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Statistical Performance Analysis of a 20 kV Circuit Breaker at Bangka Substation

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Abstract
This study evaluates the performance of 20 kV circuit breakers by analyzing insulation resistance, contact resistance, contact synchronization, leakage current, and power loss. The insulation resistance analysis indicated that phases R and S did not show significant improvement after maintenance, with significance values of 0.065 and 0.166, respectively, while phase T exhibited a significant improvement with a significance value of 0.048. Contact resistance measurements revealed no statistically significant reductions after maintenance, with significance values of 0.209, 0.243, and 0.155 for phases R, S, and T, respectively. Additionally, contact synchronization in the open condition did not experience significant variations, whereas in the closed condition, all phases showed significant declines in synchronization after maintenance, with significance values of 0.003, 0.013, and 0.007. Leakage current analysis at a 20 kV phase-to-ground voltage showed that the highest recorded leakage current was 0.297 mA in the Eks Sumberejo feeder, significantly below the 20 mA threshold. Power loss calculations identified the highest power dissipation in the Depati Hamzah feeder at 69.87 W, with the lowest in the Eks Transmart feeder at 0.376 W. Energy loss assessment further showed the Depati Hamzah feeder experiencing the highest loss at 48.317 kWh, while the Eks Transmart feeder had the lowest at 0.278 kWh. These findings underscore the importance of routine monitoring and targeted maintenance to enhance circuit breaker reliability, optimize operational efficiency, and minimize energy losses in high-voltage electrical networks.

Keywords: Circuit Breaker, Insulation Resistance, Contact Resistance, Power Loss Analysis, Energy Loss Optimization

1. Introduction

Circuit breakers play a crucial role in high-voltage transmission and distribution networks, ensuring system reliability and safety by interrupting fault currents and protecting electrical equipment [1]. Their performance directly influences the stability and efficiency of the electrical grid. As the demand for electricity continues to grow, ensuring the proper functionality of circuit breakers is vital for minimizing outages and maintaining operational continuity [2]. Regular assessments of key performance parameters are necessary to detect potential failures and optimize maintenance strategies [3].

One of the fundamental aspects of circuit breaker performance is insulation resistance, which determines the ability of the circuit breaker to withstand high voltage levels without dielectric breakdown [4]. Insufficient insulation resistance

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can lead to unintended current leakage, reducing the efficiency and reliability of the system [5]. Additionally, contact resistance is another critical factor, as excessive resistance at contact points can cause overheating, energy losses, and increased wear, ultimately compromising the long-term functionality of the circuit breaker [6].

Apart from insulation and contact resistance, contact synchronization is a key operational parameter that affects the performance of circuit breakers. Proper synchronization of contacts in both open and closed conditions ensures minimal arcing and reduces wear on the system [7]. Deviations in synchronization can lead to phase imbalances, reducing overall equipment lifespan. Leakage current measurements are also essential to assess the circuit breaker's insulation health, preventing potential electrical hazards and system inefficiencies [8].

Furthermore, power loss analysis provides insights into energy dissipation in circuit breakers due to electrical resistance at connection points [9]. Higher power losses indicate increased inefficiencies, which can significantly impact energy distribution [10]. By analyzing power loss based on injection current and feeder load current, it is possible to assess the circuit breaker's condition and predict its long-term performance [11][12]. These factors collectively influence the overall efficiency and reliability of high-voltage circuit breakers in electrical systems [13][14].

This study aims to comprehensively analyze the performance of 20 kV circuit breakers by evaluating key operational parameters, including insulation resistance, contact resistance, contact synchronization, leakage current, and power loss. The findings from this research will provide valuable insights into maintenance optimization and system reliability improvement. By employing statistical analysis and performance evaluations, this study contributes to the enhancement of circuit breaker operational integrity, ultimately supporting the stability and efficiency of high-voltage electrical networks.

2. Method

This study begins with a comprehensive literature review to examine previous research and theoretical frameworks related to circuit breaker performance. The review focuses on key operational parameters, including insulation resistance, contact resistance, load current, and contact simultaneity, which are critical for assessing the reliability and efficiency of 20 kV circuit breakers. Understanding these parameters is essential for evaluating the operational integrity of circuit breakers in high-voltage transmission and distribution networks.

The research involves systematic data collection through direct measurements of critical performance indicators. Insulation resistance measurements are conducted to assess the dielectric strength of the circuit breaker, while contact resistance measurements evaluate electrical conductivity and potential degradation. Additionally, load current data is collected to analyze operational conditions, and contact simultaneity measurements are performed to determine the synchronization of switching operations. These data points serve as essential benchmarks for assessing circuit breaker performance in the 20 kV outgoing cubicle. To ensure the accuracy and reliability of the collected data, all test instruments used—including insulation testers, micro-ohmmeters, and circuit breaker analyzers—are calibrated according to IEC standards prior to field measurements. Each measurement is repeated three times, and the average value is recorded to reduce random error. Outlier values are identified using interquartile range and standard deviation checks; any anomalies detected are verified against maintenance logs and remeasured when necessary. This validation process ensures that the data used for analysis is both consistent and representative of actual equipment performance.

The collected and validated data is analyzed using statistical methods to identify performance trends, anomalies, and potential degradation. A paired t-test is employed to compare measurements under different operating conditions, enabling a statistically rigorous evaluation of performance variations. A significance level of 0.05 is used to determine whether changes before and after maintenance are statistically significant. This approach provides valuable insights into the circuit breaker’s condition, contributing to enhanced maintenance strategies, reliability assessments, and the optimization of high-voltage electrical system operations.

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3. Results and Analysis

3.1 Comparative analysis of insulation resistance in phases R, S, and T

The analysis of insulation resistance for each phase shows varying levels of statistical significance. For phase R, the significance value of 0.065 exceeds the 0.05 threshold, leading to the acceptance of the null hypothesis (H_0). This indicates that there is no statistically significant overall increase in insulation resistance after maintenance. Similarly, for phase S, with a significance value of 0.166, the null hypothesis is also accepted, suggesting that maintenance does not result in a significant improvement in insulation resistance for this phase.

In contrast, for phase T, the significance value of 0.048 is below 0.05, resulting in the rejection of the null hypothesis. This finding indicates that maintenance has a statistically significant positive effect on the overall insulation resistance of phase T. The difference in results across the three phases suggests that the effectiveness of maintenance in improving insulation resistance may vary depending on specific phase characteristics or external influencing factors.

3.2 Comparative analysis of contact resistance in phases R, S, and T

The analysis of contact resistance across the three phases indicates no statistically significant reduction following maintenance. For phase R, the significance value of 0.209 exceeds the 0.05 threshold, leading to the acceptance of the null hypothesis (H_0). This suggests that maintenance does not result in a significant overall reduction in contact resistance. Similarly, for phase S, with a significance value of 0.243, the null hypothesis is also accepted, indicating that no significant decrease in contact resistance is observed after maintenance.

Likewise, for phase T, the significance value of 0.155 is greater than 0.05, leading to the acceptance of the null hypothesis. This confirms that maintenance does not have a statistically significant effect on reducing contact resistance in this phase. The consistent results across all three phases suggest that maintenance procedures may not substantially impact contact resistance, potentially due to stable initial conditions or the effectiveness of existing system components.

3.3 Comparison of contact synchronization in open condition for phases R, S, and T

The evaluation of contact synchronization in the open condition for the three phases reveals no significant decline following maintenance. In phase R, the significance value of 0.443 is greater than 0.05, leading to the acceptance of the null hypothesis (H_0). This indicates that maintenance has no substantial effect on reducing contact synchronization in the open condition. Similarly, in phase S, where the significance value is 0.397, the null hypothesis is also accepted, suggesting that no notable decrease in contact synchronization occurs as a result of maintenance.

For phase T, the significance value of 0.455 is also above 0.05, confirming that maintenance does not cause a statistically significant reduction in contact synchronization in the open condition. The uniformity of these results across all three phases suggests that the maintenance activities performed do not have a measurable impact on contact synchronization, possibly due to the system's stable operational state or minimal degradation of the contact components.

3.4 Comparison of contact timing in closed condition for phases R, S, and T

The assessment of contact timing in the closed condition reveals a significant decrease across all three phases following maintenance. In phase R, the significance value of 0.003 is below the 0.05 threshold, leading to the rejection of the null hypothesis (H_0). This indicates that maintenance has a statistically significant impact, resulting in an overall decline in contact timing consistency in the closed condition. Similarly, in phase S, where the significance value is 0.013, the null hypothesis is also rejected, confirming a notable reduction in contact synchronization after maintenance.

For phase T, the significance value of 0.007 is also below 0.05, signifying a significant decrease in contact timing alignment in the closed condition due to maintenance activities. The consistent decline observed across all three phases suggests that the maintenance procedures performed may have influenced the operational timing of the

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system, potentially affecting the synchronization of contact closure. These results highlight the importance of further analysis to identify underlying causes and ensure the stability and reliability of the system.

3.5 Leakage current calculation analysis of circuit breaker

The measurement was conducted at a phase-to-ground voltage of 20 kV, with the permissible leakage current limit set at 20 mA. The highest calculated leakage current was observed in the Eks Sumberejo feeder, measuring 0.297 mA, as shown in figure 1. This value remains significantly below the allowable threshold of 20 mA, indicating a substantial margin of safety.

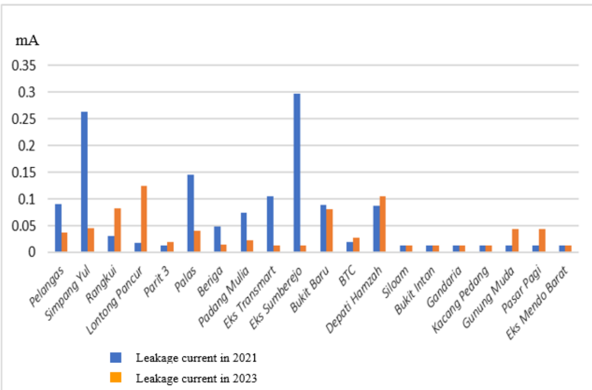

Figure 1. Leakage current

Based on the leakage current calculations performed during the insulation resistance test, the circuit breaker is confirmed to be in good condition and suitable for continued operation. Given the current measurement results, the circuit breaker is expected to remain operational and reliable for at least the next two years.

3.6 Power loss calculation analysis of circuit breaker based on injection current

As illustrated in figure 2, power losses in the circuit breaker are influenced by connection points within the breaker contacts. The highest power loss, based on injection current measurements, was observed in the Gandaria feeder at 17.89 watts, while the lowest power loss was recorded in the Parit 3 feeder at 0.991 watts. The analysis shows that as contact resistance increases, the power loss generated in each phase of the circuit breaker also increases.

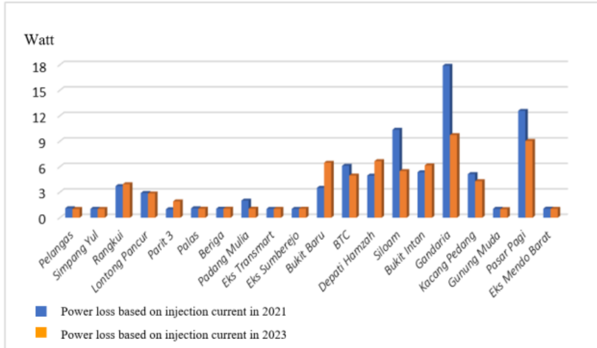

Figure 2. Power loss based on injection current

To ensure optimal performance, the contact resistance of the circuit breaker should remain below 100 μΩ to prevent excessive heating at the contact points. The heating phenomenon occurs due to the presence of multiple conductors at connection points, which introduces electrical resistance to the current flow. This resistance leads to heat generation and contributes to technical losses in the circuit breaker system.

3.7 Power loss calculation analysis based on feeder load current

The power loss calculation for circuit breakers in the Pangkal Pinang substation feeders was conducted using load current data and contact resistance test results. As shown in figure 3, the highest power loss was recorded in the Depati Hamzah feeder at 69.87 watts, while the lowest power loss was observed in the Eks Transmart feeder at 0.376 watts. The analysis confirms that higher contact resistance results in greater power loss.

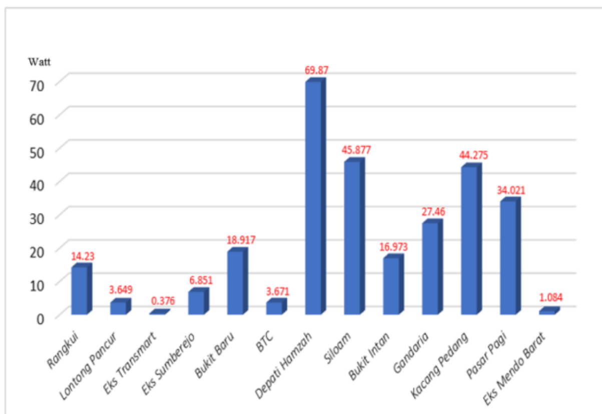

Figure 3. Power loss based on feeder load current

The feeder load significantly influences power loss, as each feeder experiences different loading conditions, leading to variations in current flow. Additionally, annual fluctuations in power loss are also affected by changes in contact resistance over time. Understanding these factors is essential for optimizing circuit breaker performance and minimizing energy losses in the distribution system.

3.8 Calculation of electrical energy loss in circuit breakers

Based on the calculation of electrical energy loss in the feeders at the Pangkalpinang substation, the highest energy loss was recorded in the Depati Hamzah feeder at 48.317 kWh, while the lowest energy loss occurred in the Eks Transmart feeder at 0.278 kWh. These variations indicate that different feeders experience different levels of energy dissipation.

The amount of electrical energy lost is influenced by the power loss in each circuit breaker. Higher power losses result in greater energy dissipation over time. Additionally, the magnitude of energy loss is affected by the current flowing through each circuit breaker, where an increase in current leads to higher energy losses. These findings highlight the importance of monitoring and minimizing power losses in circuit breakers to enhance the efficiency of the electrical distribution system.

4. Conclusion

The performance evaluation of 20 kV circuit breakers based on insulation resistance, contact resistance, contact synchronization, leakage current, and power loss has provided significant insights into their operational reliability. The analysis of insulation resistance revealed that phases R and S showed no statistically significant improvement after maintenance, with significance values of 0.065 and 0.166, respectively. However, phase T demonstrated a significant improvement with a significance value of 0.048, indicating that maintenance had a positive effect on its insulation properties. This suggests that the effectiveness of maintenance may vary depending on specific phase characteristics and external factors.

In terms of contact resistance, none of the phases (R, S, or T) showed statistically significant reductions after maintenance, with significance values of 0.209, 0.243, and 0.155, respectively. Similarly, contact synchronization in the open condition did not exhibit significant variations, with significance values exceeding 0.05 across all three phases. However, in the closed condition, all phases experienced a significant decrease in synchronization after maintenance, with significance values of 0.003, 0.013, and 0.007 for phases R, S, and T, respectively. This indicates that maintenance procedures may have influenced the timing consistency of contact closure, potentially affecting system performance.

The power loss analysis highlighted key inefficiencies in circuit breakers, with the highest power loss recorded in the Depati Hamzah feeder at 69.87 watts, while the lowest was in the Eks Transmart feeder at 0.376 watts. Similarly, energy loss calculations showed that the Depati Hamzah feeder experienced the highest energy loss at 48.317 kWh, whereas the Eks Transmart feeder had the lowest at 0.278 kWh. The study underscores the importance of monitoring contact resistance and load conditions to minimize energy dissipation. These findings emphasize the need for targeted maintenance strategies to enhance circuit breaker efficiency and extend operational lifespan in high-voltage electrical networks.

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