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Worn Power Transformers Influence on the Rural Electrical Networks Electrical Supply Reliability

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Abstract
The energy supply of agricultural enterprises is characterized by a number of significant problems, the solution of which has been an urgent task for several decades. Characteristic problems are widely known and considered in the scientific and educational literature: the location of agricultural objects on a large territory, their remoteness from central substations, remoteness from the road network, which makes it difficult for emergency teams to access in case of accidents, a high degree of operation of substation equipment and air lines At the same time, the re-equipment of the park of technological equipment of agricultural enterprises makes it necessary to look at the quality of energy supply in a new way – the microprocessor technology used in modern agricultural production makes high demands on the reliability of energy supply. Also, the issue related to emergency modes in the energy supply system, which lead to millions of losses due to product spoilage due to the termination of the technological process, does not lose its relevance. As you know, the energy supply system should be a model of high reliability, but upon inspection, the situation looks a little different: due to various reasons (including both the power deficit and the wear and tear of the equipment in use), the energy supply does not always meet the expectations of consumers in terms of the quality of the services provided. In the case of interruptions in the energy supply of enterprises (including agricultural ones), interruptions in the energy supply cause much more serious consequences, related to spoilage and underproduction of products and millions of losses.

INTRODUCTION

During the operation of transformers, the normal mode of operation of the equipment must be maintained, in which its parameters do not deviate from the nominal ones more than is acceptable [1]. Ensuring reliable energy supply and the quality of electric energy is the goal of the operational and dispatching management system in the electric power industry, and the unified national electric grid ensures a stable supply of electricity to consumers technologically connected to electric grids [2–5]. However, co-existing technical problems call for in-depth study of other aspects: the development and implementation of methods for equipment diagnostics and forecasting of its performance, organization of new forms of maintenance and repairs of worn-out power equipment, automation and informatization of management processes, redistribution of investment volumes are required [6]. The conditions of modern management in the power industry are characterized by a number of factors, the combination of which increases the risks of emergency modes in the power supply network [7–9]:

- a high percentage of worn-out equipment in operation;
- transition from scheduled and preventive maintenance of equipment to maintenance according to the current state;
- low qualification of service personnel performing equipment maintenance and repair.

Thus, the following picture emerges: inspection and maintenance of worn equipment is carried out by low-skilled personnel without conducting regular preventive inspections and scheduled preventive repairs [10]. For the timely prevention of emergency modes in power supply networks, a system of remote monitoring of the working state of the network is implemented, but this measure is characteristic, first of all, for transformer substations of class 35/10 kV and above. Substations 6(10)/0.4 kV are not subject to remote monitoring and are serviced upon occurrence

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of emergency mode. The situation is also aggravated by the fact that the equipment of substations is characterized by a high degree of wear and tear: wear of the active part of transformers is 88%, of switching equipment – 85%. Accordingly, the wear and tear tends to increase every year, which means that the situation will get worse every year [11–14].

In this study, it is proposed to give a theoretical justification for the method of increasing the reliability of transformer substations of rural electric networks without making revolutionary changes in the regulations of the electric power industry.

The purpose of the study is to increase the comprehensive indicator of the reliability of the equipment, which is operated beyond the normative period, of the transformer substation (TS) of rural electric networks by optimizing the periodicity of its technical service and controlling the factors that contribute to the development of internal defects.

EXISTING FORMS OF ELECTRICAL EQUIPMENT TS 6–10/0.4 KV TECHNICAL MAINTENANCE AND REPAIR

District transformer substations are mainly used for power supply of agro-industrial districts and their agro-industrial complexes, which provide a reduction of the network voltage from 35–110 kV to 6(10) kV. Such transformer substations are one of the main structures of electrical network enterprises. At this time, a large number of substations with a voltage of 35–110/6(10) kV are operating in distribution networks. Direct power supply of agricultural objects is carried out from 6(10)/0.4 kV substations – they account for 98% of all substations under operational control [15–17].

Most of the large objects of industry and power industry, power stations and substations were put into operation in the 1960s and early 1980s with a service life of 25 to 30 years. Predominant forecasts assumed a constant increase in the load and the replacement of electrical equipment (EE) at the end of their service life with technically and technologically modern designs. As a result of the reduction in funding, the number of new construction objects has sharply decreased, and the number of preserved and temporarily suspended construction has increased. This was accompanied by an even sharper reduction in the introduction of new capacity in the future [18].

The low rates of dismantling and write-off of production fixed assets are several times behind the normative rates of disposal of energy equipment due to wear and tear. That is why the share of fully self-contained, but in operation production fixed assets (PFA) is constantly growing. At low rates of real disposal of worn-out equipment, it will take tens of years for the equipment that has been decommissioned to date to be decommissioned [19–20].

At this time, a large amount of worn-out equipment is in operation in the energy system, that is, equipment whose service life exceeds 1.5–2 times the standard service life. Including, the share of power transformers whose service life exceeds 25 years is 40% of the total number of operated power transformers. Worn-out electrical equipment should be understood as electrical equipment in a working condition, some parameters of which are close to the maximum values in accordance with regulatory and technical and design documentation or the level of scientific and technical development, while in the case of the production of a temporary resource, depreciation deductions are no longer accrued [21].

One of the factors that negatively affect the functioning of transformer substation equipment is overheating, which can be caused by increased load, problems in the transformer cooling system, and environmental conditions. Increased heating of electrical equipment is much more dangerous than overheating of contact connections due to the fact that the further development of a defect in electrical equipment is practically impossible to predict, and failure to take timely measures will lead to damage to the equipment and further development of a technological violation. The effect of overheating, accordingly, is increased by the fact of using worn-out equipment prone to the occurrence of hidden failures [22–24].

The use of worn-out power equipment is associated with many characteristic risk factors:

- a worn EE may have worse technical and economic indicators compared to a new EE;
- worn EE is characterized by specific types of damage, increased speed of development of emerging damage, high sensitivity to wear factors;
- the proportion of irreversible changes in a worn-out EE increases, the risk of continued trouble-free operation increases, the weight of the consequences of damage increases.

During the operation of worn out electrical equipment, a large number of new interdependent indicators must be taken into account, more deep systemic connections of the modes of subsystems of the electric power complex and the production technological process are manifested.

However, the existing forms of maintenance and repair of electrical equipment of TS 6–10/0.4 kV show that wear and aging of parts, elements and subsystems of the electric power complex lead to changes in their parameters and technical condition, failures and accidents occur, leading to downtime of the main production unit, working conditions at the enterprise deteriorate, labor productivity decreases.

Regulated maintenance is carried out according to the schedules established in the operational documentation with a frequency not exceeding the frequency of current repairs. According to the method of organization, it is a system of the planned-preventive type, the essence of which is that after the expiration of a certain working time, at the moment of expected failure, different types of impact are produced: ongoing maintenance or major repairs. The regulatory and informational base is the annual schedule of technical maintenance and repair of equipment.

Planned maintenance as an independent operation is intended only for certain types of energy equipment and networks with relatively high labor intensity. During maintenance, the technical condition of the EE is checked [25].

Scheduled technical inspections of energy equipment, conducted by engineering and technical personnel of energy services, are part of regulated maintenance.

The goals of scheduled technical reviews are:

a) checking the completeness and quality of operations performed by operational and repair and maintenance personnel for maintenance of energy equipment;
b) detection of malfunctions that can lead to breakdown or emergency failure of the EE;
c) establishing the technical condition of the most responsible parts and assemblies of machines and clarifying the scope and type of future repairs.

The maintenance system of planned preventive repair (PPR) of the EE is based on the theory and practice of repair and restoration of the PFA. However, norms and regulations are primarily focused on the organization of maintenance. General disadvantages of technical operation and repair (TOR) PPR are [15, 21-23]:

- redundancy of performed repair works;
- the coverage of part of the life cycle of the EE – TOR PPR does not apply to equipment beyond the terms of depreciation deductions;
- the norms do not take into account the actual mode of operation of the EE;
- issues of organization of operation of the EE are not considered, although the maintenance of the PPR is a part of the operation.

The formed maintenance and repair system of the EE of energy enterprises provides for periodic maintenance and repair, which is not always the optimal measure. Disconnection for prevention and planned repairs of a serviceable EE leads to unjustified costs. In the interval between PPR, hidden and developing defects are not detected and lead to the need for more expensive and long-term emergency repairs, although it is believed that with proper performance of PPR maintenance, there should be no accidents. A more rational system is the maintenance of the condition of the electrical equipment (TOR EES). This is a planned type of repair, the duration and necessary volume of work of which is determined by the function of the detected defects. For the organization of such maintenance, means are needed to assess the condition of the object at the moment, to trace the change in the condition recently and to predict its possibility of functioning in the near future. The transition to TOR EES is associated with the use of new diagnostic parameters, a new technique for obtaining them and subsequent analysis. To organize such a service, technical means of monitoring, diagnosing and forecasting the state of the EE are necessary. The conducted analysis leads to the consideration of two ways (see Fig. 1), ultimately solving the general problem [18, 19–22]. Thus, in modern economic conditions and from the point of view of the rational use of resources, energy supply companies switch to the EES maintenance system, which involves the collection of up-to-date diagnostic information about the functionality of the equipment and decision-making about the need for repair and reconstruction works.

Thus, the need to identify the necessary diagnostic signs that can be adequately assessed by the onsite operative team for further decision-making on equipment repair and the formation of a qualified repair team with the necessary tools becomes particularly relevant.

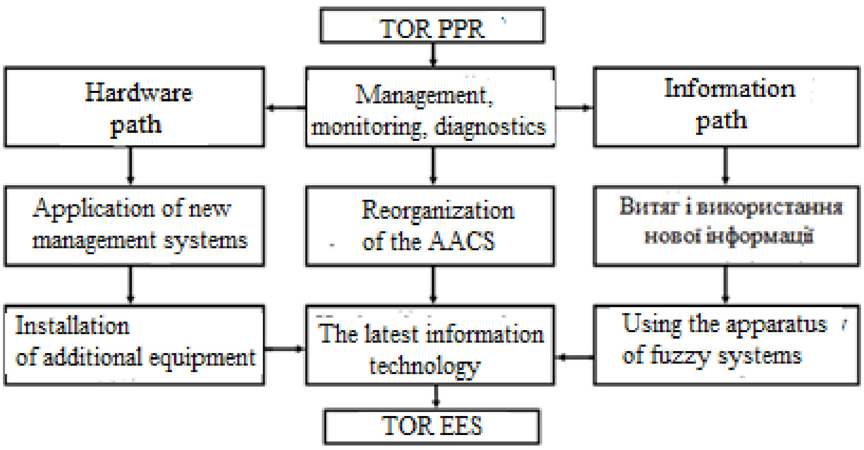

Figure 1. Ways to improve the TOR EE system

TS 10/0.4 KV ELECTRICAL EQUIPMENT TECHNICAL DIAGNOSTICS AND MONITORING

To date, 21 types of tests and controls are considered official for power transformers, starting with the chromatographic analysis of gases dissolved in oil and ending with the test of transformers by turning on the nominal voltage. A fairly high percentage of injuries (about 25%) are associated with incorrect actions of personnel [1, 3]. First of all, it is unsatisfactory operation of the transformer and poor repair. Carrying out repair work on worn out transformers by standard methods without proper diagnosis and refinement of the technology of restoration of characteristics, most often turns out to be not just a waste of money, but even a harmful procedure, which leads to a decrease in the reliability of the transformer.

However, the main task of monitoring should be considered the assessment of the technical condition of transformers.

Monitoring systems have proven their effectiveness, however, unfortunately, they have not found their application at 6(10)/0.4 kV substations due to various reasons, one of the main ones being the impracticality of investments in worn-out equipment of rural substations.

At this time, a significant number of types of monitoring systems have been developed, monitoring systems of foreign production (such as FARADAY MEDIC by GE Energy, the monitoring system by Sterling Group, etc.) are reliable, but their cost is significant, and they are mainly designed for power transformers with a voltage class of 330 kV and above.

Abroad, power transformer monitoring systems are quite widespread because they prevent up to 95% of electrical equipment failures. The calculation of the probability P of an approaching failure is determined by the Eq.:

$$P_{refusal} = f\sum(r_n \cdot d_n), \quad (1)$$

where f is the intensity of failures of electrical equipment per year, r_n is the risk of failure for each part, d_n is the degree of defect detection in each part.

Knowing the impending failure probability, the savings from failure prevention can be calculated by multiplying this parameter by the E_{mul} failure costs, which are calculated as half the cost of a new transformer C_{nt}. Thus, the annual savings will be:

$$S = P_{refusal} \cdot E_{mul} = P_{refusal} \cdot 0.5 \cdot C_{nt}. \quad (2)$$

It is possible to use this Eq. in the case when statistical data on the risks of failures of structural parts of transformers r_n and on the degree of detection of defects of structural parts of transformers d_n have already been collected, which should be the case, for example, in Germany. The level of confidence probability of calculations based on the above formulas depends on the amount of statistical data on each type of equipment and on the conditions of its operation (including climatic conditions, load level, wear and tear, number of major repairs, etc.). Reliability of power transformers is achieved only by observing all rules for handling the transformer. In the case of any deviations or violations of the rules of operation, as well as the technological discipline of the production of transformers at the manufacturing plant or violations of the current rules for the installation and transportation of transformers, their abnormal operation first occurs, and then, if measures are not taken to identify and eliminate the causes, the transformers fail and they can be restored only by means of repair [15–21]. Violation of cooling, wetting of oil and insulation, aging of oil, improper filling of oil that allows air to enter, violation of transportation rules – these are some of the many possible defects that can cause a transformer to fail due to operation. It should also be borne in mind that transformers of I-II dimensions work mainly at substations without maintenance personnel, their operation consists in periodic inspections and preventive measures; the reliability of these transformers largely depends on the qualifications of people who monitor their condition.

In Table 1 shown averaged data containing the most common causes of damage to size I-II transformers and the percentage ratio of each of the causes of the total number of damages. The weakest nodes that are often damaged, regardless of the source of these injuries, according to statistical data, are given in Table 2.

During the period of operation of the transformer for 12–25 years, the following damages occurred:

- damage to the windings of lower voltage during sharply changing loads of the arc electric furnaces of the plant;
- damage due to wetting and contamination of the insulation of the windings;
- moistening of the Bakelite insulation of the tap-changer contactor;
- damage to non-hermetic inputs due to the internal insulation moisture and contamination;
- overlapping of the oil channel of sealed inputs on the lower porcelain cover inner surface.

Table 1. Causes of damage to transformers, %

Causes of damage	The number of damages
Factory defects	50
Defects of operation	13
Poor repair or installation	10
Lightning surges	5.5
Aging of insulation	3.5
Other defects	18
In total	100

Table 2. The most frequently transformers damaged nodes

Damaged node	Share of total quantity, %
Interphase isolation	4.5
Windings and insulation (due to dynamic forces)	15.5
Interturn insulation	22
Branch switches	13
Steel of the active part	2
Introduction	18
Withdrawal	2
Current-carrying parts	7
Tank	7
Radiator	2
Other	7
In total	100

The assessment of the condition of the equipment is mainly carried out in working conditions, especially in extreme conditions regarding load, temperature, and voltage. This methodology does not necessarily require information about previous characteristics, but it does require an understanding of the design of the equipment and the availability of information about previous critical modes. Structural analysis is the first diagnostic procedure.

ANALYSIS OF DIAGNOSTIC FACTORS

Modern studies offer a large number of methods for diagnosing the state of power transformers with the involvement of modern diagnostic equipment [1, 7, 13, 22, 25] in addition to measures provided for by industry regulations.

As a rule, these methods require the availability of highly qualified personnel capable of handling high-precision diagnostic equipment, which is currently a problem in the industry due to the peculiarities of financial policy. However, the existing studies do not solve all the existing problems, caused mainly by the lack of investment for the global replacement of the equipment of transformer substations that provide energy to agricultural facilities. A high percentage of the use of equipment that is beyond the limit of the operational term does not give an adequate idea of the actual working resource of substation equipment [23]. Worn-out equipment requires the implementation of special methods of extending its working life, which requires the presence of highly qualified personnel to monitor the working condition. At the same time, 6-10/0.4 kV transformer substations are not equipped with remote monitoring systems due to the high cost of the latter for installing them on worn equipment, which is characterized by a large flow of obvious failures (specific damage of worn power transformers is 1%, and new ones – 0.2% [25]).

Thus, a problematic situation has arisen: which consists in the lack of permanent investments and an adequate approach to predicting the development of hidden failures in the TS equipment of rural electric networks, which is operated beyond the regulatory period, in the presence of modern scientific developments and high-precision diagnostic equipment.

Most of the problems of supporting the functioning of the worn-out EE are informational in nature and have the following characteristics:

- the presence of uncertainty in the source information, the narrowness of the traditional mathematical apparatus for describing uncertain and qualitative informal situations;
- the limitation of the "human factor" in extraordinary critical conditions, when it is necessary to quickly obtain an intellectual solution;
- the complexity of synthesizing optimal solutions based on unclear information, the need to operate with a large volume of data and knowledge;
- the need to involve experts to solve informal tasks, lack of such experts in the right place and at the right time;
- the unique experience of highly qualified specialists is gradually being lost [25].

The above-mentioned features of the operation of worn equipment require a mathematical description. As a rule, in such cases, extensive statistical material is used, which allows to predict with a high degree of reliability the probability of the appearance of obvious and hidden equipment failures.

With the help of statistical data processing, we can mathematically describe the function of the distribution of failures found in one of the diagnostic parameters. However, this model is adequate only if we consider developing defects as mutually independent events, as well as diagnostic factors as independent events, i.e. one developing defect manifests itself within the framework of one diagnostic factor. When eliminating such an assumption, the picture becomes much more complicated, because the number of connections between events – developing defects – increases many times over.

Thus, three of our proposed diagnostic factors are mutually independent in nature (oil level, ambient temperature, transformer load), but each of them affects the overall temperature of the transformer to be monitored.

One of the effective tools for analytical evaluation of equipment performance is the system readiness factor, which allows you to determine the degree of readiness of the system to perform its functions in a probabilistic sense. With the help of this indicator, it is possible to evaluate both the general functional state of the transformer substation and its individual elements, and based on this information, it is possible to identify which TS nodes have the lowest reliability and are subject to priority replacement.

Therefore, an important direction in solving the problems of maintaining the functioning of worn electrical equipment is also the application of reliability theory, expert interviews and modeling of the state of the equipment depending on the level of variation of the selected factors.

Using the proposed toolkit, it is possible to develop a new concept of maintenance of worn equipment of TS 6-10/0.4 kV, which allows timely warning of the dangerous degree of development of internal defects of transformers.

Thus, the study puts forward the hypothesis that the accounting of hidden failures (developing defects) will allow to adequately assess the readiness factor of those that are beyond the operational term of the TS of rural electric networks, on the basis of which it is possible to establish the optimal periodicity of maintenance for different economic groups of consumers. using the four-factor model for assessing the thermal condition of the transformer.

OPTIMIZING THE 6-10/0.4 KV SUBSTATIONS TECHNICAL MAINTENANCE TERMS BASED ON THE AVAILABILITY FACTOR

In scientific publications, it is repeatedly proven that it is best to take changes in equipment maintenance costs as a criterion for optimization from increased reliability. It is possible to cite the method of optimization of the availability function, which we also adopt in our case, but as an indicator of reliability we accept the availability coefficient. The cost of preventive maintenance inspections per year can be presented as a function depending on the period of prevention:

$$S(t_{PE}) = S_0 \cdot n = 8760 \cdot \frac{S_0}{t_{PE}}, \quad (3)$$

where S_0 is the cost of one preventive examination, n is the number of examinations per year, t_{PE} is the time between preventive examinations.

The considered readiness factor associated with hidden failures mainly depends on the periodicity of technical services, during which their detection takes place. We assume that the probability of a hidden failure turning into an overt one the next day after prevention and the probability of such a case immediately before prevention are equal. Then the average time of detecting a hidden failure will be equal to half the time between regular inspections. Thus, the readiness factor is represented by a function that depends on the recovery time or the prevention period in the following form [18, 22-24]:

$$k_g(t_{PE}) = \frac{T_0}{T_0+T_{rest}} = \frac{T_0}{T_0+\frac{t_{PE}}{2}} = \frac{2T_0}{2T_0+t_{PE}}. \quad (4)$$

Let's determine the cost of preventive examinations in relative units:

$$s_{rest}(t_{PE}) = \frac{S(t_{PE})}{S_{max}}, \quad (5)$$

where S_{max} is the maximum maintenance costs that are required to support $k_g \approx 1$, we accept at t_{PE} = 24 h.

In this way, the maximum costs are determined by the Eq.:

$$S_{max} = 8760 \cdot \frac{S_0}{24}. \quad (6)$$

Let's make the appropriate substitutions and get the expression for the relative costs of PE:

$$s_{rest}(t_{PE}) = \frac{S(t_{PE})}{S_{max}} = \frac{8760 \cdot S_0 \cdot 24}{t_{PE} \cdot 8760 \cdot S_0} = \frac{24}{t_{PE}}. \quad (7)$$

Thus, we have two functions $k_g(t_{PE})$ (4) and $s_{rest}(t_{PE})$ (7), the graphs of which can be displayed in the form presented in Fig. 2.

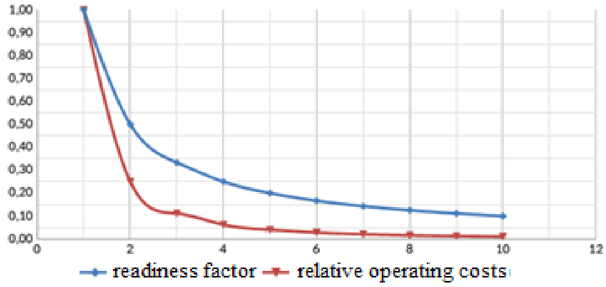

Figure 2. Dependencies of the availability ratio and relative operating costs on the periodicity of maintenance

As you can see from these graphs, operating costs and reliability decrease at different rates. It is economically beneficial to increase the reliability of an electrical installation as long as the operating costs for maintaining reliability grow more slowly than the reliability itself. This statement can be represented in the following form:

$$\frac{dk_g}{dt} = m\frac{ds_{rest}}{dt}, \quad (8)$$

where m is the coefficient of increase in the rate of change of operating costs.

The time obtained as a result of the solution of Eq. (8) will be the optimal time between regular preventive inspections. If m = 1, then the rate of increase in operating costs is equal to the rate of increase in reliability, which is economically beneficial for obtaining high reliability. It can be recommended for TSs supplying electricity to consumers of the first category of energy supply reliability. For most consumers of electricity in rural areas, it is enough to take this coefficient equal to 2.

The optimal readiness factor will be determined:

$$k_g(t_{PE}) = \frac{2T_0}{2T_0+t_{PE}} = \frac{T_0}{2T_0+24+4\sqrt{3T_0}}. \quad (9)$$

It can be seen that the value of the optimal availability coefficient depends on the average earnings per refusal.

CONCLUSIONS

Based on the above, we can draw the following main conclusions.

The current situation indicates the need to improve the system for diagnosing developing defects, which allows to localize and eliminate the defect at an early stage of its development, without causing an accident. Monitoring the parameters of power transformers directly in working condition is a progressive direction in servicing substations, which allows you to perform standardized tests without disconnecting from the network, switch to the maintenance system according to the technical condition, increase the efficiency of control and diagnostics, while maintaining operational reliability.

For rural district substations, the most suitable monitoring system with diagnostic functions is the option that requires minor changes in the structure of the control panel system and the communication line, which allows for improvements and expansion of the system's functionality without a significant increase in cost.

The rational organization of the monitoring system on power transformers presupposes the installation of primary sensors, which must be integrated into a single dispatching system, i.e. the upper level of the monitoring system is software for its integration into the single system of the automated substation control system, which will avoid serious modifications and reduce the cost of the system.

DISCLOSURE STATEMENT

No potential conflict of interest was reported by the author(s).

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Вплив зношених силових трансформаторів на надійність електропостачання сільських електромереж

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Анотація. Енергозабезпечення сільськогосподарських підприємств характеризується рядом суттєвих проблем, розв'язання яких є актуальним завданням протягом кількох десятиліть. У науковій та навчальній літературі розглядаються широко відомі та характерні проблеми: розміщення сільськогосподарських об'єктів на великій території, їх віддаленість від центральних підстанцій, віддаленість від вулично-дорожньої мережі, що ускладнює доступ аварійних бригад у разі аварій, високий ступінь експлуатації обладнання підстанцій та повітряних ліній. Разом з тим переоснащення парку технологічного обладнання сільськогосподарських підприємств змушує по-новому поглянути на якість енергопостачання – мікропроцесорна техніка, що використовується в сучасному сільськогосподарському виробництві висуває високі вимоги до надійності енергопостачання. Також не втрачає актуальності питання щодо аварійних режимів в системі енергопостачання, які призводять до мільйонних втрат через псування продукції через припинення технологічного процесу. Як відомо, система енергопостачання має бути зразком високої надійності, але при огляді ситуація виглядає дещо інакше: через різні причини (зокрема як дефіцит електроенергії, так і зношеність використовуваного обладнання) енергопостачання не завжди відповідає очікуванням споживачів щодо якості наданих послуг. У разі перебоїв з енергопостачанням підприємств (в тому числі сільськогосподарських) перебої з енергопостачанням спричиняють набагато серйозніші наслідки, пов'язані зі псуванням і недовиробництвом продукції та мільйонними збитками.

Ключові слова: мережа електропостачання, параметри мережі, щільність навантаження, ділянка провідної лінії, питоме навантаження, одиничні витрати, оптимальний параметр, електрична енергія.

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