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COMPARATIVE ASSESSMENT OF THE ADVANTAGES OF AN INNOVATIVE POWER GRID FOR INDUSTRIAL ENTERPRISES WITH RENEWABLE ENERGY SOURCES

Purpose. Reducing active energy losses at industrial enterprises by improving the efficiency of renewable energy sources integration through the creation of an energy-efficient innovative power grid.

Methodology. The work used methods of system synthesis and computer modeling to calculate active power and voltage losses in power grid components.

Findings. The use of the proposed structure of an innovative power grid for industrial enterprises significantly reduces power losses in workshop grids and unwanted power flows in inter-transformer cable lines, as well as solving the problem of electromagnetic compatibility of the grid's loads.

Originality. The paper proposes a scheme for an energy-efficient innovative power grid for industrial enterprises, according to which consumers and energy sources are connected to the corresponding local AC grids of high-quality and low-quality electricity, as well as a DC grid that combines the two above-mentioned grids into the enterprise's power supply system. The use of this approach significantly reduces the cost of integrating renewable energy sources and solves the problem of electromagnetic compatibility with regard to the elements of the enterprise's power grid.

Practical value. The use of an innovative power grid scheme for industrial enterprises does not lead to additional unwanted power flows in inter-transformer cable lines if renewable energy sources are involved, and also reduces active power losses in workshop grids. The results of a comparative analysis showed that when using the proposed innovative power grid scheme for an industrial enterprise, daily active power losses in its workshops are reduced by more than 40 %.

Keywords: *power grid, power losses, renewable energy sources, power quality*

Literature review. As is well known, unlike traditional electric power engineering, modern sustainable energy engineering [1, 2] involves the use of distributed, energy-efficient, low-capacity power plants and renewable energy sources, including wind and photovoltaic converters [3, 4]. Such units provide local electricity generation, reduce dependence on centralized power grids, and increase the stability of the power system. According to the International Renewable Energy Agency (IRENA), as of 2023, the share of distributed sources in global generation reached 25 %, with their implementation growing by more than 40 % over the past 5 years. Using distributed energy sources greatly simplifies energy transmission and distribution between consumers. However, it also requires significant changes to the power grid's structure [5, 6].

Many works by Ukrainian and foreign authors focus extensively on hybrid energy systems, which combine several energy sources with storage systems. These systems include renewable energy sources (RES) connected to the consumer's general electrical grid. Currently, solar-wind hybrid energy systems are the most common. They use photovoltaic panels and wind turbines to generate electricity, which reduces consumption from the general grid. This combination of renewable sources results from a mismatch in the peak operating periods of the aforementioned systems throughout the day, which allows for more predictable and stable electricity generation volumes. Unlike basic hybrid system models, which consist only of photovoltaic converters, wind turbines, or a combination of both, the addition of energy storage systems allows one not only to accumulate excess electricity during periods of maximum renewable energy generation, but also to supply it to the grid during periods of the day when the cost of electricity is high, and the volume of electricity generated by renewable sources is low.

Using such hybrid energy systems allows industrial enterprises to increase the reliability and consistency of their electricity supply, reduce their environmental impact, and lower their electricity costs.

The main proposal regarding the latter is that power grids should combine so-called local microsystems (individual modules), which are separate control objects [7, 8]. These microsystems are considered as elements of a specific electrical topology and can operate independently from the general power grid [9, 10]. Local microsystems are one of the most promising trends in renewable energy development because they provide energy autonomy and increased reliability of power supply by combining the generation, storage, and distribution of electricity within a single facility.

However, connecting distributed energy sources to industrial enterprise grids has its own peculiarities. Unlike household electricity consumers, industrial enterprises have a relatively stable and predictable consumption profile, so the random nature of energy generation from renewable sources complicates their integration into the enterprises' own power grids. Peaks in renewable energy generation often do not coincide with hours of production activity and, accordingly, maximum electricity consumption by the enterprise. This can lead to grid overload and problems with balancing electricity supply and demand. At the same time, the outdated infrastructure of industrial enterprises' electrical grids limits the possibilities for connecting such distributed energy sources to them.

It is obvious that the power grids of industrial enterprises, which are in fact loads on the general power grids and increasingly include renewable energy sources [11, 12], should also be considered as the aforementioned independent local microsystems [13, 14]. Therefore, they need to be designed based on principles that are completely different from the current ones, which make it possible to eliminate the main negative factors inherent in traditional power grids of industrial enterprises. These include electromagnetic incompatibility of consumers [15, 16] and, of course, poor electricity quality [17, 18]. The authors of works [16, 17] note that the most common type of power quality disturbance when using renewable sources is voltage dips, which account for more than 30 % of all recorded quality deviations. Converters and inverters used in hybrid systems also negatively affect electromagnetic compatibility due to a large number of semiconductor elements in them. In addition, a significant number of international standards, including IEEE standards, specify that renewable energy facilities must continue to operate without being disconnected from the power grid at certain levels of power quality deviations. This can lead to even greater deviations from the standard values and even to a disruption in the stability of the power system. Therefore, in order to prevent emergencies related to the operation of renewable energy sources, transmission system operators impose strict technical requirements for connecting distributed energy sources to existing electrical grids. The paper [15] notes that connecting renewable energy sources to powerful industrial power grids leads to the appearance of higher harmonic components of significant amplitude, as well as interharmonics. Thus, the total harmonic distortion coefficient (THD) of a solar inverter could considerably exceed the limits permitted by the EN 50160:2022 standard "Voltage characteristics of electricity supplied by public electricity networks", reaching 60 % during the day. Such a high level of distortion of the sinusoidal curve is caused by the operation of powerful industrial frequency converters, asymmetrical and rapidly changing loads, etc. It has also been found that the connection of high-power wind turbines has a negative impact on the quality of electricity in the grid due to its unstable generation, which can lead to significant voltage fluctuations and dips, frequency deviations, etc. The results obtained in paper [15] confirm that new approaches to the formation of renewable energy sources are necessary for their integration into the electrical grids of industrial enterprises, and that without this, it is impossible to ensure the necessary quality of electrical energy, reliability of power supply, and efficiency of the entire system.

In study [19], a schematic diagram of such an innovative enterprise power grid with distributed energy sources is proposed, which corresponds to the general characteristics of distributed systems and makes it possible to eliminate the aforementioned negative aspect, which, unfortunately, is currently spreading rapidly. This grid consists of three local components: AC grids of low-quality and high-quality electrical energy and a DC grid. Its structural diagram is shown in Fig. 1.

Consumers and corresponding distributed power sources are connected to each of these components. Thus, electricity consumers whose design features and operating modes allow deviations in power quality from standard values are connected to the so-called low-quality power grid. Wind turbines without quality assurance units are also connected to it. The corresponding electricity consumers and solar panels are connected to the direct current grid. In addition, it interconnects the above mentioned local alternating current grids. The microprocessor control system for such an innovative industrial enterprise grid, based on information about the volume of electricity generated by distributed sources and its consumption, ensures the formation of appropriate control signals, thereby reducing energy overflows in the system.

According to the proposed scheme, the three local grids are connected by only one rectifier and DC/AC converter, which also have low electrical power. From these and all available distributed generation sources, information on the amount of energy generated, accumulated in energy storage systems, and its flows from one local network to another is sent to the microprocessor control system (MCS). The MCS generates appropriate control signals for the grid, ensuring that it operates in a mode that meets the criteria specified in each particular case.

Purpose. The purpose of this study is to reduce active energy losses at industrial enterprises by improving the efficiency of renewable energy sources integration through the creation of an energy-efficient innovative power grid.

Results. In order to assess the advantages of the proposed innovative power grid of an industrial enterprise over the traditional one, let us consider this issue using the example of a certain enterprise in the Zaporizhzhia region, the current schematic diagram of which is shown in Fig. 2.

The enterprise is powered by the main 150/10 kV step-down substation. The distribution grid is made of cross-linked polyethylene (XPLE) cables containing

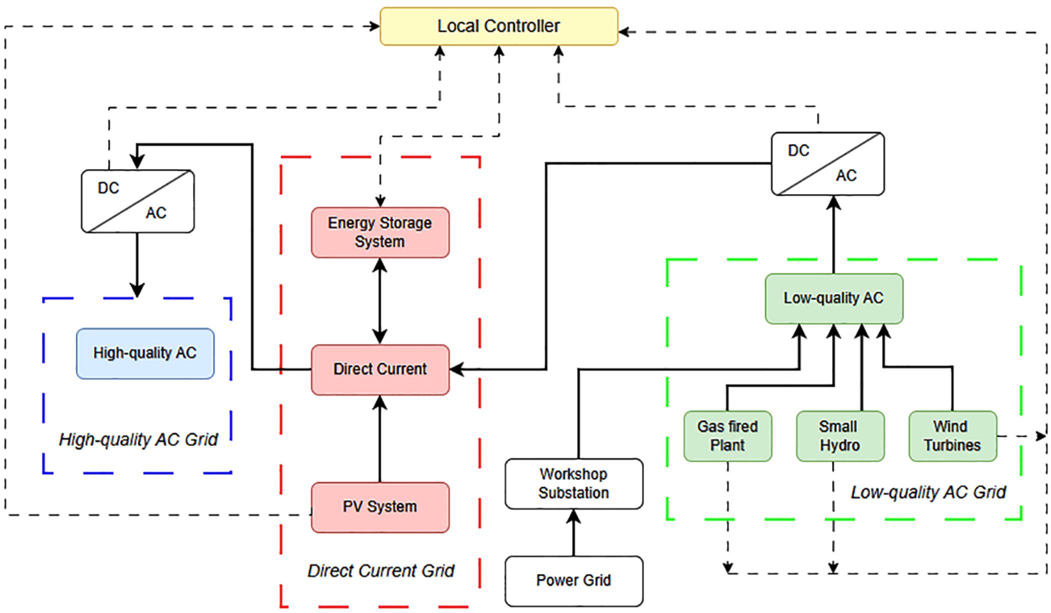

Fig. 1. Schematic structure of an innovative power grid for an industrial enterprise with distributed generation sources

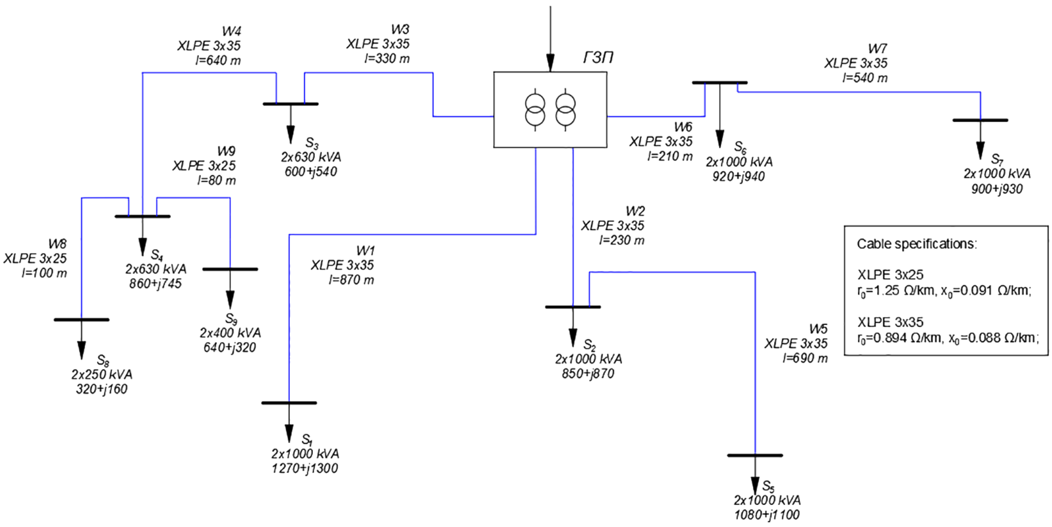

Fig. 2. Schematic diagram of the electrical grid of the enterprise under study

aluminum current-carrying conductors with a cross-section of 25 and 35 mm^2 and contains 9 integral unit transformer substations, from which nine of its workshops receive power. The complex power ratings of the above mentioned are as follows, kVA

$$\underline{S}_1 = 1270 + j390; \quad \underline{S}_6 = 920 + j280;$$
$$\underline{S}_2 = 850 + j260; \quad \underline{S}_7 = 900 + j280;$$
$$\underline{S}_3 = 600 + j160; \quad \underline{S}_8 = 320 + j80;$$
$$\underline{S}_4 = 860 + j220; \quad \underline{S}_9 = 640 + j120.$$
$$\underline{S}_5 = 1080 + j330;$$

Therefore, the total active power of the enterprise is 7,440 kW, and the reactive power is 2,120 kVAr.

The calculation of the operating modes of the above-mentioned power grid was performed on a simulation model shown in Fig. 3, and its results regarding active power losses in cable lines connecting workshop transformer substations are presented in Table 1.

The developed simulation model allows one to study steady the states of the internal electrical grid and determine the voltage values on the busbars of workshop substations, the distribution of active and reactive powers in inter-transformer cable lines both with and without renewable energy sources.

The total active power losses in the 10 kV cable lines of the enterprise's electrical grid equal 122.15 kW, which is 1.58 % of the total consumer load. Obviously, these losses will be significantly higher in the 0.4 kV distribution grid.

Consider the calculation of power losses in cable lines using the example of a metal processing workshop (BUS_8). As for electricity consumers, there are both AC and DC consumers in this workshop. The latter include electroplating units used for applying coatings to ready-made products by electrochemical methods. The above-mentioned units are powered by individual AC rectifiers. The installed power of all DC consumers is 23 % of the total.

The workshop's electrical energy receivers are connected by radial cable lines to six power units. These

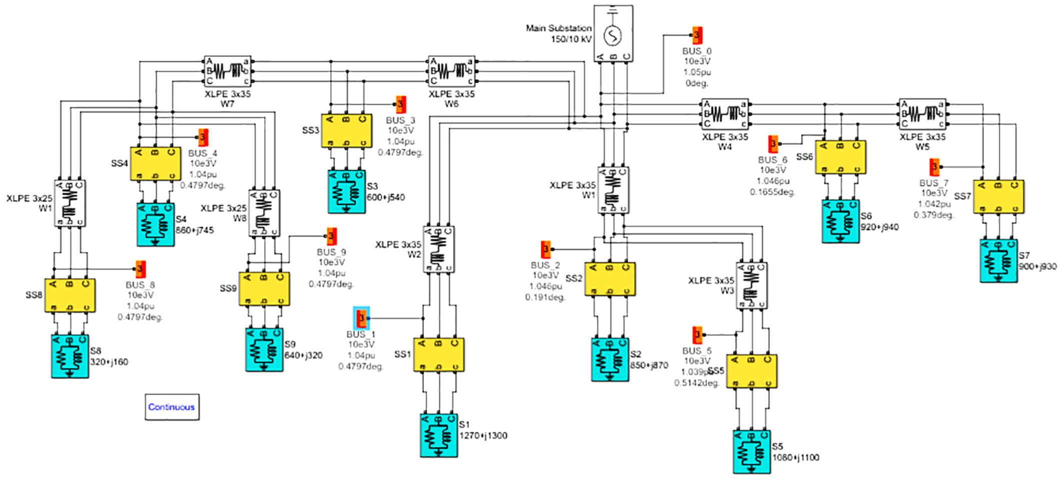

Fig. 3. Simulation model for calculating steady states of a traditional enterprise electrical grid

Table 1

Distribution and losses of active power in the enterprise's power grid

No.	Branch	Active power		Losses ΔP, kW
		Pbegin, kW	Pend, kW	
1	Main Substation – BUS_1	1,293.63	1,269.86	23.77
2	Main Substation – BUS_2	1,957.79	1,943.39	14.40
3	Main Substation – BUS_3	2,470.99	2,446.27	24.72
4	Main Substation – BUS_6	1,839.01	1,827.29	11.72
5	BUS_6 – BUS_7	907.38	899.93	7.45
6	BUS_2 – BUS_5	1,093.49	1,079.91	13.58
7	BUS_3 – BUS_4	1,846.36	1,820.48	25.88
8	BUS_4 – BUS_8	320.13	319.98	0.15
9	BUS_4 – BUS_9	640.43	639.95	0.48
Total		–		122.15

units are connected to the linear cabinets of the workshop's integral transformer substation. The following formulas are used to calculate active power losses in the cable lines of the workshop's electrical grid

$$\Delta P^M_{(n-1)n} = I^2_{(n-1)n} \cdot R_{(n-1)n};$$
$$\Delta P^M_{(n-2)(n-1)} = I^2_{(n-2)(n-1)} \cdot R_{(n-2)(n-1)};$$
$$\Delta P^M_{(n-3)(n-2)} = I^2_{(n-3)(n-2)} \cdot R_{(n-3)(n-2)};$$
$$\ldots$$
$$\Delta P^M_1 = I^2_1 \cdot R_1,$$

where $\Delta P^M_{(n-1)n}$ is active power losses in the cable line on the section $(n-1)-n$, kW; $I_{(n-1)n}$ is current in the cable line in the section $(n-1)-n$, A; $R_{(n-1)n}$ is resistance of the cable line in the section $(n-1)-n$, Ohm.

In this case, changes in the operation (electricity consumption) of each consumer during the day are taken into account. The results of the calculation of hourly losses in the BUS_8 workshop for the current power grid are presented in Table 2. According to these data, the total daily losses of active power in the workshop's cable lines equal 1,675.97 kW, which is 15.65 % of its total power. Based on the above-mentioned expressions, the calculation of active power losses in the electrical grid of the workshop during a day is carried out at one-hour intervals. Thus, over this time interval, they are numerically equal to the active energy losses, which amount to 1,675.97 kWh per day. Active energy losses will be indicated in further calculations.

As for the possibilities of using renewable energy sources in the BUS_8 workshop grid, only its roof can be equipped with, for example, Vertex Bificial TSM-DEG18MC.20(II) solar panels with a total capacity of 500 kW. These panels will be connected to the 0.4 kV busbars of the workshop transformer substation via an inverter. In addition, there is a possibility of installing 20 Euro Wind 10 wind turbines with a total installed capacity of 200 kW on the territory near the workshop.

The amount of electricity that solar panels can generate per hour is calculated using the following formula

$$W_h = E \cdot S \cdot N_{solar} \cdot P_{rated} \cdot \eta_{solar} \cdot \eta_{temp}/1{,}000,$$

where W_h is the amount of electricity generated by solar panels, kWh; E is hourly value of solar insolation, kWh/m^2; S is solar panel area, m^2; N_{solar} is the number of panels, pcs; P_{rated} is rated power of the solar panel, kW; h_{solar} is the panel efficiency coefficient; h_{temp} is the thermal coefficient of a solar panel takes into account the reduction in efficiency that occurs during heating.

In this case, the hourly value of solar insolation E can be obtained from the Photovoltaic Geographical Information System (PVGIS).

The hourly volumes of possible electricity generation by the specified RES are shown in Table 3, which, together with the total active electricity consumption of the workshop, are illustrated in Fig. 4.

As shown in Fig. 4, between 5:00 a.m. and 12:00 p.m., the total amount of electricity generated by solar panels and wind turbines significantly exceeds the amount of active energy consumed by the metal processing workshop. Excess electricity circulating in the inter-shop grid of the enterprise will create unwanted energy overflows, leading to additional energy losses. While these losses will not be as significant as those

Table 2

Hourly losses of active power in the workshop power grid's cable lines

Time, hour	1	2	3	4	5	6	7	8
ΔP, kW	21.55	21.55	21.55	21.55	21.55	21.55	93.75	89.99
Time, hour	9	10	11	12	13	14	15	16
ΔP, kW	90.45	98.86	94.87	78.95	88.35	96.36	81.13	89.04
Time, hour	17	18	19	20	21	22	23	24
ΔP, kW	84.5	89.08	107.96	86.19	77.12	102.78	37.87	37.87

Table 3

Hourly volume of electricity generation from renewable energy sources

Time, hour	1	2	3	4	5	6	7	8
Solar, kWh	0	0	0	0	51.95	138.08	248.69	338.87
Wind, kWh	48	50	51	60	62	70	112	200
Time, hour	9	10	11	12	13	14	15	16
Solar, kWh	396.03	421.38	419.15	360.42	327.37	206.44	78.14	24.85
Wind, kWh	240	244	244	246	246	244	235	220
Time, hour	17	18	19	20	21	22	23	24
Solar, kWh	0	0	0	0	0	0	0	0
Wind, kWh	190	120	113	90	76	66	62	62

directly in the workshop grid, they will remain unchanged in the case of RES and traditional connection schemes.

Finally, let us consider the power losses in the workshop's electrical grid if its structure corresponds to the innovative electrical grid proposed in Fig. 1. In this case, the grid should look like the one in Fig. 5. This requires grouping consumers and distributed energy sources appropriately.

In this case, wind turbines must be connected to the low-quality power grid, but without quality control units and consumers that can operate at any deviation of electricity quality indicators from the standard values. Solar panels, energy storage devices, existing DC consumers, and frequency-controlled AC motors are connected to the DC grid.

To ensure the operation of these motors, it will be sufficient to use DC-AC converters instead of AC-DC-AC converters, which reduces the number of power electronics devices in the grid and, accordingly, reduces its cost. Additionally, the direct current grid connects the aforementioned alternating current grids, thereby eliminating unwanted interference between consumers due to their electromagnetic incompatibility regarding electricity quality.

In accordance with the structure of the innovative electrical grid of the workshop, electricity generated by renewable sources is consumed in the specified local grids, and its surplus is directed to the storage system. During hours of minimal renewable energy sources activity, the latter transfers the stored energy to the direct current grid and, through a converter, to the high-qual-

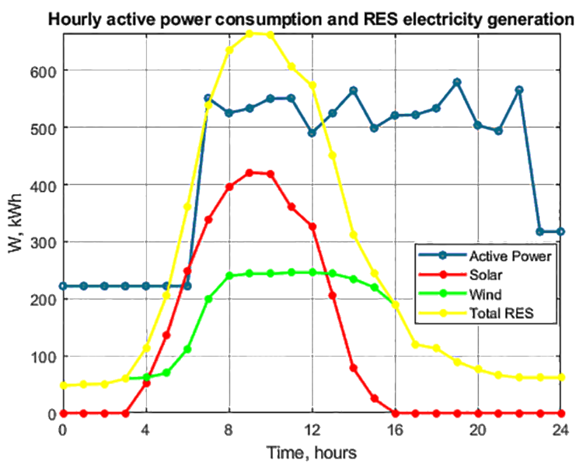

Fig. 4. Active electricity consumption by the BUS_8 workshop and generated by solar panels and wind turbines (according to PVGIS data as of April 17, 2023)

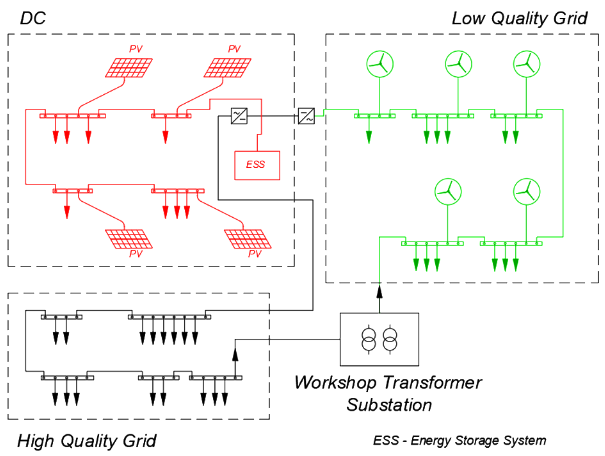

Fig. 5. Structure of the proposed innovative power grid for a metal processing workshop with renewable energy sources

ity electricity grid. Only the portion of electricity that cannot be provided by distributed energy sources is consumed from the general power grid. This approach to forming a workshop grid eliminates unwanted bidirectional energy overflows that arise due to the mismatch between consumption and renewable energy sources generation, and also increases the efficiency of their use.

The necessary calculations for the innovative power grid described above were performed using the algorithmic model proposed in paper [20], which takes the form of interconnected components corresponding to the following sequence of calculations for the specified grids: high-quality alternating current, direct current, and then low-quality electricity connected to the workshop transformer substation. The results of calculations of hourly active power losses in the cable lines of such an innovative electrical grid of the workshop are presented in Table 4, and Fig. 6 shows their comparison with active power losses in the basic distribution grid of the workshop (Table 2).

According to the calculations, when using the proposed innovative scheme for forming the power grid of an industrial enterprise, the daily losses of active energy in the metal processing shop will amount to 899.29 kWh. This is 46.34 % less than with the existing scheme. At the same time, the losses mentioned above will account for only 8.40 % of the total daily electricity consumption of the workshop. As for other workshops, active power losses in them are also reduced by more than 40 %.

Clearly, the energy efficiency of the proposed innovative power grid can be significantly increased by solving the optimization problem of where to connect consumers and energy sources, as well as where to lay cables and what their cross-sections should be. Formulating and solving such a problem is a separate issue that we are currently considering.

Conclusions. The calculations performed regarding the efficiency of the traditional power grid of an industrial enterprise and the grid designed according to the proposed innovative principle indicate the following:

1. In a traditional power grid, electricity losses in internal workshop distribution cable lines connected to their own transformer substations account for about 60 % of total losses and are several times higher than in an intra-plant grid.

2. Using renewable energy sources at industrial enterprises that are connected to the nearest transformer substations does not affect electricity loss volumes in workshop power grids. However, it can significantly increase loss volumes in inter-workshop cable lines due to additional energy overflows.

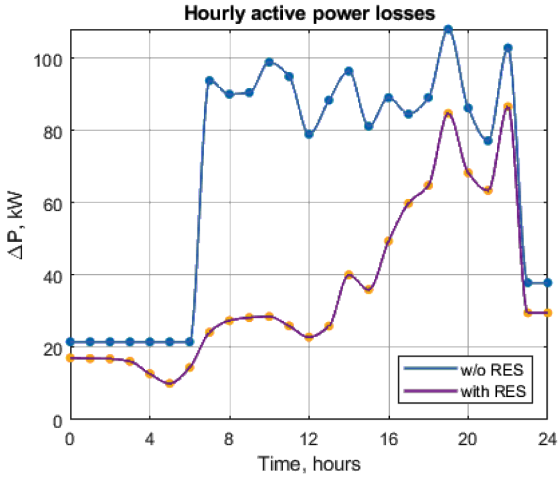

Fig. 6. Hourly active power losses in the basic distribution grid of the workshop and in the energy-efficient one

3. A large number of power converters ensure the electromagnetic compatibility of renewable energy sources with the traditional power grid of an industrial enterprise. However, this significantly deteriorates the quality of the electricity.

4. According to the innovative power grid scheme of an industrial enterprise, consumers and energy sources are connected directly to the corresponding local components (high-quality and low-quality electricity, as well as to the direct current grid) without additional converters, which significantly reduces the cost of integrating renewable energy sources and solves the problem of electromagnetic compatibility with regard to the loads of the grid itself.

5. The use of an innovative electrical grid scheme for industrial enterprises does not lead to additional unwanted electricity overflows in inter-transformer cable lines and, moreover, significantly (by more than 40 %) reduces losses in workshop electrical grids.

6. A study of the effectiveness of a real enterprise's innovative power grid compared to the existing one shows the considerable benefits of the first one and the feasibility of implementing such networks at other industrial enterprises.

7. It is obvious that in order to significantly improve the energy efficiency of the proposed innovative power grid of an industrial enterprise, its design must be carried out as a solution to the optimization problem regarding the most acceptable locations for connecting energy sources, consumers, and energy storage devices to it, as well as the routes for laying cable lines and wire cross-sections.

Table 4

Active power losses in the cable lines of the workshop's innovative power grid

Time, hour	1	2	3	4	5	6	7	8
DP, kW	17.09	16.93	16.85	16.15	12.73	10.04	14.45	24.18
Time, hour	9	10	11	12	13	14	15	16
DP, kW	27.39	28.22	28.53	25.96	22.83	25.90	40.04	35.98
Time, hour	17	18	19	20	21	22	23	24
DP, kW	49.40	59.83	64.78	84.67	68.27	63.41	86.55	29.55

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Порівняльна оцінка переваг інноваційної електромережі промислового підприємства з відновлюваними джерелами енергії

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Мета. Зменшення втрат активної енергії на промисловому підприємстві завдяки підвищенню ефективності інтеграції відновлюваних джерел шляхом створення енергоефективної інноваційної електромережі.

Методика. У роботі використовувалися методи синтезу систем, комп'ютерного моделювання під час розрахунку втрат активної потужності й напруги в елементах електричної мережі.

Результати. Використання запропонованої структури інноваційної електричної мережі промислового підприємства дозволяє суттєво зменшити втрати електроенергії у цехових мережах, небажані її перетоки у міжтрансформаторних кабельних лініях, а також вирішує проблему електромагнітної сумісності навантажень самої мережі.

Наукова новизна. У роботі запропонована схема енергоефективної інноваційної електромережі промислового підприємства згідно з якою споживачі та джерела енергії приєднуються до відповідних локальних мереж змінного струму якісної й неякісної електроенергії, а також мережі постійного струму, яка об'єднує дві вищезазначені в систему електропостачання підприємства. Використання такого підходу суттєво зменшує вартість інтеграції відновлюваних джерел енергії та вирішує проблему електромагнітної сумісності елементів електричної мережі підприємства.

Практична значимість. Використання інноваційної схеми електромережі промислового підприємства не призводить до додаткових небажаних перетоків електроенергії в міжтрансформаторних кабельних лініях при наявності відновлюваних джерел енергії, а також зменшує втрати активної енергії у цехових мережах. За результатами проведеного порівняльного аналізу встановлено, що при використанні запропонованої інноваційної схеми електромережі промислового підприємства добові втрати активної потужності в його цехах зменшуються більше, ніж на 40 %.

Ключові слова: *електрична мережа, втрати потужності, відновлювані джерела енергії, якість електроенергії*

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