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Electromagnetic Coupling and Diagnostic Test Analysis of Power Transformer Turn-to-Turn Short Circuit

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ABSTRACT: The power transformer serves as a critical hub equipment in the electric power industry, performing the core functions of voltage transformation and power transmission in power grids. Among various potential hazards, through-fault short-circuit impacts are particularly destructive, capable of inducing severe deformation of the transformer windings and even triggering internal faults, thereby posing a major threat to grid stability. Consequently, accurate diagnosis of transformer damage after short-circuit impacts and scientific formulation of targeted overhaul strategies are of vital practical significance for ensuring safe and reliable power supply. In this paper, a comprehensive diagnostic analysis method for transformer turn-to-turn short circuits is proposed, based on the electromagnetic coupling principle of the leakage circuit. To verify the method's effectiveness, two typical tripping events of 220 kV transformers caused by internal winding turn-to-turn short circuit faults are investigated as case studies. During on-site diagnostic tests, it is found that individual test items yield inconsistent fault indications, making it impossible to accurately locate the fault location and root cause relying on a single testing approach. Therefore, by integrating fault recording file analysis and multi-dimensional diagnostic test data, combined with in-depth research on the transformer's electrical and magnetic circuit fault mechanisms, this study successfully identifies turn-to-turn short circuit faults occurring in different windings of the transformers and determines their exact positions. The validity and feasibility of the proposed comprehensive diagnostic analysis method are fully confirmed by the results of subsequent on-site dismantling inspections.

KEYWORDS: Transformer; diagnostic electrical test; turn-to-turn short circuit; winding deformation; electromagnetic coupling

1 Introduction

As a core component of the electric power industry, the reliability of transformer operation is crucial for maintaining the safety and reliability of the power grid. Turn-to-turn faults in transformer windings, as a common internal insulation problem, are particularly prominent in large transformers. According to statistics, such failures account for 60% to 70% of power system faults [1–4]. Therefore, transformer winding turn-to-turn short-circuit has become an important type of fault in the power industry that cannot be ignored, and how to effectively detect and diagnose this fault has also become an urgent research hotspot [5–9].

According to the test items stipulated in the power industry standard of the PRC, DL/T596-2021 [10], “Preventive Test Procedures for Electric Power Equipment”, the fault detection encompasses various aspects, including gas chromatography in oil, DC resistance test of winding, insulation resistance test of winding, dielectric loss angle tangent measurement of insulation, oil quality detection, partial discharge detection and insulation voltage withstand test in many aspects [11–14]. Different test methods for the detection of various types of transformer faults have different relevance [15–17]. When the test results are contradictory or inconsistent, it is necessary to comprehensively consider the test results, potential causes of faults, transformer structural characteristics, and simulation data [18–20], in order to realize the comprehensive diagnosis and analysis of transformer faults [21,22].

This paper presents two actual cases of a transformer turn-to-turn short-circuit fault initiated by an external short-circuit. Under this circumstance, the transformer’s medium voltage side of winding suffered a near-zone short circuit that caused the transformer to trip. During the diagnostic tests performed in the field, there was variability in the indication of the fault by each test [23]. By considering the cause of the near-zone short-circuit, the results of the oil chromatography analysis, and the results of the tests, and analyzing the inverse of the diagnostic test data with different indications, we successfully determined that there was a turn-to-turn short-circuit within the winding of the MV side of the transformer. This case not only provides a practical basis for transformer fault analysis but also accumulates valuable experience for the comprehensive diagnosis of transformers [24].

2 Power Transformer Inter-Turn Short Circuit Diagnosis Analysis

2.1 Winding Turn Insulation and Electromagnetic Equivalent Model

The electrical characteristics of the transformer turn-to-turn insulating material can be equivalently described by a parallel circuit, as shown in Fig. 1. Where the resistance R_{turn} denotes the resistive component of the dielectric material, which reflects the insulation loss characteristics of the turn-to-turn medium; C_{turn} represents the capacitance of the dielectric; I_R is the resistive leakage current flowing through the resistance R_{turn} ; I_C is the capacitive leakage current flowing through the capacitance C_{coil} .

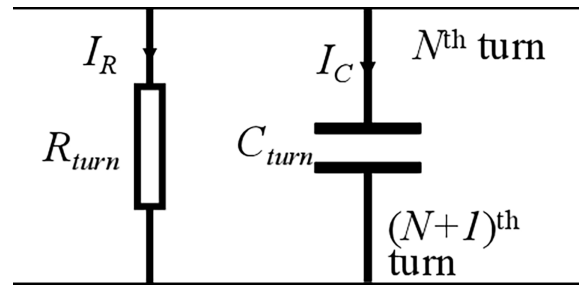


Figure 1: Parallel equivalent circuit with interturn insulation.

Transformer turn-to-turn insulation is good, the resistance R_{coils} is very large, and the current I_R is almost zero, at this time the turn-to-turn leakage current is dominated by the capacitive component I_C , and the energy loss of the insulating medium is negligible. With the deterioration of turn-to-turn insulation caused by electrical stress, thermal aging or mechanical damage, the resistance R_{turn} is getting smaller and smaller, the resistive leakage current I_R increases sharply, and the Joule heat generated by the resistive current leads to a significant increase in the energy loss of the insulating medium, forming a vicious circle of further insulation degradation. When a short-circuit occurs due to insulation breakdown between turns, R_{turn} decreases rapidly to a very low value, and the resistive leakage current I_R far exceeds the capacitive

leakage current I_C , the equivalent parallel capacitive reactance branch is negligible at this point, and the turn-to-turn equivalent circuit is approximately a pure resistive short-circuit loop.

The turn-to-turn insulation resistance R_{turn} is related to the material properties and thickness of the insulation paper. For mineral oil-immersed transformers, the initial value of R_{turn} is usually greater than $10^{12} \Omega$. When the insulation deteriorates due to thermal aging or electrical stress, R_{turn} decreases exponentially. The capacitive reactance of C_{turn} is much larger than R_{turn} under power frequency conditions, so the leakage current is mainly resistive. When R_{turn} drops below $10^6 \Omega$, the resistive current I_R increases significantly, leading to local overheating and further insulation degradation.

2.2 Interturn Short Circuit Electromagnetic Coupling Model

Taking the double-winding transformer as an example, when a turn-to-turn short circuit occurs, the fault equivalent circuit is shown in Fig. 2. Fig. 2: U_p , I_p for the primary winding phase voltage, phase current; U_L for the secondary winding phase voltage, I_L for the secondary winding phase current, Z_L for the secondary winding load impedance; I_{sc} for the short-circuit coil through the short-circuit turn-to-turn current, R_{sc} for the short-circuit turn-to-turn contact resistance.

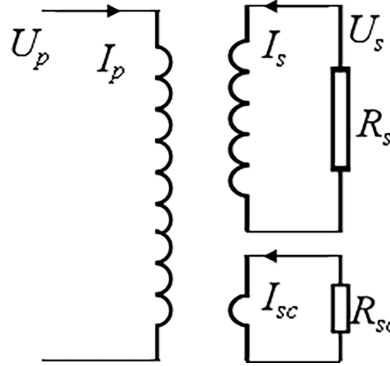


Figure 2: Equivalent model of inter-turn short circuit in transformer winding.

Normally, R_{sc} is negligible, then at this time, the primary and secondary side voltage ratio variable k_{sc} is:

$$k_x = \frac{U_p - U_{sc}}{U_s}$$

where U_{sc} is the impedance voltage of the short-circuit winding converted to the primary winding. It can be seen, whether the primary side or secondary side of the winding turn-to-turn short-circuit, short-circuit winding forms a closed independent short-circuit coil. The existence of a short-circuit coil changes the transformer's internal magnetic circuit relationship, which also affects the voltage ratio, no-load, and other diagnostic test data.

The derivation of the voltage ratio k_{sc} is as follows: According to the electromagnetic induction law, the induced electromotive force of the primary winding is $U_p = 4.44fN_p\Phi_m$, and the induced electromotive force of the short-circuit winding is $U_{sc} = 4.44fN_{sc}\Phi_m$, where N_p is the number of primary winding turns, N_{sc} is the number of shorted turns, and Φ_m is the main magnetic flux. Therefore, $k_{sc} = U_p/U_{sc} = N_p/N_{sc}$. When the short-circuit winding forms a closed loop, the short-circuit current I_{sc} generates a demagnetizing magnetic flux, which reduces the main magnetic flux Φ_m and affects the no-load current and voltage ratio of the transformer.

2.3 Diagnosis and Analysis of Inter-Turn Short Circuit

When the transformer fault trips, the historical operation and monitoring data of the transformer should be collected in time, and diagnostic tests should be carried out. In the field diagnostic test process, different test data show different fault indications, through a single test can not make a reasonable explanation of the location and cause of the transformer fault. Therefore, it is necessary to analyze the fault recording file, comprehensive diagnostic test data, etc., to establish an expert comprehensive diagnostic system to realize the comprehensive analysis based on the transformer electrical and magnetic circuit fault mechanism, and determine the transformer fault cause and fault location, as shown in Fig. 3.

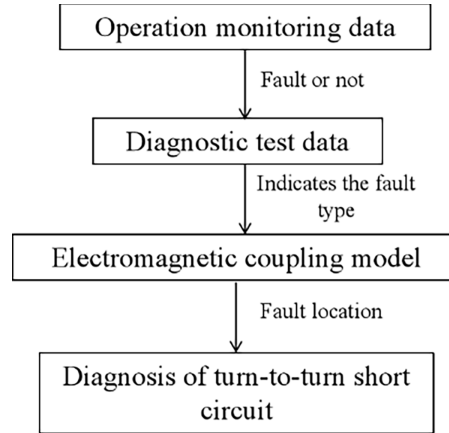


Figure 3: Expert comprehensive diagnosis system of transformer inter-turn short circuit fault.

2.4 Applicability and Limitations of the Model

The electromagnetic coupling model proposed in this paper is mainly applicable to 110–220 kV double-winding oil-immersed power transformers with a radial winding structure. The model is valid when the number of shorted turns is less than 5% of the total turns of the winding, because the demagnetizing effect of the short-circuit current is relatively weak and the magnetic circuit can be approximately linear.

The limitations of the model are as follows:

- (1) It is not applicable to dry-type transformers or transformers with special winding structures (such as interleaved windings or continuous windings with multiple parallel branches), as the leakage magnetic field distribution of these transformers is more complex;
- (2) When the number of shorted turns exceeds 10%, the demagnetizing magnetic flux generated by the short-circuit current is significant, leading to severe nonlinear distortion of the magnetic circuit, and the model's prediction accuracy will decrease;
- (3) The model does not consider the influence of temperature rise on the insulation resistance and short-circuit impedance. In actual applications, the operating temperature of the transformer should be considered for correction;
- (4) The model assumes that the short-circuit contact resistance R_{sc} is zero, but in practice, R_{sc} may be in the range of 0.1–1Ω, which will affect the magnitude of the short-circuit current and needs to be calibrated according to actual test data.

3 Failure Case and Diagnosis of Medium Voltage Winding

3.1 Fault Profile

At 21:23 on 03 November 2022, a 110 kV outgoing line (fault line) of a 220 kV substation, #1 tower C-phase cable terminal head insulation breakdown triggered a single-phase grounding fault. Subsequently, the transformer tripped due to the turn-to-turn short circuit fault induced by the external short-circuit impact, with the line protection tripping the line switch after 41 ms, the #2 transformer differential protection acting after 120 ms, and the three-side switches of the #2 transformer being tripped after 170 ms.

After the transformer tripped, on-site visual inspection was immediately carried out, and the appearances of the #2 transformer body and the primary equipment in the three-side intervals were found to be normal; the gas relay of the transformer body had no gas accumulation, the pressure relief valves of the transformer body and the on-load tap-changer did not act, and no oil spraying phenomenon was found on the ground.

Checking the on-site recording files and reports, on 03 November, at 21:23:01 228 ms 110 kV line fault occurred, 8 ms later, line switching protection was activated; 11 ms later, #2 transformer B set differential protection was activated; 15 ms later, line longitudinal differential protection was exported; 41 ms later, line longitudinal differential protection action jumped 118 switch; 120 ms later, #2 B set differential protection of transformer exits; 170 ms later, #2 transformer differential protection action jumps the three-side switch; 588 ms later, #2 transformer heavy gas protection action; 1063 ms later, 118 switch recloses on the permanent fault, and then accelerates to jump open the switch again. The protection action time sequence is shown in Fig. 4.

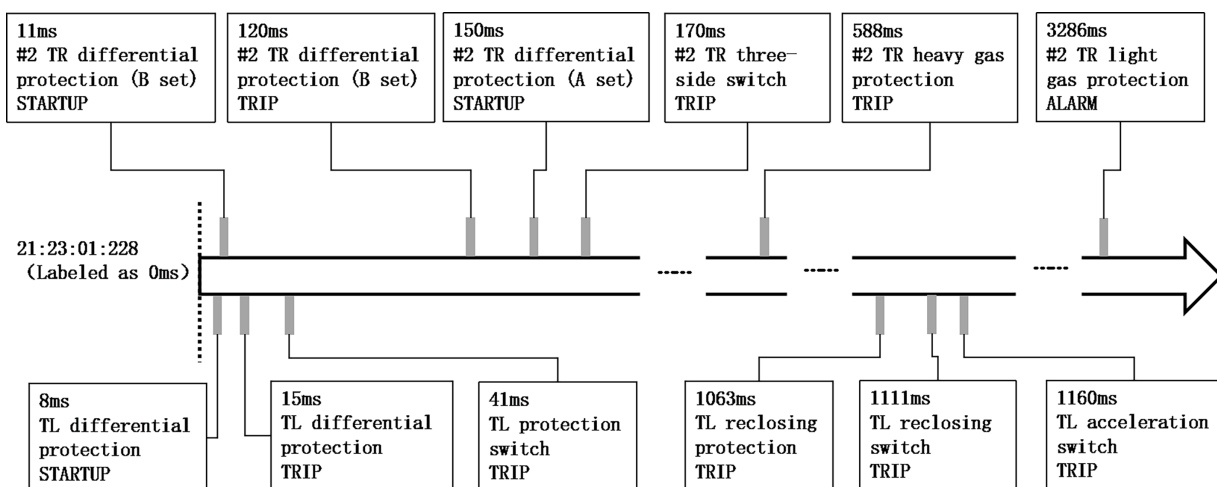


Figure 4: Sequence diagram of protection action.

Check the bus fault recording, fault line C phase line single-phase ground fault, after converting a fault current RMS value of 5.702 kA, the fault 110 kV system C-phase voltage drops to 0, line fault removal 110 kV system C-phase voltage back to normal. Line voltage and current waveforms at the moment of fault are shown in Fig. 5.

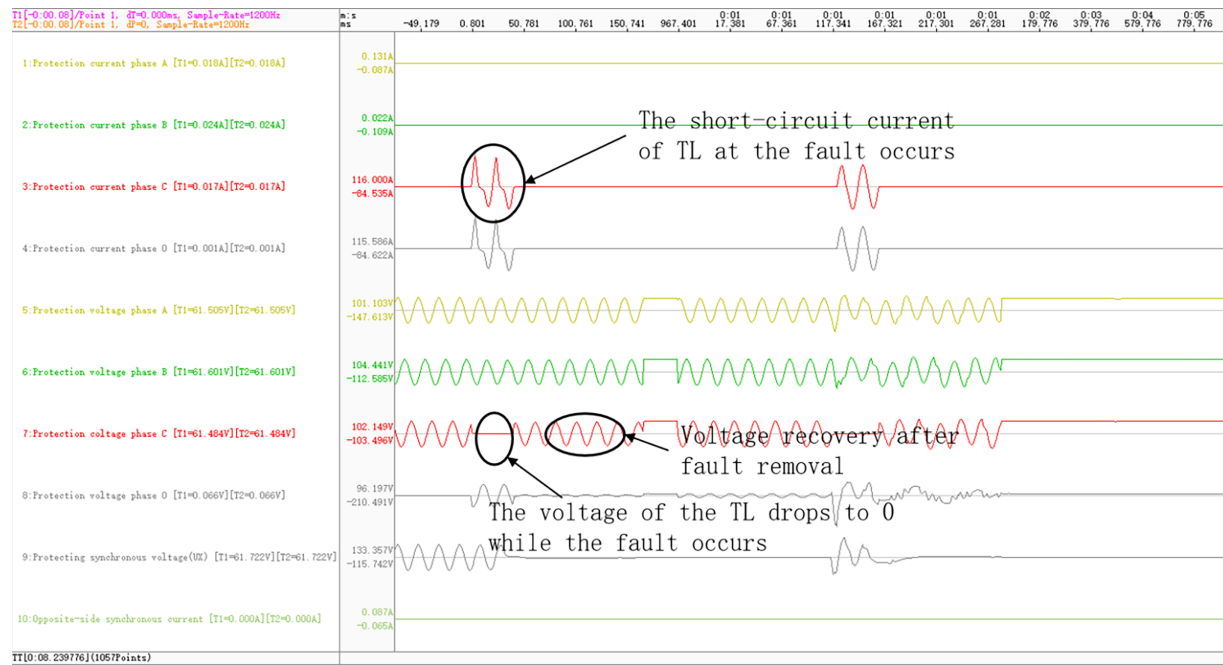
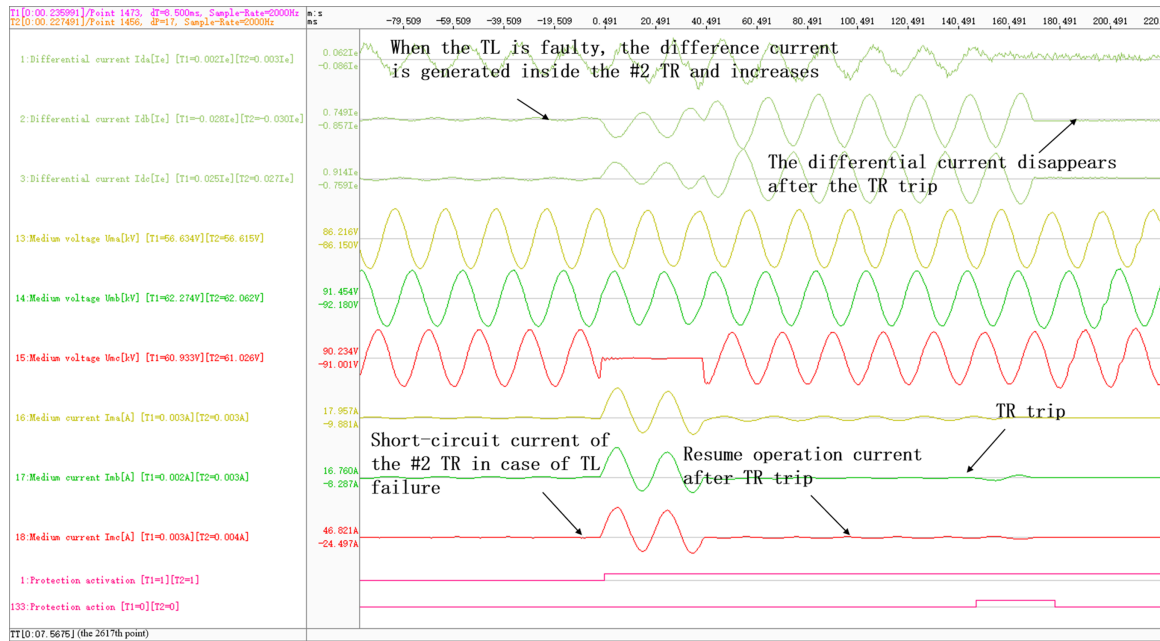


Figure 5: Voltage and current waveform at the time of the line fault.

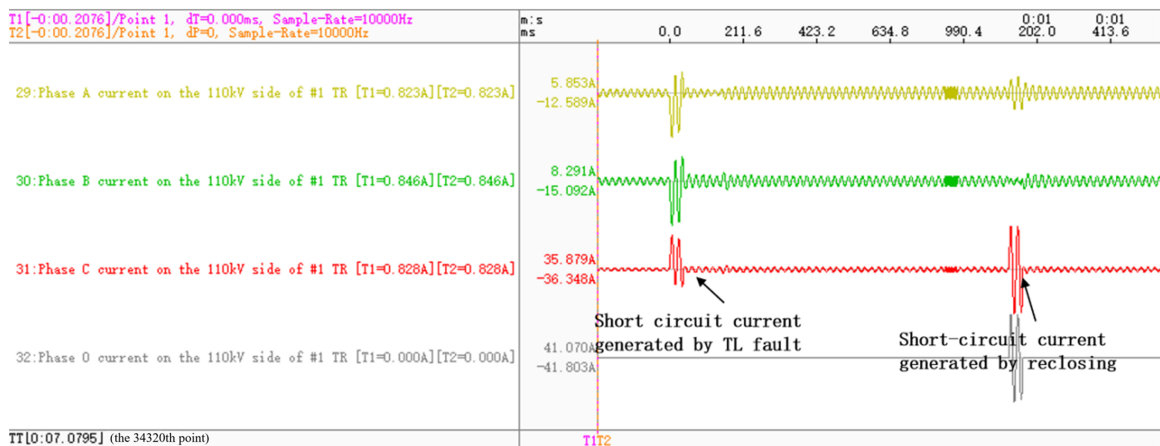
Checking the transformer fault recording, #1, #2 transformer high and medium voltage short-circuit inrush current exists, the peak short-circuit current is shown in Table 1, of which the peak short-circuit current of phase C of the medium voltage side of #1, #2 transformer is 8.724 and 11.297 kA, respectively. At the same time as the line fault occurs, the fault transformer's winding generates a differential current ($0.296I_e$), but the differential current does not reach the fixed value ($0.5I_e + \text{ratio braking}$), and the differential current gradually increases until 120 ms of transformer B set longitudinal differential protection action. The transformer differential current gradually increases until 120 ms transformer B set longitudinal differential protection action, longitudinal differential current maximum $0.609I_e$. transformer fault moment recording waveforms as shown in Fig. 6a,b.

Table 1: Peak short circuit current of transformer.

Placement	Phase A	Phase B	Phase C
#1 Transformer high voltage side	—	—	1.057
#1 Transformer medium voltage side	3.021	3.622	8.724
#2 Transformer high voltage side	—	—	2.518
#2 Transformer medium voltage side	4.347	4.054	11.297



(a)



(b)

Figure 6: Recorded waveform of transformer at the moment of fault; (a) Fault current waveforms of the high and medium voltage sides of the #2 transformer; (b) Waveform of current at the MV side of #1 transformer.

3.2 Transformer Test Conditions

3.2.1 Detection of Dissolved Gases in Oil

2 h after the transformer trip, take the transformer body C-phase winding side of the lower oil samples to carry out oil chromatography: oil dissolved gas C_2H_2 content of 198.6 $\mu\text{L/L}$, H_2 content of 663.7 $\mu\text{L/L}$, the total hydrocarbon content of 476.2 $\mu\text{L/L}$. Transformer trip 24 h later, once again in the same location to take the oil chromatograms, the characteristics of the other content is slightly reduced (Table 2). According to DL/T 722-2014. Guide to the analysis and the diagnosis of gasses dissolved in transformer oil, the contents of C_2H_2 , H_2 and total hydrocarbons dissolved in the transformer oil have all exceeded the limit significantly [25].

Table 2: #2 Main Transformer C-phase body Insulating Oil Chromatography.

Sample Name	Component Content ($\mu\text{L/L}$)							Total Hydrocarbon
	H ₂	CO	CO ₂	CH ₄	C ₂ H ₆	C ₂ H ₄	C ₂ H ₂	
November 3rd	663.7	605.7	5023.9	134.9	13.3	129.2	198.7	476.2
November 4th	413.4	475.2	4682.0	69.6	8.1	65.7	99.2	242.9

Oil samples were collected using a vacuum oil sampler (model: ZJ-100) from the lower part of the C-phase winding side of the transformer body. The test was performed using an HP 7890A gas chromatograph with a detection limit of 0.1 $\mu\text{L/L}$. Each sample was analyzed for 45 min, including sample injection, separation, and detection. The test environment temperature was $25 \pm 2^\circ\text{C}$, and the relative humidity was less than 60%.

3.2.2 Diagnostic Tests

A short-circuit impedance test was carried out on the transformer, in which the test value of short-circuit impedance of the center-to-low winding was 7.415%, and the difference from the initial value was -2.43% (Table 3). The test was strictly implemented in accordance with *DL/T 596-2021 Preventive Test Procedures for Electric Power Equipment*, and the specific operation procedure was as follows: (1) The transformer was in a no-load state, and the non-tested winding was short-circuited at the outlet terminal; (2) The tested winding was supplied with 50 Hz rated frequency alternating current, and the voltage was adjusted to make the tested winding reach the rated current; (3) Record the stable voltage value U_t and current value I_t at the inlet end of the tested winding; (4) Calculate the short-circuit impedance value according to $Z_k = U_t/I_t$, and repeat the test 3 times for each gear position, taking the average value as the final test result; (5) The test was carried out at the ambient temperature of $25 \pm 2^\circ\text{C}$, and the test data was corrected to the reference temperature of 75°C in accordance with the standard to ensure the comparability with the initial test data.

Table 3: Short-circuit impedance test data.

Gear Position	High-Medium			High-Low			Medium-Low		
	Initial Value	Test Value	Initial Value Difference	Initial Value	Test Value	Initial Value Difference	Initial Value	Test Value	Initial Value Difference
1	15.05	14.99	-0.40%	24.55	24.46	-0.37%	–	–	–
9	14.18	14.35	1.20%	23.73	23.58	-0.63%	7.6	7.415	-2.43%
17	13.8	13.83	0.22%	23.46	23.29	-0.72%	–	–	–

The short-circuit impedance test was carried out using the voltage-drop method in accordance with DL/T 596-2021. The test power supply was an AC 50 Hz variable voltage source with a rated current of 10 A. Before the test, the instrument was preheated for 30 min to ensure stable operation. For each gear position, the test was repeated three times, and the average value was taken as the final test result. The measurement error of the test instrument is $\pm 0.01\%$.

The high-to-medium and high-to-low-voltage ratios of all the C-phase gears are increased by 15%–20%, and there is no abnormality in the medium-to-low-voltage ratios. Low-voltage no-load test is conducted on the low-voltage side, in which the current reaches 3.98 A when the ac phase is pressurized to 10.8 V, and the current reaches 4.25 A when the bc phase is pressurized to 11.6 V, which is much higher than that of 0.347 A when the ab phase is pressurized to 101 V (seeing Table 4).

Table 4: Low-voltage no-load test.

Test Location	Pressurized Terminals	Shorting Terminal	Voltage/V	Current/A
Low voltage side	a-b	b-c	101	0.347
	b-c	c-a	11.6	4.25
	a-c	a-b	10.8	3.98

Comparison of pre-failure routine test and post-failure diagnostic test winding deformation data found that the pre-failure high, medium and low voltage three-phase winding between the three phases of the frequency response curve coincidence degree is high, the peaks and valleys corresponding to the amplitude and frequency of basically the same; after the failure of the C-phase three-side three-phase winding, whether it is a horizontal comparison of the A, B two-phase, or vertical comparison of the pre-failure C-phase data, the frequency response curve in the mid-frequency and low-frequency band has a significant deviation. The frequency response curve in the mid-frequency and low-frequency bands has an obvious offset, with a low degree of coincidence, and there is no abnormality in the data of A and B-phase windings. The frequency response test was implemented in accordance with *DL/T 911-2016 Frequency Response Analysis on Winding Deformation of Power Transformers*, adopting the end-to-end test method, and the specific procedure was as follows: (1) Disconnect the transformer from the power grid and discharge the winding to the ground to ensure zero residual voltage; (2) Connect the test signal generator to the high-voltage end of the tested winding, and connect the low-voltage end and the non-tested winding to the ground; (3) Output 1~1 MHz sinusoidal sweep excitation signal, collect the voltage signal at the test end and the reference end synchronously, and calculate the transfer function $H(f) = U_{out}(f)/U_{inb}(f)$; (4) Complete the frequency response test of A, B, C three phases in turn, and ensure the same test connection mode, instrument parameters and ambient conditions for each phase test; (5) Use the correlation coefficient method to compare the similarity of the frequency response curves before and after the fault, with the correlation coefficient lower than 0.9 indicating a significant deviation of the winding characteristics.

The frequency response test was performed using a transformer winding deformation tester (model: FRA-600) with a frequency range of 1–1 MHz. The excitation signal was a sinusoidal sweep signal with an amplitude of 5 V. The data acquisition interval was 10 Hz per point, and the test duration for each phase was 15 min. The test was carried out under no-load conditions, and the winding terminals were connected in accordance with the manufacturer's specifications.

3.3 Comprehensive Diagnostic Analysis

3.3.1 Analysis of the Protection Situation

The No. 2 transformer differential protection recording shows that after the line tripping, the second harmonic current of the C-phase longitudinal difference current of the MV side occurs at 10, 41, 52 and 170 ms, respectively, as shown in Fig. 7, of which 41 and 170 ms correspond to the two moments of the line fault resection and transformer tripping, respectively, and at this time, the second harmonic is the transformer's internal because of the excitation inrush formed by the core of the magnetic flux in the transformer reaching saturation. The second harmonic is caused by the saturation of the magnetic flux in the core of the transformer. Related literature [16] shows that in the transformer in the inter-turn short-circuit state, the core excitation saturation near the short-circuit turn, will produce the second harmonic inside the winding, judging that the second harmonic in the 10 and 52 ms differential currents are related to the inter-turn short-circuit and its development process, respectively.

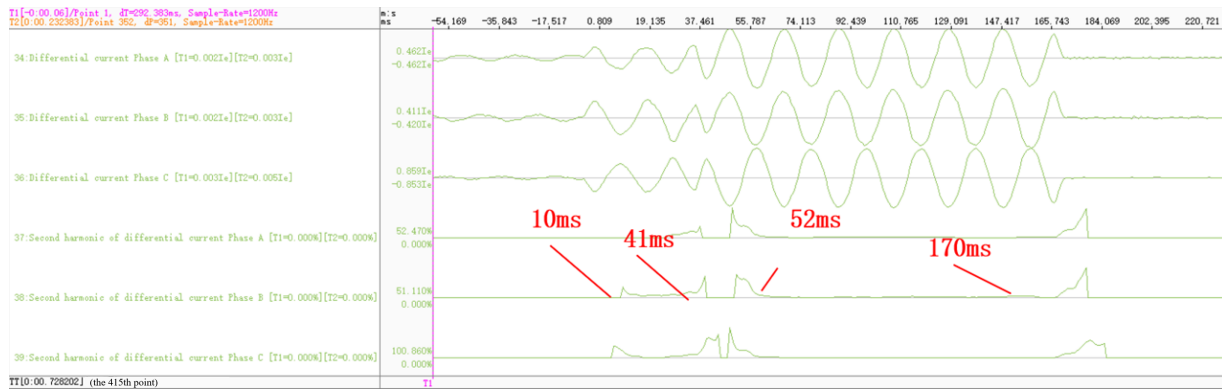


Figure 7: C-phase longitudinal difference current second harmonic generation time.

3.3.2 Variable Ratio Test Analysis

Ratio test results show that the C-phase HV- MV and HV-LV gear ratios are increased by 15%–20%, MV-low-voltage ratio results are normal, only from the surface of the data, it may be that the high-voltage windings have anomalies, but through an in-depth analysis of the transformer electrical and magnetic circuit structure, the transformer is judged to exist in the MV side of the turn-to-turn short-circuit, the analysis is as follows:

Failure of the transformer high-voltage turns 750 turns, medium-voltage turns 412 turns, low-voltage turns 62 turns, high-voltage winding turns to increase is impossible, if the short-circuit turns is caused by the high-medium-voltage and medium-low-voltage ratio is the direct cause of the bias of the large, to be satisfied at the same time the medium-voltage windings and low-voltage windings short-circuited between the turns of the total turns of 15%–20% (medium-voltage short-circuit of about 60 turns, short-circuit low-voltage of about 10 turns), the possibility of both the fault recording information or direct resistance test data can not be supported, and the number of short-circuited turns within the coil fault is generally very small (short-circuit between turns is 1, short-circuit between disks is 4). This possibility is not supported by either the fault recording information or the direct resistance test data, and the number of short-circuited turns in case of short-circuiting faults inside the coil is generally very small (1 for a turn-to-turn short-circuit, and 4 for a disk-to-disk short-circuit).

Therefore, the reasons for the increase of high-MV and high-low voltage ratio are analyzed as follows: there is a short circuit between turns within the MV winding, when the number of short-circuit turns is very small, the short circuit itself is very small on the straight resistance and ratio test, but the short circuit is formed in the transformer MV winding short-circuit ring, due to the short-circuit ring at the two ends of the winding isotropic, can be divided into short-circuit winding on the MV side of the winding and the non-short-circuit winding, the short-circuit winding short-circuited at both ends, the non-faulty The short-circuit winding is short-circuited at both ends, and the non-fault winding is open-circuited at both ends. Therefore, the transformer phase C can be equivalent to a four-winding transformer consisting of high-voltage (HV) winding, medium-voltage (MV) non-fault winding, short-circuit (SC) winding, low-voltage (LV) winding, the number of winding turns were NH, NM-ΔN, ΔN, NL, as shown in Fig. 8.

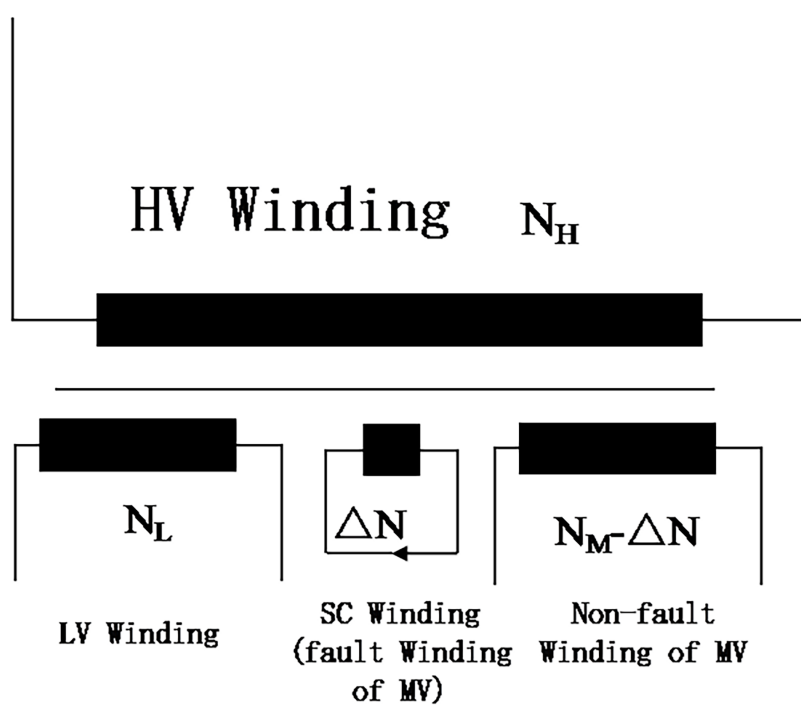


Figure 8: Schematic diagram of the effect of short-circuit loops on the variable ratio test.

When testing the high-medium winding ratio, the relationship between the measured ratio k_{T-HM} and the actual ratio k_{HM} when the pressurized end is the high voltage side is shown in Eq. (1).

$$\begin{aligned}
 k_{T-HM} &= \frac{U_M \cdot \frac{N_H}{N_M - \Delta N} + Z_{c-H}\% \cdot U_H}{U_M} \\
 &= \frac{N_H}{N_M - \Delta N} + k_{HM} \cdot Z_{c-H}\% \\
 &\approx k_{HM} (1 + Z_{c-H}\%)
 \end{aligned} \tag{1}$$

When testing the high-low winding ratio, when the pressurized end is the high voltage side, the relationship between the measured ratio K_{T-HL} and the actual ratio K_{HL} is shown in Eq. (2).

$$\begin{aligned}
 K_{T-HL} &= \frac{U_L \cdot \frac{N_H}{N_L} + Z_{c-H}\% \cdot U_H}{U_L} \\
 &= k_{HL} (1 + Z_{c-H}\%)
 \end{aligned} \tag{2}$$

When testing the medium-low winding ratio, the relationship between the measured ratio K_{T-ML} and the actual ratio K_{ML} is shown in Eq. (3) when the pressurized end is the medium voltage side.

$$\begin{aligned}
 K_{T-ML} &= \frac{U_L \cdot \frac{N_M - \Delta N}{N_L} + Z_{c-M}\% \cdot U_M}{U_L} \\
 &\approx k_{ML} (1 + Z_{c-M}\%)
 \end{aligned} \tag{3}$$

where: $Z_{c-H}\%$ is the short-circuit impedance of the short-circuit winding to the high-voltage winding, $Z_{c-M}\%$ is the short-circuit impedance of the short-circuit winding to the medium-voltage winding.

From the above equation, it can be seen that the measurement deviation of the ratios of the high-medium and high-low windings is the same and is determined by $Z_{c-H}\%$, and the measurement deviation of the ratio of the medium-low winding is determined by $Z_{c-M}\%$, whereas the short-circuit winding is embedded in the medium-voltage winding itself, and there is almost no leakage of magnetism between the two windings, and the corresponding $Z_{c-M}\%$ is also very small. It can be seen that in the case of an inter-turn short-circuit in the MV winding of phase C, the ratio of HV-MV and HV-LV increases, while the ratio of MV-LV changes very little. Therefore, based on the results of the ratio test, it can be inferred that there is an inter-turn short-circuit within the C-phase medium-voltage winding.

3.3.3 Frequency Response Method Winding Deformation and Short Circuit Impedance

From the frequency response method winding deformation data, the C-phase winding, whether compared horizontally or vertically, in which the location of the peak and trough of the low-frequency band changed significantly, according to DL/T911-2016 of China's power industry standards [26], when the change of the peak or trough of the low-frequency band "usually predicts a change in the inductance of the windings, the A turn-to-turn short circuit may exist".

At the same time, the short circuit between turns inside the winding will change the leakage distribution, that is, the short-circuit impedance will change. At this time, the short-circuit impedance change does not mean that the winding must have deformation, but may be the leakage of magnetic changes caused by the short-circuit impedance measurement error. Therefore, the change of short-circuit impedance in the middle-low short-circuit impedance changes with the short-circuit between the disk caused by the leakage of magnetic changes in the fault coincide.

3.3.4 Joint Diagnostic Criteria

The comprehensive diagnosis of turn-to-turn short circuit faults relies on the complementary information from multiple test indicators. Oil chromatography analysis can quickly determine the presence of electrical discharge faults; the variable ratio test and low-voltage no-load test can reflect the change in the number of effective turns of the winding; the frequency response test and short-circuit impedance test can detect the change in the magnetic circuit and leakage magnetic field. Only by integrating these test results and combining the electromagnetic coupling mechanism can the fault location and cause be accurately identified.

3.4 Deconstruction and Inspection

According to the test and investigation, it was judged that there was a turn-to-turn short circuit on the medium voltage side of the #2 transformer, and the #2 transformer was dismantled and inspected on-site. Combined with the comprehensive diagnosis conclusion of multi-source test data, the disassembly inspection focused on the C-phase medium-voltage winding, and the following typical fault phenomena were found in turn:

There are insulation cracks in four pressure bowls on the top of the C-phase coils, and the insulation paper at the bottom of one of the pressure bowls is completely broken and detached, as shown in Fig. 9a. The top of each of the three-phase coils is equipped with 12 nails, 12 nails are arranged symmetrically on both sides of the coil, and the position of the nails and the cracked bowls are arranged as shown in Fig. 9b, and the 4 cracked bowls are located in the upper part of the medium-voltage winding.

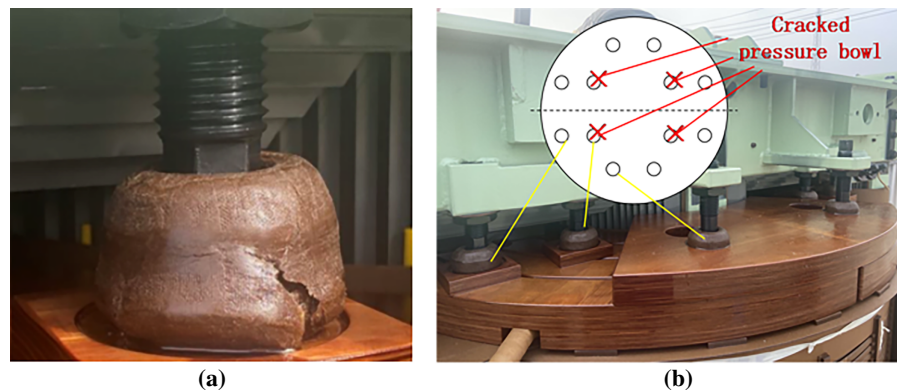


Figure 9: Installation and cracking of the pressure bowl. (a) The broken bowl. (b) The installation and cracking situation of the bowl.

The windings were pulled out sequentially at the scene, and obvious discharge traces such as damage, broken strands, deformation, carbonization, etc. were found in the middle of the C-phase MV-side winding, as shown in Fig. 10a. This fault phenomenon is highly consistent with the conclusion of the frequency response test that the “C-phase medium-voltage winding has low-medium frequency band curve deviation and inductance change”, and also verifies the judgment of turn-to-turn short circuit fault in the medium-voltage winding derived from the variable ratio test and low-voltage no-load test.

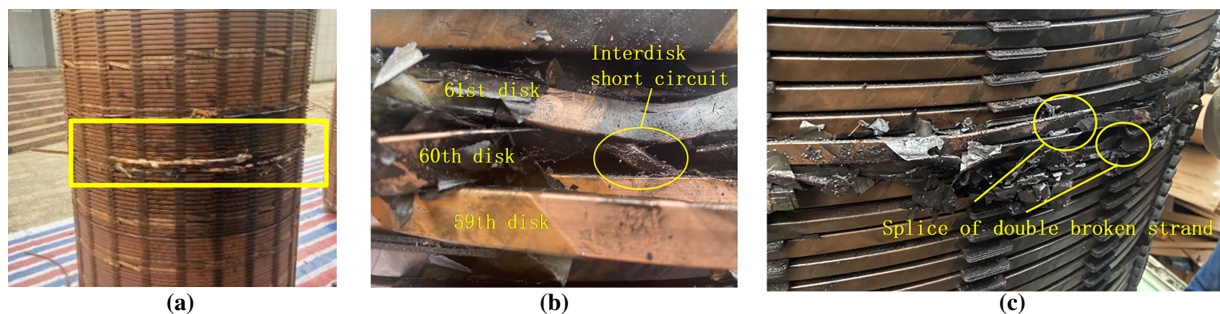


Figure 10: Inspection of medium-voltage windings. (a) Discharge position; (b) Short circuit between disks; (c) Broken strands.

Strip the faulty winding inside, inspection found that the C-phase medium-voltage side of the winding of the 59th disk to 61st disk occurred inter-disk short circuit, see Fig. 10b, 60th disk first turn within the first half-turn conductor broken strand fault, see Fig. 10c, the fault schematic diagram shown in Fig. 11.

According to the dismantling inspection, the first half-turn of the first turn of the 60th disk of the C-phase medium-voltage winding has the most serious disconnection and damage, which is determined as the initial fault location of the turn-to-turn short circuit. it is inferred that the location of the fault starting position, in the external short-circuit current generated by the axial force of the 59th disk and 60th disk first occurred between the two disk short-circuit, then induced a short-circuit fault with the 61st disk three disks.

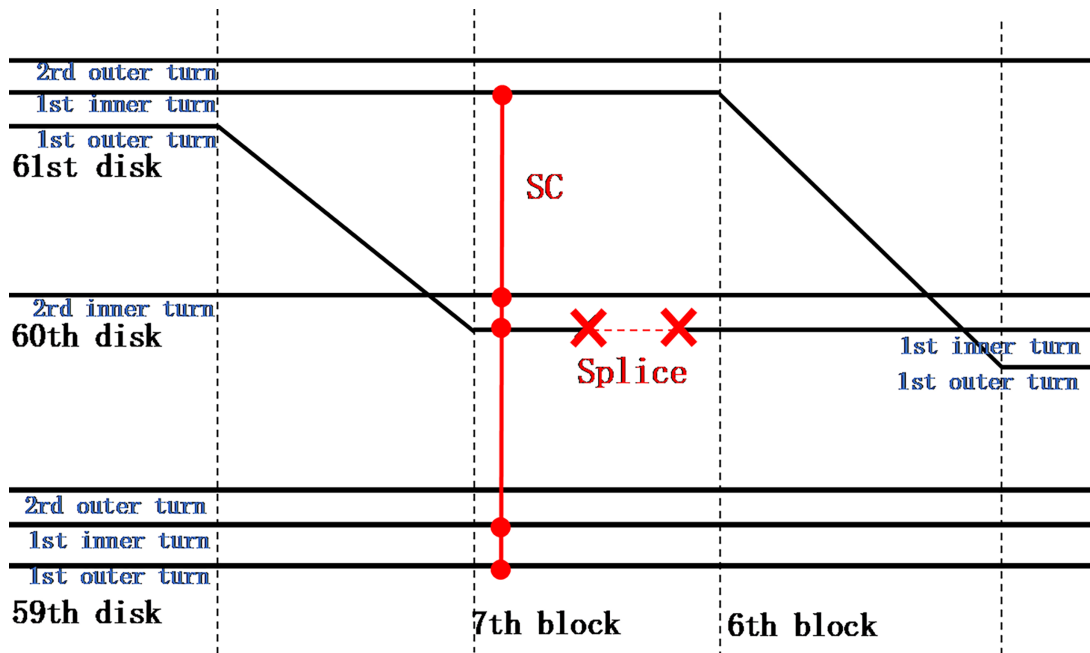


Figure 11: Schematic diagram of winding failure.

4 Failure Case and Diagnosis of High Voltage Winding

4.1 Fault Overview

On 24 June 2024, at 9:58:53, a 220 kV transformer carried out voltage regulation operation of 9–10 gears, and the gears were adjusted in place at 9:59:08. Fifty-one seconds later, the differential protection for Transformers A and B operated, the Buchholz gas protection activated, and the circuit breakers on all three sides tripped. 10 kV self-transmission correctly acted, causing no load loss. The weather was clear at the time of failure.

4.2 Recorded Wave Inspection

There is no fault current in phase A and B of the high voltage side of this transformer, and there is no fault current in the medium and low voltage side. The current in phase C of the high voltage side surges (4.196 A in the secondary side, converted to 1.342 kA in the primary side) and there is a zero-sequence current (3.701 A in the secondary side, converted to 1.184 kA in the primary side), and the fault current reaches the value of the action of differential protection, and the transformer protection A set and B set are correctly operated. The secondary voltage of phase C on the high-voltage side dropped to 57.15 V (converted to primary 125.73 kV), and phases A and B were 59.81 V (converted to primary 131.58 kV). Combined with the main transformer non-electricity body weight gas, body pressure release action, analyze the fault point in the main transformer internal high-voltage side C phase. Fault wave recording is shown in [Fig. 12](#).

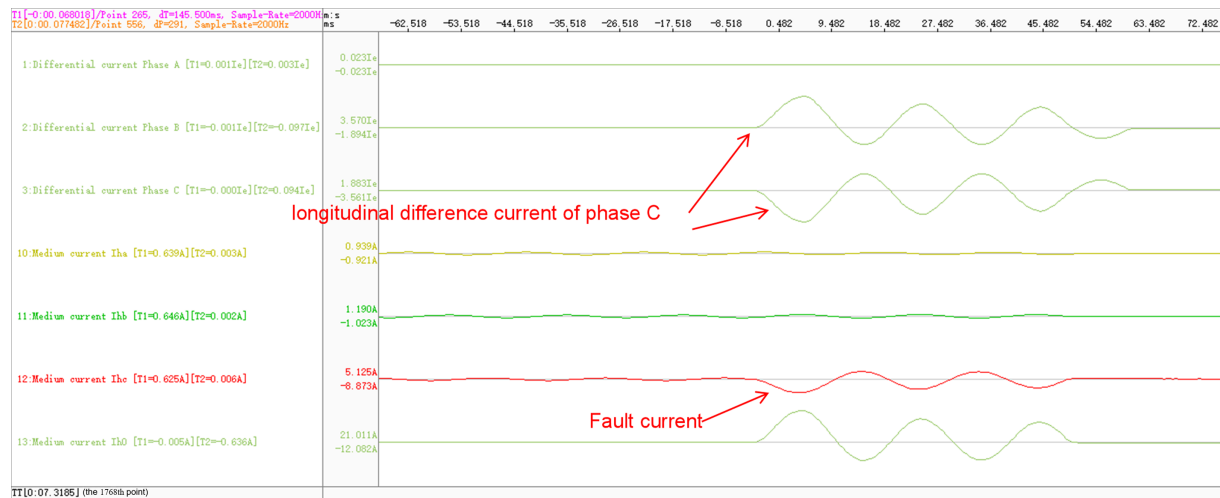


Figure 12: Recorded current waveform of main transformer A set protection.

4.3 Fault Diagnosis Test Analysis

After the failure, oil samples were taken from the middle and lower parts of the #2 main transformer body and the on-load tap-changer, and oleochemical tests were carried out. It was found that the oil chromatographic data of the middle and lower parts of the main transformer body were unqualified, and that the acetylene in the oil was seriously exceeded (47.63 $\mu\text{L/L}$ in the lower part, 55.88 $\mu\text{L/L}$ in the middle part), and the three-ratio value coded 102, which was judged to be an electric arc discharge. On-load tap-changer oil chromatographic data hydrogen in oil exceeds the standard with no acetylene.

Diagnostic tests are conducted, and the items include insulation resistance of the winding together with the casing, dielectric loss and capacitance of the winding together with the casing, transformation ratio, DC resistance, insulation resistance of the iron core and clamping parts, low-voltage short-circuit impedance, low-voltage no-load test, and deformation test of the winding by frequency response method. The details are as follows:

- (1) Frequency response method of winding deformation test. The low frequency correlation of high, medium and low winding of phase C does not meet the standard requirements, the correlation of high and medium frequency bands meets the requirements, and there is no abnormality in the data of the winding of phase A and B. Winding deformation low frequency band abnormality usually predicts the change of inductance.
- (2) Variable ratio test. The phase A and B voltage ratio is normal, while HV to MV and HV to LV phase C data are abnormal; MV to LV test is unable to be measured due to current overload; the data is shown in Table 5.

- (3) The no-load current of phase C is large, exceeding the requirement of “the difference of no-load current should not exceed 10%” in Q/GDW 1168-2013 “Test Procedures for Conditional Maintenance of Transmission and Substation Equipment”. Analyze the existence of a short-circuit loop in the C-phase winding, resulting in a large no-load current.
- (4) Winding insulation, DC resistance, dielectric loss, and capacitance test data are normal.

Table 5: Example 2: variable ratio test.

Placement	Phase A	Phase B	Phase C
HV-MV	1.975	1.976	4.32
HV-LV	12.64	12.64	27.63
MV-LV	6.41	6.40	–

According to the diagnostic test results and the established expert diagnosis system, in the event of a turn-to-turn short-circuit, the HV winding to MV winding ratio and high-voltage winding-to-low-voltage ratio offset are determined by the short-circuiting turn-to-high-voltage winding leakage magnetism (i.e., $Z_{C-H}\%$), whereas the medium-voltage winding-to-low-voltage winding ratio is determined by the short-circuiting turn-to-medium-voltage winding leakage magnetism (i.e., $Z_{C-M}\%$), and therefore it is judged that a turn-to-turn short-circuit exists in the C-phase winding, and combined with the fault recording, the fault point is in the high-voltage winding, and it is judged that the turn-to-turn short-circuit is in the C-phase high-voltage side. Therefore, it is judged that the C-phase winding is short-circuited between turns (cakes), and combined with the fault recording, the fault point is in the high-voltage winding, and it is judged that the short-circuited between turns (cakes) is in the high-voltage side of the C-phase. As the DC resistance test is qualified, it is judged that the short-circuit between turns (cakes) is in the regulator winding on the high-voltage side of the C phase [27,28].

4.4 Disintegration Inspection

According to the test and investigation, the transformer regulator winding was judged to have an inter-turn short circuit, and the transformer was disassembled and inspected on the spot. Inspection found that the transformer C-phase regulator coil is seriously damaged, with coil deformation of large areas, scattered, in the upper part of the two discharge traces found, judging the fault regulator winding occurred in the turn-to-turn short-circuit discharge, dismantling and inspection verified the validity of the diagnostic analysis, show in Fig. 13.



Figure 13: Location of the interturn short circuit fault.

5 Conclusion

This paper gives the electromagnetic coupling model of turn-to-turn short circuit inside the transformer, establishes the expert analysis system of transformer turn-to-turn short circuit diagnostic test, and verifies the accuracy of the model through the analysis of two fault cases.

The results show that after the occurrence of the fault, due to the different test data appear to be certain different indications, which interfere with the judgment of the fault cause and location. A single test method can only reflect a certain aspect of the fault characteristics and cannot make an accurate and comprehensive judgment of the transformer internal fault state; it is necessary to take the fault trigger source (external short-circuit impact) as the starting point, combine the transformer internal electromagnetic circuit fault mechanism, and integrate the multi-dimensional diagnostic test data (including oil dissolved gas analysis, electrical test, fault recording, etc.) for systematic comprehensive analysis, so as to accurately lock the fault winding and determine the specific fault location.

It should be noted that the current research is limited by the number of actual fault cases, and the verification of the proposed method is mainly focused on C-phase turn-to-turn short circuits. For faults in A-phase, B-phase, and different winding locations, further verification with more actual cases is needed. In future research, we will collect more fault data, optimize the diagnostic method, and explore the integration of AI algorithms to develop a real-time fault diagnosis system, so as to provide more efficient and economical technical support for transformer fault handling and maintenance.

6 Discussion on Fault Diagnosis Extension and Future Prospects

6.1 Limitation of Current Fault Case Coverage

The comprehensive diagnostic method proposed in this paper is verified based on two actual cases of turn-to-turn short circuit faults (one in the medium-voltage winding and one in the high-voltage winding, both in C-phase). Due to the low occurrence probability of transformer turn-to-turn short circuit faults and the difficulty in collecting complete on-site test data and disassembly results, the current research lacks sufficient actual engineering cases involving faults in A-phase, B-phase, and different winding locations (upper, lower parts of the winding). Therefore, the applicability of the proposed method to faults in other phases and locations has not been fully verified through actual cases.

6.2 Prospects for Fault Diagnosis in Different Phases and Locations

For turn-to-turn short circuit faults in different phases (A-phase, B-phase), the core electromagnetic mechanism remains consistent: the short-circuit loop formed by the fault will change the effective number of winding turns, distort the internal magnetic circuit, and thus affect test indicators such as oil dissolved gas content, short-circuit impedance, variable ratio, and frequency response curve. In future research, we will focus on collecting on-site fault data of transformers with A-phase and B-phase turn-to-turn short circuits, and verify whether the diagnostic criteria established in this paper (such as C_2H_2 content exceeding the alarm threshold, short-circuit impedance variation exceeding $\pm 2\%$, frequency response curve deviation in low-medium frequency band) are equally applicable to these faults. For faults in different winding locations (upper, lower parts), the distribution of leakage magnetic field and the degree of winding deformation may differ, leading to differences in the sensitivity of each test indicator. We will collect relevant fault cases to analyze the variation characteristics of key indicators under different location faults, and optimize the diagnostic weight of each indicator to improve the accuracy of location identification.

6.3 Prospect of AI-Based Real-Time Diagnosis System

In response to the demand for rapid fault identification after transformer tripping, future research will focus on integrating the diagnostic indicators proposed in this paper (oil chromatographic parameters, short-circuit impedance variation, variable ratio deviation, no-load current ratio, frequency response curve characteristics) with AI algorithms. We plan to use machine learning models such as random forest and deep learning to train a multi-dimensional fault diagnosis model based on a large amount of fault data. This model will realize the following functions: (1) Real-time acquisition of fault recording data (phase voltage, phase current), on-site test data, and oil chromatographic data after the transformer trips; (2) Automatic analysis of the variation of each diagnostic indicator, and rapid identification of the fault phase, location, and type; (3) Display of diagnostic results in real time, providing clear maintenance suggestions for power grid operators. This system will help reduce the time cost of fault diagnosis and maintenance, and improve the economic efficiency of transformer renewal and operation for suppliers and power grid enterprises.

6.4 Summary

The current research provides a feasible comprehensive diagnostic method for transformer turn-to-turn short circuit faults based on existing cases, which takes the electromagnetic coupling principle as the theoretical basis and multi-source test data fusion as the core means. The practical application of two actual cases shows that this method can effectively solve the problem of inconsistent fault indications of a single test, and the diagnostic conclusion can be highly matched with the on-site disassembly inspection results. In the future, we will address the limitation of insufficient case coverage, further expand the application scope

of the method, and explore the integration with AI technology to enhance the real-time and practicality of fault diagnosis, making greater contributions to the safe and reliable operation of the power grid.

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