Fault Analysis and Improvement Measures for a Batch of Oil-immersed Inverted-type Current Transformers: Postprint

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Abstract

Through dissection, testing, and comparative analysis of a batch of oil-immersed inverted current transformer failure cases, the causes of mass failures are summarized, and recommendations are proposed from the aspects of equipment manufacturing, transportation, installation, handover acceptance, and operation and maintenance.

Full Text

Preamble

Fault Analysis and Improvement Measures of Oil-Immersed Inverted Current Transformers

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Abstract: This paper analyzes a series of accident cases involving oil-immersed inverted current transformers through dissection, testing, and comparative analysis. The root causes of these batch failures are summarized, and recommendations are proposed from the perspectives of equipment manufacturing, transportation, installation, commissioning acceptance, and operation and maintenance.

Keywords: Inverted current transformer, accident cases, suggestions

1 Introduction

In recent years, oil-immersed inverted current transformers have gradually replaced conventional upright oil-immersed current transformers due to their significant advantages, though they impose higher requirements on design standards and manufacturing processes [1]. Designers must thoroughly understand equipment operating environments, particularly oil level variations caused by temperature differences. Manufacturing processes demand stricter quality control and more careful material selection, while oil level control during operation requires greater caution, and transportation stability requirements are also more stringent [2]. This paper analyzes the failure conditions of 330kV current transformers at Lanzhou-Xinjiang Railway dedicated line substations and proposes improvement recommendations. The objective is to fundamentally address the deficiencies of this type of current transformer, optimize design structures, improve manufacturing quality, strictly control manufacturing processes, reduce grid accidents caused by oil-immersed inverted current transformer failures, and ensure safe and stable grid operation.

2 Current Transformer Fault Statistics

The Lanzhou-Xinjiang Railway dedicated line (Gansu-Qinghai section) integrated power and electrification project installed a total of 102 AGU-330 current transformers. These units were commissioned between June 28 and December 1, 2014. From June 28 to November 6, 45 units were energized, with no abnormalities observed through December 8. However, between November 24 and December 8, five units experienced failures and three exhibited abnormal oil levels, as detailed in Table 1 . The data reveals that from November 17 to December 8, a total of 57 units were energized, with eight experiencing faults or abnormalities, representing a failure rate of 14.03%. Among the failed transformers, 62.5% involved rupture and fire of the porcelain bushing or oil conservator, indicating that the accidents caused severe damage with extremely serious consequences.

3 Accident Investigation and Analysis

3.1 Field Dissection and Analysis

On December 6, field dissection was performed on the phase A unit (model: AGU-363, serial number: 13A07251-1) with abnormal oil level at Hongliuhu South Substation, as shown in Figure 1 [Figure 1: see original paper]. Oil samples were collected for chromatographic analysis. The dissection images revealed that the insulation wrapping paper showed no wrinkles, and the manufacturing process complied with standards. Oil test results showed: CO content 18.44 L/L, CO content 128.46 L/L, CH content 366.23 L/L, C H content 75.17 L/L, C H content 0.64 L/L, and H content 1,249.33 L/L. The presence of characteristic gases such as C H , CH , and H indicates internal insulation moisture contamination in the transformer. Based on multiple field observations, no oil leakage was found in the transformers, making it impossible for moisture to enter the internal components. The likely cause was incomplete drying during the manufacturing process. Under the action of the electric field, water electrolyzes to produce H . When H content becomes high, bubbles form. These bubbles experience higher electric field strength than the oil, and under high field strength, further ionization occurs. The resulting ions impact hydrocarbon molecules, breaking C-H and C-C bonds and accelerating insulation material degradation, leading to partial discharge, overheating, and minor arcing [3]. The manufacturer reviewed the complete process records for this batch, from design, process, raw materials, insulation wrapping, core drying, product assembly, testing to packaging, and discovered that during the core drying process, the furnace loading quantity seriously exceeded standards. The regulation specifies that for 330kV current transformers, each drying furnace should contain 10-12 units [4], but this batch loaded more than 18 units per furnace, resulting in uneven heating and incomplete drying of some products. Due to local defects and moisture contamination, the insulation strength was reduced. Under operating voltage, local overheating at defect locations generated gas that gradually accumulated, eventually causing the expansion device to rupture.

Inspection of five burning current transformers at Qingshuibei, Datong, and Shibandun South substations revealed that the metal expansion devices had ruptured and caught fire, and the oil conservators had exploded, as shown in Figure 2 [Figure 2: see original paper]. The primary windings were severely damaged, and most of the external insulation layers of the secondary windings were seriously burned, as shown in Figures 3 [Figure 3: see original paper] and 4 [Figure 4: see original paper]. The inner surface of the secondary winding shield showed obvious discharge traces, as shown in Figure 5 [Figure 5: see original paper]. Expert group dissection confirmed that all five transformers experienced main insulation failure, with discharge occurring between the primary winding conductor and the secondary winding shield. The discharge arc caused sudden internal pressure increase, resulting in explosion of the transformer head oil conservator and ignition of combustible gas upon contact with air.

3.2 Factory Disassembly Inspection

To further investigate the accident causes, one abnormal transformer was returned to the factory for testing and disassembly, as shown in Figure 6 [Figure 6: see original paper]. From December 16-17, the current transformer underwent relevant verification tests at the factory. Routine tests (such as winding DC resistance, current ratio, and low-voltage dielectric loss) revealed no abnormalities. Based on accident analysis requirements, a special 5-hour test under power frequency voltage was conducted, consisting of partial discharge measurements followed by high-voltage capacitance and dielectric loss measurements after each partial discharge test.

(1) Partial Discharge Test

Test data are presented in Table 2 . The regulation specifies that for 330kV current transformers, partial discharge should not exceed 20pC at 1.1U /√3 voltage.

This transformer exhibited 118pC partial discharge when voltage was increased to 109kV, with discharge increasing as voltage rose. At 200kV, discharge increased to 6,000pC, though it decreased over time. The first test indicated that the transformer insulation oil contained bubbles or voids that broke down under electric field action. The second test broke down remaining bubbles or discharge products, stabilizing the condition, though fixed discharge persisted based on the values. To further develop the discharge, the third test conducted long-duration partial discharge detection at 1.2U /√3 voltage. After approximately one hour, discharge began to increase rapidly under electric field action.

(2) Capacitance and Dielectric Loss Measurement
Test data are presented in Table 3 . The first two measurements showed capacitance and dielectric loss values close to factory test data. In the third test, after voltage increased to 100kV, dielectric loss increased significantly by 0.13 compared to the second test. The fourth test showed even more pronounced changes compared to the third, with changes exceeding double and dielectric loss increasing abnormally, indicating possible damage to some capacitive screens in the secondary winding section.

(3) Insulation Oil Chromatographic Analysis
After partial discharge detection, chromatographic analysis of insulation oil revealed that as test duration extended, gas contents of H and CH increased slightly while other gases showed no significant change, indicating no possibility of arc discharge. The changes in H and CH content resulted from breakdown of attached bubbles during partial discharge [5-6].

(4) Low Temperature and Temperature Difference Tests
To identify the root cause of the family defect, the manufacturer placed this transformer and another qualified unit from the same batch in a heating container, heated to 60°C, completed vacuum oil filling, then cooled to 5°C. The transformer oil level remained within normal range. After opening the top sealing cover, the oil level dropped approximately 3.5-5 cm, requiring 17L of oil replenishment to restore normal level. Literature [3] research on insulation oil thermal expansion shows that with a thermal expansion coefficient of 0.00073 in the temperature range of -17.5°C to 65°C, this transformer' s oil filling volume is approximately 420L. Assuming 400L of insulation oil was injected at 60°C, cooling to 5°C would reduce volume to 384L, representing a 16L change. Investigation revealed this batch completed vacuum oil filling in August (at 28°C), while equipment commissioning occurred in early December during severe winter (temperature -10°C to -30°C), representing a temperature difference of 38-58°C, consistent with simulation experiments. With constant transformer volume, insulation oil contracted at low temperatures. Under low pressure and surface tension, oil climbed along the walls, creating intermediate voids and bubbles, as shown in Figure 7 [Figure 7: see original paper]. The secondary winding external insulation separated from the oil surface, causing uneven voltage distribution. Under light load and high field strength conditions, bubble breakdown and gap discharge reduced insulation medium strength, gradually destroying

capacitive screens [12], eventually causing discharge between the primary winding conductor and secondary winding shield. The discharge arc caused sudden internal pressure increase, resulting in explosion of the transformer head oil conservator. Additionally, for small-volume equipment after drying treatment, moisture is inevitably introduced during vacuum oil filling at normal temperature, which does not affect insulation under normal operation. However, at low temperatures, the solubility of water differs between insulation materials and oil. At low temperatures, moisture in insulation oil is released into insulation materials to reach new equilibrium. After absorbing moisture, insulation material performance further degrades [13], and the incomplete drying defect in this batch further accelerated insulation material deterioration (more prominent for electrical equipment commissioned in low-temperature environments).

4 Improvement Measures

4.1 Technical Transformation

(1) When introducing foreign technology, carefully study the structure of inverted current transformers and fully consider equipment operating environments, particularly in regions with low temperatures, large temperature differences, and high altitudes. Comprehensively evaluate insulation oil characteristics after thermal expansion/contraction and electric field distribution [8], establish mathematical models, calculate insulation margins, and verify through repeated testing to find optimal design solutions. Address accidents caused by negative pressure, bubble or gap formation, and uneven electric field distribution due to insulation oil contraction at low temperatures. For defects in this batch, experts and manufacturers recalculated and increased the magnetic bushing diameter from 500mm to 600mm, adopting 500kV oil-immersed inverted transformer design for the head dimensions, increasing total container volume by approximately 150L. Calculations further optimized electric field distribution and increased insulation margins. Temperature tests on modified products effectively reduced oil climbing along walls after low-temperature contraction and decreased electric field distribution between end screens.

(2) Develop new capacitive screen materials with excellent flexibility, air permeability, small expansion coefficient, corrosion resistance, and high tensile strength.

(3) Further research on fixing of inverted current transformer head support components and capacitive screen connections to prevent capacitive screen damage and secondary winding displacement caused by vibration, jolting, and lifting during transportation [14].

(4) For small-volume, vacuum oil-filled products, design sampling valves should be considered to facilitate oil sampling and live oil replenishment during operation, with clear specifications for allowable sampling frequency and volume per sampling.

(5) For equipment operating in harsh environments, manufacturers must clearly specify required tests and inspections before commissioning in low temperatures.

(6) Oil-immersed inverted current transformers should adopt series-connected expansion devices (with 适当增加串组数量 -适当增加串组数量), enhancing internal cavity interconnection, oil flow, pressure transmission, and pressure relief buffering capabilities [15]. Improve oil level indicators by setting oil level limit marks to ensure adequate oil volume during sudden temperature drops.

4.2 Improving Product Manufacturing Quality

(1) Equipment manufacturing must strictly follow production processes. Prohibited practices include rushing schedules due to supply factors, violating production control procedures, and allowing defective products to leave the factory. Strict control of processes such as winding insulation wrapping, drying, impregnation, and testing is essential to improve product quality from the source.

(2) Improve equipment material and component quality. Manufacturers should select the highest quality capacitive screen materials, winding materials, housing materials, and reliable component suppliers. Eliminate electrical breakdown accidents caused by improper material selection at the root, replacing cast iron components and sealing materials with high-quality new materials.

(3) Strictly control materials selected for transformer top sealing covers, high-voltage insulation bushings, and base flange sealing surfaces, using materials with consistent contraction coefficients to prevent oil leakage caused by sudden temperature changes.

4.3 Equipment Testing

(1) In addition to completing routine and special tests, factory tests should include high-voltage capacitance and dielectric loss measurements at half operating voltage and operating voltage.

(2) DL/T417-2006 "Guide for On-site Measurement of Partial Discharge in Electrical Equipment" specifies partial discharge measurement duration of 5 minutes at 1.1U $/\sqrt{3}$ voltage. It is recommended to extend partial discharge measurement duration to 30 minutes before transformer delivery to verify manufacturing quality.

(3) Newly installed electrical equipment should complete full-item tests, actively conduct comparative tests, and communicate with manufacturers promptly when differences from factory test data are found. Where conditions permit, spot-check partial discharge and capacitance tests before commissioning are recommended.

(4) Before equipment installation and commissioning, complete handover acceptance tests according to relevant standards.

(5) Equipment stored for extended periods should repeat handover tests. For new products commissioned in low-temperature environments, strictly complete relevant tests and inspections according to factory instructions and increase equipment patrol frequency.

4.4 Operation and Maintenance

(1) Before commissioning, check whether grounding connections at all locations are reliable, such as end-screen grounding of capacitive transformers, to prevent false grounding with internal suspension, and check grounding grid conditions to prevent virtual connection between end screens and grounding grids.

(2) Develop and install transformer online monitoring devices and live detection equipment, utilizing condition-based maintenance methods such as partial discharge and infrared temperature measurement to promptly understand transformer operating status and eliminate accidents in their infancy.

(3) During operation, in addition to actively conducting condition-based maintenance and online monitoring, strictly implement relevant provisions of testing procedures for preventive testing and closely monitor equipment operating conditions.

5 Conclusion

Through tracking and analysis of a batch of oil-immersed inverted current transformers with family defects, this paper identified accident causes and proposed solutions, presenting countermeasures from the perspectives of technical transformation, product manufacturing, equipment testing, and operation and maintenance.

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Note: Figure translations are in progress. See original paper for figures.