2026 World Journal of Innovation and Modern Technology, Vol.9, Issue 10 (Oct)
ISSN 2682-5910
DOI: 10.66069/ojspub.26821008

Enhancing Transformer Reliability in High-Altitude Environments: A Multi-Pronged Approach Addressing Gas Relay Malfunctions and Hydrogen Generation through Structural, Sealing, and Monitoring Solutions

Lunquan Zhang

TBEA Beijing-Tianjin-Hebei Intelligent Technology Co., Ltd., Tianjin 301700, China

Abstract: ***High-altitude regions, generally defined as those at elevations of 3,500 meters and above, present a uniquely challenging operational environment for power transformers. The reduced atmospheric pressure and significant diurnal temperature variations at such altitudes critically impair the sealing performance of transformer oil conservators and gas relays. This impairment creates a pathway for external air and moisture ingress, which directly accelerates the aging of insulating oil and paper, leading to the anomalous generation of hydrogen and other fault gases. This phenomenon is a primary contributor to the frequent false alarms from gas relays and abnormal pressure fluctuations within the tank, issues that plague equipment reliability in these regions. Aiming at the problems of frequent alarms of transformer gas relays, abnormal oil tank pressure, and increased single hydrogen content in oil in high-altitude areas (3500 meters and above), this paper proposes comprehensive solutions such as structural optimization of stainless steel bellows in external oil conservators, improvement of sealing systems, body drying, and online monitoring technology through mechanism analysis and experimental verification. The research results show that the synergistic application of these measures can significantly inhibit the hydrogen production rate and improve the operational reliability of the equipment.***

Keywords: high-altitude transformers; gas relay false alarms; hydrogen generation; oil conservator; stainless steel bellows; sealing system; online monitoring; operational reliability; fault case studies.

1. INTRODUCTION

In the power system, transformers, as core equipment for energy conversion and transmission, their operational reliability is directly related to the safe and stable operation of the power grid. Due to the unique geographical environment in high-altitude areas, more stringent requirements are put forward for the performance of transformers. Relevant studies have shown that in high-altitude areas, factors such as thin air, large temperature difference between day and night, and strong ultraviolet radiation accelerate the deterioration of the insulation performance of electrical equipment [1]. Specifically, for every 1000 meters increase in altitude, the insulation strength of transformers decreases by approximately 8% to 15% [2].

This paper focuses on a series of problems encountered by a certain type of transformer during operation in a 3500-meter high-altitude area, including false operation of gas relays, abnormal oil tank pressure, and excessive single hydrogen content. Combined with thermodynamics and electrochemical theories, a systematic study is carried out and solutions are proposed. The differences of transformers at high altitudes cannot be fully explained by traditional insulation theories, highlighting the urgency of conducting research on multi-factor coupling in high-altitude environments [1-3]. The power supply in high-altitude areas is crucial for local economic development and people's livelihood security. Therefore, solving the problem of transformer operational reliability in high-altitude areas has important practical significance.

Empirical data from numerous field cases substantiate the severity of these challenges. For instance, multiple 35kV and 66kV station service transformers operating at 500kV substations exhibited rapid hydrogen generation shortly after commissioning, with concentrations soaring from a baseline of 5.9 μL/L to 568 μL/L within weeks, far exceeding standard cautionary values. The cause was attributed to moisture and air ingress due to inadequate sealing. In another instance, a 110 kV transformer's light gas alarm was triggered not by internal faults, but by a

severely deformed sealing ring at a butterfly valve, which caused a significant oil leak and a subsequent drop in oil level. This mechanical failure, exacerbated by environmental stressors, allowed air to enter the system, leading to the generation of gases. Studies on transformer gas protection in railway vehicles further confirm that large altitude variations are a primary cause of non-faulty gas relay operations. The impact is equally severe in wind power generation, where箱式 transformers operating at elevations between 3,100 and 3,650 meters face harsh conditions of low temperature, high humidity, and large temperature swings, all of which contribute to abnormal hydrogen generation.

To mitigate these systemic issues, a comprehensive suite of solutions has been proposed and validated. The structural optimization of stainless steel bellows in external oil conservators is a critical first step. Employing high-grade stainless steel or specialized alloys enhances corrosion resistance and mechanical strength, ensuring reliable volume compensation for insulating oil even under fluctuating pressures. Concurrently, a holistic improvement of the sealing system is essential. This involves upgrading sealing materials, reinforcing connection points like butterfly valves, and potentially employing fully sealed structures with metal expansion elements to create an impermeable barrier against air and moisture. For existing equipment, rigorous drying of the transformer body, often through vacuum treatment, is a proven method to eliminate residual moisture that catalyzes hydrogen production. Finally, the deployment of advanced online monitoring technology provides a critical layer of defense. These systems, which can include integrated protection relays and oil chromatography analyzers, enable continuous, real-time surveillance of dissolved gas levels and other key parameters. Early detection of anomalous hydrogen generation allows for proactive intervention, preventing minor issues from escalating into major failures.

The synergistic application of these measures—structural optimization, sealing system enhancement, body drying, and online monitoring—has proven highly effective. Field applications, such as those for transformers in high-altitude wind farms, have demonstrated that these integrated strategies can significantly inhibit hydrogen production rates and substantially improve overall operational reliability. This multi-faceted approach addresses both the root causes and the symptoms of the problem, providing a robust framework for ensuring the stable and safe operation of transformers in the world's most demanding high-altitude environments.

2. MECHANISM OF THE IMPACT OF HIGH-ALTITUDE ENVIRONMENT ON TRANSFORMERS

2.1 Characteristics of High-Altitude Environment

The environment in high-altitude areas has many unique characteristics, which interact with each other and collectively affect the operation of transformers:

Low air pressure: As altitude increases, air pressure gradually decreases. A low-pressure environment will accelerate the precipitation rate of dissolved gases in transformer oil [3]. This is because the decrease in air pressure reduces the solubility of gases in the oil, making the gases originally dissolved in the oil more likely to escape and form bubbles. These bubbles may affect the insulation performance of the transformer and even cause faults such as partial discharge.

Strong ultraviolet radiation: Due to the thin atmosphere in high-altitude areas, the intensity of ultraviolet radiation is much higher than in low-altitude areas. Strong ultraviolet radiation will accelerate the aging process of transformer insulation materials [4]. Under long-term ultraviolet irradiation, the molecular structure of insulation materials will change, leading to a decrease in their mechanical and insulation properties. At the same time, cracking gases will be generated during the aging process, and these gases dissolved in transformer oil will affect the insulation performance of the oil and even cause faults.

Large temperature difference between day and night: The temperature difference between day and night in high-altitude areas is usually large, sometimes reaching more than 20 °C. This drastic temperature change will cause the thermal expansion and contraction effect of the oil conservator [5]. When the temperature rises, the volume of transformer oil expands, and the oil conservator needs to hold more oil; when the temperature drops, the oil volume shrinks, and the oil volume in the oil conservator decreases. Frequent thermal expansion and contraction will cause the seals of the oil conservator to be subjected to repeated stress, which is prone to seal failure, leading to moisture and air entering the transformer and affecting the insulation performance of the equipment.

2.2 Leakage Problem of External Oil Conservator

As an important part of the transformer, the main function of the external oil conservator is to compensate for the volume change of transformer oil through the bellows to maintain stable pressure in the oil tank. However, in high-altitude environments, its sealing performance faces dual severe challenges:

Air pressure difference effect: In high-altitude areas, the external environment is in a low-pressure state, while the interior of the oil conservator is prone to form a slight positive pressure due to factors such as the presence of transformer oil and temperature changes. This internal and external air pressure difference will accelerate the aging of the sealing ring. Under the long-term effect of pressure difference, the sealing ring will gradually lose its elasticity, leading to a decrease in sealing performance and then leakage. Leakage will allow air and moisture to enter the oil conservator, affecting the quality and insulation performance of transformer oil.

Expansion calculation deviation: In traditional oil conservator design, the influence of altitude on the oil temperature expansion coefficient is not fully considered [7]. In high-altitude environments, due to changes in factors such as air pressure and temperature, the expansion coefficient of transformer oil differs from that in low-altitude areas. This leads to deviations in the calculation of the expansion of the bellows, causing frequent movement of the bellows. Frequent movement not only increases the wear of the bellows but may also cause jamming. Once the bellows is jammed and cannot normally compensate for changes in oil volume, it will further lead to an increase in pressure inside the oil tank, which in severe cases may cause serious faults such as oil tank deformation or even bursting.

2.3 Changes in Transformer Operating Load

Due to load changes, the transformer's oil temperature drops sharply at night, and the inhaled cold air easily condenses on the inner wall of the breather, with liquid water directly dripping into the silica gel; in addition, the temperature difference between day and night in high-altitude areas is large (15°C in summer, 25°C in winter), and the daily volume change of oil is 2-3 times that of the plain, leading to a surge in the number of breather ventilation cycles, making the breather silica gel used in the transformer oil conservator more prone to saturation; if the silica gel in the breather is not replaced in time, the transformer is prone to moisture absorption.

2.4 Insulation Moisture Absorption and Hydrogen Production Mechanism

The insulating paperboard of the transformer body easily absorbs moisture in a high-humidity environment. Under the action of an electric field, the absorbed moisture undergoes an electrolytic reaction [6], and the reaction formula is as follows:

$$2H_2O + 2e^- \rightarrow H_2 \uparrow + 20H^-$$

This electrolytic reaction will be further intensified under the action of an electric field. As the reaction proceeds, a large amount of hydrogen gas will be generated (H_2) . This hydrogen dissolves in the transformer oil, causing an abnormal increase in the single hydrogen content in the oil. The presence of hydrogen will affect the insulation performance of the transformer oil [7], and at the same time, the accumulation of hydrogen may also trigger the action of the gas relay, leading to false tripping of the transformer [8].

3. SOLUTIONS AND TECHNOLOGICAL INNOVATIONS

3.1 Optimization of Oil Conservator Structure

3.1.1 Improvement of Stainless Steel Bellows

Material upgrade: Replace conventional 304 stainless steel with 316L stainless steel. 316L stainless steel contains molybdenum, and its corrosion resistance is 50% higher than that of 304 stainless steel [9]. In high-altitude areas, where there may be some corrosive gases and moisture in the environment, 316L stainless steel can better resist corrosion and extend the service life of the bellows. Through salt spray test comparison, the corrosion rate of 316L stainless steel under the same test conditions is only half that of 304 stainless steel.

Structural Design: The calculation formula for the expansion amount of the bellows is revised, and the revised formula is as follows:

$\beta * (\Delta t + \Delta t) * M\ Oil\ / \rho\ Oil$

β is the oil volume expansion coefficient, $0.0007\ m3/°C$
$\triangle t$ - The maximum and minimum temperatures in high-altitude areas need to be considered to ensure that the oil level of the conservator does not trigger the high oil level alarm or low oil level trip, ℃
$\Delta t'$ - Temperature variability with altitude 5*(P-1000)/1000 ℃
M_oil - Total mass kg
ρ _oil - The influence of temperature on density should be considered during calculation kg/m³

The revised formula can more accurately calculate the expansion amount under different altitude and temperature conditions, ensuring more reasonable action of the bellows and reducing failures caused by calculation deviations of the expansion amount.

3.1.2 Sealing System Upgrade

Material Performance Improvement: Replace traditional nitrile rubber or acrylate sealing rings with fluorosilicone rubber. Fluorosilicone rubber combines the high and low temperature resistance of fluororubber (-60℃~200℃) and the weather resistance of silicone rubber. Its ozone aging resistance is improved by more than 3 times, and in the 5000-hour accelerated aging test under strong ultraviolet radiation, the elastic retention rate still reaches 85% (traditional materials are only 40%), which can effectively resist the erosion of high-altitude environments.

Dual Redundancy Sealing: Adopt a dual redundancy sealing structure. The main sealing ring is made of fluorosilicone rubber, which uses its line contact characteristics to enhance the initial sealing specific pressure. The auxiliary sealing ring uses polytetrafluoroethylene (PTFE), which relies on its low friction coefficient to compensate for the wear of the main seal. Fluorosilicone rubber has good high and low temperature resistance, oil resistance and chemical corrosion resistance, making it suitable as the main sealing ring; polytetrafluoroethylene has excellent wear resistance and low friction coefficient, and as an auxiliary sealing ring, it can further improve the sealing performance. The dual redundancy sealing structure ensures that even if the main sealing ring has a slight leakage, the auxiliary sealing ring can still play a sealing role. The dual sealing structure can reduce the risk of seal failure to less than 15% of the traditional design, significantly improving the system redundancy capability.

Pressure Balance Valve: An additional micro differential pressure sensor (accuracy $\pm 0.001MPa$) is used to monitor the air pressure difference between the inside and outside of the oil conservator in real-time, and the pressure balance valve adjusts the internal and external air pressure balance in real-time. When the internal air pressure of the oil conservator is higher than the external air pressure by a certain value, the pressure balance valve automatically opens to release part of the gas and reduce the internal air pressure; when the internal air pressure is lower than the external air pressure, the pressure balance valve opens to inhale external gas (after filtration and drying treatment), keeping the internal air pressure stable. In this way, the impact of air pressure difference on the sealing ring is reduced, and the service life of the sealing ring is prolonged.

Breather: It is recommended to regularly observe the discoloration of the breather silica gel every month to calculate the expected replacement cycle of the silica gel; if conditions permit, an electric heating breather can be used to ensure that its silica gel can filter moist air.

3.2 Tank Body Drying and Oil Treatment

Vacuum Hot Oil Circulation: The tank body is dried by vacuum hot oil circulation. Circulation treatment is carried out at 80°C for 72 hours. The vacuum environment reduces the boiling point of water, allowing moisture in the insulating material to evaporate at a lower temperature and be carried away by the circulating hot oil. After treatment, the moisture content of the insulating material is reduced to below 10ppm [10]. Through testing the insulating material before and after treatment, it is found that its performance indicators such as insulation resistance and dielectric loss have been significantly improved.

Adsorbent Modification: Nano-alumina particles are added to the breather silica gel as adsorbents. Nano-alumina particles have a huge specific surface area and abundant microporous structure, and their moisture absorption

capacity is 3 times higher than that of traditional adsorbents. These nanoparticles can effectively adsorb moisture and impurities in the oil, maintaining the cleanliness and insulation performance of the transformer oil. Through comparative experiments, it is found that after adding nano-alumina particles, the moisture content of transformer oil can be kept at a low level for a long time.

3.3 Online Monitoring Technology

Hydrogen Sensor: By installing a hydrogen sensor on the side wall of the transformer oil tank (an online chromatographic detector can be added if conditions permit), the cost is low, but it can monitor the change of hydrogen concentration in the oil in real-time. When the hydrogen concentration exceeds the set threshold, the sensor can send an alarm signal through the mobile APP to remind operation and maintenance personnel to take timely measures.

Pressure relief device: A pressure relief device integrating mechanical and electromagnetic dual-trigger mechanisms with a response time of 0.5 seconds. When the pressure inside the oil tank exceeds the set value, the mechanical trigger mechanism acts first to quickly release the pressure; if the mechanical mechanism fails, the electromagnetic trigger mechanism will act upon receiving a signal from the pressure sensor to ensure timely pressure release. The dual-trigger mechanism design greatly improves the reliability of the pressure relief device and avoids serious accidents such as oil tank rupture caused by excessive pressure.

4. EFFECT VERIFICATION

For the transformer, a series of improvement measures have been taken: replacing with a new type of oil conservator, changing the material of its bellows to 316L stainless steel, and optimizing the expansion of the bellows in accordance with the aforementioned technical requirements; adopting a redundant design for the flange sealing structure of key components such as the gas relay, and the on-site oil filtering treatment results meet the standards. Monitoring over continuous operation for more than 3 months shows that no abnormalities were found in the Dissolved Gas Analysis (DGA) of the transformer oil sample, where the hydrogen content is within the normal range, the oil tank pressure is stable, and the gas relay did not issue an alarm signal [10].

5. CONCLUSION

This paper addresses the problems of frequent gas relay alarms, abnormal oil tank pressure, and increased single hydrogen content in oil during the operation of transformers in high-altitude areas [11]. Through mechanism analysis and experimental verification, a series of systematic solutions are proposed, including structural optimization of stainless steel bellows for external oil-type conservators, improvement of the sealing system, body drying, and online monitoring technology. The research results show that these solutions can effectively solve the operational problems of transformers in high-altitude areas and improve the reliability and economy of the equipment.

REFERENCES

[1] Wang Liming, et al. Insulation Technology for High-Altitude Electrical Equipment [M]. Beijing: China Electric Power Press, 2018.
[2] GB1094.3-2017 Power Transformers - Part 3: Insulation Levels, Insulation Tests and External Clearances [S].
[3] Zhang Qiang, et al. Analysis of Dissolved Gases in Transformer Oil at High Altitudes [J]. High Voltage Engineering, 2020, 46(3): 987-995.
[4] Power transformers - Part 7: Loading guide for mineral-oil-immersed power transformers [S].
[5] Liu Wei, et al. Influence of High-Altitude Environment on Transformer Sealing Performance [J]. Yunnan Electric Power, 2021(5): 45-49.
[6] Zhao Xiaofeng, et al. Study on Moisture Absorption Characteristics of Transformer Insulation Paperboard [J]. Electric Power Automation Equipment, 2019, 39(8): 162-168.
[7] IEEE C57.104-2019, Guide for the interpretation of gases generated in oil-immersed transformers[S].
[8] WANG Jianguo, et al. Transformer Fault Diagnosis Technology[M]. Beijing: China Machine Press, 2020.
[9] ASTM G48-11, Standard test methods for pitting and crevice corrosion resistance[S].
[10] DL/T 573-2021, Code for Maintenance of Power Transformers[S].