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Analysis of Abnormal Nitrogen Leakage in 500KV Circuit Breaker

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Abstract: High-voltage switches are widely used in 500kV substations, where nitrogen leaks are a common occurrence during operation. This paper provides a detailed analysis of the abnormal nitrogen leak incident involving the No.5041 switch of the No.3 main transformer at the 500kV Danxi Substation. By examining the monitoring backend signals, inspecting on-site equipment, and studying the relay circuits, the cause of the anomaly was identified, and effective solutions were proposed. The analysis revealed that the anomaly was caused by a fault in the K15 relay, not a genuine nitrogen leak. The paper summarizes the handling process and the issues exposed, providing a reference for the analysis and handling of similar anomalies.

Keywords: 500kV substation; main transformer switch; nitrogen leakage; relay fault

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1. Introduction

The stable and reliable operation of high-voltage switchgear plays a critical role in ensuring the overall safety and stability of the power grid. Among the various faults that may occur in such equipment, nitrogen leakage is a relatively common but serious issue. When nitrogen leaks from high-voltage switches, it can lead to the malfunctioning of key components, resulting in equipment lockout or disconnection. These failures, if not addressed promptly and effectively, have the potential to trigger cascading faults and cause more severe disruptions within the power grid. This article takes the nitrogen leakage incident at the 5041 switch of the No.3 main transformer in the 500 kV Danxi Substation as a detailed case study. By integrating thorough on-site inspections with in-depth circuit logic analysis, it identifies the root causes behind the anomaly and evaluates the effectiveness of the handling measures implemented. The insights and technical solutions derived from this investigation not only resolve the immediate fault but also serve as valuable references for diagnosing and managing similar nitrogen leakage problems in other substations, thereby contributing to improved maintenance practices and grid reliability [1].

2. Overview of Anomalies

At 18:56 on June 12, 2024, the Danxi transformer monitoring background reported an alarm of N_2 leakage for the No.3 main transformer 5041 switch. On-site inspection found that the pressure of phase A of the 5041 switch was 35.5MPa, and the other two phases were 35MPa, and the oil pump of phase A frequently started.

A nitrogen leak in a circuit breaker can trigger severe chain reactions: as the critical medium for maintaining insulation and arc quenching, a drop in pressure can cause a sudden decrease in gas insulation strength, potentially leading to internal discharge or explosion within the equipment. It also weakens the circuit breaker's ability to interrupt faults, preventing fault currents from being effectively cut off. If nitrogen is used for energy storage in the operating mechanism, insufficient pressure can directly result in delayed or failed operations of the circuit breaker, leading to failure in fault clearance and causing system-wide incidents such as over-level tripping and grid instability. Additionally, the leakage can force the equipment to shut down urgently, causing unplanned power outages. Water intrusion accelerates insulation degradation, and abnormal operation of the mechanism exacerbates mechanical wear [2]. Ultimately, the costs of emergency repairs and economic losses due to power outages can be dozens of times higher than routine maintenance. If the failure to operate is due to nitrogen leakage from the accumulator, it can lead to the burning of the main transformer, resulting in losses exceeding tens of millions of yuan. Therefore, nitrogen leakage is an urgent defect that could trigger grid-level accidents and must be addressed immediately [3].

3. Fault Equipment Information

The 5041 switch of the No.3 main transformer is Hangzhou high voltage 3AT2EI, which was put into operation in December 2005 and last overhauled in May 2019.

The causes of nitrogen leakage in circuit breakers can be summarized into four types of systematic failures, which affect from micro sealing to macro structure.

3.1. Sealing System Degradation

The core issue is the hardening and cracking of rubber seals (such as O-rings and gaskets) due to thermal cycling, ozone exposure, and arc decomposition products. Additionally, local stress concentration can result from burrs in the sealing groove or assembly misalignment. Furthermore, uneven installation torque can cause plastic deformation of the sealing surface, and high-temperature carbonization of the sealing grease can lead to failure, all of which can compromise the airtightness [4].

3.2. Connection Structure Defects

In mechanical connections, flange bolts are prone to loosening over extended periods of vibration, particularly when subjected to the resonant frequency range of 15 to 30 Hz commonly encountered in Gas-Insulated Switchgear (GIS) equipment. This persistent vibration prevents the threaded interfaces from maintaining the necessary yield tightening torque, which compromises the mechanical integrity of the connection and may lead to equipment malfunction or failure. Additionally, during the manufacturing process, defects such as welding porosity in aluminum alloy tanks and internal shrinkage cavities within cast components can gradually develop into fully penetrating channels under the influence of operational pressures reaching up to 80 bar. These evolving defects further threaten the structural reliability of the equipment, increasing the risk of leakage or rupture during service [5,6].

3.3. Key Component Failure

For valve-type equipment, the sealing packing around the pneumatic valve stem tends to wear out over time due to continuous mechanical movement and pressure fluctuations. Additionally, the bellows component of the density relay is susceptible to fatigue failure, with the risk of breakage increasing sharply after approximately 100,000 operational cycles [7]. These degradations significantly elevate the likelihood of leakage and system malfunction. In the operating mechanism, aging of the vulcanization layer within the hydraulic spring accumulator capsule can cause nitrogen to infiltrate into the hydraulic oil, thereby compromising the hydraulic system's integrity. Furthermore, uneven wear or misalignment of the piston rod seal ring can create gaps that result in leakage, with rates potentially reaching up to 5 liters per minute. Such leakages degrade system performance and increase maintenance demands, posing substantial risks to reliable operation [7].

3.4. Environmental Erosion and External Damage

-40℃ to +80℃ drastic temperature change causes the sealing member to shrink beyond the limit; coastal station salt spray corrosion of aluminum shell forms electrochemical perforation); equipment transportation impact leads to micro-cracks in thin wall pipe fittings.

The essence of leakage is the result of the imbalance between material performance boundary, manufacturing process tolerance and dynamic operating stress. To prevent leakage, it is necessary to establish a "sealing life spectrum", promote laser welding instead of TIG welding to improve weld density, and predict the risk of bolt loosening through vibration spectrum analysis [8].

4. On-Site Inspection and Circuit Analysis

4.1. Rapid Disposal Analysis

4.1.1. Background Signal Verification

Check the alarm information of the monitoring system: confirm the alarm type, occurrence time, and whether it is continuous or intermittent. Compare the historical pressure curve: check whether the pressure is really continuously decreasing or suddenly jumping and then stabilizing [9]. Check the related signals: whether there are auxiliary alarms such as "relay fault" and "control circuit disconnection".

4.1.2. On-Site Pressure Verification

Read the on-site pressure gauge: First, check the mechanical pressure gauge on the switch body or the mechanism box. If the pressure is normal and stable, it is highly suspected that there is a fault in the relay or circuit. If the pressure continues to drop, confirm a real leak and initiate the emergency leak process. Compare with the backend data; if the on-site meter is normal but the backend shows low pressure, check whether the transmitter or acquisition module is faulty.

4.2. Monitoring Background Signal Analysis

The analysis of the monitoring background signals reveals that, prior to the nitrogen leakage alarm, there was no indication of frequent pressure suppression events involving the oil pump. This suggests that the oil pump was operating within normal parameters and was not undergoing abnormal cycling or interruptions that could have triggered early warnings [10,11].

Furthermore, the duration of the pressure suppression periods did not show any significant reduction before the alarm was issued. This stability in pressure suppression timing indicates that the anomaly was not caused by transient pressure fluctuations or typical operational variations, thereby narrowing the scope of potential fault sources for further investigation.

4.3. Relay Action Analysis

Contact test: the multimeter measures the alarm/locking contact state of the relay. When the pressure is normal, it should be open; if it is continuously closed, it is determined to be adhesion or jamming. Simulate the pressure change and test whether the contact action value conforms to the set value.

Internal inspection: disassemble and inspect the relay, check whether the bellows is broken, whether the mechanical mechanism is stuck, whether the microswitch is oxidized.

4.4. Clean Internal Oil and Dust

On-site inspection revealed that the K14 (first jump ring nitrogen leakage lockout breaker relay) and K82 (second jump ring nitrogen leakage lockout breaker relay) were flashing green, indicating that the lockout breaker timing was in progress. After resetting with the S4 key, the signal temporarily disappeared, but the oil pump start signal reappeared. Shortly after resetting, the oil pump start signal was triggered again. However, since the motor power had been disconnected, the actual pressure did not increase. The inspection results are shown in Figure 1 and Figure 2.

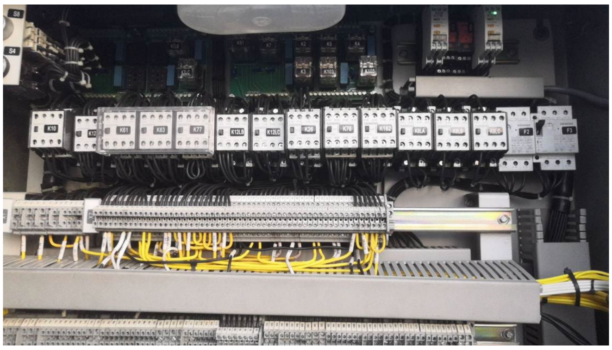

Figure 1. Relay in the Switchgear Box of No.3 Main Transformer 5041.

Figure 2. Inspection of K15 Relay and K67 Relay.

At the same time, the background reports the 5041 switch A phase pressure timeout signal. On-site inspection shows that the K67 signal light of the pressure timeout lock oil pump relay is flashing, and the K15 switch oil pump start control time relay is working. The on-site personnel use the S4 key to reset the pressure timeout.

4.5. Circuit Logic Analysis

Loop insulation test: Measure the insulation resistance between K15 output terminal and ground to eliminate the ground misoperation. Terminal fastening: Check whether the relay terminal strip and cable joint are loose. Power voltage detection: Confirm that the working voltage of the relay is within the rated range.

By analyzing the nitrogen leakage signal circuit and the oil pump control circuit, the causes of the abnormality are determined as follows:

1) K15 relay fault: The abnormal operation of K15 relay leads to the frequent start of the oil pump and triggers the false nitrogen leakage signal.
2) False signal reset: After the S4 key is reset, the K15 relay acts again to form a cycle (Figure 3).

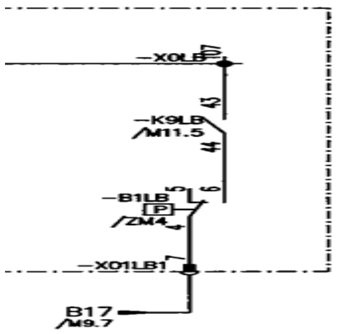

Figure 3. Nitrogen Leak Signal Circuit.

5. Cause Analysis and Verification

5.1. Abnormal Reasons

The primary cause of the abnormality was identified as a fault within the K15 relay. Specifically, the internal contact of the relay exhibited abnormal behavior, which led to the oil pump starting prematurely, even before the required pump pressure was reached. This malfunction disrupted the normal control sequence and contributed directly to the nitrogen leak anomaly.

Additionally, a false nitrogen leakage signal was generated due to the frequent and unintended starting of the oil pump. This abnormal operation repeatedly triggered the K81 relay, causing it to activate a lockout mechanism and open the timing circuit. As a result, the system was further compromised, amplifying the operational irregularities and complicating the fault diagnosis process.

5.2. Verification Method

To verify the cause of the abnormal operation, the B1 wire connected to the K15 relay was disconnected and removed. Despite this disconnection, it was observed that the oil pump continued to start frequently, indicating that the issue was not related to the B1 contact itself. This crucial test effectively ruled out the B1 contact as the source of the problem.

Based on this verification, attention was focused on the K15 relay, which was determined to be the root cause of the fault. The relay was confirmed to be locked in a malfunctioning state, leading to the abnormal behavior of the oil pump and the subsequent nitrogen leak anomaly.

6. Treatment Measures and Effects

After accurately identifying the faulty component responsible for the malfunction, the on-site maintenance team swiftly proceeded to replace the defective K15 relay with a new, fully functional unit. This immediate corrective action successfully restored the normal start and stop operations of the oil pump, indicating that the root cause of the malfunction had been effectively eliminated and that the equipment had returned to its proper operational condition. To further verify the robustness of the repair and ensure the long-term reliability of the system, a rigorous three-cycle functional test was conducted. This procedure involved executing three consecutive cycles of starting and stopping the oil pump following the depressurization of the system. Throughout the entire testing phase, no abnormal behaviors or operational issues were observed, providing compelling evidence that the repair was successful and that the equipment was functioning in a stable and reliable manner. This comprehensive verification process not only confirmed the resolution of the original fault but also demonstrated the effectiveness of the maintenance measures implemented.

7. Exposure Problems and Control Measures

7.1. Exposure Issues

Inherent Defects in Relay Family: The K15 relay series may possess inherent design or manufacturing defects, which can compromise performance and reliability under certain operating conditions. These latent issues increase the likelihood of failures during prolonged use or in high-stress scenarios.

Inadequate Spare Parts Management: The current management and reserve of spare parts are insufficient, particularly when responding to emergency situations. A lack of critical components can delay repairs and system recovery, thereby affecting overall equipment availability and reliability.

7.2. Control Measures

Inventory and Replacement of Similar Relays: Conduct a comprehensive statistical survey of relays similar to the K15 series across the system. Replace relays with identified or potential defects. In addition, establish a preventive maintenance program that includes inspection of contact action pressure for density relays at regular intervals — specifically, every two years.

Enhancement of Operation and Maintenance Records: Improve the integration between background system data and on-site operation and maintenance records to enable better linkage analysis. Incorporate real-time pressure data into the online monitoring system to facilitate automatic detection of anomalies such as gradual nitrogen leakage or erratic signal fluctuations ("signal jump"). This enables early warning and timely intervention.

Key Equipment Management: Establish robust emergency response protocols to ensure that critical equipment can be quickly restored to normal operation when faults occur. This includes maintaining an adequate inventory of key spare parts, ensuring rapid access to essential tools, and training personnel to perform emergency repairs effectively.

8. Conclusion

This article presents an in-depth analysis of a nitrogen leak anomaly that occurred at switch 5041 of the No.3 main transformer in the 500 kV Danxi Substation. Through a comprehensive investigation of the equipment status, circuit logic, and on-site inspection results, it was determined that the primary root cause of the incident was a failure of the K15 relay. The malfunction of this critical component disrupted the normal operation of the system, ultimately leading to the nitrogen leakage event. Based on the findings of this case study, the article proposes a set of targeted and practical solutions to mitigate similar risks in the future, including improvements in relay testing protocols, enhanced preventive maintenance strategies, and optimized equipment configuration. Furthermore, the analysis highlights key lessons learned, emphasizing the vital role of rigorous relay quality management and the importance of maintaining an adequate inventory of spare parts. These measures are essential to ensuring the long-term reliability, stability, and safety of power grid equipment, and this case study offers a valuable technical reference for industry practitioners addressing similar equipment anomalies.

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