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CHAPTER 2

ELECTRICITY CONSUMPTION AND RENEWABLE ENERGY SOURCES GENERATION SCHEDULES COORDINATION IN ELECTRIC NETWORKS FOR BALANCE RELIABILITY INCREASING

ABSTRACT

The chapter analyzes the schedules of electricity consumption and generation in the electricity network with renewable energy sources (RES) as an opportunity to improve the electricity balance in it. It is shown that in order to achieve a positive effect from the introduction of RES into the electric grid, a balance of electricity generation and consumption must be ensured in it. To do this, first of all, the values of the optimal installed power of RES are determined to coordinate the generation and electricity consumption schedules, and the principles of consumption management in the electric network are formed. In order to increase the stability of power supply systems, it is proposed to use electric power accumulators, which, if there is a certain energy reserve in the accumulator, can be used in case of an insufficient amount of RES generation. An algorithm for the method of matching the generation schedules of the PV power plants and the electric load of the network has been developed. At the same time, the cost of displacement of consumption power is estimated, for which a corresponding indicator has been developed. Since the quality of power supply depends not only on the balance of active power, but also reactive power, RES with inverter energy conversion devices are considered as a means of regulating reactive power in the electrical network in order to maintain the voltage within acceptable limits.

KEYWORDS

Electric network, renewable energy sources, electric energy balance, generation and consumption schedules, coordination.

Determining the priority of solving problems in local electric networks (LEN), we determine balance reliability, when its calculation model is determined by the balance of consumption and own generation of electricity, taking into account external income. How other tasks are successfully solved depends on how and by what means balance reliability is ensured [1–3]. Its technical and economic indicators depend on the balance of active and reactive power in LEN [4, 5]. The process of power balancing in LEN is significantly affected by the instability of the generation of renewable energy sources (RES), in particular, photovoltaic and wind power plants (PV and wind power plants).

The instability of RES generation is compensated by the power supplied to LEN from the power system. Because of that, the balancing conditions of the LEN mode also affect the modes of the electric power system (EPS). A number of works [6–9] have been devoted to the optimization of the joint operation of LEN and EPS. In today's conditions, ensuring the balance is entrusted purely to the centralized power supply system. However, changes are gradually taking place in the energy market functioning mechanisms, which encourage RES owners to work according to a given schedule, in particular, the introduction of fines for non-compliance with the stated daily generation schedule.

Increasing RES generation in distribution networks by reducing the load on the centralized power supply system allows for a number of positive effects. They are manifested in the reduction of power and electricity losses in power transmission lines, which are used to transport power, the improvement of the quality of electricity, and the unloading of electrical networks [10]. However, this applies only to cases where the RES generation schedule is consistent with the local electricity consumption schedule. Therefore, the task of artificial coordination of RES generation and electric load schedules arises. It should also be taken into account that the schedule of electrical loads is also non-uniform. For example, the daily dip in the load schedule falls on the peak of generation of the PV power plant, which thereby increases such unevenness. There is a need to motivate consumers to shift their daily schedule of electric loads to the hours of peak generation of PV power plant.

In order to successfully solve the problem of coordinating the schedules of electricity consumption and its generation by renewable energy sources in electric networks as a means of increasing balance reliability, it is first necessary to first of all determine the value of the optimal installed power of RES and form the principles of consumption management in LEN to coordinate the schedules of generation and electricity consumption.

2.1 DETERMINATION OF THE OPTIMAL INSTALLED RES CAPACITY

The RES generation schedule depends on the natural conditions of the region in which the source is located. The value of the installed capacity of the RES should be chosen under the condition of maximum compliance of the generation schedule with the consumption schedule. Given the stochastic nature of both graphs, the method is based on probability analysis.

The starting information for starting the calculation is: statistical data (minimum for the previous year) and a forecast of natural conditions (solar radiation, wind currents); graphs of power consumption of feeder nodes; diagram and parameters of replacement of electrical network elements [11].

Step 1. An annual base of daily insolation (wind flow) schedules is formed to a dimensionless form by dividing by the maximum value. An annual base of total daily schedules for the feeder is formed and reduced to a dimensionless form.

Step 2. Annual schedules are formed by duration, respectively, for RES and consumers.

Step 3. The coefficient of energy security is estimated

$$k_{es} = \frac{M\left(E_{cons}\right)}{M\left(E_{RES}\right)},$$

where $M\left(E_{cons}\right)$ – mathematical expectation of annual consumption; $M\left(E_{RES}\right)$ – mathematical expectation of annual RES generation.

Step 4. If necessary, the RES schedules obtained in Step 1 are refined in order to obtain an energy security factor equal to 1.

Step 5. For refined schedules, let's determine the probabilities of ensuring the balance:

$$k_{stab} = \sum_{i=1}^{24}\left[p_{daily\ i}\sum_{j\in D}\left(p_{RES\_year_j}\sum_{l\in F}p_{Aons\_year_l}\right)\right],$$

where p_{daily} – the probability of the appearance of the degree of the daily schedule $\left(p_{daily} = 1/24\right)$; p_{RES_year} – the probability of the occurrence of a degree of generation during the year; D – set of non-zero powers; p_{Aons_year} – the probability of the degree of consumption occurring during the year; F – set of levels of consumption that are below the generation level of the corresponding period of the day.

Step 6. Let's determine the coefficients of current distribution according to the equation:

$$\mathbf{C}_r = \mathbf{R}^{-1}\mathbf{M}^T\left(\mathbf{M}\mathbf{R}^{-1}\mathbf{M}^T\right)^{-1},$$

where **R** – the matrix of resistances of the branches of the electric network; **M** – the matrix of connections of the branches of the circuit in the nodes (T is the transformation symbol).

The coefficients of current distribution depend on the installation point of the RES, so let's choose the line of the matrix $\mathbf{C}_r$ corresponding to the line through which the generated power of the RES flows into the network. All possible (according to technical conditions) connection points are considered.

Step 7. By analyzing the received vectors $\mathbf{C}_r$, for each of the nodes, the one with the largest sum of coefficients is selected.

Step 8. Based on the original daily consumption schedules, let's calculate the mathematical expectation of the power consumed by each node of the feeder.

Step 9. Let's determine the mathematical expectation of generation power

$$M\left(P_{RES}\right)=M\left(P_{cons}\right)^{T}C_{r}^{T}.$$

Step 10. Let's determine the installed capacity of RES as

$$P_{RES}=k_{stab}k_{es}M\left(P_{RES}\right).$$

The use of the coefficient of energy security and the probability of ensuring the balance in the algorithm allows not only to take into account the features of the generation and consumption schedules, but also to determine the RES capacity, which will ensure that the generation schedule is as close as possible to the consumption schedule [12].

The effectiveness of the proposed method can be shown by an example. Let's consider the feeder, the diagram of which is shown in **Fig. 2.1**.

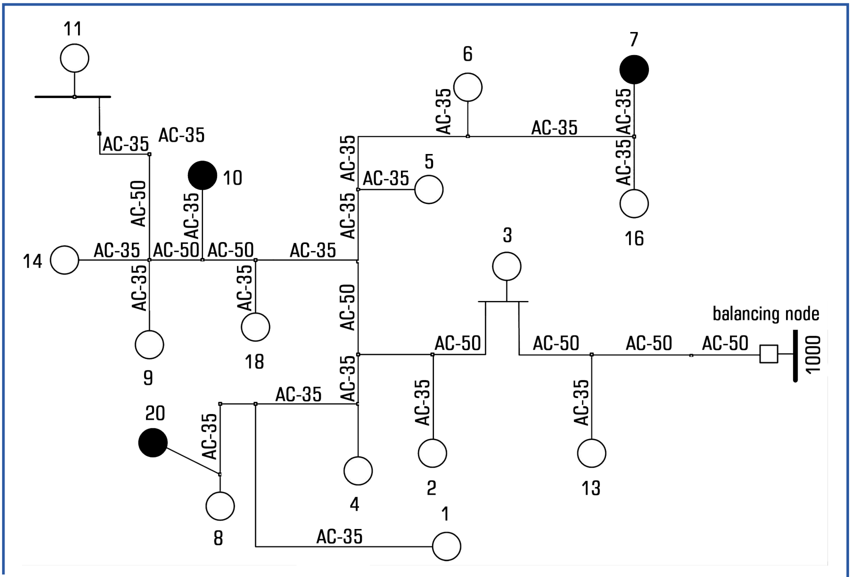


Fig. 2.1 A fragment of the electrical distribution network diagram

Let's consider how nodes for connecting RES 20, 10 and 7 are possible according to the technical conditions. To choose the best of them according to the criterion of electrical energy losses, let's determine the current distribution coefficients for each of the options. Let's summarize the values of the coefficients **C_r** in the **Table 2.1**. Since the total value of the coefficients is greater for node 10, this node is the best node for connecting RES. This is confirmed by the results of calculations. From **Fig. 2.2, 2.3** (for node 20), **Fig. 2.4** (for node 10) and **Fig. 2.5** (for node 7), it can be concluded about a greater unloading effect when the PV power plant is installed in node 10.

For comparison, the calculation of losses of active power in the EN with the selection of PV power plant capacities for the studied schedule of generation and consumption was carried out. Graphical interpretation of the results is shown in **Fig. 2.2–2.5**.

Table 2.1 Results of vector analysis of current distribution coefficients

The total value of current distribution coefficients		
in relation to node 20	in relation to node 10	in relation to node 7
9.914	11.805	9.041

In **Fig. 2.2** shows the results of calculating daily electricity losses during the year. Accordingly, three cases were considered:

– without taking into account PV power plant generation (curve 1);

– with PV power plant generation at its optimal (according to the proposed method) installed capacity (81.5 kW) (curve 2);

– with PV power plant generation with an installed capacity of 200 kW (curve 3).

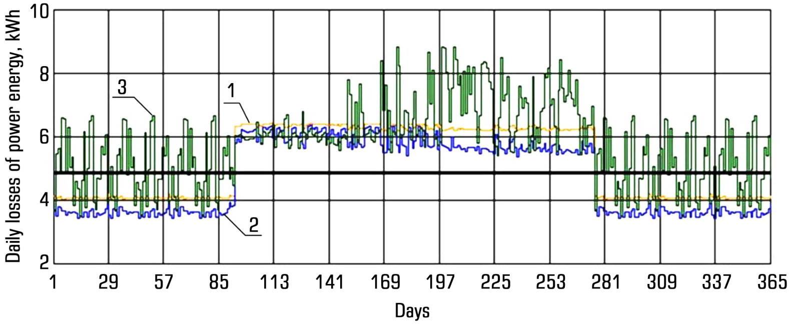
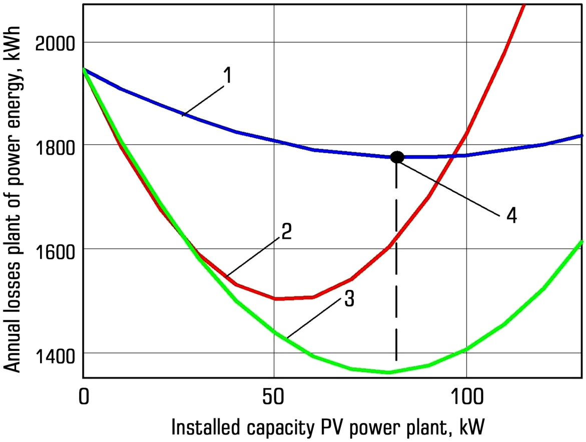
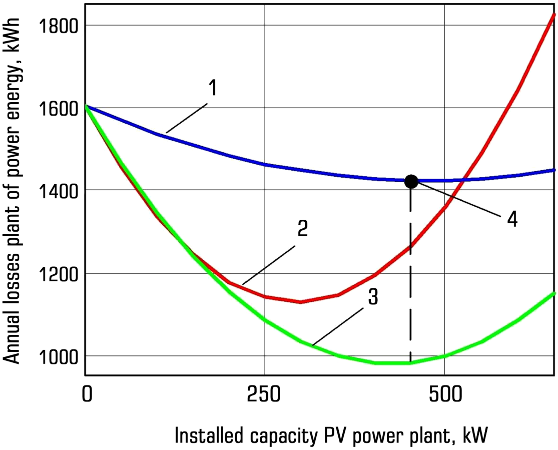


Fig. 2.2 Loss calculation results during the year when the PV power plant is installed at node 20

From the analysis of the obtained graphs, it is possible to ascertain the adequacy of the results obtained by the proposed method.



⬡ **Fig. 2.3** Calculation results when installing the PV power plant at node 20



⬡ **Fig. 2.4** Calculation results when installing the PV power plant at node 10

In **Fig. 2.3–2.5**, curve 1 – change in losses of active power during the year, obtained by counting the installed capacities of the PV power plant; curve 2 – the change in losses of active power during the year, obtained by searching the installed capacities of the PV power plant, provided that the installed capacity of the source is selected from the analysis of the most likely level of electricity consumption; curve 3 – the change in losses of active power during the year, obtained by overestimating the installed capacities of the PV power plant, provided that the mode of operation of the station is dictated not only by natural conditions, but also by the electricity consumption schedule; point 4 is the result of calculation according to the proposed method.

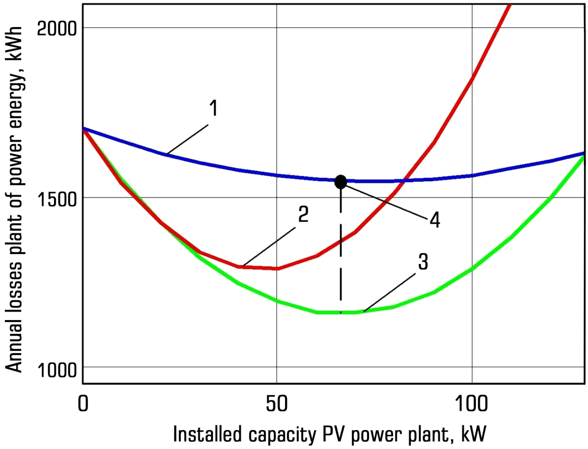


Fig. 2.5 Calculation results when installing the PV power plant at node 7

The results are obtained under the condition that the power consumption schedules match, that is, the coefficient of stability of the coverage of the schedules is the same for each of the consumers. It is clear that this is a certain idealization of the real course of things, but this assumption is made in order to show the effectiveness of the established principle. To take into account real electricity consumption schedules, it is necessary to specify the current distribution coefficients by multiplying by the corresponding probability of ensuring the balance.

The proposed method allows to choose the optimal connection location and installed capacity of RES [13]. Based on the obtained results, it is possible to carry out a comprehensive analysis to assess the ensured quality of the operation of the electric network.

The result of the dependence of the quality of LEN operation for the most probable state depending on the installed generating capacity of the PV power plants is shown in **Fig. 2.6**.

The value of the PV power plant generation capacity is presented in relative units of the actual installed capacity of $P_{inst.PV} = 1.431$ MW (the calculation was made for the second stage of PV power plant input). The results of the calculation show that to ensure a high-quality power supply, the power of the PV power plant would be optimal in the range of 47 % – 80 % of the actually installed. Namely, the recommended capacity of the PV power plant should be 0.95 MW. The indicator of the quality of functioning for the optimal capacity of the PV power plant will be $E_{q\_opt.PV} = 0.41$.

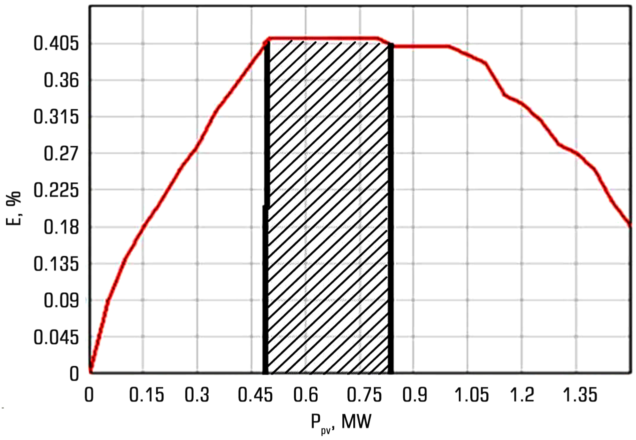


Fig. 2.6 Determination of the optimal installed capacity of the PV power plant

The selection of the optimal generation power of the PV power plant allows to improve the voltage levels in the nodes and increase the probability of ensuring the economy of the regime in the LEN [14]. Coordination of generation and consumption schedules within the framework of the consumption regulation program is also effective [15–17].

The proposed method is implemented as a separate module in PC "Losses". The window of the software module for forming optimal RES connection schemes has the following form (**Fig. 2.7**).

The main window is intended for the user to initialize the corresponding modes of the automated system:

1. Entering information on potential connection locations and existing distributed generation facilities. In this mode, the structure of the distribution network, the number and names of fragments (feeders) and objects (TS) are entered into the "Objects" table.

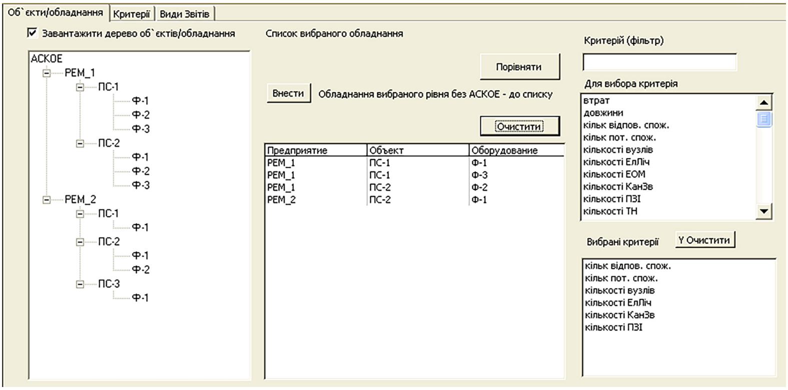
2. Entering information on 10(6) kV feeders. In this mode, information about the number and names of the corresponding 10(6) kV feeders is entered in the "Equipment" table.

3. Selection of potential sites for RES connection to power grids. This mode is implemented in the main window of the module by selecting fragments and objects from the structural tree (**Fig. 2.7**).

4. Selection of a set of optimization criteria. In this mode, the user selects the criteria by which a multi-criteria analysis of the distribution network objects will be conducted to determine the feasibility of connecting RES (**Fig. 2.7**).

5. Output of results is carried out after performing computational procedures at the operator’s initiative. At the same time, a report is created in Microsoft Excel format, an example of which is shown in **Fig. 2.8**.

The results of optimization calculations are shown in **Fig. 2.9**, which are obtained for a real example of the connection of RES, consisting of three stages of photovoltaic generation (500 kW, 570 kW, 630 kW) and a small hydropower plant with a capacity of 250 kW. According to the results of the research, a RES connection scheme was formed, which was implemented in practice and showed sufficient technical and economic efficiency.



☑ Завантажити дерево об`єктів/обладнання

- АСКОЕ
  - РЕМ_1
    - ПС-1
      - Ф-1
      - Ф-2
      - Ф-3
    - ПС-2
      - Ф-1
      - Ф-2
      - Ф-3
  - РЕМ_2
    - ПС-1
      - Ф-1
    - ПС-2
      - Ф-1
      - Ф-2
    - ПС-3
      - Ф-1

Список вибраного обладнання

Обладнання вибраного рівня без АСКОЕ - до списку

Предприятие	Объект	Оборудование
РЕМ_1	ПС-1	Ф-1
РЕМ_1	ПС-1	Ф-3
РЕМ_1	ПС-2	Ф-2
РЕМ_2	ПС-2	Ф-1

Для вибора критерія:

втрат
довжини
кільк відпов. спож.
кільк пот. спож.
кількості вузлів
кількості ЕлЛіч
кількості ЕОМ
кількості КанЗв
кількості ПЗІ
кількості ТН

Вибрані критерії:

кільк відпов. спож.
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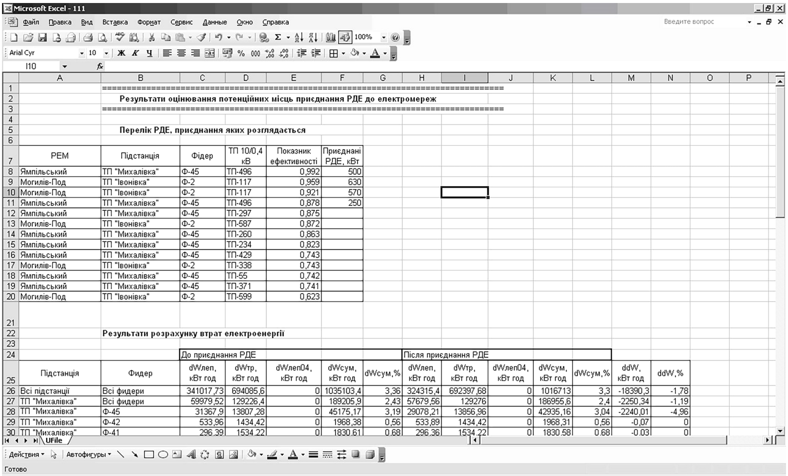
кількості ЕлЛіч
кількості КанЗв
кількості ПЗІ

Fig. 2.7 The window of the software module for forming optimal RES connection schemes



Результати оцінювання потенційних місць приєднання РДЕ до електромереж

Перелік РДЕ, приєднання яких розглядається

РЕМ	Підстанція	Фідер	ТП 10/0,4 кВ	Показник ефективності	Приєднані РДЕ, кВт
Ямпільський	ТП "Михалівка"	Ф-45	ТП-496	0,992	500
Могилів-Под	ТП "Івонівка"	Ф-2	ТП-117	0,959	630
Могилів-Под	ТП "Івонівка"	Ф-2	ТП-117	0,921	570
Ямпільський	ТП "Михалівка"	Ф-45	ТП-496	0,878	250
Ямпільський	ТП "Михалівка"	Ф-45	ТП-297	0,875	
Могилів-Под	ТП "Івонівка"	Ф-2	ТП-587	0,872	
Ямпільський	ТП "Михалівка"	Ф-45	ТП-260	0,863	
Ямпільський	ТП "Михалівка"	Ф-45	ТП-234	0,823	
Ямпільський	ТП "Михалівка"	Ф-45	ТП-429	0,743	
Могилів-Под	ТП "Івонівка"	Ф-2	ТП-338	0,743	
Ямпільський	ТП "Михалівка"	Ф-45	ТП-55	0,742	
Ямпільський	ТП "Михалівка"	Ф-45	ТП-371	0,741	
Могилів-Под	ТП "Івонівка"	Ф-2	ТП-599	0,623	

Результати розрахунку втрат електроенергії

		До приєднання РДЕ					Після приєднання РДЕ						
Підстанція	Фидер	dWлеп, кВт год	dWтр, кВт год	dWлеп04, кВт год	dWсум, кВт год	dWсум,%	dWлеп, кВт год	dWтр, кВт год	dWлеп04, кВт год	dWсум, кВт год	dWсум,%	ddW, кВт год	ddW,%
Всі підстанції	Всі фидери	341017,73	694085,6	0	1035103,4	3,36	324315,4	692397,68	0	1016713	3,3	-18390,3	-1,78
ТП "Михалівка"	Всі фидери	59979,52	129226,4	0	189205,9	2,43	57679,56	129276	0	186955,6	2,4	-2250,34	-1,19
ТП "Михалівка"	Ф-45	31367,9	13807,28	0	45175,17	3,19	29078,21	13856,96	0	42935,16	3,04	-2240,01	-4,96
ТП "Михалівка"	Ф-42	533,96	1434,42	0	1968,38	0,56	533,89	1434,42	0	1968,31	0,56	-0,07	0
ТП "Михалівка"	Ф-41	296,39	1534,22	0	1830,61	0,68	296,36	1534,22	0	1830,58	0,68	-0,03	0

Fig. 2.8 An example of a report on multi-criteria evaluation and ranking of RES connection points to power grids

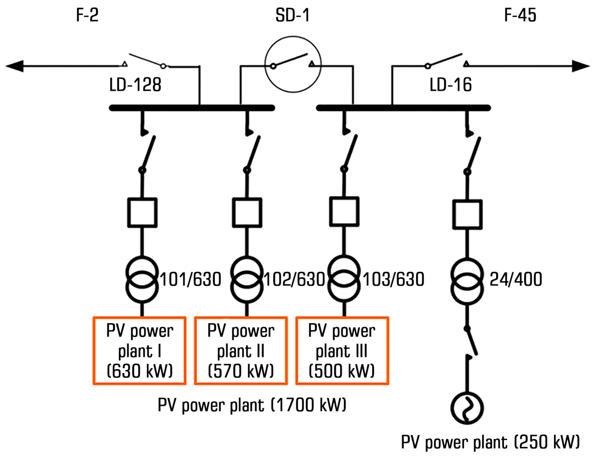


Fig. 2.9 Scheme of connection of renewable energy sources to distribution grids

The integral quality indicator was determined before the introduction of the PV power plant ($E = 0.876$) and after the introduction of the PV power plant ($E = 0.78$) (**Fig. 2.10**). The decrease in the quality indicator is explained by the overload of the feeder. After the introduction of the 1,700 kW power plant, the electricity and voltage losses in the feeder nodes, where a small 250 kW power plant is already operating, increased. It is possible to unload the feeder if part of the power will be distributed to the substation of the neighboring district electric network. Due to the reduction of electricity and voltage losses and improvement of reliability, the overall technical and economic efficiency of electric networks and renewable energy sources increases. Transferring part of the PV power plant electricity to another substation allows to increase the effect on the feeder ($E = 0.93$).

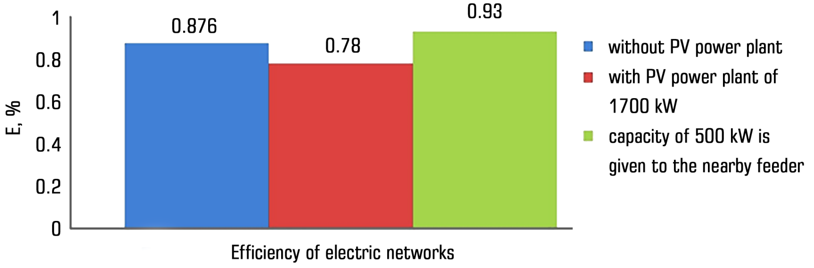


Fig. 2.10 The results of the evaluation of the integral indicator of the quality of functioning

2.2 CONSUMPTION MANAGEMENT TO COORDINATE GENERATION AND ELECTRICITY CONSUMPTION SCHEDULES

As noted in [15–17], consumption management is a fairly effective means of increasing the efficiency of power supply systems. The implementation models of such regulation are different in each state. However, the underlying principles are similar. A generalized diagram of the principles of implementing demand management is shown in **Fig. 2.11**.

According to this scheme, every consumer who has a certain freedom in the amount of electricity consumption, the so-called "active consumer", (due to the flexibility of the technological process, the ability to minimize its consumption in certain periods at the expense of its own sources or energy storage devices, etc.) can independently or through the aggregator to provide paid services in changing your consumption at the request of the system. Each country develops the financing mechanism for such services individually.

In conditions of RES development, demand management can improve the quality of operation of electrical networks.

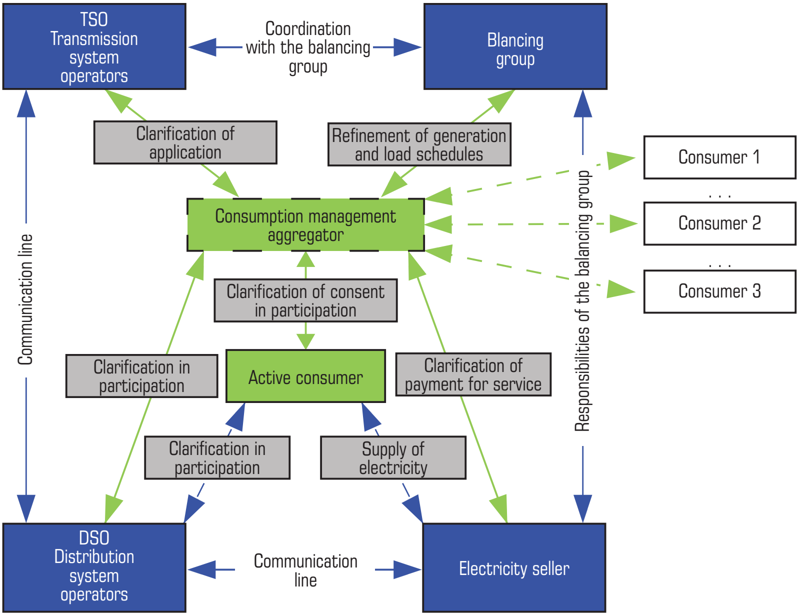


Fig. 2.11 A generalized diagram of the principles of implementation of demand management

The analysis of the overall schedule of the feeder load shows that there are hours during the day when the generation of the PV power plant is greater than the local consumption. Such an extension increases the loss of electricity in the LEN, has a negative effect on the voltage deviation and increases the total unevenness of the daily generation.

The principle of the "ideal" regime, which is the basis for evaluating the quality of the operation of electrical networks, allows to evaluate the efficiency of each consumer in the task of coordinating the schedules of RES generation and consumption. The choice of consumers whose consumption schedule change will have the maximum efficiency for LEN (**Fig. 2.1**) is proposed to be made on the basis of the analysis of the coefficients of the current distribution matrix for *r* the scheme in relation to the generating unit. The row of the matrix $\mathbf{C}_r$ corresponding to the line that connects the PV power plant to the distribution electrical network feeder is given in the **Table 2.2**.

⬢ **Table 2.2** Fragment of the matrix of current distribution coefficients of the feeder of distribution electric networks

No. node	14	9	18	11	5	6	7	4
The value of the current distribution coefficient	0.998	0.997	0.853	0.75	0.74	0.79	0.61	0.75
No. node	8	20	2	1	3	13	16	–
The value of the current distribution coefficient	0.689	0.66	0.68	0.71	0.64	0.59	0.6	–

It is obvious that it is advisable to level the schedule by changing the load of nodes located near the generation source and with a relatively large power consumption, that is, with the largest current distribution coefficients. Losses of active power in power transmission lines will be reduced by reducing the distance of electric energy transportation from the PV power plant. Such nodes are nodes 14, 9, 18.

The method is based on the application of the transport problem algorithm and is solved in tabular form [18]. The result of matching the schedules depends on the coefficients of the cost of displacement of the consumption capacity.

Estimation of the cost of displacement of consumption capacity in the conditions of a multi-zone tariff for electric energy can be carried out according to the expression [19]:

$$B_{ij} = P_{sh} \cdot C_t \left(K_{Tj} - K_{Ti} \right) + \beta - \Delta P \cdot C_t, \tag{2.1}$$

where K_{Tj} – coefficient of the cost of electricity according to the zone tariff of the level of the schedule from which the capacity is planned to be transferred, in the central office; K_{Ti} – coefficient of the cost of electricity according to the zone tariff of the stage of the schedule to which the power is planned to be transferred, in the central office; P_{sh} – the power that the consumer must shift to level the LEN load schedule, kW; C_t – tariff for electricity according to the energy supply company, hryvnias/kWh; β – the cost of the technological shift in production, which must be compensated by the power system, hryvnias; ΔP – reduction of power losses due to adjustment of the consumer's load schedule, kW.

The indicator of the cost of transferring the load B_{ij} from one stage of generation to another is expedient to use in the task of matching the RES generation schedules to the load. Application of this approach, in the problem of equalization of daily generation, will allow not only to reduce the unevenness of the latter, but also to reduce the loss of electricity in the LEN.

To reduce the unevenness of the total daily generation of distribution electrical network and to minimize losses of active power, it is suggested to adjust the schedule by each node in turn according to the current distribution coefficient.

In **Table 2.3**, in which it is conditionally possible to highlight *m* the hours in which the actual consumption of the node is greater than the generation of the PV power plant, $A_i,\ldots,A_m$, and *n* the hours in which PV power plant generation will exceed node consumption, $Z_i,\ldots,Z_m$. For this purpose, node capacities are used, refined by multiplying by the current distribution coefficient. The relative cost B_{ij} of power transfer from one time interval of the schedule to another will be determined by (2.1).

It is obvious that the value of relative values B_{ij} will differ for each node.

Table 2.3 Distribution of consumption displacement values according to the transport problem

B_{11}	B_{12}	B_{13}	B_{14}	B_{15}	B_{16}	B_{17}	…	…	B_{1i}	Z_1
B_{21}	B_{22}	B_{23}	B_{24}	B_{25}	B_{26}	B_{27}	…	…	B_{2i}	Z_2
…	…	…	…	…	…	…	…	…	…	…
B_{j1}	B_{j2}	B_{j3}	B_{j4}	B_{j5}	B_{j6}	B_{j7}	…	…	B_{ji}	Z_n
A_1	A_2	A_3	A_4	A_5	A_6	A_7	…	…	A_m	…

In accordance with the given task, let's write down the objective function:

$$\sum_{i=1}^{m}\sum_{j=1}^{n} B_{ij}\cdot P_{ij} \to \min, \tag{2.2}$$

where P_{ij} – the power that needs to be shifted from the *j*-th stage of the load schedule to the *i*-th.

The first group of restrictions indicates that the power at any generation stage must be equal to the total power consumption of this generation stage:

$$\sum_{i=1}^{m} P_{ij} = A_i. \tag{2.3}$$

The second group of restrictions indicates that the total shift in consumption for a certain level of generation must fully compensate for the generation at this level:

$$\sum_{i=1}^{n} P_{ij} = Z_j. \tag{2.4}$$

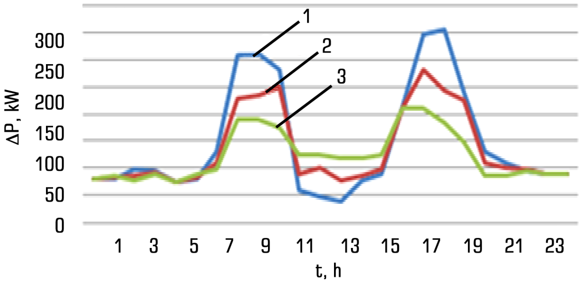
There is also a restriction on the impossibility of shifting negative values of capacity consumption:

$$P_{ij} \geq 0,\ i = 1,2,\ldots,m,\ \ j = 1,2,\ldots,n. \tag{2.5}$$

The dependence of the mode of operation of renewable energy sources on natural conditions in most cases leads to the deterioration of the mode of operation of distribution electric networks. Therefore, it is necessary to carry out artificial coordination of load and RES schedules. This is especially true of photovoltaic plants.

According to the developed method, the transport matrix of the displacement values of the load capacities at node 14 is given in the **Table 2.4**. The results of optimizing the load schedule for node 96 are presented in the **Table 2.5**.

As mentioned earlier, leveling the load schedule of the local electrical system due to the selection of consumers based on the current distribution coefficient allows to reduce losses of active power in it. **Fig. 2.12** shows the change in active power losses depending on the time of day for all stages of optimization. A total reduction in electrical energy losses is also achieved – the result is shown in **Fig. 2.13**.



⬡ **Fig. 2.12** Change in losses of active power in LEN: 1 – taking into account PV power plant generation; 2 – after leveling the graph at node 14; 3 – after leveling the graph at node 9

The evaluation of the effect of coordinating the generation and load schedules of the PV power plant is carried out on the basis of the developed LEN functioning quality coefficient, which for the agreed generation and load schedules is $E_{q\_agreed} = 0.84$.

Table 2.4 Transport matrix of power consumption of 14 nodes

Time intervals of generation	Z_m	Time intervals of generation															Fictitious node load
		0	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**17**	**18**	**19**	**20**	**21**	**22**	**23**	
8	270	3.6	3.5	3.4	3.3	3.2	3.1	3	2.9	2.7	3.1	3.2	3.3	2.9	3	3.6	0
9	410	4.2	4.1	4	3.9	3.8	3.7	3.6	3.5	3.1	3.5	3.6	3.7	3.3	3.4	4	0
10	600	4.3	4.2	4.1	4	3.9	3.8	3.7	3.6	3	3.4	3.5	3.6	3.2	3.3	3.9	0
11	760	3.9	3.8	3.7	3.6	3.5	3.4	3.3	3.2	2	3	3	3	3	3	3	0
12	790	4	3.9	3.8	3.7	3.6	3.5	3.4	3.3	2.3	2.7	2.8	2.9	2.5	2.6	3.2	0
13	790	4.1	4	3.9	3.8	3.7	3.6	3.5	3.4	2.2	2.6	2.7	2.8	2.4	2.5	3.1	0
14	630	4.2	4.1	4	3.9	3.8	3.7	3.6	3.5	2.1	2.5	2.6	2.7	2.3	2.4	3	0
15	270	4.3	4.2	4.1	4	3.9	3.8	3.7	3.6	2	2.4	2.5	2.6	2.2	2.3	2.9	0
16	110	4.4	4.3	4.2	4.1	4	3.9	3.8	3.7	1.9	2.3	2.4	2.5	2.1	2.2	2.8	0
A_m		80	110	50	60	100	150	70	10	80	100	100	120	50	80	60	3410

Table 2.5 Optimization result for node 14

Time intervals of generation	Z_m	Time intervals of generation															Fictitious node load
		0	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**17**	**18**	**19**	**20**	**21**	**22**	**23**	
8	270	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	270
9	410	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	410
10	600	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	600
11	760	26	32	0	0	11	27	3	0	5	13	10	16	0	13	5	599
12	790	27	35	20	22	32	43	25	6	27	31	32	37	19	25	21	386
13	790	27	35	19	23	32	44	25	4	28	32	33	37	19	25	21	387
14	630	0	8	11	15	24	36	17	0	20	24	25	30	11	17	13	379
15	270	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	270
16	110	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	110
A_m		80	110	50	60	100	150	70	10	80	100	100	120	50	80	60	3410

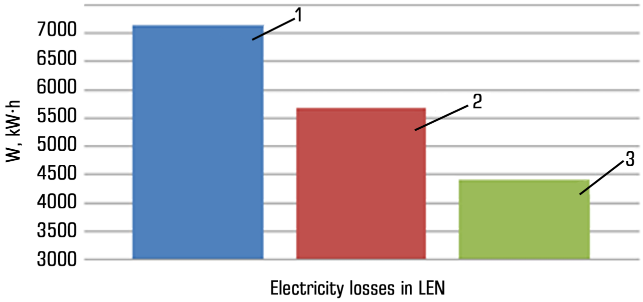


Fig. 2.13 Electricity losses in LEN: 1 – taking into account PV power plant generation; 2 – after leveling the schedule at node 14; 3 – after leveling the schedule at node 9

Coordination of generation and load schedules leads to improvement of technical and economic and mode parameters of LEN operation. But since the generation of PV power plant has the nature of generation dependent on variable weather parameters, even in the case of agreed schedules, the use of capacity reserve is mandatory.

2.3 ELECTRIC ENERGY ACCUMULATORS AS AN ELEMENT OF INCREASING THE BALANCE RELIABILITY OF LOCAL ELECTRIC SYSTEMS

One of the ways to increase the stability of power supply systems is the accumulation of excess energy, which is formed as a result of the imbalance between the energy produced by RES and consumed in the LES. The presence of a certain energy reserve in the accumulator can be used in case of an insufficient volume of RES generation. Control of the charge/discharge process is most often performed based on the presence/absence of a positive difference between the energy generated by RES and consumed by the load.

It is clear that in case of installation of the accumulator within the limits of the balance sheet ownership of the energy source, the calculation of its technical characteristics should be based on the assessment of the instability of the RES generation process [19, 20]. As an example, this can be shown by the results of calculations of excess and deficit capacity of the Galzhbiyiv PV power plant. **Fig. 2.14** illustrates the excesses and deficits of capacity in the form of a graph that displays the value of the possibility of accumulating a certain amount of capacity $Q(t)$ – provided that the initial capacity of the storage $Q_0(t)=0$.

From **Fig. 2.14**, it can be seen that for this PV power plant, the mathematical expectation of surplus is greater than the mathematical expectation of deficit $M_{sup l\ t} > M_{def\ t}$ in the time interval from 10:30 to 13:30. Therefore, for the installed generating capacity of this PV power plant, the storage capacity will be equal to:

$$Q(t)=\frac{W_{\sup}(t)}{U_{stor}}=\frac{2756.35}{12}=230\,kA\,h. \tag{2.6}$$

Due to the surplus that can be accumulated during the PV power plant generation hours from 10:30 a.m. to 1:30 p.m., it is possible to increase the number of hours in which the PV power plant will independently ensure the balance between the generation and electricity consumption of the PV power plant (**Fig. 2.15**). Another advantage of using accumulators is that excess generation will not lead to an increase in additional losses of active power and deterioration of the quality of electricity in the electrical network.

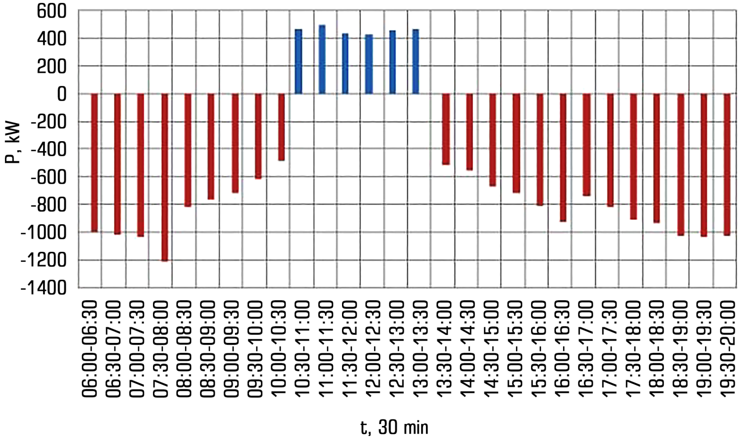


Fig. 2.14 Change in the mathematical expectation of generation deficit and surplus during the day

Taking into account the installed energy storage (SE), the quality of the LES operation will increase to $E_{q\_inst\_RES\,stor}=0.583$.

Installation of a storage device of such capacity requires substantial capital investment. The amount of stored electricity depends directly on the capacity of the energy storage, as well as on the installed generating capacity of the PV power plant.

According to the Law of Ukraine on the electric energy market [21], renewable energy sources must announce the hourly schedule of electric energy production a day in advance. Taking into account the insufficient accuracy of the forecast of meteorological parameters, in order to ensure the accuracy [22, 23] of working out the declared generation schedule, it is necessary to use a system of accumulating excess energy, which can be used as an additional source in periods of insufficient generation.

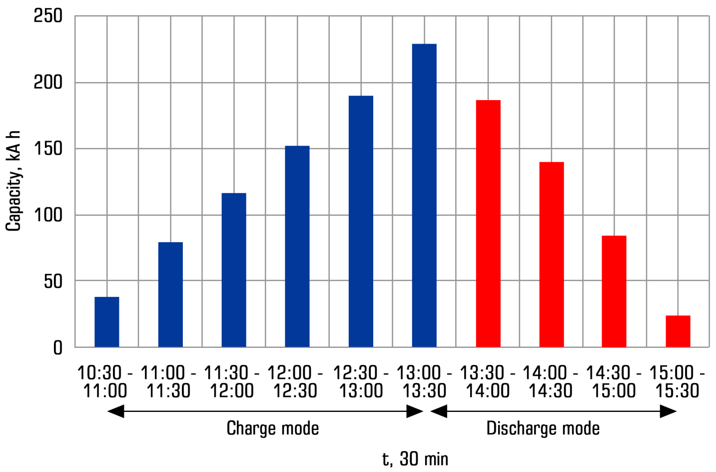


Fig. 2.15 Operation schedule of the full-cycle "charge/discharge" storage device

For this purpose, a mathematical model of such a system was developed in the work and simulation modeling of its operation was carried out.

Matlab/Simulink PC was used to develop the mathematical model. **Fig. 2.16** and **2.17** show the Simulink model of the PV power plant complex and the electrochemical storage. **Fig. 2.18** shows the operation logic of the storage management system in the mode of maintaining the declared generation schedule.

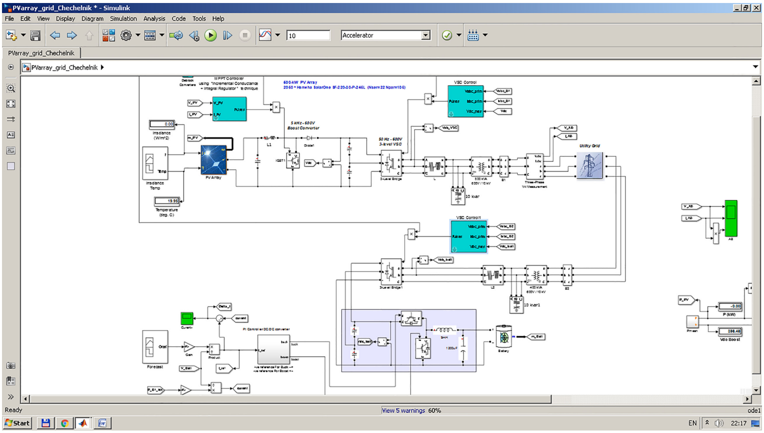


Fig. 2.16 Simulink model of the PV power complex and electrochemical storage

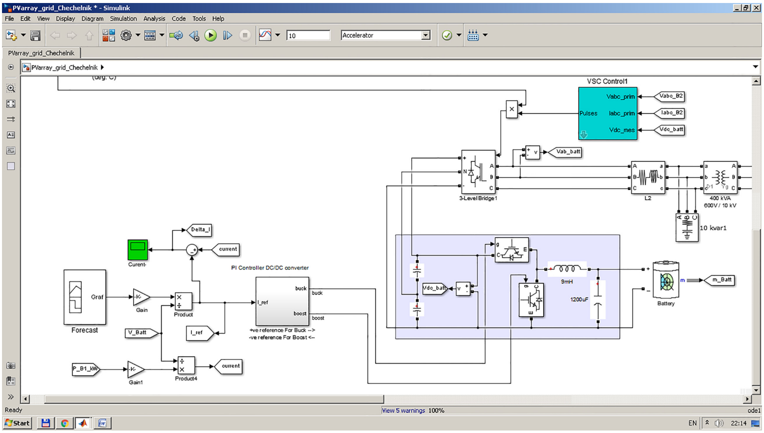


Fig. 2.17 Simulink model of the electrochemical storage control complex

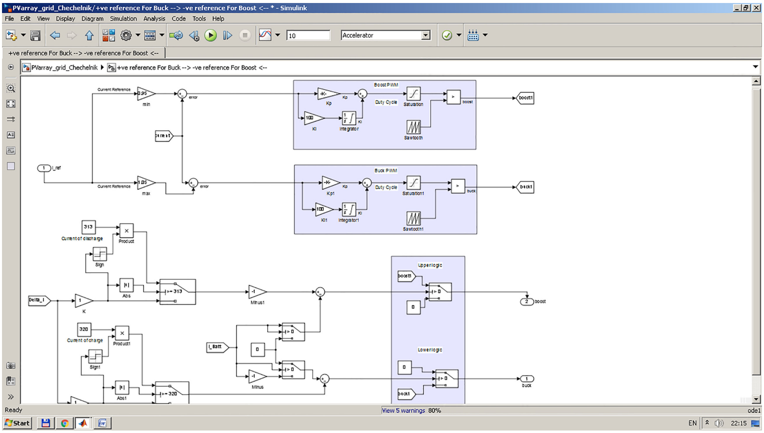


Fig. 2.18 Simulink model of the control logic of the electrochemical storage device

The Simulink model was used as a model of an electrochemical energy storage device. The characteristics correspond to a Li-Ion battery. The discharge and charge curves are shown in **Fig. 2.19**.

The results of simulation modeling of the operation of the energy storage system at various PV power plants are shown in **Fig. 2.20–2.22**.

For a day characterized by an average level of cloud cover, an hourly schedule was forecast (**Fig. 2.20–2.22**, the red curve takes into account the provision of the area of permissible deviations of ±10 %). Taking into account the actual schedule of operation of the PV power plant (black curve), a simulation of the operation of the energy storage system was performed, taking into account 50 % battery charge (blue curve). The simulation was carried out for storage systems with batteries of different capacities. As a result, the smallest capacity was selected, at which the predicted generation schedule was provided as accurately as possible.

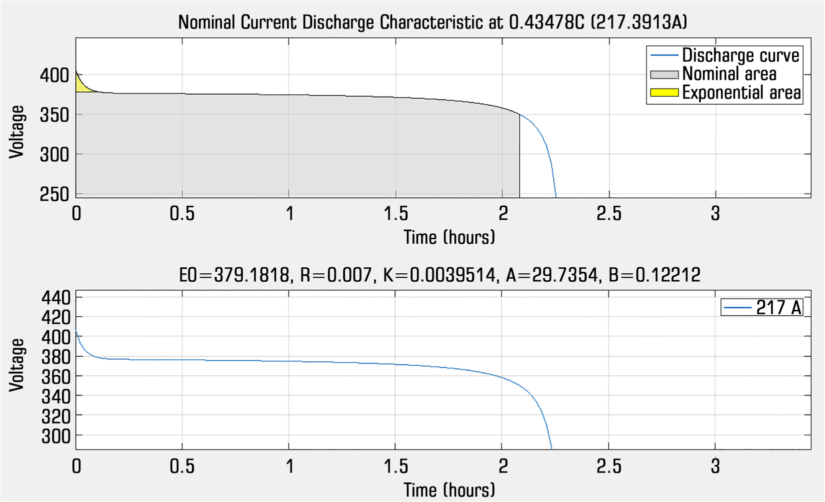


Fig. 2.19 Characteristics of the chemical accumulator

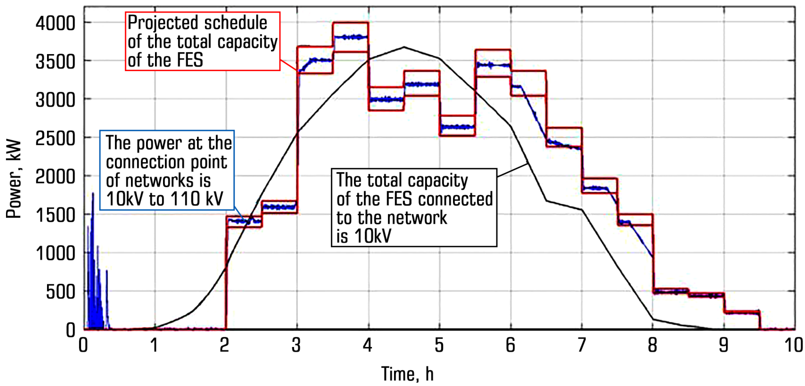
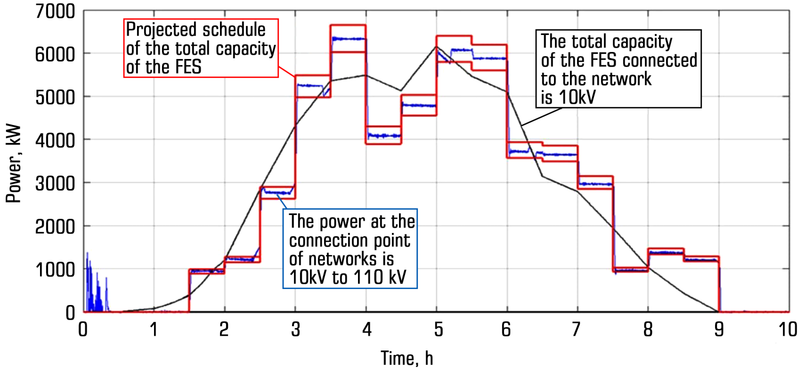
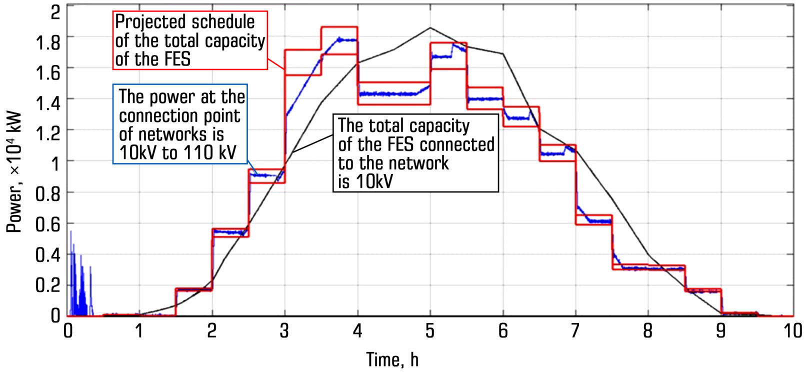


Fig. 2.20 Daily power change schedules at the Porogy PV power plant



⬡ **Fig. 2.21** Daily power change schedules at Bar PV power plant



⬡ **Fig. 2.22** Daily power change schedules at Chechelnyk PV power plant

The results of the simulation analysis are shown in **Fig. 2.23** and **2.24**. **Fig. 2.23** and **2.24** show the values of discharge and charge energy for storage systems installed at each station and at a group of stations. We can clearly conclude that it is economically feasible to install storage devices on a group of stations, as it allows reducing the total capacity of batteries. In addition, the group storage can be used when solving a number of other problems (balancing modes, providing system services for regulating mode parameters, etc.), which increases the profitability of invested funds.

Since it is practically impossible to ensure balance reliability purely by PV power plant generation, it is necessary to determine the capacity of the reserve, which should be provided by the power system to maintain the balance between consumed and generated electricity in the LES.

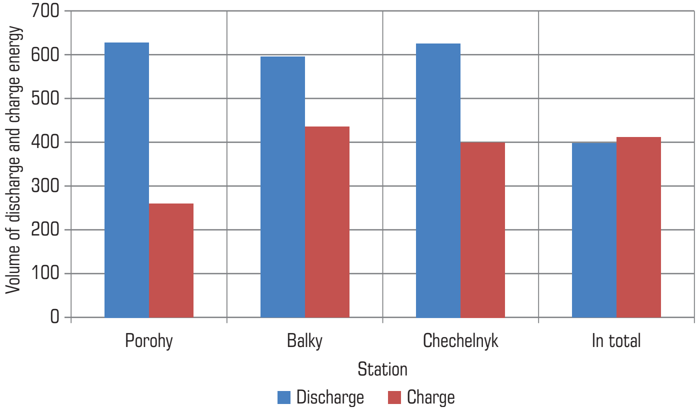


Fig. 2.23 Volume of discharge and charge energy for the simulated period

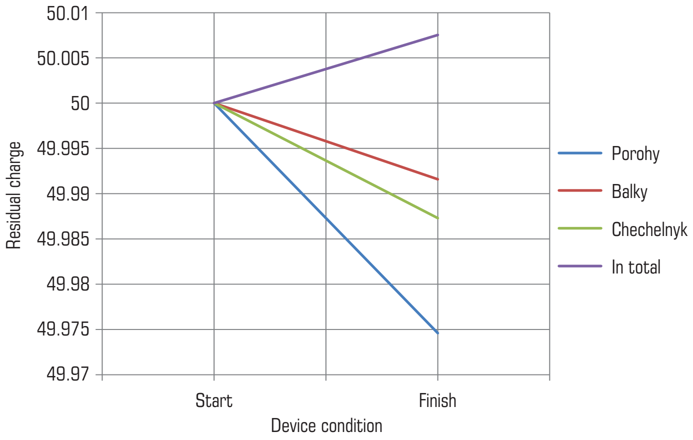


Fig. 2.24 Changing the residual charge on the storage device

It is possible to get benefits from the generation of photovoltaic plants due to the introduction of additional means. The paper considers the possibility of using electric energy storage to coordinate the schedules of PV power plant generation and local electricity consumption, determine the optimal power of PV power plant generation, and determine the reserve capacity that should be provided by the energy supply company. All the means listed above have different effects on the quality of the operation of the LES. According to the proposed quality indicator, it is possible to determine which of them is able to improve the quality of electricity supply to the LES to a greater extent (**Fig. 2.25**) [24].

Among the considered means, the highest coefficient of quality of functioning has an agreed schedule of generation of PV power plant with electricity consumption of LES with a defined reserve capacity $E_{q\_agr.with\_reser.} = 0.989$.

What is more, for the PV power plant generation schedule coordinated with local electricity consumption, the required reserve capacity will be the smallest (**Fig. 2.26**).

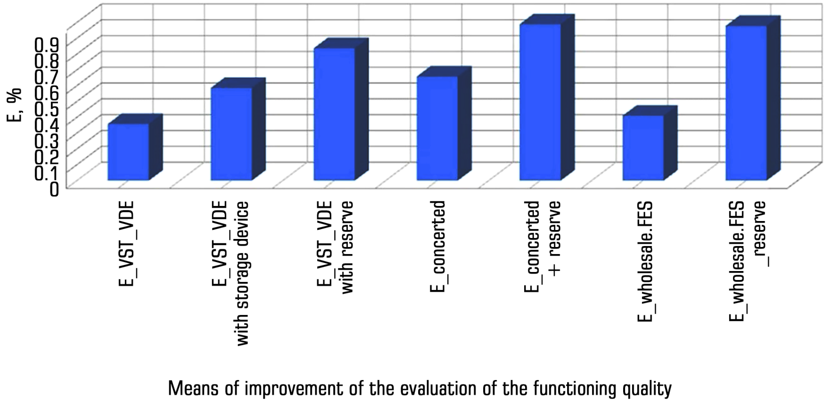


Fig. 2.25 Evaluation of the functioning quality of during the use of various means of its improvement

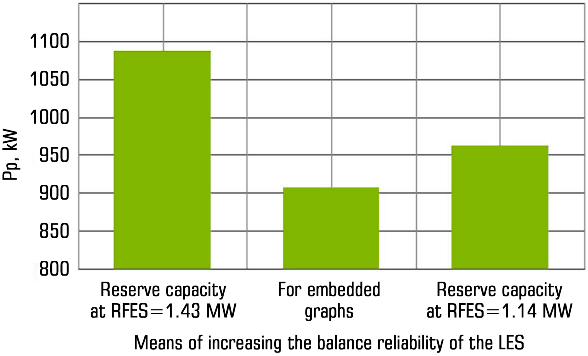


Fig. 2.26 Change in reserve capacity for various means of increasing the balance reliability of the LES

2.4 ALGORITHM FOR MATCHING SCHEDULES OF PV POWER PLANT GENERATION AND ELECTRIC LOAD OF LES

The increase in the generation of photovoltaic power plants in distribution networks due to the reduction of the load on the centralized power supply system makes it possible to obtain a positive effect in the electric power system (EPS). They are manifested in the reduction of power and electricity losses in transmission lines and transformers, which are used to transport power, in the improvement of the quality of electricity, and the unloading of electrical networks. However, this applies only to cases when the generation schedules of the PV power plant are consistent with the level of local electricity consumption and the topology of electrical networks [25, 26]. That is, the positive effect on the PV power plant should also be taken into account in the algorithm for matching the generation schedules of the PV power plant and the electric load of the LES.

In order to develop a method of coordinating the generation schedules of the PV power plant and the load of the LES, it is necessary to evaluate the influence of the generation of distributed energy sources on the unevenness of the daily schedule of electric loads (SEL).

Among the existing methods of assessing the unevenness of the daily load schedule, the means of morphometric analysis should be noted [27, 28]. To analyze and evaluate the influence of renewable energy sources on the total load schedule of the electric network, it is possible and appropriate to use morphometric indicators of the unevenness of SEL. The advantage of such indicators when analyzing the unevenness of load schedules lies in their integrality. Taking into account the integral characteristics of morphometric indicators, it is possible to more accurately justify the alignment of SEL and coordination with the RES generation schedule.

Given that the schedule of electric loads is uneven, and the peak generation of the PV power plant falls on a daily dip in the load schedule, which increases such unevenness, there is a need to motivate consumers to shift the daily schedule of electric energy and loads up to the peak generation hours of the PV power plant. For this, the concept of virtual power plants and regulator consumers is used, which greatly simplifies such a task.

The main idea of this approach is not to generate electricity, but to create new or motivate existing electricity consumers to maneuver their own consumption. Currently, the main measure of motivation for electricity consumers is the zonal electricity tariff (**Table 2.6**), according to which the cost of electricity is differentiated by periods of the day. Thus, the consumer can reduce the electricity bill without reducing the amount of consumption. At the same time, the unevenness of electricity consumption schedules is reduced. A similar approach can be used to evaluate the effectiveness of coordination of schedules of generation and consumption of RES in the electric network.

In order to estimate the cost of shifting consumption power, it is necessary to develop an indicator that would take into account the change in the coefficient of the cost of electricity according to the zone tariff, the cost of compensatory costs to the consumer for shifting the electricity consumption schedule, the cost of reducing power losses due to the coordination of the total daily SEL with the generation schedule:

$$B_{ij} = \left(K_{tj} - K_{ti}\right) \cdot C_t + \beta - \delta P \cdot C_t, \tag{2.7}$$

where 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; C_t – electricity tariff according to the energy supply company; β – cost of the technological shift in production, which must be compensated by the energy system; δP – reduction of power losses due to adjustment of the consumer's load schedule.

Table 2.6 The zonal tariff for electricity is differentiated by time periods

Period of time	**Night**	**Day**	**Peak**
Two-zone tariffs, differentiated by time periods			
Tariff coefficients	0,5	1	–
Duration of the period	23:00 – 07:00	07:00 – 23:00	–
Three-zone tariffs, differentiated by time periods			
Tariff coefficients	0,4	1	1,5
Duration of the period	23:00 – 07:00	07:00 – 08:00 11:00 – 20:00 22:00 – 23:00	08:00 – 11:00 20:00 – 22:00

The indicator of the cost of transferring the load B_{ij} from one stage of SEL to another is expedient to use in the task of coordinating RES generation schedules for the load.

The appearance of sources of decentralized generation in distribution electric networks allows to consider them not as main-radial networks, but as networks with two-way power supply or local electric systems. Since the configuration of the electrical network can be considered relatively constant, using the coefficients of the current distribution matrix, it is possible to determine the consumers whose load schedule will have the greatest impact on the total unevenness of the daily electrical load schedule of the LES caused by the generation of the PV power plant.

The use of such an approach, in the task of equalizing the daily SEL, will allow not only to reduce the unevenness of the latter, but also to reduce the loss of electricity in the LES.

To reduce the unevenness of the total daily REL DEN and minimize losses of active power, it is suggested to adjust the schedule by each node in turn according to the current distribution coefficient. To solve this problem, let's use the classical transport problem (**Table 2.3**), in which it is possible to conditionally allocate m hours in which the actual consumption of the node is greater than the generation of SES, $A_i, \ldots, A_m$, and n hours in which the generation of SPP will prevail over the consumption of the node, $Z_i, \ldots, Z_m$. For this purpose, node capacities are used, refined by multiplying by the current distribution coefficient. The relative cost B_{ij} of power transfer from one-time interval of the schedule to another will be determined by (2.7).

The dependence of the mode of operation of renewable energy sources on natural conditions in most cases leads to the deterioration of the mode of operation of distribution electric networks. Therefore, it is necessary to carry out artificial coordination of load and RES schedules. This is especially true of photovoltaic power plants.

A method based on the application of morphometric analysis of consumption schedules, optimal coefficients of current distribution and transport problem is proposed to solve the problem of equalizing the total schedule of electric power consumption of DEN and reducing electricity losses in distribution electric networks.

The algorithm for matching the generation schedules of the PV power plant and the load of the LES is shown in **Fig. 2.27**. Having information about these schedules and information about the number of consumers in the LES, the initial data for the operation of the algorithm are formed. Taking into account the topology of the electrical network and the value of the load and generation capacities, the matrix of current distribution coefficients is determined for each consumer in relation to the PV power plant. It should be noted that this matrix has the dimension of the number of nodes per the number of branches in the network. To determine the current distribution coefficients of the PV power plant, only the row corresponding to the node in which the plant is installed is selected from the matrix.

To determine the power that can be maneuvered by the consumer, the technological minimum is determined for each consumer. Based on this, the power that can be displaced by the consumer will be equal to the difference between the actual consumption power P_{Hi} and the technological minimum $P_{min\,i}$ and at a certain hour of the load schedule. Next, consumers are ranked according to their current distribution ratio.

The hours in which the actual consumption of the node is less than the generating capacity of the PV power plant are conditionally referred to as "generation" hours. That is, the hours for which consumption capacity will need to be shifted.

The hours in which the load is greater than the generation capacity and the condition $P_{load_{it}} - P_{\min_{it}} > 0$ is fulfilled are the hours from which the power can be transferred. It is this difference that determines the amount of excess power $P_{\sup l_{it}}$ that can be shifted at a certain cost and $P_{def_{it}}$ – the power that is not enough at a certain hour of the day to balance the daily schedule. Taking into account the identified deficit and surplus capacities, a transport matrix of capacity transfer from surplus hours to deficit hours is formed to equalize the daily load schedule. In the event that the total generation power will exceed the power that can be shifted to equalize the electric load schedule, let's introduce an additional fictitious load source $P_{FLS} = \sum_t P_{SEL_{it}} - \sum_t P_{\sup l_{it}}$ (FLS) to obtain a balanced transport problem. In the case when the own generation of the PV power plant is not enough to meet the electricity needs of consumers, let's introduce a conditional source of centralized power.

The solution to the transport problem is a recommendation to shift the schedule of electric loads of consumers, which have the greatest impact on the unevenness of the total load schedule of the LES.

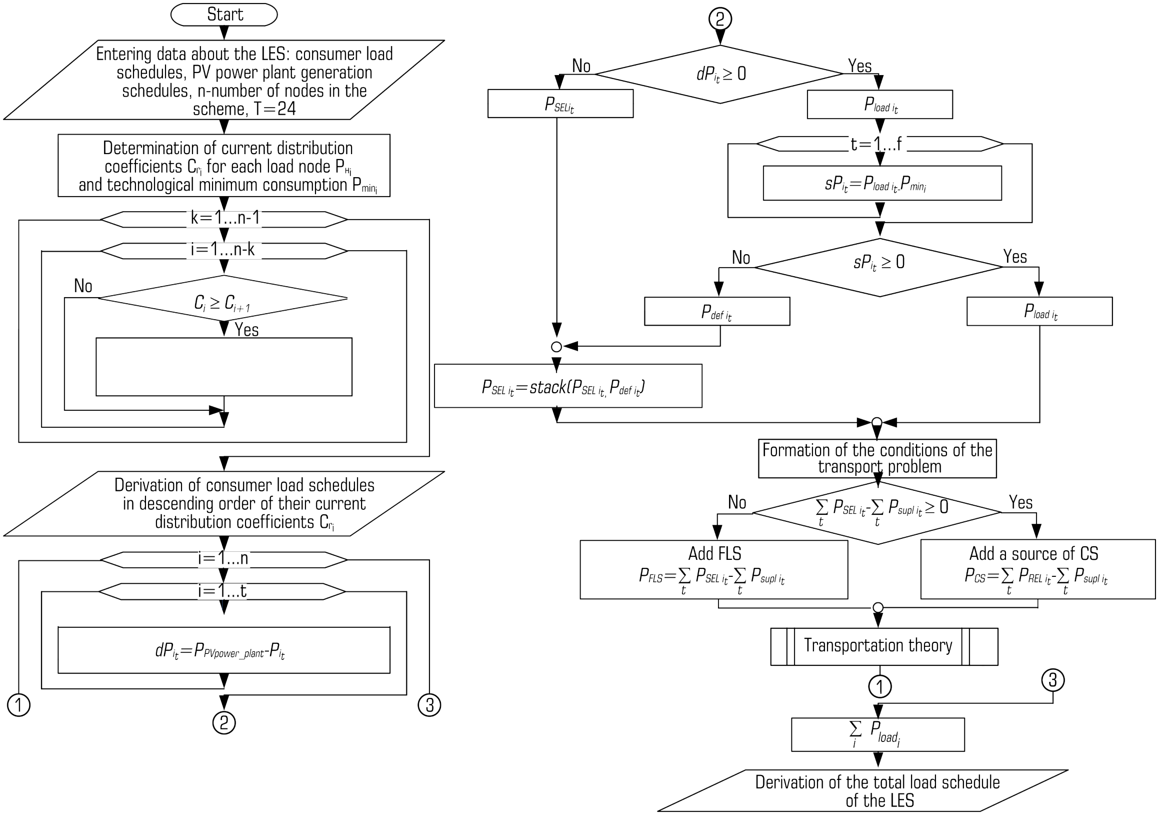


Fig. 2.27 Algorithm of the method of matching the generation schedules of the PV power plant and the electric load of the LES

2.5 RENEWABLE ENERGY SOURCES WITH INVERTER ENERGY CONVERSION DEVICES AS A MEANS OF REGULATING REACTIVE POWER IN THE ELECTRICAL NETWORK

The impact of RES on the quality of electrical energy has an ambiguous result, especially with regard to the non-sinusoidal nature of voltages and currents and voltage deviations [29].

Ensuring the quality of electricity directly depends on ensuring the balance of active and reactive power in the electrical system. As a source of electrical energy, RES is an element capable of influencing the quality of electricity supply. As for the balance of active capacity, the necessity of forecasting the daily schedule of active capacity for a day ahead is foreseen at the legislative level. As for the reactive power balance, since RES such as PV power plant are not its source, we cannot talk about the impact on the balance. However, the technical ability of the inverter to influence the angle between the current and the voltage at its output allows it to influence the flows of reactive power in the electrical network.

Since one of the main elements of a photovoltaic plant is an inverter, we will consider its possible modes. **Fig. 2.28** shows a fragment of an electrical circuit with an inverter with PWM control and a vector diagram for it.

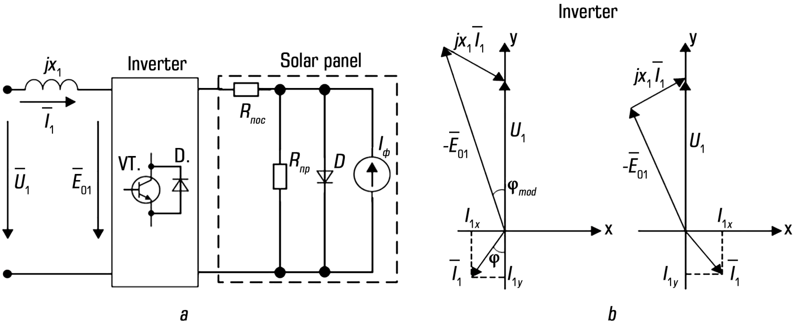


Fig. 2.28 An electrical circuit with an inverter with PWM control: *a* – a fragment of the electrical circuit; *b* – vector diagrams

The equation compiled according to Kirchhoff's second law for the circuit (**Fig. 2.28, *a***) will be written as follows:

$$\overline{U}_1 = \overline{E}_0 + jx_1\overline{I}_1, \tag{2.8}$$

where $\overline{E}_0$, $\overline{U}_1$, $\overline{I}_1$ – the resulting vectors of the EMS at the output of the inverter, the network voltage and current:

$$\overline{E}_0 = \mu U_0 e^{j\varphi_{\text{mod}}}, \tag{2.9}$$

where μ – modulation coefficient, φ_{mod} – the phase of the modulation voltage in relation to the mains voltage.

In the supply network, an increase $\overline{E}_0$ compared to $\overline{U}_1$ leads to an effect corresponding to the appearance of capacitive currents at the point of connection of the PV power plant to the electric network. So, it is possible to say that by changing the opening angle of the thyristors of the inverter, it is possible to achieve different angles between current and voltage, which will cause a change in reactive power flows in the electrical network.

To confirm these conclusions, mathematical modeling was performed in the Simulink Matlab R2015a environment. It is based on the model presented in the Matlab example base (**Fig. 2.29**) – 'power_PVarray_grid_det' [30]. Since this model worked out only one of the possible modes implemented by modern inverters, the model of the inverter control system was improved for the possibility of implementing the active power output mode with a power factor equal to unity. The model also allows maintaining a given value of it other than unity and maintaining a given level of reactive power at the connection point of the PV power plant. In addition, the parameters of the model were changed in accordance with the parameters of the real PV power plant to check the adequacy of the model (data on solar insolation and temperature of solar panels are taken for an average day without precipitation, significant cloudiness and wind).

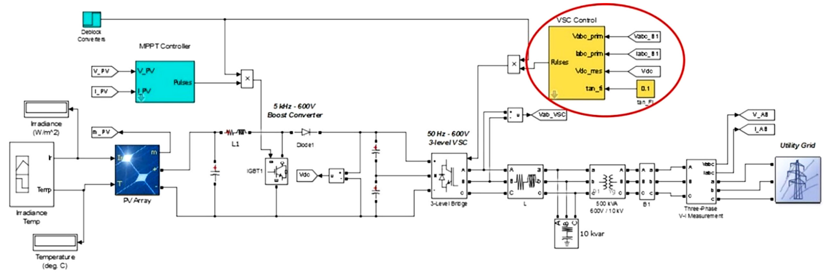


Fig. 2.29 Simulink model with improved inverter control system

Fig. 2.30 shows the results of modeling the graph of active power generation for different reactive power modes. Curve 1 corresponds to the change in the generated active power in the DC network.

Curve 2 corresponds to the graph of active power generation in the alternating current network at the point of connection of the PV power plant to the 10 kV network, in the mode when the inverter is set to $cos\varphi=1$. Curve 3 corresponds to the generated active power at the point of connection of the PV power plant to the 10 kV network in the mode when the inverter is adjusted to maintain the specified voltage level by influencing the reactive power balance. All curves shown in **Fig. 2.30**, obtained under the same conditions.

Therefore, photovoltaic stations have the technical ability to influence the flows of reactive power in the electrical system. Depending on the power and voltage class of the electrical network to which the PV power plant is connected, it is possible to provide different modes of influence on reactive power flows. In **Fig. 2.31** schematically shows the area of possible impacts.

The change in reactive power flows affects the losses of active power in the network, that is, photovoltaic stations can be used to increase the efficiency of electrical systems [31].

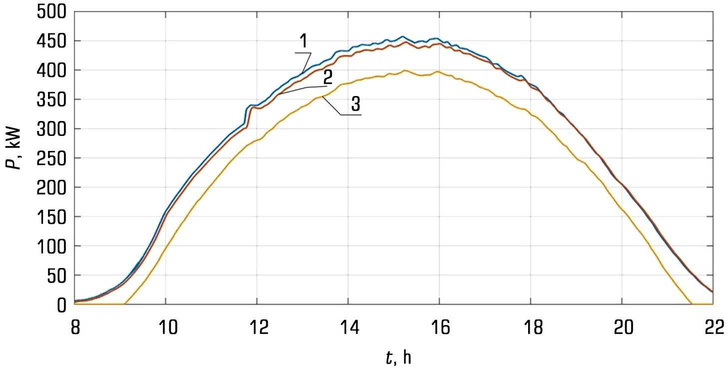


Fig. 2.30 Results of simulation of the active power generation schedule

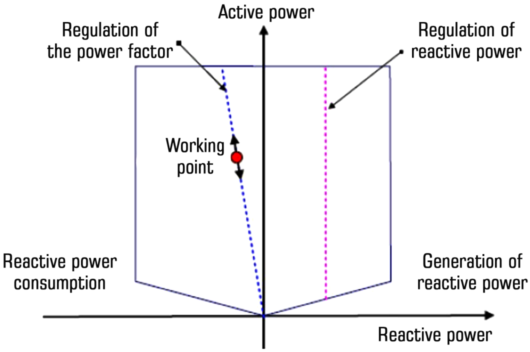


Fig. 2.31 Reactive power regulation function for a photovoltaic station

Therefore, it is possible to draw a conclusion about the technical possibility of using sources of electrical energy such as PV power plant to maintain the necessary level of power supply quality by using inverters in modes that allow influencing the flows of reactive power in the electrical network. As a result, it is possible to influence not only voltage deviations in network nodes, but also their cost-effectiveness.

CONCLUSIONS

Renewable energy sources can be used as a means of improving the quality of electricity supply. However, due to the dependence of their generation mode on natural conditions, it requires the development of methods to determine the conditions for their appropriate development. The results of the conducted research confirm the positive influence of distributed generation sources on the balance reliability of distribution electric networks. However, this positive effect is obtained only if a detailed analysis of the connection point and the power of the electrical energy source is performed. The methods of estimating the probabilistic characteristics of RES proposed in the work allow to improve the methods of determining the value of the installed capacity, which should be connected to a certain point of the electric network. At the same time, the configuration of the network and the features of the connected load, which is fed from it, are taken into account.

Taking into account the possibilities that open up during the development of "smart" networks, a method of coordinating the schedules of RES generation and consumption is proposed. This approach allows obtaining conditions for the effective use of renewable energy sources and improving the quality of electricity supply. This approach is especially effective if electricity storage is provided in the electrical network. In this case, it is possible to regulate not only the schedule of electricity consumption, but also to actively influence the balance of electricity in the electrical network, using the charge/discharge of accumulators. In addition, the use of electrical energy storage systems in networks would allow to reduce the reserve volume in the electric power system.

The availability of inverter equipment on a number of sources of renewable energy expands their use also for regulating reactive power flows in electrical networks. Modeling of different modes of inverters and studies of modes of electrical networks carried out on their basis confirmed the technical feasibility and effectiveness of such use of RES.

CONFLICT OF INTEREST

The authors declare that they have no conflict of interest in relation to this research, whether financial, personal, authorship or otherwise, that could affect the research and its results presented in this paper.

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