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TECHNICAL AND ECONOMIC ASPECTS OF IMPLEMENTING AUTOMATION AND VACUUM EQUIPMENT IN DISTRIBUTION NETWORKS

ТЕХНІЧНІ ТА ЕКОНОМІЧНІ АСПЕКТИ ВПРОВАДЖЕННЯ АВТОМАТИЗАЦІЇ ТА ВАКУУМНОГО ОБЛАДНАННЯ В РОЗПОДІЛЬНИХ МЕРЕЖАХ

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Abstract *– The article examines current approaches to optimizing the operating modes of distributed technical systems based on automation and intelligent control technologies, using the example of 10 kV electric networks. The analysis is based on current trends in electrical engineering aimed at increasing energy efficiency, operational reliability, and safety of distribution networks. A comparison of oil and vacuum circuit breakers is performed in terms of their design, maintenance requirements, environmental impact, and suitability for integration with automated monitoring and control systems. Oil circuit breakers, despite their long history of use, have significant drawbacks, including fire hazards, regular maintenance needs, and oil degradation. In contrast, vacuum circuit breakers demonstrate higher dielectric strength, minimal environmental risks, and extended maintenance intervals. The study outlines how the use of vacuum technology in circuit breaking enhances overall system performance, particularly under increasing grid loads and renewable energy integration scenarios. Furthermore, the role of automation is explored as a key factor in optimizing the performance of medium-voltage networks. Automation allows for real-time fault detection, remote control, predictive maintenance, and dynamic network reconfiguration. These capabilities contribute to reduced outage durations, improved service continuity, and more efficient energy distribution. A technical and economic assessment shows that while the initial investment in vacuum technology and automation may be higher, the lifecycle cost is significantly reduced due to lower maintenance and outage-related expenses. The findings are supported by recent case studies and simulation data from Ukrainian and international energy networks. The article concludes that a systematic transition to vacuum circuit breakers, combined with automation technologies, is a viable strategy for ensuring the long-term reliability and sustainability of 10 kV distribution networks. The proposed methodological approaches to automation and control are universal and can be adapted for use in other distributed systems.*

Анотація *– У статті розглядаються сучасні підходи до оптимізації режимів роботи розподілених технічних систем на основі технологій автоматизації та інтелектуального керування на прикладі електричних мереж 10 кВ. Аналіз базується на сучасних тенденціях в електротехніці, спрямованих на підвищення енергоефективності, експлуатаційної надійності та безпеки розподільчих мереж. Проведено порівняння масляних та вакуумних вимикачів з точки зору їхньої конструкції, вимог до обслуговування, впливу на навколишнє середовище та придатності для інтеграції з автоматизованими системами моніторингу та управління. Масляні вимикачі, незважаючи на тривалу історію використання, мають суттєві недоліки, включаючи пожежну небезпеку, потребу в регулярному технічному обслуговуванні та деградацію оливи. Натомість*

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вакуумні вимикачі демонструють вищу діелектричну міцність, мінімальні екологічні ризики та збільшені інтервали технічного обслуговування. У дослідженні окреслюється, як використання вакуумної технології у розмиканні підвищує загальну ефективність системи, особливо за умов зростання навантажень мережі та інтеграції відновлюваних джерел енергії. Крім того, досліджується роль автоматизації, як ключового фактору, в оптимізації ефективності мереж середньої напруги. Автоматизація дозволяє виявляти несправності в режимі реального часу, здійснювати дистанційне керування, проводити прогнозне обслуговування та динамічну реконфігурацію мережі. Ці можливості сприяють скороченню тривалості простоїв, покращенню безперервності обслуговування та ефективнішому розподілу енергії. Техніко-економічна оцінка показує, що хоча вакуумні комутаційні технології та системи автоматизації потребують більших початкових вкладень, у експлуатації вони є вигіднішими, що пояснюється меншими витратами на обслуговування та простоєм обладнання. Ці висновки підтверджуються тематичними дослідженнями та даними моделювання з українських та міжнародних енергетичних мереж. У статті робиться висновок, що систематичний перехід на вакуумні вимикачі в поєднанні з технологіями автоматизації є життєздатною стратегією для забезпечення довгострокової надійності та стійкості розподільчих мереж 10 кВ. Запропоновані методологічні підходи до автоматизації та управління є універсальними та можуть бути адаптовані для використання в інших розподілених системах.
Keywords: automation, 10 kV electric networks, oil circuit breakers, vacuum circuit breakers, energy efficiency, reliability.

Ключові слова: автоматизація, електричні мережі 10 кВ, маломасляні вимикачі, вакуумні вимикачі, енергоефективність, надійність.

I. INTRODUCTION

The reliability and efficiency of medium-voltage power networks, in particular at the 10 kV level, are critically important for the stable operation of the power system, especially in conditions of increasing load and integration of renewable energy sources. Traditionally, low-oil circuit breakers were used in such networks; however, modern requirements for safety, energy efficiency and operational reliability determine the need to modernize the equipment and switch to vacuum circuit breakers, which have better technical characteristics and a longer service life.

Along with the hardware update, the relevance of implementing automated control systems is increasing, which allows for a prompt response to emergency situations, real-time network monitoring and optimization of maintenance processes. This approach provides not only increased operational efficiency, but also reduced costs associated with downtime, repairs and electricity losses.

II. STATE-OF-ART

Modern 10 kV electrical networks play a key role in the distribution of electricity between substations and consumers. In Ukraine, a significant part of these networks was built back in the Soviet period and is still operated using outdated technical solutions. The main switching device in such networks remains low-oil circuit breakers, which, although they provide a basic level of functionality, no longer meet modern requirements for energy efficiency, safety and automation [1].

Low-oil circuit breakers have a number of significant disadvantages: the need for regular maintenance, the risk of oil leaks and the threat of ignition, and the limited resource of mechanical parts. In the event of short circuits or emergency overloads, the operation time of such devices may not be short enough to minimize equipment damage, which requires increased sensitivity and speed of switching elements.

In addition, the level of automation of most 10 kV networks remains low. The lack of integrated monitoring and remote control systems complicates the prompt detection of accidents, localization of faults and performance of preventive maintenance. This leads to increased downtime, reduced reliability of power supply and increased operating costs.

In the context of the global transition to intelligent energy systems (smart grids), such a situation requires immediate intervention. Research results [2–6] demonstrate that the integration of modern control technologies, including the use of sensor devices, communication tools and artificial intelligence, can radically change the functioning of distribution networks. At the same time, updating the hardware base, in particular, replacing low-oil circuit breakers with vacuum ones, creates conditions for increasing the speed and reliability of switching operations.

Thus, the technical condition of most 10 kV networks requires comprehensive modernization, which should include both the replacement of key equipment elements and the implementation of automated monitoring and control systems.

III. THE PURPOSE OF THE RESEARCH

This article examines the technical aspects of the transition from low-oil to vacuum circuit breakers in 10 kV networks, analyzes the benefits of automation of control systems, and provides a justification for the feasibility of such modernization, taking into account economic and technological factors. The following sections will examine in detail the technical features of vacuum circuit breakers and the economic advantages of their use in the conditions of modern energy.

IV. ADVANTAGES OF VACUUM CIRCUIT BREAKERS COMPARED TO LOW-OIL CIRCUIT BREAKERS

Vacuum circuit breakers in modern 10 kV electrical networks are increasingly replacing low-oil circuit breakers, which are associated with significant advantages of vacuum switching in both technical and operational aspects. The main difference lies in the environment in which arc extinguishing occurs: in vacuum circuit breakers it is implemented in a vacuum, while in low-oil circuit breakers – in an insulating oil liquid, which significantly affects the reliability, safety and durability of the device.

From a technical point of view, vacuum circuit breakers provide much faster extinguishing of the electric arc that occurs during switching processes. Due to the high vacuum (about 10^{-6} – 10^{-7} mm Hg), the current is instantly interrupted without the formation of significant overvoltages. In addition, vacuum circuit breakers have a higher resource for the number of switching operations – more than 20 thousand on/off cycles without the need for maintenance, while low-oil circuit breakers require regular checking of the oil condition, cleaning of contacts and replacement of seals [3].

From an operational point of view, vacuum circuit breakers are devoid of the risk of ignition inherent in low-oil circuit breakers due to the use of flammable liquids. This increases the overall level of fire safety of electrical installations. An additional advantage is environmental friendliness: vacuum circuit breakers do not contain oil decomposition products that can be toxic, and the device itself does not require special measures for oil disposal after the end of operation.

An important advantage of vacuum circuit breakers is their compatibility with automated control systems. Most modern vacuum circuit breakers are equipped with contact position, current, voltage and temperature sensors, which allow for constant monitoring of their condition and real-time diagnostics. Such integration is a necessary prerequisite for creating intelligent distribution networks.

Table 1 shows the comparative characteristics of low-oil and vacuum circuit breakers, illustrating the advantages of the vacuum circuit breakers.

Table 1. Comparative characteristics

Parameter	Low-oil circuit breakers	Vacuum circuit breakers
Arc extinguishing environment	Oil	Vacuum
Switching life	Up to 2000 cycles	Up to 2000 cycles
Maintenance frequency	Frequent	Minimal or none
Fire hazard	High	None
Environmental safety	Requires oil disposal	Does not require disposal
Automation capability	Limited	Full
Dimensions and weight	Large	Compact

In summary, vacuum circuit breakers are technically more advanced, safer and more economically advantageous in the long term. They meet the requirements of modern energy infrastructure, which is focused on automation, uninterrupted operation and environmental sustainability. It is these characteristics that determine the feasibility of switching to vacuum breakers in the process of modernization of 10 kV networks.

V. TECHNICAL FEATURES OF THE DESIGN OF VACUUM CIRCUIT BREAKERS AND THEIR IMPACT ON OPERATIONAL CHARACTERISTICS

As mentioned earlier, vacuum circuit breakers provide highly efficient arc extinguishing due to the specifics of the working environment. However, to understand the reasons for their reliability and durability, it is important to consider in detail the technical features of the design that determine the operational characteristics of these devices.

The main component of a vacuum circuit breaker is an arc extinguishing chamber filled with a vacuum with a pressure of about 10^{-5} Pa. Under such conditions, the electric arc is extinguished due to rapid plasma dissipation and the inability to maintain an ionized channel between the contacts. Structurally, the chamber is made of durable metal materials that withstand significant thermal and mechanical loads during switching operations [4].

The contact system of a vacuum circuit breaker is a separate key element. It consists of moving and fixed contacts made of materials with high electrical conductivity and wear resistance, such as copper coated with zirconium or chromium alloys. The choice of materials determines the resistance of contacts to erosion caused by arcing processes and reduces the resistance in the closed state, which has a positive effect on the total electricity losses in the network.

The contact drive mechanism in vacuum circuit breakers ensures fast and clear circuit opening. It is important that the contact opening time does not exceed several milliseconds, which allows to minimize the duration of the arcing process and avoiding damage to the equipment. The mechanism is equipped with springs or electromagnetic drives with high reliability, capable of operating in a wide range of temperatures and in vibration conditions.

A feature of the design is the tightness of the vacuum circuit breaker housing. This avoids the penetration of dust, moisture and other contaminants that can lead to malfunctions. Due to this, vacuum circuit breakers have stable characteristics even when operating in difficult climatic conditions, including high humidity or dustiness.

As a result of the design features, vacuum circuit breakers have a low noise level during switching, which is an additional advantage in urban and industrial areas, where reducing noise pollution is a pressing task.

It is also important to note the possibility of standardization and unification of vacuum circuit breaker elements. Modern manufacturers ensure that the equipment complies with international IEC and GOST standards, which simplifies the integration of these devices into existing distribution systems and guarantees compatibility with other network components.

Thus, the technical design of vacuum circuit breakers is a determining factor in their high reliability, durability and safety. Understanding these features allows you to optimize the operation processes and planning for the modernization of 10 kV electrical networks.

VI. COMPARATIVE ANALYSIS OF RELIABILITY AND MAINTENANCE INDICATORS OF VACUUM AND LOW-OIL CIRCUIT BREAKERS

The technical features of vacuum circuit breakers that ensure their high efficiency were discussed in the previous section. Now it is important to consider how these design solutions affect operational performance, in particular, reliability and maintenance complexity compared to low-oil circuit breakers.

In terms of reliability, vacuum circuit breakers significantly outperform low-oil counterparts. The absence of a liquid medium reduces the risk of short circuits due to oil leakage, which is one of the main causes of failure in low-oil circuit breakers. Vacuum breakers provide stable arc extinguishing even after many thousands of on/off cycles, which extends the service life of the equipment.

In addition, vacuum circuit breakers are characterized by a lower failure rate, which significantly reduces the risks of emergency situations in a 10 kV power grid. Their hermetic design, as previously mentioned, protects the internal components from contamination, moisture and corrosion, which often affect the reliability of oil-less circuit breakers, where the oils can become contaminated and degraded [5–8].

In terms of maintenance, vacuum circuit breakers require significantly fewer resources. They do not require periodic oil changes, monitoring of their condition and cleaning, which are mandatory procedures for oil-less devices. This reduces not only operating costs, but also the risk of human errors during maintenance.

However, vacuum circuit breakers have their own specific diagnostic requirements, including checking the condition of the vacuum and monitoring the contact system, but these procedures are usually less labor-intensive and can be performed less frequently due to the higher stability of operation.

Another important factor is the operational duration between major repairs. Vacuum circuit breakers have a service life that often exceeds 20 years without significant loss of performance, while low-oil devices require more frequent maintenance and oil changes approximately every 5-10 years.

A general comparative analysis indicates that vacuum circuit breakers are more reliable, durable and cost-effective in operation. This makes them the optimal choice for the modernization of 10 kV networks, taking into account the reduction of operating costs and increased safety of electrical equipment [9, 10].

VII. IMPLEMENTATION OF AUTOMATION IN 10 KV NETWORKS: TECHNOLOGIES AND PRACTICAL ASPECTS

Automation of control systems for 10 kV electrical networks is an important area of modernization, which increases the reliability and efficiency of their operation. This section considers key technological solutions and practical aspects of implementing automation that allow for operational monitoring, remote control and optimization of network operation modes.

One of the main components of automated systems is data collection devices (current, voltage, temperature, short-circuit current sensors, etc.), which provide constant monitoring of the state of network elements in real time. Information from these sensors is transmitted to control centers using reliable communication channels (for example, radio channels, fiber optic lines, PLC – data transmission over power lines) [11–13].

To increase the efficiency of data processing, SCADA (Supervisory Control and Data Acquisition) systems are used, which provide centralized monitoring, visualization, archiving and analysis of information. These systems allow you to remotely perform operations of switching on and off switches, change the network configuration according to current needs and promptly respond to emergency situations.

In addition, the implementation of artificial intelligence and machine learning algorithms in automated systems allows you to predict possible accidents, plan preventive maintenance and optimize load distribution. This approach helps to increase energy efficiency and reduce electricity losses.

Practical aspects of automation implementation include analyzing the compatibility of new equipment with existing infrastructure, training personnel, adapting technological processes and assessing economic feasibility. A phased approach is important, which allows you to minimize risks when transitioning from traditional control schemes to modern automated solutions.

In general, automation of 10 kV electrical networks helps to increase the reliability of power supply, reduce the time to eliminate accidents and reduce operating costs, which corresponds to modern trends in the development of the energy industry.

VIII. ECONOMIC ASSESSMENT OF THE TRANSITION FROM LOW-OIL TO VACUUM CIRCUIT BREAKERS IN 10 KV NETWORKS

The process of upgrading 10 kV networks by replacing low-oil circuit breakers with vacuum circuit breakers requires significant investments; however, as previously noted, this is justified in terms of increased reliability and reduced operating costs. This section provides an economic analysis of the main components of costs and benefits associated with the implementation of vacuum technology.

First of all, it is worth considering the capital costs for the purchase of vacuum circuit breakers, installation work and integration with the existing control system. The cost of vacuum devices usually exceeds the price of low-oil analogues, which is associated with their more complex design and modern materials. At the same time, due to the reduction in the need for frequent maintenance and routine work, operating costs are significantly reduced.

One of the key factors of economic efficiency is the longer service life of vacuum circuit breakers, which often exceeds 25 years, which is almost twice as long as compared to low-oil devices. This allows you to reduce the costs of replacing equipment and the associated network downtime.

Additionally, the reduction of recovery time after emergencies due to faster operation of vacuum circuit breakers contributes to the reduction of financial losses associated with power outages, especially for enterprises with high requirements for continuity of work.

Also, the reduction of risks of environmental damage, which is associated with the lack of oil in vacuum circuit breakers, can reduce the costs of eliminating accidents and penalties, which is relevant in light of modern environmental regulations.

As a result of the analysis, it can be concluded that, despite the higher initial investment, the total cost of ownership of vacuum circuit breakers is lower in the long term. This approach aligns with the sustainable development strategy of energy systems and yields economic benefits when automation is implemented in a comprehensive manner.

IX. CONCLUSIONS

The article provides a comprehensive analysis of the current state of 10 kV electrical networks and identifies the main technical and operational limitations of low-oil circuit breakers, which have been used in distribution networks for a long time. As noted earlier, these limitations include increased fire hazard, high maintenance costs and limited service life, which reduces the overall reliability of the system.

The advantages of vacuum circuit breakers considered in the article confirm their feasibility as the main element of the modernization of 10 kV electrical networks. They are characterized by increased speed, better insulation properties, environmental safety and reduced operating costs, which ensures increased efficiency of the networks.

Special attention is paid to the importance of automation of electrical network control systems. The implementation of automated solutions, as noted, allows for operational monitoring, remote control, rapid detection and localization of accidents, as well as the implementation of preventive maintenance based on real-time data analysis. These factors contribute to reduced downtime, improved power quality and cost optimization.

The feasibility study shows that although the initial investment in the implementation of vacuum circuit breakers and automated systems can be significant, the total life cycle cost of operation is significantly reduced due to reduced maintenance requirements and reduced electricity losses.

Therefore, a systematic approach to the modernization of 10 kV networks with the replacement of low-oil circuit breakers with vacuum circuit breakers in combination with automation is an effective strategy for improving the reliability, safety and energy efficiency of distribution power networks. The proposed measures will contribute to the sustainable development of the energy infrastructure, taking into account modern technological challenges and prospects.

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