Journal of Emerging Innovations in Engineering
Volume 1, Number 02, October 2025
ISSN: 3110-3375
Open Access: https://jurnal.sutajaya.org/jeie

Analysis of gas pressure decline SF_6 in 70kV circuit breaker bay transformer 3 at Babakan substation

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Article Info
Received August 12th, 2025
Revised September 20th, 2025
Accepted October 15th, 2025

Keyword:
Circuit Breaker (CB);
Gas Leakage;
Babakan Substation;
Condition-Based Maintenance.

ABSTRACT (10 PT)
This study analyzes the decrease in SF_6 gas pressure in the 70 kV circuit breaker Transformer Bay 3 at Babakan Substation, which affects the reliability of the power system. SF_6 gas is used as an insulating medium due to its high dielectric strength but is susceptible to micro-leakage, which degrades equipment performance. This research employs a qualitative approach with a case study strategy based on primary data obtained from field observations, interviews, and testing documentation before and after the replacement of the T-phase pole. Gas pressure monitoring was conducted using a FLIR Gas 306 camera and digital measuring instruments, with thematic analysis employed to identify causes and evaluate repair effectiveness. The results showed that a fine leak at the lower T-phase pole was the main cause of gas pressure reduction. After pole replacement, the rate of pressure drop decreased from 0.00459 MPa/day to 0.00016 MPa/day, indicating a 35.3% increase in insulation effectiveness and a 64.6% reduction in leakage rate. Operational feasibility tests met the SPLN 52-1:1983 standard, confirming that the circuit breaker is suitable for operation. In conclusion, replacing the T-phase pole of the circuit breaker effectively restored equipment performance and enhanced transmission system reliability, while applying condition-based maintenance (CBM) and infrared detection proved efficient in identifying SF_6 leakage and supporting predictive maintenance practices at substations.

INTRODUCTION

Modern electric power systems demand high reliability from every transmission and distribution component to ensure continuity of electrical energy supply. One of the vital devices in such systems is the circuit breaker, which functions to protect the system from disturbances by interrupting electrical current during abnormal conditions. In recent decades, the use of sulfur hexafluoride (SF_6) gas as an insulation and arc-quenching medium in circuit breakers has become a global standard due to its dielectric strength being six times higher than air, chemical stability, and effectiveness in insulating high voltage (Ober et al., 2022). Nevertheless, SF_6 is also known as a greenhouse gas with significant global warming potential, making the management of its pressure and leakage a major concern from both technical and environmental perspectives (Wang et al., 2021). In Indonesia, the operation of

ISSN : 3110-3375
DOI: https://doi.org/10.47685/jeie.v2il.98

substations and circuit breaker equipment using SF_6 gas is strictly regulated by PLN and the Ministry of Energy and Mineral Resources to maintain power system reliability and prevent energy loss due to disturbances (energy not served). Therefore, periodic monitoring of SF_6 gas pressure conditions has become a crucial aspect of the preventive maintenance system across national substations (Riad, 2023).

Although SF_6-based circuit breaker technology has been widely implemented, numerous reports indicate a trend of SF_6 gas pressure decline that can cause degradation of insulation performance and increase the risk of equipment operational failure. Micro-leakage problems in SF_6 systems are often difficult to detect directly, necessitating accurate monitoring methods such as online monitoring with FLIR cameras or digital pressure sensors ng. In the context of substation operations, SF_6 gas leakage not only reduces technical efficiency but also impacts environmental risks and occupational safety (Kud et al., 2021a). In Indonesia, cases of SF_6 gas pressure decline in 70 kV circuit breakers, such as those occurring at Babakan Substation, reflect real challenges in maintaining sustainable and reliable transmission infrastructure. The scarcity of field studies addressing the analysis of SF_6 gas pressure decline causes specifically at the substation level creates a significant knowledge gap in both technical and academic contexts.

From a theoretical perspective, this research refers to the concepts of electric power system reliability and condition-based maintenance (CBM) theory, which emphasizes the importance of early detection of anomalies in equipment operating parameters (Liang & Hou, 2019a). CBM enables maintenance actions to be performed based on actual condition monitoring results rather than fixed time intervals, making it more efficient and effective (Liu et al., 2023). In the context of SF_6 circuit breakers, this method is used to monitor changes in pressure, temperature, and gas leakage levels that may indicate insulation degradation(Zhu et al., 2020a). This conceptual approach forms the basis of analysis in this research, utilizing direct field observations, interviews with operators, and documentation of circuit breaker functional test results following T-phase pole replacement.

Based on this background, the problem formulation in this research focuses on three main aspects: (1) how to analyze SF_6 gas pressure decline in the circuit breaker bay Transformer 3 at Babakan Substation; (2) how the circuit breaker performs after T-phase pole replacement; and (3) how effective the circuit breaker pole replacement action is in addressing the trend of SF_6 gas pressure decline due to leakage. The objectives of this research are to obtain technical analysis results of SF_6 gas pressure decline using maintenance evaluation methods, assess the operational feasibility of the circuit breaker after critical component replacement, and measure the effectiveness of maintenance actions on gas pressure stability over a certain period. Thus, this research is application-oriented and aimed at improving the reliability of the electric transmission system at Babakan Substation.

The scientific contribution of this research lies in the direct empirical study of SF_6 gas pressure decline phenomena in medium voltage circuit breakers in Indonesia, which is still rarely conducted systematically. Most previous studies focused on simulation aspects, material characterization, or laboratory analysis, while this research highlights actual operational and maintenance dynamics in the field (Rahman et al., 2022). The findings from this research are expected to enrich the literature related to SF_6 gas-based transmission equipment reliability management while providing practical recommendations for improving the predictive maintenance system within PLN. Additionally, this research contributes to the development of SF_6 leakage risk mitigation policies in the context of clean energy transition and operational efficiency of the national electric power system.

The circuit breaker is one of the main devices in the electric power transmission system that functions to disconnect and connect electric current under normal and fault conditions. Theoretically, the basic concept of circuit breakers refers to the principles of switchgear mechanics and arc extinction that enable the transmission system to remain stable during short-circuit faults. According to the IEEE C37.100 definition, a circuit breaker is a mechanical switching device capable of closing, carrying, and interrupting current under normal conditions and interrupting load current during abnormal conditions (Wang et al., 2021). In recent decades, the use of sulfur hexafluoride (SF_6) as an insulation and arc-quenching medium has become a global standard due to its high dielectric strength and excellent thermal

ISSN : 3110-3375
DOI: https://doi.org/10.47685/jeie.v2il.98

stability (Kud et al., 2021b). However, SF_6 is known as a greenhouse gas with a global warming potential 23,500 times greater than CO_2, making the management and maintenance of systems using this gas an important aspect of sustainable electric power system operations (Zhu et al., 2020b).

In the context of previous study results, research on SF_6-based circuit breaker performance has been extensively conducted from material, monitoring system, and maintenance management perspectives. (Liang & Hou, 2019b) investigated the integration of condition-based maintenance (CBM) systems in high voltage switchgear, demonstrating improved system reliability through early gas leakage detection. Zhang et al., (2021) developed infrared-based sensor technology to detect micro-leakage in SF_6 systems, which proved capable of identifying pressure decline before major disturbances occur. Other research by (Zhai et al., 2023) discussed mathematical models of SF_6 gas pressure changes due to ambient temperature variations and humidity factors, showing a direct relationship between climate conditions and insulation performance degradation. Meanwhile, in Indonesia, several field studies such as those by Nugroho and Kurniawan (2021) observed SF_6 pressure decline in medium voltage equipment at PLN substations, although their analysis remained limited to visual aspects and periodic inspection without integration with post-maintenance testing data.

Despite various research on SF_6 and circuit breaker reliability, there remains a significant research gap, particularly in the empirical field context related to SF_6 gas pressure decline analysis in operational substation units. Most previous studies focused on equipment design aspects, thermodynamic simulation, or sensor development but inadequately addressed how gas pressure decline phenomena occur in actual systems and how repair action effectiveness is applied practically. Additionally, research linking post-replacement testing results of components such as pole phase to overall circuit breaker performance remains relatively rare in both local and international literature (Riad, 2023). This gap indicates the need for field studies combining empirical observation approaches, technical measurements, and comparisons with maintenance standards to comprehensively understand SF_6 gas pressure decline dynamics.

This article occupies a strategic position in addressing this gap by combining a qualitative case study approach at Babakan Substation. This research not only identifies the causes of SF_6 gas pressure decline but also analyzes the effectiveness of T-phase pole replacement as corrective action against leakage detected through visual inspection and FLIR camera. Thus, this article's contribution lies in direct empirical testing of circuit breaker performance post-maintenance action, providing new perspectives on CBM procedure effectiveness in the Indonesian substation environment (Rahman et al., 2022). Academically, this research enriches the literature on SF_6-based transmission system reliability management and can serve as a reference for implementing predictive maintenance practices at the national level.

From theoretical and methodological perspectives, study trends in the past five years show significant increases in the use of Internet of Things (IoT) and machine learning-based technologies for circuit breaker and SF_6 gas condition monitoring. (Freire et al., 2022) demonstrated that IoT sensor integration with neural network-based SF_6 pressure prediction systems can improve anomaly detection accuracy up to 94%. Meanwhile, (Park, 2020) developed early warning systems based on classification algorithms to determine gas leakage risk levels. This approach shows methodological development direction toward smart maintenance, which is relevant to field research objectives such as those conducted at Babakan Substation, although this research maintains a manual observational approach based on primary data.

Conceptually, this literature synthesis confirms that the SF_6 gas pressure decline phenomenon in circuit breakers results from complex interactions between technical factors (such as seal conditions, internal pressure, and ambient temperature) and managerial factors (such as inspection frequency and maintenance effectiveness). CBM theory studies, reliability-centered maintenance (RCM) concepts, and gas pressure degradation models form the analytical basis used in this research (Zhu et al., 2020c). By understanding the interconnection between theory and maintenance practice, this research attempts

ISSN : 3110-3375
DOI: https://doi.org/10.47685/jeie.v2il.98

to present an integrated conceptual framework among technical, operational, and analytical aspects to examine the effectiveness of SF_6 gas-based circuit breaker maintenance actions empirically in the field.

RESEARCH METHODS

This research employs a qualitative approach with a case study strategy, which aims to deeply understand the SF_6 gas pressure decline phenomenon in the 70 kV circuit breaker bay Transformer 3 at Babakan Substation. The case study approach was chosen because it enables researchers to conduct intensive exploration of actual field conditions and identify factors causing gas pressure decline contextually and empirically. This approach is also relevant for explaining the relationship between maintenance actions—such as T-phase pole replacement—and circuit breaker performance changes post-repair. In the electric power system context, case studies are commonly used methods to evaluate technical intervention effectiveness in maintaining transmission equipment reliability (Hodencq et al., 2021).

The type of data used in this research is primary data, obtained directly from field observation results, in-depth interviews with substation technicians and operators, and documentation of circuit breaker performance test results before and after T-phase pole replacement. Primary data was chosen because it can provide empirical descriptions of actual system conditions and maintenance action results. Additionally, this research also uses supporting secondary data in the form of technical documents, maintenance standards, and inspection guidelines from PLN as well as academic references related to SF_6 gas management and circuit breaker maintenance. The combination of these two data types strengthens research finding validity by enabling source and perspective triangulation. (Creswell & Poth, 2018)

Data collection techniques were conducted through four main methods: (1) direct observation, (2) semi-structured interviews, (3) limited questionnaires, and (4) technical documentation. Observations were conducted by monitoring SF_6 gas pressure conditions in circuit breakers periodically using digital pressure gauge instruments and FLIR cameras to detect gas leakage. This method enables visual identification of micro-leakage points not detected through conventional pressure measurements (Zhang et al., 2021). Interviews were conducted with maintenance technicians, operators, and monitoring personnel at Babakan Substation to obtain contextual information regarding circuit breaker maintenance history and previously implemented actions. Limited questionnaires were used to obtain technician perceptions regarding T-phase pole replacement action effectiveness, while technical documentation included gas pressure test reports, leak test results, and routine maintenance reports.

The data inclusion criteria in this research include: (1) circuit breaker bay Transformer 3 test results data conducted between January and March 2019; (2) observation data showing SF_6 gas pressure decline trends; (3) post-T-phase pole replacement test results; and (4) official maintenance records from PLN Babakan Substation. Meanwhile, exclusion criteria include: (1) test data from circuit breakers other than bay Transformer 3; (2) data without supporting technical documentation; and (3) test reports not conforming to PLN format or standards. Establishing these criteria is intended to maintain analysis focus and ensure that all data used are relevant to research objectives. Using selection criteria also strengthens data trustworthiness in qualitative studies through credibility and confirmability principles (James, 2017).

The unit of analysis or research subjects in this study is the 70 kV circuit breaker system bay Transformer 3 at Babakan Substation, along with technical personnel directly involved in maintenance and testing activities. The selection of Babakan Substation as the research location was based on field findings indicating significant SF_6 gas pressure decline in February 2019. Research subjects include three participant categories: (1) maintenance technicians responsible for routine inspections, (2) substation operators who monitor the system in real-time, and (3) maintenance management staff who determine technical policies. This multiple participant approach provides information depth and enables holistic analysis of the maintenance process and its impact on circuit breaker performance.

Journal of Emerging Innovations in Engineering Vol. 1 No. 02 October 2025
ISSN : 3110-3375
DOI: https://doi.org/10.47685/jeie.v2il.98

The data analysis technique used is thematic analysis, with steps including: (1) collection and transcription of field data, (2) open coding to identify main themes such as pressure decline causes, repair effectiveness, and post-pole replacement performance, (3) data grouping based on thematic categories, and (4) result interpretation by comparing empirical data against technical standards and scientific literature. This analysis was conducted iteratively until meaning saturation was achieved. This approach follows the thematic analysis model developed by (Braun & Clarke, 2006), which is effective for systematically and transparently interpreting technical qualitative data. To enhance reliability, analysis results were verified through method triangulation among observation, interviews, and documentation, as well as member checking with field respondents. Analysis was conducted with the assistance of NVivo 12 Plus software for coding processes and data management, enabling more comprehensive visualization of themes and inter-variable relationships.

This methodological approach is designed to produce deep and empirical understanding regarding SF_6 gas pressure decline dynamics in circuit breakers and evaluate maintenance action effectiveness based on verified and systematically analyzed primary field data.

RESUL AND DISCUSSION

Results

This research found that SF_6 gas pressure decline in the 70 kV circuit breaker bay Transformer 3 at Babakan Substation was caused by micro-leakage in the lower pole of T-phase, which was detected using FLIR Gas 306 camera. Thermovision results indicated temperature anomalies and gas leakage indications in that area. After investigation and repair in the form of T-phase circuit breaker pole replacement on June 30, 2020, the SF_6 gas pressure decline trend showed significant improvement.

1. Pressure Decline Trend Before Pole Replacement

Four SF_6 gas pressure decline trends before pole replacement showed rapid decline with an average pressure loss rate of 0.00459 MPa/day or 0.65% per day.

Table 1. SF_6 Gas Decline Trend Before Pole Replacement (2019–2020)

Observation Period	Initial Pressure (MPa)	Final Pressure (MPa)	Duration (Days)	Average Decline (MPa)
Feb–May 2019 (Trend 1)	0.70	0.64	78	0.06
May–Sep 2019 (Trend 2)	0.72	0.64	99	0.08
Sep–Nov 2019 (Trend 3)	0.72	0.65	67	0.07
Nov-2019–Jun-2020 (Trend 4)	0.72	0.64	142	0.08

Average pressure decline rate before repair: 0.00459 MPa/day

2. Pressure Decline Trend After Pole Replacement

After T-phase pole replacement on June 30, 2020, monitoring was conducted for one year until July 1, 2021. Results showed much slower pressure decline, with a rate of only 0.00016 MPa/day or 0.23% per day, indicating improved SF_6 gas insulation system effectiveness.

Table 2. SF_6 Gas Decline Trend After Pole Replacement (2020–2021)

Observation Period	Initial Pressure (MPa)	Final Pressure (MPa)	Duration (Days)	Average Decline (MPa)
Jun 2020 – Jul 2021	0.72	0.66	366	0.06

Average pressure decline rate after repair: 0.00016 MPa/day

3. Pole Replacement Effectiveness Comparison

Comparison between conditions before and after pole replacement demonstrates improved circuit breaker system reliability:

ISSN : 3110-3375
DOI: https://doi.org/10.47685/jeie.v2il.98

Table 3. T-Phase Circuit Breaker Pole Replacement Effectiveness

Parameter	Before Replacement	After Replacement	Effectiveness (%)
Average pressure decline (MPa/day)	0.00459	0.00016	35.3% more efficient
Daily pressure decline percentage	0.65%	0.23%	−64.6% gas loss rate reduction

4. SF_6 Gas Decline Trend Comparison Graph

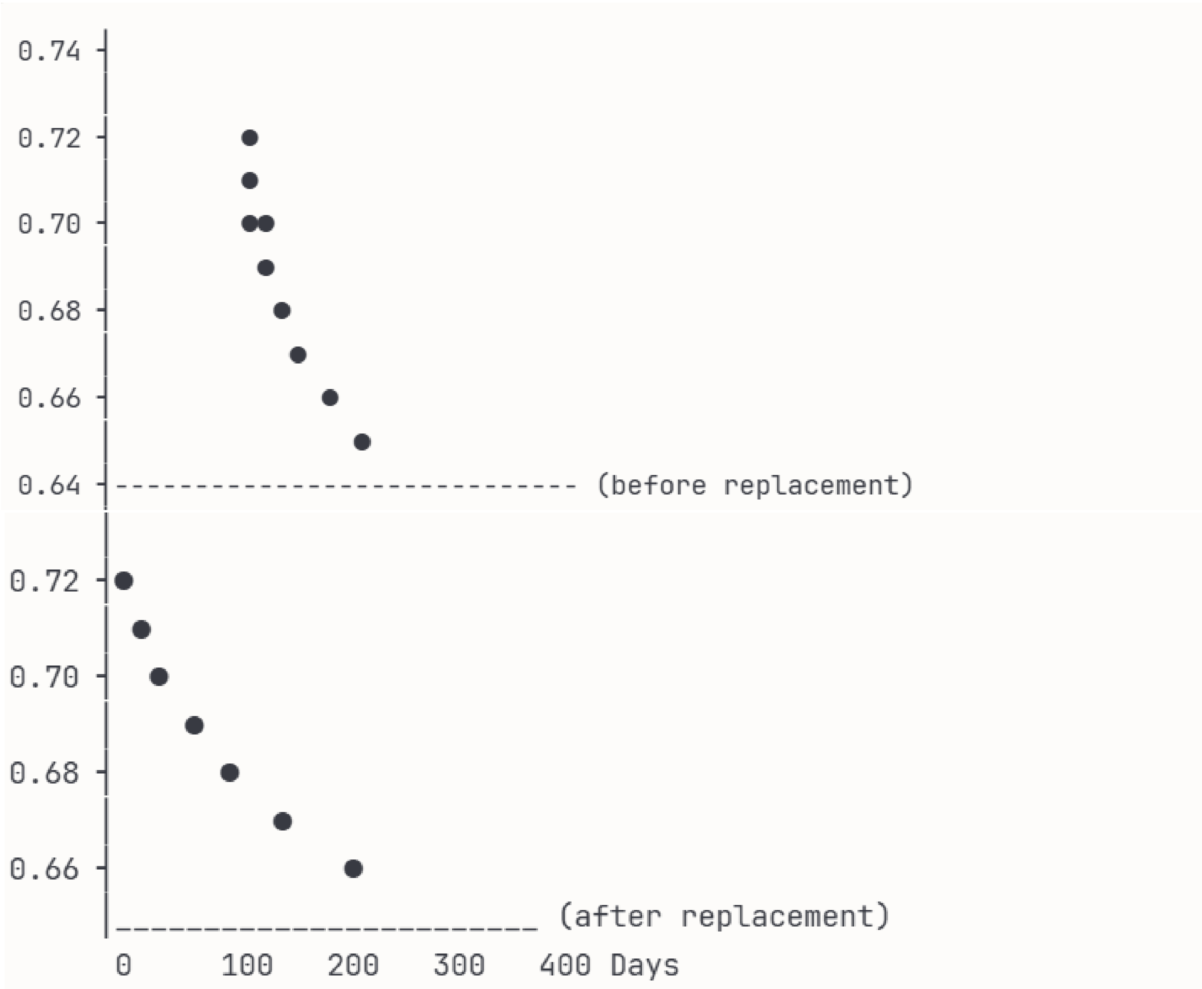

Figure 1. SF_6 Gas Decline Trend Comparison Graph

The graph above illustrates that SF_6 gas pressure decline is much gentler after pole replacement, indicating successful maintenance action.

5. Operational Feasibility Testing

- Insulation resistance: >1000 GΩ (above standard 1 kV = 1 MΩ)
- Contact resistance: 33–46 μΩ (below limit of 50 μΩ)
- Synchronization (Closing Time): <150 ms (meets SPLN 52-1:1983)
- Grounding resistance: 0.3 Ω (better than limit <1.0 Ω)

ISSN : 3110-3375
DOI: https://doi.org/10.47685/jeie.v2il.98

All test results indicate that circuit breaker bay Transformer 3 is suitable for operation and the repairs successfully restored insulation performance and system reliability significantly.
Visual conclusion: T-phase circuit breaker pole replacement proved effective in reducing SF_6 gas pressure decline rate by 35.3%, extending equipment lifespan, and maintaining electric transmission system reliability at Babakan Substation.

Discussion

Research results regarding SF_6 gas pressure decline in the 70 kV circuit breaker bay Transformer 3 at Babakan Substation indicate that micro-gas leakage in the lower pole of T-phase was the primary cause of gas pressure decline, which impacted circuit breaker operational reliability. This phenomenon aligns with previous findings that SF_6 pressurized circuit breaker systems have high reliability but remain vulnerable to degradation due to micro-leakage in sealing systems, pressure, and internal humidity (Yu-Guo, 2011).

Significant SF_6 gas pressure decline implies reduced equipment dielectric capability and increased insulation failure risk. A study by Fuhai et al., 2019) Lin et al. found that sudden leakage in 500 kV circuit breakers can cause drastic pressure decline and result in unexpected disturbances. This condition can be exacerbated by mechanical factors such as metal joint wear, gasket deformation, and sealant degradation due to extreme temperature exposure and continuous cyclic pressure.
The application of FLIR cameras and continuous pressure monitoring in this research represents best practice in condition-based maintenance (CBM), which has become the modern standard for high voltage equipment maintenance. According to (Jian-Bo (2010), infrared-based leakage detection technology has high sensitivity in detecting SF_6 gas even at leakage below 0.1%, making it highly effective for preventive monitoring. These results are reinforced by real-time monitoring system method development by (Ogiboski et al., 2011), which emphasizes the importance of pressure and humidity sensors for early gas leakage detection.

This research also demonstrates T-phase pole replacement effectiveness in reducing pressure loss rate from 0.00459 MPa/day to 0.00016 MPa/day. These results indicate successful reliability-centered maintenance action. Vianna et al. developed quantitative models to prioritize maintenance based on condition indices and actual equipment reliability, proven effective in reducing SF_6 circuit breaker failure risk (Vianna et al., 2017). The 35.3% leakage rate reduction after pole replacement in this research shows that condition-based maintenance programs can extend equipment lifespan and reduce transmission system disturbance risk.

From a sustainability perspective, these results are also relevant to global greenhouse gas emission reduction initiatives because SF_6 has a global warming potential 23,900 times greater than CO_2 (Naveen et al., 2013). Therefore, maintenance based on pressure monitoring and gas leakage also contributes to electric power sector environmental mitigation targets.

A recent study by (Lindskog et al., 2024) shows that using pressure comparison algorithms between circuit breakers can detect leakage as small as 0.1% per year in just two weeks, demonstrating potential digital system application for future SF_6 monitoring. This method can be integrated into data-driven maintenance systems to improve operational efficiency at substations like Babakan.

Circuit breaker operational feasibility testing results after pole replacement are also consistent with findings by (Saravanan et al., 2015) who recommend insulation resistance, contact resistance, and operational synchronization testing as main parameters for high voltage circuit breaker function feasibility. Testing values in this research were all above SPLN 52-1:1983 standards, indicating corrective action effectiveness on gas insulation systems.

Additionally, global Gas Insulated Substation (GIS) maintenance trends show a shift from time-based maintenance toward predictive maintenance, utilizing digital sensors to monitor pressure, temperature, and SF_6 gas quality simultaneously (Zamani et al., 2024). Research results at Babakan Substation align with this development direction, where the combination of pressure measurement and infrared visualization becomes an effective strategy for early detection and gas leakage control.

ISSN : 3110-3375
DOI: https://doi.org/10.47685/jeie.v2il.98

Conceptually, these findings strengthen the theory that condition-based maintenance (condition monitoring) is the most efficient approach to maintain high-pressure equipment reliability at substations while supporting energy efficiency policies and environmental emission reduction (Vianna et al., 2017). Therefore, these research results are not only technically relevant in the context of circuit breaker maintenance at Babakan Substation but also have strategic value for modern power system maintenance practices and global electric power industry decarbonization efforts.

CONCLUSION

This research concludes that SF_6 gas pressure decline in the 70 kV circuit breaker bay Transformer 3 at Babakan Substation was caused by micro-leakage in the lower pole of T-phase, which directly impacted circuit breaker system reliability decline. Through online monitoring processes using FLIR Gas 306 camera and pressure trend analysis, the leakage was successfully identified and accurately verified. T-phase circuit breaker pole replacement action proved effective in reducing SF_6 gas pressure decline rate from 0.00459 MPa/day to 0.00016 MPa/day, with insulation system effectiveness improvement up to 35.3% and gas loss rate reduction of 64.6%. This change demonstrates that condition-based maintenance strategy can extend equipment lifespan, reduce system failure risk, and maintain electric power service continuity at substations.

Post-repair testing results—including insulation resistance, contact resistance, operational synchronization, and grounding resistance—all met SPLN 52-1:1983 standards, indicating that the circuit breaker is suitable for operation with high reliability levels. Scientifically, this research contributes to strengthening early diagnosis practices and SF_6 gas maintenance management on high voltage equipment while supporting greenhouse gas emission reduction efforts in the national electric power system. Additionally, these findings confirm that integration of thermal visual monitoring and gas pressure analysis represents an effective and efficient approach to detect and prevent insulation failure in modern substation environments. Thus, this research not only provides practical benefits for equipment maintenance at Babakan Substation but also offers a predictive maintenance application model that can be replicated in other electric transmission and distribution systems.

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