system. If the power system has a surplus, it is advisable to use hydrogen in other industries and in transport. The difference between the forecast and actual generation of wind power plants in the balancing group can be reduced programmatically by correcting the forecast, as shown in **Fig. 4.4**.

There are two ways to reduce the difference between the forecast and actual values of the electricity generation graphs for solar and wind power plants: by influencing the forecast value W_f or the actual value W_{ac}.

The actual generation W_{ac} can only be influenced in the direction of its reduction, which is not economically feasible. Actual electricity generation can only be reduced on the orders of the transmission or distribution system operator when necessary to ensure the stability of the power system. Therefore, under normal conditions, it is only possible to adjust the forecast values of electricity generation for a specific time period Δt. The actual values of electricity generated are approximated for the same time Δt based on preliminary data from ACEAS.

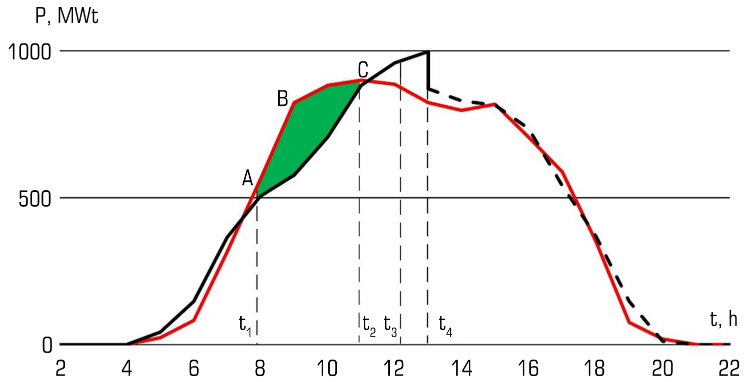

Fig. 4.4 Combination of different methods to reduce imbalance

The logical scheme for calculating the adjusted value of the hourly forecast of wind power generation for the next hour of the current day is illustrated in **Fig. 4.5**. At point t_1, for example, $\delta_1 \succ 0$ and $\delta_1 \succ \delta_{PER}$ then the forecast must be reduced by *k*. Accordingly, the forecast will be $W_f = k\, W_f$ where $k = 1 - \delta_1$ and $\delta_1 = (W_{f1} - W_{ac1}) / W_{ac1}$ At point t_3, for example, $\delta_3 \prec 0$ and $\delta_3 \prec -\delta_{PER}$ then the forecast needs to be increased by *k*. Accordingly, the forecast will be $W_f = k\, W_f$ where $k = 1 - \delta_3$ and $\delta_3 = (W_{f3} - W_{ac3}) / W_{ac3}$ If the difference between the forecast and actual values is within the acceptable range, i.e. $|\delta| \prec |\delta_{PER}|$ then the coefficient *k*=1 and the forecast values do not need to be adjusted.

The frequency with which the forecasting error is controlled is determined by the capabilities of the automatic control system (ACS) for forecasting the generation schedule of solar and wind power plants, the capabilities of the ACEAS, and the bandwidth of communication channels. Control is carried out evenly in cycles of no more than 1 hour and is organized as follows.

The hour *i* is determined, from which the i_b begins and the i_e ends of the electricity generation of the PVPP, where *i* is the current value of the hour number. Next:

– $i=i_b$, the prediction error for the *i*-th hour is determined $\delta_i = \dfrac{W_i^f - W_i^{ac}}{W_i^{ac}}$

– $i=i+1$, the prediction error for the *i*-th+1 hour is determined $\delta_{i+1} = \dfrac{W_{i+1}^f - W_{i+1}^{ac}}{W_{i+1}^{ac}}$

If $\delta_{i+1} \succ 0$ then:

if $\delta_{i+1} \leq \delta_{PER}$, then k=1 and $w^f_{i+1} = k\, w^f_{i+1}$ (that is, the forecast remains the same, within the allowable range);

if $\delta_{i+1} \leq \delta_i$, then go to the beginning of the cycle i=i+1 ("forecast" is approaching "fact");

if $\delta_{i+1} \succ \delta_i$ ("forecast" differs from "fact") and $\delta_{i+1} \succ \delta_{add}$, then $k = 1 - \delta_i$ and $w^n_{i+1} = k\, w^n_{i+1}$ and go to the beginning of the cycle i=i+1.

If $\delta_{i+1} \prec 0$, then:

if $\delta_{i+1} \geq -\delta_{PER}$, then k=1 and $w^f_{i+1} = k\, w^f_{i+1}$ (that is, the forecast remains the same, within the allowable range);

if $\delta_{i+1} \succ \delta_i$, then go to the beginning of the cycle i=i+1 ("forecast" is approaching "fact");

if $\delta_{i+1} \prec \delta_i$ ("forecast" differs from "fact") and $\delta_{i+1} \prec -\delta_{PER}$, then $k = 1 - \delta_i$ and $w^f_{i+1} = k\, w^f_{i+1}$ and go to the beginning of the cycle i=i+1.

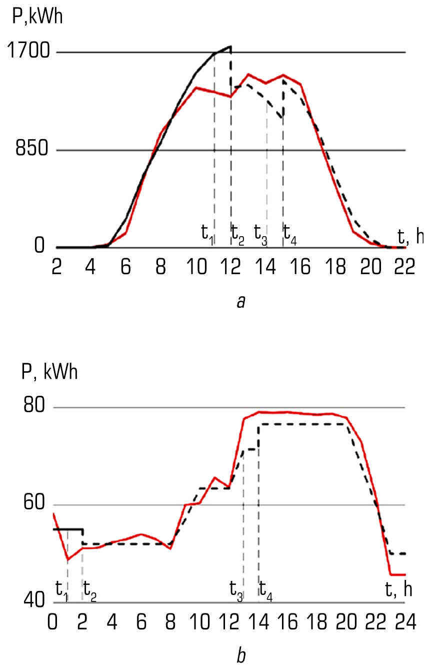

Fig. 4.5 Correction of the forecast graph for: *a* – PVPP; *b* –WPP generation

According to the above algorithm, a program for hourly adjustment of wind and solar power generation forecasts has been developed. **Fig. 4.6** shows an example of the results of hourly forecasting of wind power generation using a program for adjusting forecasts with error compensation δ_i. As can be seen, the error in forecasting PVPP per day decreased from 15.6% to 4.7%.

That is, the algorithm with compensation for hourly errors in forecasting PVPP gives satisfactory results. It can be used in conjunction with the PVPP adjustment based on hourly refinement of daily meteorological parameters.

A local electrical system for the IPS is essentially an active consumer that can be used in generation or consumption mode by the transmission system operator (TSO) or distribution system operator (DSO) as necessary [20].

Another case is when it comes to coordinating generation and consumption schedules in the LES for its internal electricity balancing.

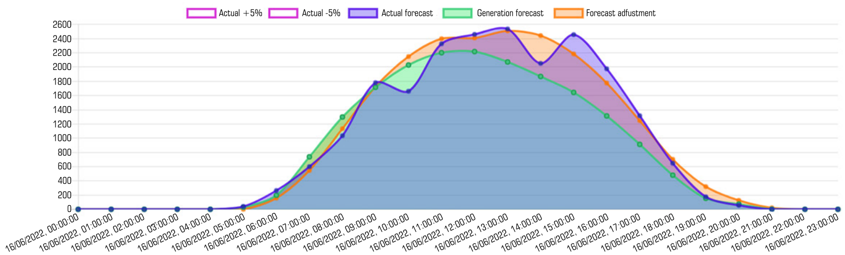

Fig. 4.6 Example of adjusting PVPP generation based on error control results δ

This is especially true when the LES operates separately from the power system, in autonomous mode. In this case, it is necessary to influence not only the generation of renewable energy sources, the consumption/generation of the electricity storage system, but also the electricity consumption schedules of utilities and technological processes.

Influencing load schedules is a complex process that requires changes to the technological processes of electricity consumers. Therefore, changes to the electrical load schedule (ELS) must be thoroughly justified. To do this, it is necessary to select a convenient method for analyzing and comparing load schedules and electricity generation parameters in the LES. In [19], it is shown that the use of a morphometric apparatus for analyzing the unevenness of schedules has a number of advantages and allows for a comprehensive and detailed assessment of the ELS shape. The basis for the application of morphometric analysis is the transition from a rectangular coordinate system to a polar coordinate system (**Fig. 4.7**). Therefore, the aim of the study is to formalize the unevenness of ELS using morphometric analysis, which allows for a more detailed characterization of the unevenness of ELS using indicators that differ from the classical ones describing the nature of the ELS unevenness (dispersion, shape factor, filling coefficient, ELS unevenness coefficient). A detailed analysis of ELS allows for increasing the productivity of energy sources, including renewable energy sources, in the task of covering a specific load schedule within the consumer's balance and, as a result, reducing ELS unevenness.

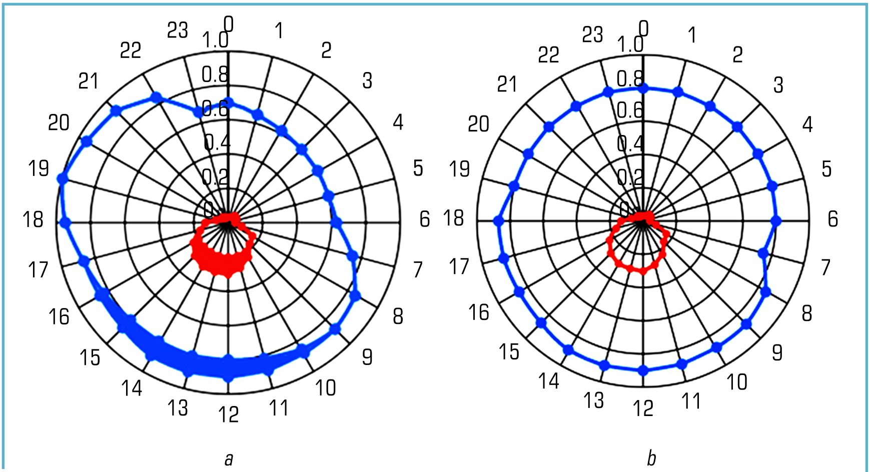

Fig. 4.7 Daily electricity consumption graphs in LES

Fig. 4.7 shows, as an example, the coverage of the daily electricity consumption schedule in the spring-summer period, where consumption and generation by own renewable energy sources and inflows from the EPS are balanced. **Fig. 4.7** is constructed in relative units, where the starting point is the evening peak power.

It is characteristic that in the afternoon, electricity consumption decreases, while RES production increases under favorable weather conditions, i.e., the peak of RES production occurs during the daytime in the load schedule. If the LES mode is currently excessive, "excess" capacity of solar and wind power plants is generated for the purpose of balancing the mode. "Excess" electricity is either stored by the storage system, or the DSO is forced to limit the production of renewable electricity. That is, it is necessary to coordinate the generation and consumption schedules in the RES.

This can be done by consumers, but they must be motivated to shift the daily electricity load schedule to the hours of maximum production of solar and wind power plants. In order to develop a method for coordinating RES generation with the load in the RES, it is necessary to assess the impact of RES generation on the unevenness of the daily electricity load schedule. Integral morphometric indicators of ELS unevenness are used to analyze and evaluate RES in the total load schedule of the power grid [19].

The main incentive is the zonal electricity tariff, according to which the cost of electricity is differentiated by time of day. Consumers can reduce their electricity bills without reducing consumption. This reduces the unevenness of ELS. If the electricity consumer is in a balance group, reducing the difference between the forecast and actual generation schedules using formula (4.3) in the LES is also an additional incentive.

To estimate the cost of displacement of consumption capacity, it is necessary to develop an indicator that would take into account the change in the tariff coefficient of electricity consumption under the zone tariff. The cost of compensation to the consumer due to changes in the electricity consumption schedule and the cost of electricity losses due to daily balancing of ELS are determined as follows:

$$B_{ij} = P_{sh} \cdot C_t \left(K_{tj} - K_{ti} \right) + \beta \pm \delta P \cdot C_t, \tag{4.4}$$

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

In order to reduce the overall unevenness of the daily ELS LES and minimize electricity losses, it is proposed to sequentially adjust the load schedule of transformer substations (TS) in accordance with load factors. Obviously, the relative values B_{ij} for each node will differ. In accordance with this task, the objective function is recorded:

$$\sum_{i=1}^{m} \sum_{j=1}^{n} B_{ij} \cdot P_{ij} \to \min, \tag{4.5}$$

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

The first set of constraints indicates that the power of any ELS stage must be equal to the total power consumption of that ELS stage. The second set of constraints indicates that the total shift in consumption at this ELS level must fully compensate for production at that level. The possibility of transferring negative values of consumed power is also limited.

To solve this problem, it is possible to use the transportation problem method. A corresponding algorithm and program have been developed. To determine the power regulated by the consumer, a technical minimum is determined for each consumer. Based on this, the transmitted power of the consumer is equal to P_{li} – the difference between the actual power consumption and the technical minimum for a given hour of load P_{tmi}. At the same time, consumers are classified according to the TP utilization coefficient.

Hours when actual TP consumption is lower than RES generating capacity are conventionally referred to as "production hours". That is, hours for which consumption capacity must be transferred. Hours when the load exceeds the generation capacity and the condition $P_{li}(t) - P_{tmi}(t) > 0$ is met are the hours from which electricity can be transferred. It is this difference that determines the excess capacity $P_{ex\,i}(t)$ that can be transferred at a certain price and the capacity $P_{lack\,i}(t)$ that is lacking at a certain hour of the day to adjust the daily schedule. Based on the identified deficit and excess capacity, a transport matrix is formed to transfer capacity from excess hours to deficit hours in order to adapt the daily load schedule. If the total generation capacity exceeds the capacity that can be transferred to adjust the electricity load schedule, an additional imaginary load generation source (virtual power plant) $P_{vir\,i}(t) = \sum_{i \in \theta} P_i(t) - P_{ex\,i}(t)$ is introduced for the balanced transportation task (a set of electrical power sources in the LES). If the own production of renewable energy is insufficient to meet the electricity needs of consumers, a conditional source of centralized electricity is introduced:

$$P_{EPSi}(t)=\sum_{i\in\theta}P_i(t)-P_{ex\,i}(t). \tag{4.6}$$

The solution to the transport problem is to recommend shifting the electricity load schedule of consumers that most affects the unevenness of the overall load schedule of the power system. The daily electricity load schedule is adjusted until conditions (4.3) are met. Upon completion, a graphical representation of the morphometric model of the electrical load schedule is displayed, without taking into account the formation of RES, taking into account the RES generation schedule and the adjusted electrical load of the power system and the corresponding morphometric indicators for the listed schedules.

Fig. 4.7, *a* shows the daily electricity consumption schedule, where the unbalanced surplus of RES electricity (highlighted in red) is consumed during the daytime minimum (highlighted in blue). To this end, the necessary changes have been made to the electricity consumption process. **Fig. 4.7, *b*** shows a daily electricity consumption graph, where, in addition to the electricity generated by the wind power plant, the evening maximum electricity consumption is shifted to the nighttime minimum. Thus, the electricity consumption graph can be smoothed out and approximated to a circle.

Thus, it is possible to compensate for the natural instability of RES production in RES not only by means of electricity storage, but also by a method that is not directly related to electricity storage. This involves coordinating electricity generation and consumption schedules in RES. This method is also proposed because energy supply systems have accumulated experience in smoothing load schedules using zonal electricity metering at different tariffs. An algorithm and software have been developed to provide recommendations for coordinating electricity generation and consumption schedules in RES.

4.3 FORMATION OF AN INTELLECTUAL CONTROL SYSTEM FOR THE LES MODE AS PART OF THE ELECTRIC POWER SYSTEM

4.3.1 LES AS AN OBJECT OF AN INTELLIGENT CONTROL SYSTEM

Thanks to the development of renewable energy sources in power systems, in particular in distribution power networks, it has become possible to create consumer power supply systems based on RES. In addition to the fact that this provides certain advantages in terms of energy efficiency of power supply, there is a possibility of forming local electrical systems based on RES as balancing groups in the electric power system [21, 22]. **Fig. 4.1** shows the structure of such a LES, which, in addition to RES, necessarily includes an energy storage (accumulation) system. ESS may include small hydroelectric power plants, electrochemical storage and cogeneration plants running on natural gas and biogas with hydrogen additives.

In LES, the RES generation, which is mainly photovoltaic and wind power plants depends on natural conditions and has an unstable, time-varying capacity. The electricity consumption schedule is also variable in the LES. Even if the average generation and consumption capacities of electricity in such the LES as a balancing group are commensurate, then the problem of mode balancing in it arises. In a LES, it is necessary to create an automated or, taking into account the current state of hardware and software in the industry, an intelligent automatic control system for the LES mode [23]. The functions of the ACS are to maintain the forecasted RES generation schedule for the next day in the LES and coordinate it with the consumption schedule. In this case, active consumers are used, which, by adjusting their technological process, affect the total consumption/generation schedule of the LES in relation to the EPS [24]. When an LES operates with a surplus, the excess electricity is stored in the ESS or can be transferred to the EPS. If, due to their natural limitations, PVPP and WPP cannot cover the load schedule of the LES, then the ESS or EPS services are involved. Under such conditions, LES can maintain their operational capacity and provide electricity to consumers both in normal parallel mode with the power system and in autonomous mode.

Since LES are part of the EPS, they must operate in the conditions and according to the rules, without disrupting the EPS operation, which currently provides a stable electricity supply. This applies to all modes of LES operation. Therefore, it is important, based on the real technical capabilities and the state of generating capacities and electrical networks, to determine with what characteristics and what tasks LES as balancing groups of the EPS can solve. Due to the limited technical and human resources, the process of forming LES can be phased. Individual parts of the system develop according to a certain plan and are formed according to a certain concept. Compliance with the adopted concept is controlled by an integral indicator of the quality of resource use according to the final result [25]. The concept of forming a plan (roadmap) for the formation of LES in the EPS can be based on the "Concept of "smart" electrical networks as an intelligent system". It lays down the technical policy for the development of electric power systems, scientific foundations on the principles of SMART Grid, as well as forms of training qualified personnel.

To substantiate the conditions and principles, it is possible to consider the isolation of a part of the EPS in the form of local electric power systems as an object of an intelligent system [26]. At the first stage of forming a LES with renewable energy sources to balance its capacity, it is advisable to explore the possibilities of using well-proven and relatively inexpensive methods, such as, for example, active consumers [24, 27]. To study the problem of renewable energy consumption, let's consider the LES as a balancing group, which is shown in **Fig. 4.8**. It includes a photovoltaic plant as a source of electricity, an energy storage system and electricity consumers. The sources of electricity are photovoltaic plants, as well as sources of centralized power supply from the EPS (nuclear power plants (NPP), thermal power plants (TPP), hydroelectric power plants (HPP), pumped storage hydroelectric power plants (PSHPP)).

The electricity balance in the LES, shown in **Fig. 4.8**, as in the balancing group, will be written:

$$\pm P_{EPS}(t) + P_{PVPP}(t) \pm P_{ESS}(t) - P_{cons}(t) - P_{accons}(t) - \Delta P(t) = 0, \quad (4.7)$$

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where $P_{EPS}(t)$ power from the EPS; $P_{PVPP}(t)$ power of the PVPP; $P_{ESS}(t)$ power of the energy storage system; $P_{cons}(t)$ power of electricity consumers working according to their schedule; $P_{accons}(t)$ power of active consumers working according to the adjusted schedule; $\Delta P(t)$ – technological costs in electrical networks.

Fig. 4.9 shows an example of covering the daily load schedule of the LES, given in **Fig. 4.8**. The task is to form the LES as a balancing group. To do this, forecasting the generation and consumption schedule for the next day, an electricity balance is drawn up (**Fig. 4.9, *a***): $W_L = \sum_{i=1}^{24} \Delta t P_{L_i}(t)$ – total load electricity, including losses; $W_{PVPP} = \sum_{j=t_s}^{t_e} \Delta t P_{PVP}(t)$ – electricity generated by the PVPP, where t_s, t_e – time of start and end of generation; $W_{ESS} = \sum_{j=t_1}^{t_2} \Delta t P_{PVP}(t) - \sum_{j=t_1}^{t_2} \Delta t P_{L_i}(t)$ – surplus electricity in the LES, which can be transferred to the energy storage system or to the EPS; Δt – in the hourly schedule is equal to 1 hour.

The amount of load electricity is determined in the hours when PVP generation is absent: $W_{EPS} = W_L - W_{PVPP} + \Delta W$ – electricity that must be taken from the EPS or from the ESS for the balance in the PV plant. There are two options here: when the PV plant operates in parallel with the EPS and when it operates autonomously. In the first option, the electricity deficit in the PV plant is covered from the EPS – directly or through the ESS. To operate in autonomous mode, the ESS electricity must be sufficient to cover the load at "night" time. To ensure the autonomous operation of the LES, it is necessary to increase the PVPP power, as shown in **Fig. 4.9, *b***, and, accordingly, increase the ESS capacity. Another way is to limit the power of consumers and use the potential of active consumers, as shown in [24].

The local system isolated in the EPS includes electricity sources, a backup energy storage system and electricity consumers, which are united by developed electrical networks of different voltages. From the point of view of the control system, the LES are a complex distributed object consisting of individual agents designed to respond to the changing current states of the LES and form collective actions to ensure reliable electricity supply to consumers. Autonomous agents make control decisions and constitute a multi-agent system [22, 23, 28].

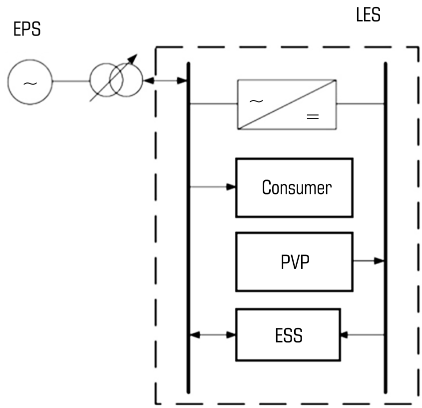

Fig. 4.8 Local electric power system as part of the EES

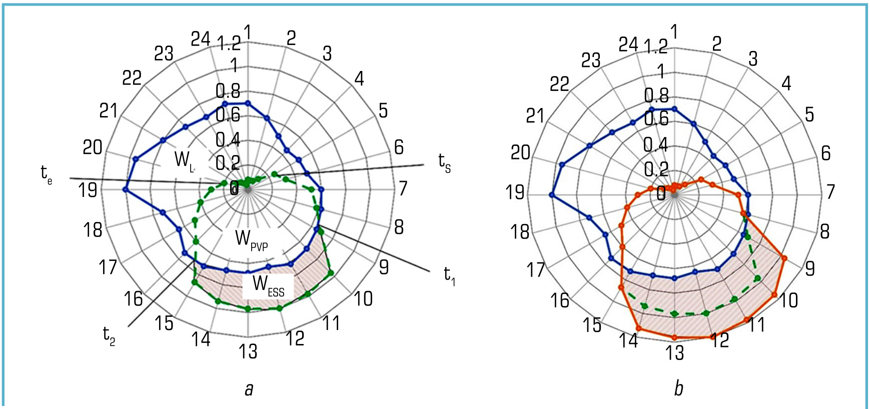

Fig. 4.9 Examples of coverage of the daily electricity consumption schedule of a LES

4.3.2 INTELLIGENT CONTROL SYSTEM OF THE LES MODE

The local system isolated in the EPS includes electricity sources, a backup energy storage system and electricity consumers, which are united by developed electrical networks of different voltages. From the point of view of the control system, LES are a complex distributed object consisting of individual agents designed to respond to changing current states of LES and form collective actions to ensure reliable electricity supply to consumers. Autonomous agents make control decisions and form a multi-agent system [22, 29].

Fig. 4.10 shows the hierarchical structure of the intelligent LES system. At the top level, the local agent LESA is an element of the lower level of the distribution system operator (DSO). Under the condition of parallel operation with the EPS at this level, the LESA performs the functions of a balancing group within the EPS, coordinating its actions with the DSO. At this level, the main current task is to forecast electricity consumption and generation at LES and exchange electricity with the EPS. For this purpose, a database is formed through requests for information from the middle-level agents of the microgrid MGA and MGAi. During the LES separation from the EPS, the tasks and content of the functions to be performed by the ACS change. The LESA are entrusted with the functions of internal balancing of power and electricity and maintaining the technical and economic indicators of the power supply system within permissible values. First of all, this concerns maintaining the frequency and voltage on the consumer buses in the LES. This is carried out by collective actions of the middle-level and technical agents by submitting the relevant work commands to them. Optimal control of active consumers is carried out within the limits of energy consumption W_{ESS}, as well as limiting, if necessary, the power of inactive consumers.

The MGA agent is an agent of the energy storage system, an agent of controlled distributed energy sources, and also within the daily correction of generation by the LESA command. It controls the common ESS, maintaining the frequency, and also controls the reactive power sources, maintaining the voltage.

The MGA agents are microgrids that are responsible for communicating with their agents at the technical level: PVPP, active consumer, inactive consumer, local ESS.

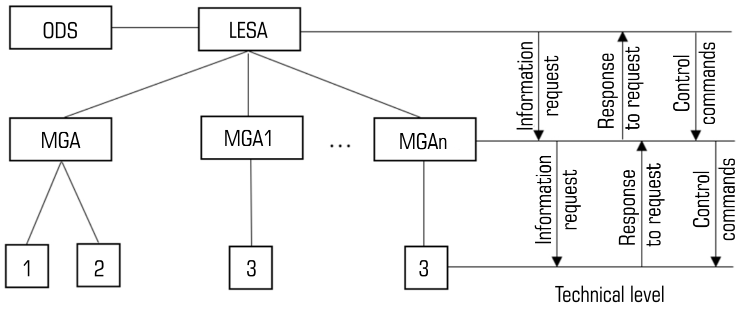

Fig. 4.10 Hierarchical structure of the intelligent LES system

They optimize the technical and economic parameters based on data from local agents and load the optimization result of the corresponding microgrid zone (excess/deficit of power, state of the energy storage, capabilities of the active consumer). They are responsible for communicating to load the relevant data and receive work commands.

The LESA is also entrusted with the functions of switching the LES with the electrical network of the EPS. When the LES and the EPS operate in parallel, the point of their junction is a reference point in terms of voltage. In it, the joint actions of the DSO and LESA maintain a voltage level that ensures the transmission of electricity from the EPS to the LES and vice versa. When transferring the LES to isolated operation, two options are possible: forced, when for some reason the voltage in the electrical network is lost, or in normal mode, when the disconnection of the LES is carried out on the initiative of the DSO or LESA. In these cases, commands are executed on the MGA according to the ACS software and the LES is transferred to autonomous mode. When connecting the LESA to the EPS, all procedures related to the synchronization of the two electrical networks are performed before the command is given to the switch.

Thus, in order to decentralize generation, it is advisable to separate local electric power systems based on RES from the EPS with the creation of intelligent mode control systems in them. It is proposed to form a LES with RES and electricity storage facilities as separate microgrids, which are a key part of the transition to LES operating on the principles of SMART Grid. Local MGs, in addition to generation sources and consumers, also have means of accumulating a certain amount of energy. Due to the hierarchical structure of the intelligent system, the LES can operate both in parallel with the EPS and in isolation from it. Thanks to the intelligent system, the LES implements the principles of SMART Grid and functions as an information and electrical system.

The LES formed in this way can operate as a balancing group within the EES, performing the tasks of the distribution system operator depending on the voltage and power of its MGA components.

In autonomous mode, the LES, depending on the capacity of the energy storage system, can be a full-fledged reserve of renewable energy sources and be used to optimize power flows and maintain frequency and current. The participation of active electricity consumers to coordinate generation and consumption schedules in the LES as a way of balancing power and electricity in it is effective. In the proposed LES with aggregated microgrids and an intelligent control system, its self-recovery after extreme events is implemented and the disturbed load is automatically restored.

The proposed hierarchical structure of the intelligent system of the local electric power system can operate both in parallel with the EPS and in isolation from it. Thanks to the intelligent system, the principles of SMART Grid are implemented in the LES and it functions as an information-electrical system. The LES formed in this way can work as a balancing group within the EPS, performing the tasks of the distribution system operator depending on the voltage and power of its MGA components. In the autonomous mode, the LES, depending on the capacity of the energy storage system, can be a full-fledged reserve of renewable energy sources and be used to optimize power flows and maintain frequency and current. The participation of active electricity consumers to coordinate generation and consumption schedules in the LES as a way of balancing power and electricity in it is effective.

4.4 LOCAL ELECTRIC POWER SYSTEM FORMED FROM MICROGRID

Due to the constant change in time of consumption and generation schedules in LES, it is necessary to create an automated or, taking into account the current state of hardware and software in the industry, an intelligent automatic control system (ACS) for the LES mode [22, 29]. Since LES are part of the EPS, they must operate in conditions and according to the rules, without disrupting the functioning of the EPS, which currently provides a stable power supply. This applies to all modes of operation of LES. Therefore, it is important, based on the real technical capabilities and state of generating capacities and electrical networks, to determine with what characteristics and what tasks LES can solve as balancing groups of the EPS. Due to the limited technical and human resources, the process of forming LES can be phased. Individual parts of the system develop according to a certain plan and are formed according to a certain concept. It lays down the technical policy for the development of electric power systems, scientific foundations, as well as forms of training qualified personnel on the principles of SMART Grid.

Elements of the LES can be formed as separate microgrids. For example, biogas production, its transportation to gas-piston cogeneration plants, distribution heat and electricity networks, system of automatic control (SAC) for this complex can be considered as an independent aggregated object. The same applies to photovoltaic and wind power plants with an electrical network, an hourly generation forecasting system, a backup system to compensate for generation instability due to dependence on weather conditions. The not-so-simple technical and economic task of maintaining the balance of power and electricity in a microgrid is solved more easily if such complexes are implemented and operated as separate microgrids with local SAC, combining them into an intelligent system for controlling the modes of the local electrical system.

Depending on the technical and financial and economic capabilities, LES can be formed in different ways. There are two main options: there is an infrastructure with developed electricity consumption, including industrial, and a distributed generation system is being developed around it; the LES is designed and built practically from scratch with the consumer of electricity and its energy supply. There are real examples. For example, an operating poultry farm as a complex with fattening and processing of raw materials, a feed mill, elevators, etc. with a total capacity of an average of 20–100 MW with power supply from the 10–35 kV power supply (**Fig. 4.11**).

a

b

Fig. 4.11 LES of the MHP complex: *a* – 110/35/10 kV substations; *b* – biogas production complex

Another option – for example, a recreation center is being designed with separate fully electrified houses, a photovoltaic power plant and a power transmission line from the power plant (**Fig. 4.12**). Both the first and second options are characterized by the phased development of renewable energy sources and backup means for their unstable generation in LES. The question arises of substantiating their composition, power and capacity, and the order of implementation.

Fig. 4.13 shows the structure of a real sufficiently powerful LES at different voltages, which is formed from a microgrid (MG) with its local SAC. Microgrid MGi in various sets can contain photovoltaic and wind power plants, electricity storage systems (ESS), diesel generators for restoring generation of PVPP in an isolated state, cogeneration units (CU) on biogas and electricity consumers (C), including active ones. Powerful microgrid MG_i unite microgrids of lower power mg_i. Depending on the capacity of the stored electricity, the ESS are stored on MG_i buses or on higher voltage busbars. In the latter case, ESS can replenish electricity reserves directly from the EPS as a commercial service. Sources of centralized power supply from the EPS are nuclear power plants (NPP), thermal power plants (TPP), hydroelectric power plants (HPP), and pumped storage hydroelectric power plants (PSHPP). If consumers of electricity from the LES are motivated to receive electricity from RES or from decarbonized sources located in the EPS, then the software is installed in the LES SAC according to the method described in [30].

Fig. 4.12 10 kV LES with microgrid based on photovoltaic modules and energy storage system

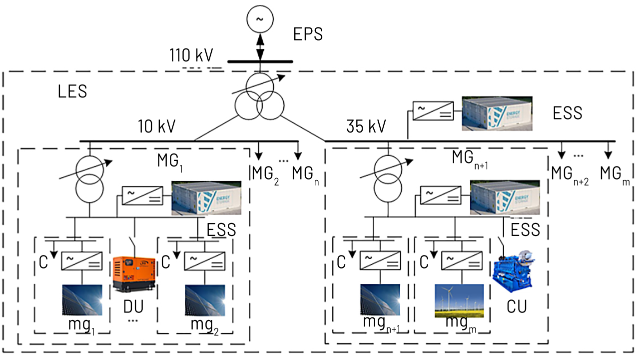

Fig. 4.13 Local electrical system formed from microgrid

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In the formed LES based on MG with renewable energy sources and their generation instability backup in the form of ESS, reliability of power supply, as well as observability and controllability of modes are achieved. Due to the LES intellectualization and the use of SMART Grid principles, self-healing is implemented as the ability of the system to automatically recover after failures and resilience as a measure of the ability to withstand emergency situations with severe consequences. As an element of Smart Grid, self-healing is based on the functions of two-way communications in the network, remote monitoring and self-diagnosis of equipment, standards for preventing the development of system accidents, power and voltage flow control, etc.

4.5 INCREASING THE EFFICIENCY OF ELECTRICAL NETWORKS THROUGH THEIR INTELLECTUALIZATION

Fig. 4.14 shows part of the scheme of the district electrical network (DEN) in the area of the 110/35/10 kV substation, in which a local electric power system is being formed. At the first stage, photovoltaic power plants are installed in feeder 12 near substation 63 with a capacity of 2.5 MW and in feeder 13 near substation 122 with a capacity of 5 MW.

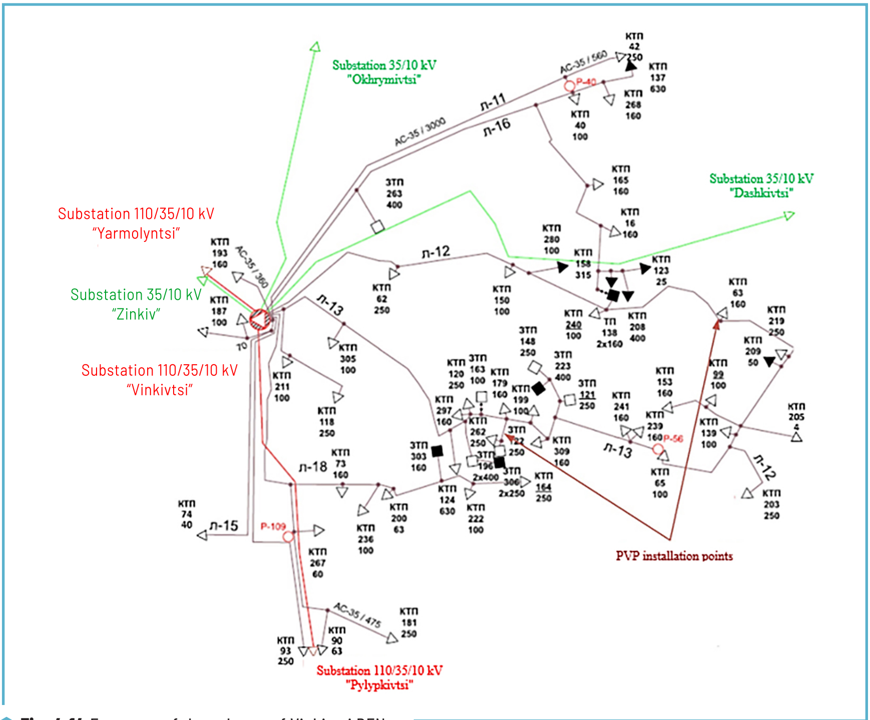

Fig. 4.14 Fragment of the scheme of Vinkivtsi DEN

Both photovoltaic power plants are formed as aggregated microgrids (MG) with local ESS and the use of active consumers. At the next stage, it is planned to install a gas piston unit (GPU) with a capacity of up to 5 MW and a biogas production plant using local raw materials. **Fig. 4.15** shows a structural diagram of such a LES. To ensure the redistribution of active power between feeders 12 and 13, compensation of reactive power in each of the feeders in order to reduce electricity losses, as well as optimal joint use of energy of local GPU in MG_1 and MG_2 and collective GPU in MG_3, a Soft Open Point (SOP) is established. To assess the efficiency of the formation of Vinkivtsi LES, calculations were performed before the installation of the PVPP and after the installation of the PVPP. The calculations were performed using the "Vtrati-110" software package. Below are the results of calculations of the maximum load regime of the 110/35/10 kV substation. The purpose of the calculations is to assess the possibility of installing PVPP and their power, based on the capacity of the power transmission line, the impact on electricity losses and voltage levels.

Fig. 4.16 shows the structure of annual electricity losses by feeders. The largest electricity losses are in F-13 and F-14, followed by F-12, F-15, and F-16.

Fig. 4.17 shows the values of electricity losses in the 110/35/10 kV substation in transformers and 10 kV power lines. Since electricity losses in power transmission lines are quite high, to reduce them, it is advisable to place PVPP closer to the end of the feeder and, preferably, in the area of the active consumer of electricity to enable joint control of generation and consumption schedules.

For the average load mode, the parameters of the feeders of the 110/35/10 kV substations of the "candidates" for the installation of the PVPP were calculated. According to the requirements formulated above (capacity, electricity losses, permissible voltage levels), F-13 and F-12 are appropriate. The sites for the construction of the PVPP with a capacity of 5 MW are located near ZTP-122 and with a capacity of 2.5 MW near substation 63. This also corresponds to the recommendations for the construction of the PVPP in the middle or closer to the end of the feeder, as well as near consumers who may be active in the future.

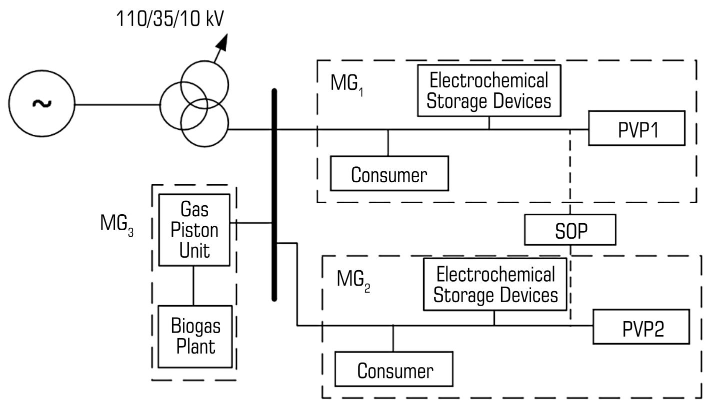

Fig. 4.15 Structural diagram of Vinkivtsi LES

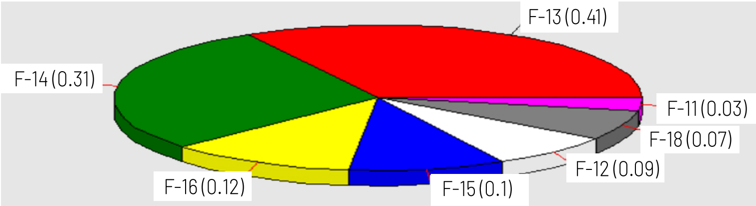

Fig. 4.16 Structure of losses in electrical networks of the Vinkivtsi substation

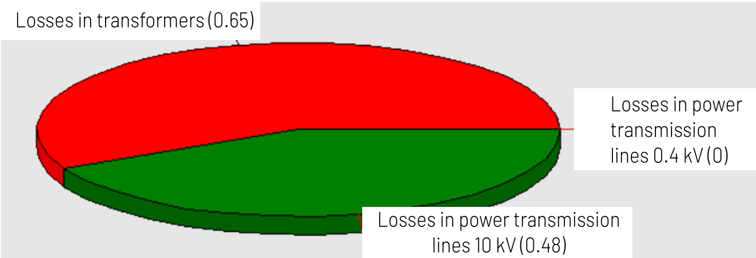

Fig. 4.17 Loss structure at the Vinkivtsi substation in transformers and 10 kV power transmission lines

Calculations were performed under the same conditions as in the previous paragraph, with the exception that in the diagram shown in **Fig. 4.14**, at substations 63 and 122, photovoltaic power plants with a capacity of 2.5 and 5 MW are connected, respectively. **Fig. 4.18** shows the structure of annual electricity losses by feeders. Compared with the previous regime, electricity losses in feeders F-12, F-13 and F-16 decreased the most. Electricity losses in the transformer practically did not change, and losses in the power transmission line of the network decreased by 12% (**Fig. 4.19**).

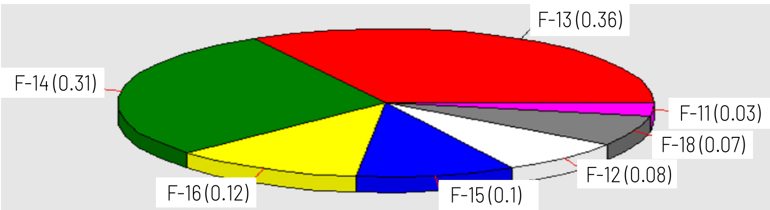

Fig. 4.18 Structure of losses in the electrical networks of the Vinkivtsi substation in the mode with a PVPP

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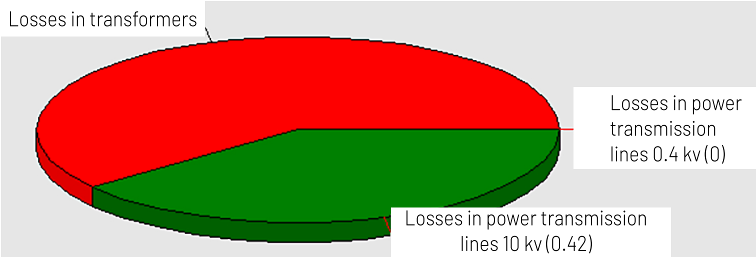

Fig. 4.19 Loss structure at the Vinkivtsi substation in the mode with a PVPP

With normal voltage quality, power losses in F-12 decreased by 25%, in F-13 in different areas power losses decreased from 12 to 24%.

CONCLUSIONS

Distribution electrical networks with an increase in the share of renewable energy sources in them acquire the characteristics of a local electric electrical system and there is a need to create conditions in them to maintain the balance of active and reactive power, taking into account the fact that the generation of electricity from RES depends on natural conditions and is unstable. Since balance reliability as a complex indicator characterizes the quality of the functioning of the power supply system, it is important to provide electrical networks with means that would compensate for the instability of RES generation, especially photovoltaic and wind power plants (PVPP, WPP). The task of choosing methods and means of RES backup is a technical, economic and optimization task.

The feasibility of integrating RES into distribution power grids in the form of separate microgrids (MG), which are a key part of the transition to LES operating on the principles of SMART Grid, is shown. Local MGs, in addition to generation sources and consumers, also have means of accumulating a certain amount of energy. To ensure technical and economic efficiency, MGs are combined into an intelligent control system, which allows for more rational use of MG resources, effective interaction with the distribution network and use the capabilities of active electricity consumers in the process of balancing the LES regime. It is proposed to form the hierarchical structure of the intelligent LES system in such a way that LES with intelligent power grids could not lose RES during the limitation of centralized power supply, but fully use their advantages together with energy storage systems for reliable power supply to consumers.

Calculations and analysis of their results confirmed the positive impact of PVPP on the regime of the distribution power grid under certain conditions. It is shown that the maximum effect of PVPP on the distribution network is achieved when they are connected in the middle or closer to the end of the feeder. It is desirable to choose the feeder with the highest load with consumers, which in the future may be active and used to coordinate PVPP generation schedules and local electricity consumption. This allows to obtain a number of advantages, such as reducing electricity losses and improving its quality, as well as compensating for the instability of PVPP generation during the day and, accordingly, the negative impact on the balance reliability of the LES. The example of the DEN LES illustrates the effectiveness of the methods and algorithms proposed in the work for determining electricity losses caused by the introduction of PVPP, as well as the formation of the LES in such a way as to ensure the ability of active consumers and other means of reservation to influence its balance reliability as a balancing group.

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