COMPARATIVE ANALYSIS OF THE RELIABILITY OF VACUUM AND OIL CIRCUIT BREAKERS

I.N. Rahimli[1], A.L. Bakhtiyarov[2]

•

Azerbaijan State Oil and Industry University, Baku, Azerbaijan
[1] ilham.raqimli@asoiu.edu.az ; [2] baxtiyarov.aliashraf@asoiu.edu.az

Abstract

In modern power systems, switching equipment plays a crucial role in ensuring the safe and reliable connection and disconnection of electrical circuits. A failure of a circuit breaker can lead to serious consequences, including prolonged power outages and damage to expensive equipment. This paper presents a comparative analysis of the reliability of vacuum and oil circuit breakers, considering operational, technical, and economic factors. It examines the main causes of failures, methods of reliability assessment, and provides a comprehensive evaluation of the effectiveness of each type of breaker under various conditions. The novelty of the proposed solution lies in the in-depth analysis of operational characteristics and a multifaceted evaluation of the impact of external factors on equipment reliability. Modern diagnostic and monitoring methods, including thermography, ultrasonic diagnostics, and the integration of IoT systems for real-time monitoring, are used. These approaches improve the processes of equipment selection and operation, ultimately contributing to the overall reliability of power systems. The paper aims to support informed decision-making in equipment selection to enhance the overall reliability of power systems.

Keywords: vacuum circuit breakers, oil circuit breakers, reliability, failure analysis

I. Introduction

In modern power systems, switching equipment plays a key role in ensuring the safe and reliable connection and disconnection of electrical circuits. A circuit breaker failure can lead to serious consequences, ranging from prolonged power outages to the failure of expensive equipment [1]. Therefore, the reliability of circuit breakers is one of the most important criteria when selecting equipment for medium- and high-voltage systems.

Among the most common types of circuit breakers today, vacuum and oil circuit breakers can be distinguished. Each of them has its own design features, operating principles, and operational characteristics. Oil circuit breakers have been widely used for decades and have proven to be a cost-effective and reliable solution. However, with the development of technology, vacuum circuit breakers have actively started to replace them, especially in medium-voltage installations, due to their high reliability, environmental friendliness, and ease of maintenance.

The purpose of this article is a comparative analysis of the reliability of vacuum and oil circuit breakers, taking into account operational, technical, and economic factors [2-4]. The paper examines the main causes of failures, methods of reliability assessment, and provides a comprehensive evaluation of the effectiveness of each type of circuit breaker under various conditions.

Understanding the strengths and weaknesses of both types of circuit breakers allows for an informed choice in favor of one type of equipment or another and contributes to improving the overall reliability of power systems.

II. Formulation of the problem

Reliability analysis of vacuum circuit breakers: The reliability of vacuum circuit breakers depends on many factors, including their design, operating conditions, and diagnostic methods. Among the main causes of failures in vacuum circuit breakers, several typical aspects can be identified. First, wear of the contact elements, which over time reduces their ability to effectively transmit electrical current. The second important cause is the loss of vacuum integrity in the vacuum chamber. Vacuum is a key factor in the operation of such breakers, and any vacuum leakage can significantly affect their efficiency [5]. Another common issue is the failure of the drive mechanisms, which can lead to the inability of the device to function properly. In some cases, a malfunction in the control system can also occur, potentially leading to a failure.

Operating conditions play a significant role in the reliability of vacuum circuit breakers. Under ideal conditions, such as stable temperatures and the absence of contaminants in the air, these devices can operate for a long time without significant damage. However, under real-world conditions, such as frequent temperature fluctuations or the presence of moisture and dust, their reliability may decrease. These external factors can accelerate material wear, which leads to the need for more frequent maintenance.

Modern diagnostic and monitoring methods for vacuum circuit breakers allow for the detection of potential issues at an early stage [6-7]. Thermography, ultrasonic diagnostics, and systems for monitoring mechanical wear—all of these approaches help prevent breakdowns, ensuring long and stable operation of the equipment. Additionally, with the development of technology, the integration of IoT systems allows for real-time monitoring of the breakers' condition, enabling prompt responses to changes in their performance. As for the mean time between failures (MTBF), vacuum circuit breakers can boast relatively high figures, sometimes reaching tens of thousands of hours, which gives them an advantage over other types of circuit breakers.

Analysis of the reliability of oil circuit breakers: Oil circuit breakers, despite their durability and traditional use in the power industry, have several vulnerable elements that reduce their reliability. One of the main issues is the wear and contamination of the oil. Over time, the oil loses its insulating and quenching properties, which can lead to deterioration in switching quality and an increased risk of emergency situations [8-10]. Furthermore, oil circuit breakers are prone to oil leaks, which also negatively affect their performance. Corrosion of metal parts, as well as contamination of the oil by external impurities, are other significant factors that can significantly shorten the lifespan of these devices.

The impact of the external environment plays a significant role in the reliability of oil circuit breakers. Temperature fluctuations can alter the viscosity of the oil, which in turn affects its ability to perform its functions effectively. Air pollution and increased humidity can accelerate the degradation process of the oil, necessitating more frequent inspections and maintenance [11-12]. These devices are also sensitive to the presence of water in the oil, which can lead to gas formation and increased pressure inside the device, disrupting its operation.

The frequency of maintenance for oil circuit breakers is significantly higher than that of vacuum counterparts. The oil must be regularly replaced, and the device's sealing must be checked. Cleaning and inspecting contacts also play an important role, as contamination or corrosion of the contacts can cause failure.

Compared to oil circuit breakers, vacuum circuit breakers require less attention and maintenance (Table 1). Vacuum circuit breakers are smaller in size and weight and also demonstrate higher durability [13]. Moreover, they virtually require no regular maintenance, making them more cost-effective in the long term. In contrast, oil circuit breakers require frequent maintenance, oil replacement, and monitoring of component conditions, which increases their operating costs and reduces overall reliability. Environmentally, vacuum circuit breakers are also superior to oil breakers, as they do not contain hazardous liquids that could leak and harm the environment.

Table 1: *Comparative reliability of vacuum and oil circuit breakers*

Parameter	Vacuum Circuit Breakers	Oil Circuit Breakers
Mean Time Between Failures	High (up to 50,000 hours)	Medium (up to 20,000 hours)
Maintenance Requirement	Minimal	High (oil replacement and seal check)
Environmental Impact	High (no oil)	Low (risk of oil leakage)
Size and Weight	Compact	Large and heavy
Durability	Long-lasting	Shorter durability
Sensitivity to External Factors	Resistant to contamination and temperature fluctuations	Sensitive to contamination and humidity
Dependence on Oil	None	Issues with oil quality
Risk of Leakage	None	Present (oil)

Thus, vacuum circuit breakers, due to their design, reduced maintenance requirements, and durability, offer higher reliability and cost-effectiveness, especially in modern operating conditions where minimizing maintenance costs and extending equipment lifespan are crucial.

III. Problem solution

The reliability of switching equipment is a set of its properties that allows it to maintain operability for a specified period under certain operating conditions. In the energy sector, where the failure of a switching device can lead to serious consequences, including disruption of power supply and equipment damage, reliability becomes a key criterion when selecting circuit breakers [14-15].

According to regulatory documents, reliability includes the device's ability to operate without failure, durability, maintainability, and preservation. Reliability is quantitatively assessed using indicators such as Mean Time Between Failures (MTBF), Mean Time To Repair (MTTR), failure rate (λ), and overall probability of no-failure operation R(t).

Mean Time Between Failures (MTBF) is defined as the ratio of total operating time to the number of failures and reflects the average duration of uninterrupted equipment operation. For oil circuit breakers, this value is typically around 12,000 hours, while for vacuum circuit breakers, it reaches 50,000 hours or more.

The failure rate, which is the reciprocal of MTBF, is calculated using the formula:

$$\lambda = \frac{1}{MTBF}$$

For oil circuit breakers:

$$\lambda = \frac{1}{12000} \approx 8.33 \times 10^{-5} \text{ failures per hour}$$

For vacuum circuit breakers:

$$\lambda = \frac{1}{50000} = 2 \times 10^{-5} \text{ failures per hour}$$

Thus, the failure intensity of vacuum circuit breakers is significantly lower, which indicates their higher reliability.

The average recovery time after a failure also plays an important role: for vacuum circuit breakers, it is on average 1.5 hours, while for oil circuit breakers it is about 4 hours, which is due to the need for oil replacement, cleaning, and additional maintenance.

To assess the probability of failure-free operation over time, the reliability function is used, which reflects the exponential decrease in reliability at a constant failure rate. It is calculated using the formula:

$$R(t) = e^{-\lambda t}$$

where t is the operating time of the equipment.

Table 2 includes the main parameters used for calculating the function R(t)=e−λt.

Table 2: *Comparative reliability parameters of vacuum and oil circuit breakers*

Type of Circuit Breaker	Mean Time Between Failures (MTBF), hours	Mean Time to Repair (MTTR), hours	Failure Rate λ, 1/hour
Oil Circuit Breaker	12,000	4.0	8.33×10^{-5}
Vacuum Circuit Breaker	50,000	1.5	2.00×10^{-5}

For the vacuum circuit breaker at t = 1000 hours:

$$R_{vacuum}(1000) = e^{-2\times10^{-5}\times1000} = e^{-0.02} \approx 0.9802$$

Thus, after 1000 hours of operation, the probability that the vacuum circuit breaker will remain in good condition is 98.02%.

For the oil circuit breaker at t = 1000 hours:

$$R_{oil}(1000) = e^{-8{,}33\times10^{-5}\times1000} = e^{-0.0833} \approx 0.9207$$

That is, after 1000 hours of operation, the probability that the oil circuit breaker will remain in good condition is 92.07%.

As can be seen, the lower failure rate of vacuum circuit breakers ensures a consistently high value of R(t) over a long operational period [16-18]. The graph in Figure 1 shows the dependence of R(t) on time for vacuum and oil circuit breakers. It is evident that the reliability of the vacuum circuit breaker remains at a significantly higher level throughout its entire lifecycle, making it the preferred option for modern power systems.

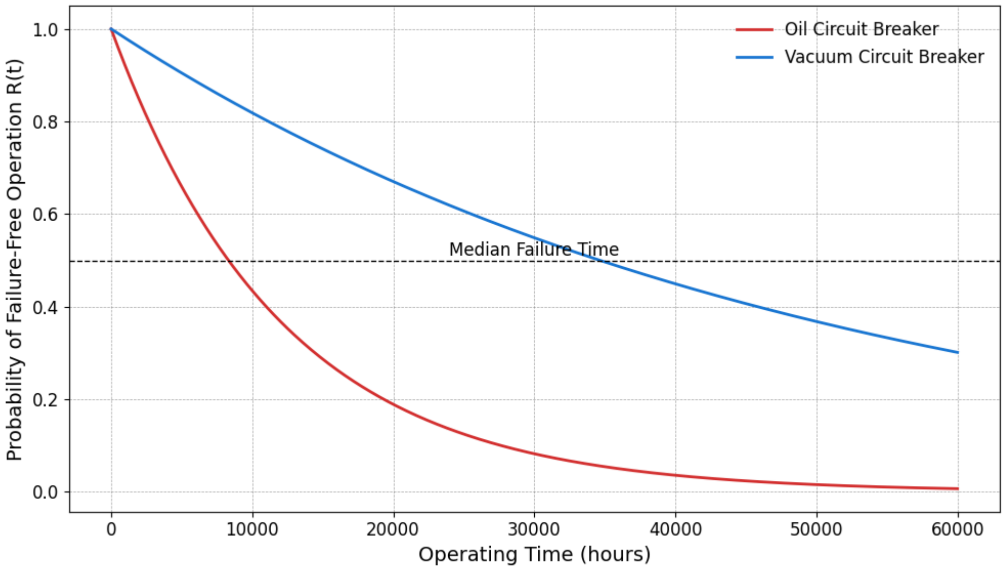

Figure 1. *Reliability function R(t) graph for vacuum and oil circuit breakers.*

For comprehensive evaluation, methods of statistical analysis of operational data, reliability modeling, and failure analysis by design components are often used [19]. Practice shows that the main causes of failure in oil circuit breakers are related to oil leaks, insulation degradation, and contact burn-out. In contrast, vacuum circuit breakers demonstrate high stability even with a large number of switching cycles, thanks to their sealed design and the lack of need for maintenance of the contact medium.

IV. Conclusions

As a result of the comparative analysis, it has been established that vacuum circuit breakers offer higher reliability and durability compared to oil circuit breakers. They require minimal maintenance and demonstrate excellent Mean Time Between Failures (MTBF) performance, making them more cost-effective in the long term. Oil circuit breakers, despite their durability, require frequent maintenance, oil replacement, and regular seal checks, which increase operating costs and reduce their overall reliability. Therefore, vacuum circuit breakers are the preferred choice for modern power systems, offering greater stability and a lower risk of failure during operation.

References

[1] Rzayeva, S. V., Ganiyeva, N. A., & Piriyeva, N. M. (2024). Modern approaches to electrical equipment diagnostics. *International Journal on Technical and Physical Problems of Engineering (IJTPE)*, 16(1), 182–189.

[2] Rzayeva, S. V., Piriyeva, N. M., & Guseynova, I. A. (2024). Analysis of reliability of typical power supply circuits. *Reliability: Theory and Applications (RTA)*, 19(3), 173–178.

[3] Rahimli, I., Karimova, R., & Piriyeva, N. (2024). Development of a two-parameter inductive sensor for use in digital program control systems for machine tools. *Przegląd Elektrotechniczny*, 100(8), 194–197.

[4] Rzayeva, S. V., Ganiyeva, N. A., & Piriyeva, N. M. (2023, October 31). Modern methods of diagnostics of electric power equipment. In *Proceedings of the 19th International Conference on Technical and Physical Problems of Engineering* (pp. 105–110). International Organization of IOTPE, Romania.

[5] Piriyeva, N. M., Rzayeva, S. V., & Mustafazadeh, E. M. (2022). Evaluation of the application of various methods and equipment for protection from emergency voltage in 6–10 kV electric networks of oil production facilities. *Internauka: Elektronnyy Nauchnyy Zhurnal*, (39), 40–44.

[6] Rzayeva, S. V., Mammadov, N. S., & Ganiyeva, N. A. (2023). Overvoltages during single-phase earth fault in neutral-isolated networks (10–35) kV. *Journal of Energy Research and Reviews*, 13(1), 7–13.

[7] Rzayeva, S. V., & Guseynova, I. A. (2024). Application of automatic monitoring and control systems for reliability of power transmission lines. *Reliability: Theory & Applications*, 19(2), 64–69.

[8] Rzayeva, S., & Ganiyeva, N. (2022). Analysis of the design and operational advantages of vacuum circuit breakers. *Universum: Tekhnicheskiye Nauki*, (10-7), 39–42.

[9] Piriyeva, N. M., Mammadov, N. S., & Rzayeva, S. V. (2025). Development of new methods for protecting substation and overhead lines from overvoltages. *Reliability: Theory & Applications*, 19(1), 683–689. https://doi.org/10.24412/1932-2321-2025-182-683-689

[10] Rzayeva, S. V., Mammadov, N. S., & Ganiyeva, N. A. (2022). Neutral grounding mode in the 6–35 kV network through an arcing reactor and organization of relay protection against single-phase ground faults. *German International Journal of Modern Science*, (42).

[11] Ahmedov, E., Rzayeva, S., Ganiyeva, N., & Safiyev, E. (2023). Improving the lightning resistance of high-voltage overhead power line. *Przegląd Elektrotechniczny*, (11).

[12] Piriyeva, N. M., Abdullayeva, G. K., & Bakhtiyarov, A. L. (2024). Engineering approaches to minimizing the environmental impact of thermal power plants. *International Journal on Technical and Physical Problems of Engineering (IJTPE)*, 61, 231–243.

[13] Mammadov, N., Piriyeva, N., & Ismayilova, S. (2024). Research of lightning protection systems for wind electric installations. *Przegląd Elektrotechniczny*, (9), 2024.

[14] Piriyeva, N. M., & Agazade, N. S. (2024). Исследование эксплуатационных характеристик современных вакуумных выключателей. *Vestnik Nauki*, 3(1), 963–974.

[15] Su, J., Chen, K., & Wang, Q. (2022). Difference analysis of operation stability of vacuum circuit breaker in 10kV power distribution system. *Journal of Physics: Conference Series*, 2202(1), 012047.

[16] Shores, R. B., & Phillips, V. E. (2006). High voltage vacuum circuit breakers. *IEEE Transactions on Power Apparatus and Systems*, 94(5), 1821–1830.

[17] Bumblauskas, D., Meeker, W., & Gemmill, D. (2012). Maintenance and recurrent event analysis of circuit breaker data. *International Journal of Quality & Reliability Management*, 29(5), 560–575.

[18] Slade, P. G., et al. (2007). Vacuum interrupter, high reliability component of distribution switches, circuit breakers and contactors. *Journal of Zhejiang University-Science A*, 8(3), 335–342.

[19] König, D. (2012). The role of vacuum in circuit breaker technology. In *2012 25th International Symposium on Discharges and Electrical Insulation in Vacuum (ISDEIV)* (pp. A1–A14). IEEE.