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Study on Characteristics and Test Judgment of Electrical Fault of High-Voltage Equipment

Zhumao Lu, Tao Jin, Yaning Zhao

State Grid Shanxi Electric Power Research Institute, Taiyuan, Shanxi, China

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ABSTRACT

Since the "big five," the proposed large-scale planning and construction system of substations has seen rapid development, providing enough energy for people while also causing a series of problems, such as a gradual increase in radiation and magnetic fields. It not conducive to artificial operation, such as in case of frequent high-voltage electrical equipment failure, which again negatively influences the whole electric power system operation. Especially, the electrical failure of high-voltage equipment, if not found and solved in time, could cause a major power accident, bring economic losses to the power company, and even threatening the life safety of staff. None of these risks can be ignored. Based on this, in order to reduce the risk of substation accidents and to promptly discover and solve the problem of electrical failure in high-voltage equipment, this paper studies the substation in BX area as an example, by using the frequency response method, such as a low impedance of transformer for the winding deformation test. The winding has carried out with the handover testing and hoisting cover inspection With the collapse of the experiment, not only are the problems causing the fault found, the fault type and location are also determined. The feasibility of this method for detecting electrical faults of high-voltage equipment is confirmed, and the fault characteristics, location, and other information can be accurately judged, which provides support for the formulation of fault strategies in the later stage.

***Index Terms*—**Electrical failure, handover test, hanging cover inspection, high-voltage equipment, the collapse of the experiment, the test, transformer, winding.

I. INTRODUCTION

With the increasing demand for electric power, the domestic power grid has also expanded, with new transformers and other measures to meet people's demand for electric power. This indirectly increases the operational requirements of the power system. In the power system, the safety and stability of high-voltage equipment is a problem that cannot be ignored. If the fault of high-voltage equipment occurs and is not discovered due to improper operation or accident in transportation, installation, use, and other factors, it may cause major power accidents with damaging consequences [1–3]. Therefore, whether collision of high-voltage equipment occurs in the process of transportation, or any abnormal reaction occurs during the use, it is necessary to conduct systematic verification to eliminate the existence of hidden faults and identify the specific problems causing the fault. Only in this way can the occurrence of high-voltage equipment faults be effectively avoided [4–6]. In order to solve the above problems, this paper will consider the high-voltage equipment in BX area as the research object, verify the feasibility of the electrical fault test and the determination method of the high-voltage equipment through case analysis, accurately identify the problems causing the fault, and give reasonable solutions to ensure the normal operation of the power system. Specific research ideas are shown in Fig. 1.

Corresponding Author:
Zhumao Lu

E-mail:
luji64654362924@163.com

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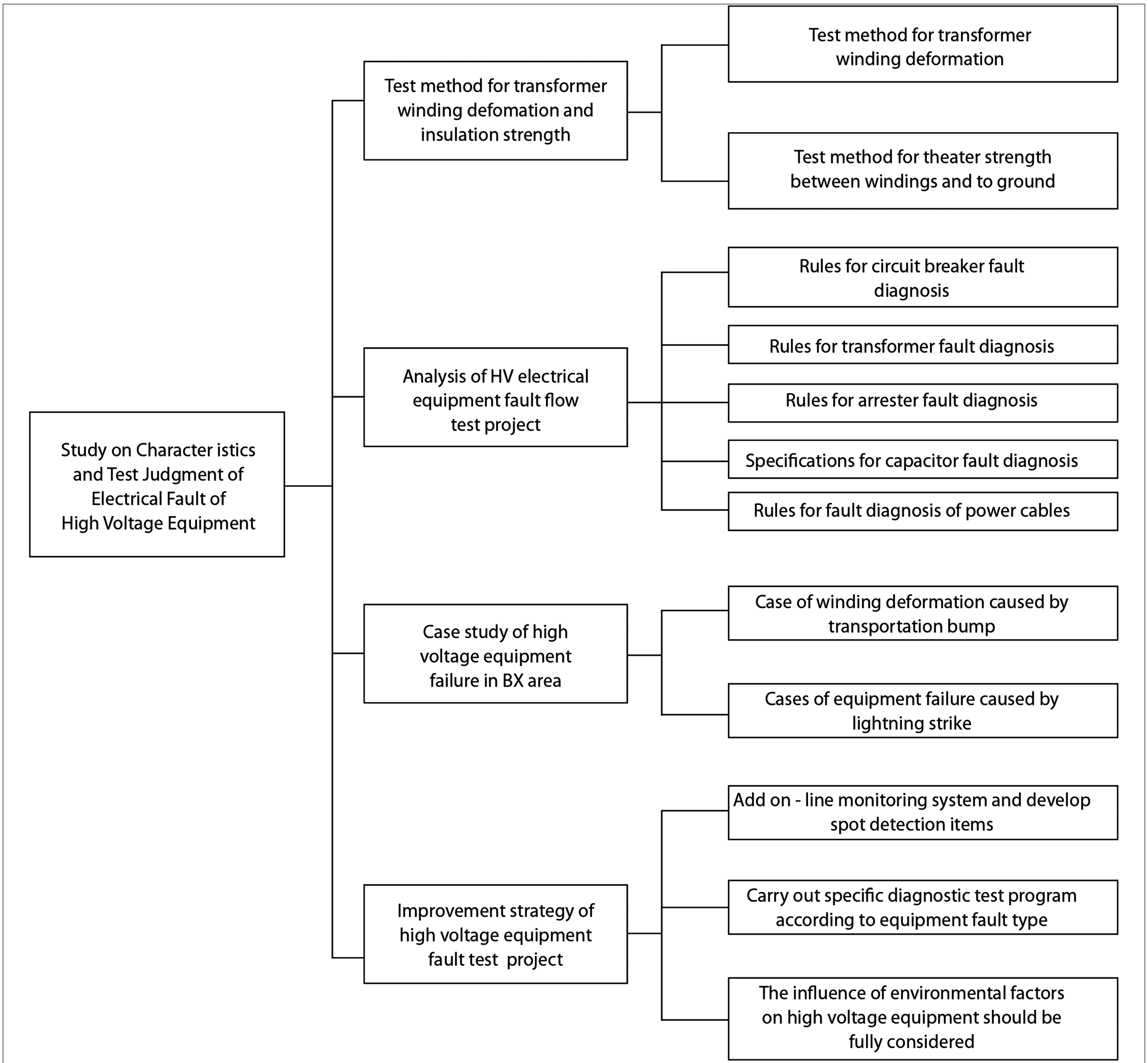

Fig. 1. Schematic diagram of proposed research.

II. AN OVERVIEW OF THE METHOD OF TRANSFORMER WINDING DEFORMATION TEST AND INSULATION STRENGTH TEST

A. Test Method for Transformer Winding Deformation

There are many methods to test transformer winding deformation. This paper explains the main testing methods, as shown below:

1) Frequency Response Method

When the transformer frequency exceeds 1 kHz, each winding of the transformer can be regarded as a passive linear double-ended network, and each network is composed of distributed parameters such as inductance and capacitance. The structural characteristics of the network depend on the transfer function $H(j\omega)$, and $H(j\omega)$ will change with the change of ω. The curve formed in the process of change is called the frequency response characteristic curve, which can be used to describe the characteristics of the transformer [7]. If the winding deforms, its inductance, capacitance, and other parameters are bound to change, leading to changes in the zero and pole of $H(j\omega)$. This will affect the frequency response characteristics of the network and make the frequency response characteristic curve change, providing a basis for the judgment of the winding deformation. Because $H(j\omega)$ is very easy to identify with the changes of inductance and capacitance, the frequency response method can be effectively applied to the macro deformation of winding and small local problems, and it is one of the

TABLE I. DETERMINATION METHOD OF WINDING DEFORMATION DEGREE

Degree of Winding Deformation	Correlation Coefficient R
Normal winding	$R_{LF} \geq 2$, $R_{MF} \geq 1$, $R_{HF} \geq 0.6$
Mild deformation	$2 > R_{LF} \geq 1$ or $R_{MF} < 1$
Obvious deformation	$1 > R_{LF} \geq 0.6$ or $R_{MF} < 0.6$
Severe deformation	$R_{LF} < 0.6$

main testing methods at present. The method of the frequency response method to judge the degree of winding deformation through the correlation coefficient is shown in Table I.

In Table I, R_{LF} is the correlation coefficient of the curve in the low-frequency band; R_{MF} is the correlation coefficient of the curve in the middle-frequency band; R_{HD} is the correlation coefficient of the curve in the high-frequency band. Compared with the historical atlas, the frequency response method has no obvious difference in the requirement of winding deformation. However, the frequency response method still has some shortcomings, such as poor anti-interference during the field test, which is prone to misjudgment events. In addition, the judgment of displacement and global displacement is weak.

2) Low-Voltage Impedance Method

When the transformer load impedance is 0, its internal equivalent impedance is represented by the short-circuit impedance, which can be regarded as the leakage reactance of the winding [8]. Leakage reactance is determined by the geometrical size and mutual position of windings, and the function of relative position of windings is expressed by leakage inductance $L_K = f(RH)$. The function L_K is composed of reactance function Z_K and short-circuit impedance function X_K. If the geometric size of the winding is also changed when the winding is deformed, then L_K, Z_K and X_K will all change. At this time, it can be compared with the nameplate to determine whether the winding has deformation behavior. According to the "Guide for Detection and Judgment of Power Transformer Winding Deformation by Reactance Method," the relative change of longitudinal comparison should be less than $\pm 2.0\%$, and the relative change of transverse comparison should not be more than $\pm 2.5\%$. It is easy to detect the winding displacement and global deformation by the low-voltage impedance method, but it is more difficult to detect the local winding deformation.

3) Capacitance Method

There is a certain correlation between the capacitance of the winding and the relative position, size, and insulating medium of the winding. By observing the equivalent capacitance of the winding, information such as the structure of the winding itself and the relative position of the winding to the box body and the ground can be obtained [9]. The capacitance of windings will change with the change of the relative positions between windings. The method to judge the winding deformation by capacitance is as follows: when the capacitance change exceeds the initial value by 5%, it is a mild deformation; when it exceeds the initial value by 10%, it is a moderate deformation; when it exceeds the initial value by 15%, it is a severe deformation. In fact, the capacitance value of the winding belongs to the distributed parameter, and it is easy to measure the winding problems with serious deformation, while the measurement effect is not obvious for the local problems such as winding distortion and bulge.

B. Insulation Strength Test Method Between Windings and to Ground

The insulation strength between windings and the ground can be regarded as the distance between windings and the ground. The specific test method is as follows:

1) Insulating Oil Analysis

Before the failure of transformer equipment, a large amount of gas is emitted inside. Based on this phenomenon, chromatography has become one of the effective methods for transformer fault diagnosis, and the transformer fault type can be determined by the dissolved gas in the oil [10]. Nowadays, the ratio-of-three method and characteristic gas method are commonly used in the study area to judge the potential problems of the transformer, especially for arc discharge, partial discharge, high temperature overheating, and other faults that can be quickly detected. In the chromatographic analysis of dissolved gas in oil, the following requirements should be met: First, after the transformer voltage grade exceeds 66 kV, the test can be sampled after 24 hours. Second, the test should meet the requirements in the "Guide for Analysis and Judgment of Dissolved Gas in Transformer Oil." Third, there should be no significant difference between the characteristic gas content detected and the historical data. Characteristic gases such as total hydrocarbon, acetylene, and hydrogen can be decomposed by heating the insulating oil and paper insulation around the fault point. By measuring the content of these characteristic gases, the type and degree of the transformer fault can be accurately judged. The three-ratio method (IEC) is a detection method to judge the nature of the transformer fault by measuring the content ratio of characteristic gases (H_2 CH_4 C_2H_2 C_2H_4 CH_3CH_3). Because the relative concentration of gas formed by oil and insulation decomposition is intrinsically related to temperature in the fault transformer, it is a reliable method to detect the fault status of the transformer. The measurement of trace moisture in oil should meet the following requirements: First, when the pressure grade is 66 kV, the trace moisture content should be less than 20 mg/L. Second, when the pressure level is 220 kV, the trace moisture content should be less than 15 mg/L.

2) The Insulation Resistance, Absorption Ratio, or Polarization Index of the Winding and the Sleeve are Measured

Through the measurement of these indicators, one can quickly grasp the overall insulation of the transformer, check whether the transformer has damp insulation, check the surface pollution of parts and penetration concentration defects, etc. The following are the measurement requirements that need to be met: First, the insulation resistance value should be greater than 70% of the factory test insulation resistance value. Second, when the transformer is 35 KV and the capacitance is greater than 4000 KVA, the absorption ratio needs to be measured. The measurement formula is K=R60s / R15s, and the absorption ratio should not be less than 1.3 at room temperature. Third, when the transformer is 220 kV and the capacity is 120 MVA, the polarization index needs to be measured. The measurement formula is k=R600s / R60s, and the polarization index should not be less than 1.3 at room temperature.

3) The Dielectric Loss Factors of Winding and Bushing Are Measured

The measurement of this factor is actually the measurement of its capacitance C and TANR, and through the detection results, the transformer fault state (damp, oil deterioration, winding adhesion sludge, etc.) can be judged. External factors and surface leakage problems commonly interfere in the measurement of dielectric loss factors, so efforts should be made to measure in sunny weather; however, the shielding line can also be used to improve the accuracy of the measurement results. The specific requirements are as follows: First, the tangent angle value of the dielectric loss factor tan $\delta < 0.8\%$. In the same temperature environment, there should be no obvious difference between tan δ and tan δ over the years, and the difference value should be less than ±30%. Second, compared with the value of the nameplate, the measured capacitance of the casing should be less than ±5%.

4) AC Pressure Test

The AC voltage test belongs to the destructive experiment method, and is one of the most effective methods of transformer insulation strength detection, especially in the detection of local defects in the main insulation (main insulation dampness, cracking, loose winding, etc.), and has a decisive role. During the test, the applied voltage shall be 80% of the factory test. In short, there are two main methods to detect the insulation strength of the transformer: the insulation resistance test, and the voltage test. Through these two test methods, one can quickly respond to the transformer as a whole, or in the part of the book whether there are insulation defects.

III. ANALYSIS OF HIGH-VOLTAGE ELECTRICAL EQUIPMENT FAULT DIAGNOSIS TEST ITEMS

A. Circuit Breaker Fault Diagnosis Rules

In the BX region, only two kinds of fault diagnostic tests have been carried out on the circuit breaker. Second, the AC pressure first, loop circuit test. It should be noted that, in the fault diagnostic test of the SF6 circuit breaker, the circuit conductive resistance should be controlled to make the circuit resistance less than 50μΩ, and the (*H*)*GIS* circuit conductive resistance should be less than the manufacturer's design value. For SF6 gas, the gas decomposition test and trace water content test can be carried out. The detailed rules of the gas decomposition test are as follows: the content of CO, HF, SO_2 and H_2S is required to be less than 1. The moisture content test rules: under the handover test, the moisture content should be less than 150 ppm; during the routine test, the moisture content should exceed 300 ppm.

TABLE II. REQUIREMENT FOR DIELECTRIC LOSS VALUE OF TRANSFORMER

Dielectric Loss Value	Oil-Immersed	Dry-Type
66 kV	<0.8	<0.5
220 kV	<0.6	<0.5

B. Rules for Transformer Fault Diagnosis

In the BX area, only the dielectric loss test and insulation resistance test were carried out on the transformer to complete the diagnosis of the transformer's electrical faults. Details of the dielectric loss value of the transformer are shown in Table II.

C. Rules for Arrester Fault Diagnosis

The BX area regularly carries out resistance current test on the lightning arrester every year. If problems in the operation of the lightning arrester are found, then it is necessary to carry out leakage current, insulation resistance, DC voltage resistance, and other diagnostic tests on the lightning arrester. The diagnostic rules are as follows: when the voltage exceeds 35 kV, select 5000 V MΩm to measure the arrester, and the insulation resistance should be greater than 2500 MΩ When the voltage is less than 35 kV, select a 2500 V MΩ meter to measure the arrester, and the insulation resistance should be greater than 1000 MΩ Base insulation resistance should be greater than 5MΩ. Under 1 mA current, the difference between the DC reference voltage and the DC reference voltage of the nameplate should be less than ±5%. At 70% DC reference voltage, the leakage current should reach the factory technical standard, or less than 50μA.

D. Capacitor Fault Diagnosis Rules

In the high-voltage electrical equipment, capacitors and other large capacitor equipment are consumable goods. Capacitance measurement, insulation resistance measurement, and AC withstand voltage test are common test methods for capacitor fault diagnosis in the BX area. The detailed rules are as follows: First, when measuring the capacitance of the capacitor, its rated capacitance needs to be kept between 95% and 110%. If it exceeds this range, it can indicate that the capacitor is in trouble. Second, the insulation resistance of the fully insulated capacitor should be greater than 1000MΩ. Third, the AC withstand voltage test of the fully insulated capacitor should be carried out at 80% voltage of factory test.

E. Rules for Fault Diagnosis of Power Cables

Power cables are mainly concentrated at the outlet of the 66 kV substation line, so it is necessary to measure the insulation of the outer shielding layer of the cables, which can be tested through the voltage resistance test of the outer shielding layer

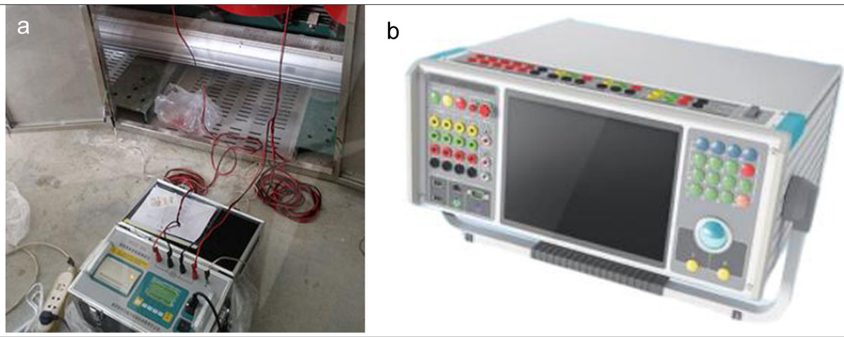

Fig. 2. Key equipment and instruments in the test. (a) Loop resistance tester. (b) DC resistance tester.

and the ground insulation test. In the fault diagnosis of power cables below 35 kV, the insulation resistance test and the ground voltage resistance test of the main cable core can be carried out. In general, when a power cable withstand voltage test is performed using AC withstand voltage, it is necessary to apply two times the U_0 voltage and continue for five minutes before a diagnostic test can be performed. However, due to the influence of the actual environment, the AC withstand voltage test is inhibited, and the DC withstand voltage is often used instead. In the BX area, two times the U_0 voltage is generally applied, and a DC withstand test lasting one minute replaces the AC withstand test.

IV. CASE ANALYSIS OF HIGH-VOLTAGE EQUIPMENT FAILURE IN THE BX AREA

Through the above theoretical analysis, we have a deep understanding of the characteristics, detection methods, and detailed rules of electrical faults of high-voltage equipment. In order to take this understanding beyond the theoretical level, a case study was conducted using high-voltage equipment faults in the BX area as an example, as shown below. The core equipment used during the test, is shown in Fig. 2.

A. Case Analysis of Winding Deformation Caused by Transportation Turbulence

In May 2018, the XC66KV substation started the capacity-increase project to replace the #1 and #2 substations. During the transportation of the #2 main transformer, due to the bumpy road, the transport vehicle tilted while turning, resulting in a collision between the #2 main transformer shell and the transport vehicle. After the transportation and installation, the outer part of the #2 main transformer was checked first, and no abnormal problems were found. Simultaneously, the other accessories (casing, heat sink) were also checked, and no abnormal problems were found. Secondly, a handover test was conducted, and it was found that there was a significant difference between the DC resistance values of the primary side winding (Table III) and those of the factory test winding (Table IV), indicating that the primary winding had deformation.

Finally, the suspension cover of the #2 main transformer was checked, and it was found that the pad between the primary side windings had fallen off, and the primary winding was seriously deformed. In order to solve this problem, BX Power Equipment Manufacturing Co., Ltd. organized personnel to carry out maintenance treatment on the #2 main transformer. After the maintenance, the handover test was conducted

TABLE III. DC RESISTANCE VALUE OF HIGH-VOLTAGE WINDING R(Ω)

Gear	AO	BO	CO	E%
1	0.3825	0.4123	0.3956	7.51
2	0.3756	0.4053	0.3825	7.65
3	0.3725	0.4014	0.3856	7.47
4	0.3698	0.3945	0.3748	6.50
5	0.3596	0.3904	0.3645	8.29
6	0.3569	0.3847	0.3691	7.50
7	0.3456	0.3745	0.3512	8.09
8	0.3492	0.3751	0.3469	7.89
9	0.3365	0.3712	0.3452	9.54
10	0.3461	0.3752	0.3417	9.79
11	0.3553	0.3866	0.3547	8.72
12	0.3563	0.3845	0.3621	7.67
13	0.3566	0.3941	0.3756	9.98
14	0.3621	0.3954	0.3714	8.84
15	0.3755	0.4012	0.3721	7.59
16	0.3829	0.4122	0.3854	7.44
17	0.3827	0.4165	0.3969	8.47
18	0.3736	0.4025	0.3965	7.39
19	0.3847	0.4196	0.3865	8.79
20	0.3769	0.4021	0.3765	6.64

TABLE IV. DC RESISTANCE VALUE OF FACTORY TEST WINDING R(Ω)

Gear	AO	BO	CO	E%
1	0.3765	0.4025	0.3845	6.70
2	0.3714	0.4015	0.3804	7.82
3	0.3645	0.3967	0.3736	8.51
4	0.3612	0.3977	0.3745	9.66
5	0.3569	0.3911	0.3666	9.20
6	0.3521	0.3854	0.3657	9.05
7	0.3456	0.3748	0.3514	8.17
8	0.3495	0.3745	0.3512	6.97
9	0.3348	0.3632	0.3498	8.13
10	0.3411	0.3752	0.3417	9.66
11	0.3498	0.3847	0.3569	9.59
12	0.3585	0.3941	0.3622	9.58
13	0.3598	0.3941	0.3682	9.17
14	0.3621	0.3988	0.3723	9.71
15	0.3711	0.4025	0.3748	8.20
16	0.3785	0.4125	0.3844	8.67
17	0.3847	0.4166	0.3952	7.99
18	0.3874	0.4166	0.3987	7.28
19	0.3955	0.4018	0.3645	9.63
20	0.3847	0.3945	0.3643	7.92

TABLE V. MEASURED VALUES OF WINDING DC RESISTANCE R(Ω)

Gear	AO	BO	CO	E%
1	0.3755	0.3792	0.3786	0.97
2	0.3699	0.3734	0.3723	0.94
3	0.3638	0.3670	0.3621	1.34
4	0.3588	0.3552	0.3541	1.32
5	0.3527	0.3496	0.3499	0.88
6	0.3401	0.3441	0.3433	1.16
7	0.3345	0.3311	0.3296	1.47
8	0.3347	0.3386	0.3377	1.15
9	0.3281	0.3315	0.3296	1.03
10	0.3344	0.3386	0.3372	1.24
11	0.3406	0.3442	0.3438	1.04
12	0.3466	0.3496	0.3495	0.86
13	0.3521	0.3565	0.3554	1.24
14	0.3579	0.3610	0.3606	0.86
15	0.3632	0.3674	0.3661	1.14
16	0.3651	0.3621	0.3625	0.82
17	0.3756	0.3784	0.3786	0.79
18	0.3741	0.3766	0.3764	0.66
19	0.3642	0.3648	0.3701	1.61
20	0.3721	0.3756	0.3748	0.93

again. The obtained DC resistance data of the primary side winding are shown in Table V.

Generally speaking, the fault is caused by improper transportation of high-voltage electrical equipment. It is obvious that the fault cannot be found just through appearance inspection. It is necessary to carry out other tests, such as the handover test, to identify the fault. The fault type is determined by diagnostic tests, and a disassembly test of high-voltage electrical equipment is carried out to determine the specific fault location.

B. Case Analysis of Equipment Failure Caused by Lightning Strike

On August 13, 2018, there was a thunderstorm in the BX area. The local weight gas protection of the main transformer #2 of CHK220kV substation was in action, the differential protection was not activated, and the circuit breakers on both sides tripped, leading to the full stoppage accident of the 66 kVII section bus. At this time, chromatographic analysis was conducted for the # 2 main transformer, to obtain the measurement of dissolved hydrogen and the overall situation. The data were compared with the measurement data of August 13, 2017, and the results found that the CPC dissolved total hydrocarbon in the # 2 main Transformer showed an obvious growth Trend in hydrogen. The results show that The total dissolved hydrocarbon and hydrogen in #2 main Transformer have an obvious growth trend in hydrogen. On August 14, 2018, test data were compared, and the total hydrocarbon and hydrogen were still rising, At this time, the fault nature of the #2 main transformer was determined as high-energy arc discharge, with the help of the three-ratio method. Then, the characteristic gas method was used to detect the fault in the #2 main transformer. It was found that the total hydrocarbon of the transformer after being struck by lightning was 488.4 ppm, and the hydrogen content was 646.8 ppm, confirming the discharge inside the transformer. The specific measured data are shown in Table VI.

In order to further determine the fault situation of the #2 main transformer, a diagnostic test was carried out. The test results

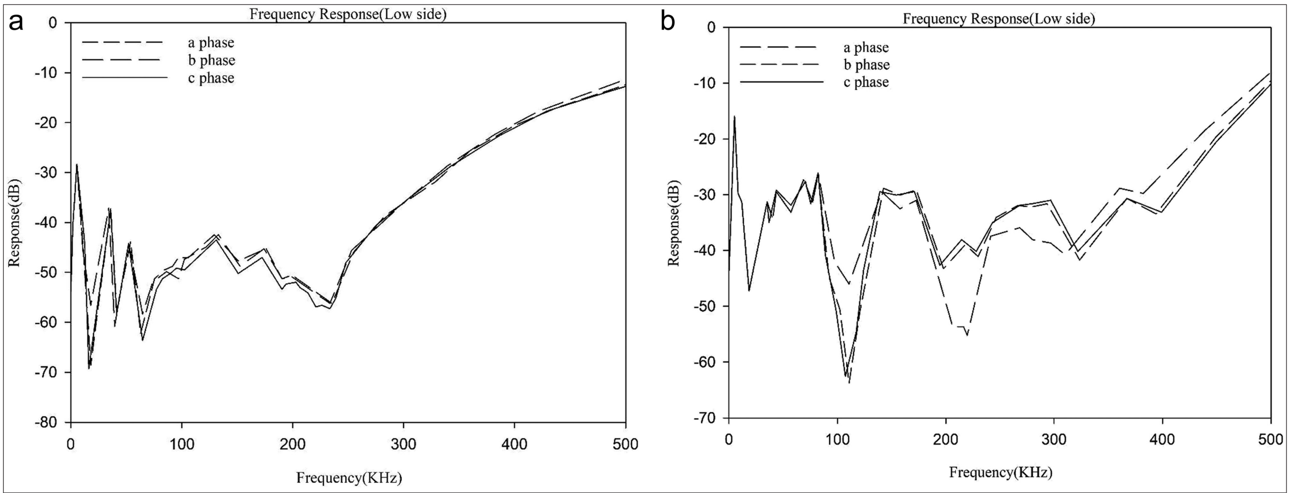

Fig. 3. Winding deformation atlas. (a) High- voltage side winding deformation atlas. (b) Low-voltage side winding deformation atlas.

TABLE VI. #2 COMPARISON OF MEASURED DATA BEFORE AND AFTER MAIN TRANSFORMATION

Time	H_2	CO	CO_2	CH_4	C_2H_6	C_2H_2	C_2H_4	Total Hydrocarbon
August 13, 2017	165.3	676	8545	24.9	7.8	0	30.9	63.6
August 13, 2018	646.8	876	9458	135.8	15.9	147.8	188.9	488.4
August 14, 2017	1058	1096	9874	236.4	18.7	218.6	254.9	728.6

TABLE VII. DC RESISTANCE MEASUREMENT OF HIGH AND LOW WINDING R(Ω)

	Gear	AO	BO	CO	E%
High-voltage winding	Running gear	0.8269	0.8298	0.8275	0.35
Low-voltage winding	Running gear	0.1456	0.1248	0.1469	15.88

indicated that no abnormality occurred in the diagnostic test items of the 220 kV-side of the #2 main transformer; The resistance value of A-phase DC resistance of 66 kV-side winding was abnormal; The three-phase unbalance rate of the DC resistance of the 66 kV side winding was 13.18%, exceeding the set value in the Test Standard for the Handover of Electrical Equipment in Electrical Equipment Installation Engineering, indicating that the 66 kV side winding of the #2 main transformer had a fault. The specific test data are shown in Table VII.

Then, the frequency response method was used to conduct deformation tests on the winding of the high-voltage side and the low-voltage side of the #2 main transformer, and the obtained atlases are shown in Fig. 3 (a) and (b) respectively.

It can be seen that there are abnormal phenomena in the high-voltage side winding. Based on the above tests, it can be concluded that there is no fault in the 220 kV side of the #2 main transformer. However, in the low-voltage side winding deformation test of the #2 main transformer, A-phase has obvious deformation. Finally, the suspension cover of the substation was checked, and it was found that the insulation pad was scattered inside the transformer. After in-depth inspection, it was found that the 220 kV side winding of #2 main transformer did not have abnormal problems, and the A-phase of the 66 kV side winding had serious deformation, while the B and C phases did not have abnormal problems. Thus, the test was ended and the #2 main transformer was replaced. Because the differential protection was not activated, it can be concluded that the #2 main transformer was damaged by lightning strike and that caused the fault, which further indicates that the lightning protection measures of CHK220KV substation are defective and need to be improved actively to avoid the occurrence of major substation accidents.

V. IMPROVEMENT STRATEGY OF HV EQUIPMENT FAULT TEST PROJECT

A. Increase Online Monitoring System and Develop Live Detection Items

In order to reduce the probability of substation failure, the application of the online monitoring system should be improved to detect some specific defects of HV electrical equipment as soon as possible and avoid the occurrence of substation accidents. In order to ensure the safety of the operation of the 220 kV substation, BX Power Supply Company of State Grid has basically promoted the device to comprehensively detect and analyze the oil in the line spectrum, and provided two channels for the online analysis of transformer oil chromatography, with automatic and manual operation. However, the sampling accuracy of the transformer oil chromatographic online analysis system has some limitations. Therefore, it is often necessary to combine manual sampling for rational analysis. At the same time, the automatic infrared thermal imaging diagnosis system can be applied to the 220 kV substation to monitor the defects of high-voltage electrical equipment. Through computer calculation and comparison, it can judge whether there is overheating of high-voltage electrical equipment and whether there are defects (insulation fault, poor contact, oil shortage for oil-immersed equipment, etc.). Through these online detection systems, the defects of electrical equipment can be captured in time to prevent the second deterioration of defects. Combined with the diagnostic test, the position and degree of defects can be determined, which provides a favorable reference for the solution of the problems. In recent years, the charged monitoring technology, infrared imaging detection, SF6 micro water, decomposition, GIS ultrasonic, etc. have become effective detection methods that guarantee normal operation of power grid equipment. The charged detection project of the power supply company and BX remains to be improved, with issues such as how to carry out some of the more mature charged the test items, how to put an end to transverse development of defects and ensure the normal and safe operation of the substation.

B. Carry Out Targeted Diagnostic Test Items According to Equipment Fault Types

Although there are many diagnostic tests at present, not all of them are related to the fault type, and some faults require comprehensive analysis to reach specific conclusions. Therefore, diagnostic tests cannot provide effective support., and it is necessary to carry out targeted tests according to the fault types of high-voltage electrical equipment. Specifically, in the face of equipment failure due to overheating and similar issues, the equipment contact, whether there is pollution, and other issues can be considered; In the face of local discharge faults, dielectric loss angle and insulation strength can be checked from the two sides. In the face of deformation faults, it can be checked from voltage ratio, DC resistance, winding deformation, and other aspects. Thus, only by carrying out targeted diagnostic test projects can the problems of equipment failures be solved quickly and the power grid can operate safely and smoothly.

C. The Influence of Environmental Factors on High-Voltage Electrical Equipment Should Be Fully Considered

Environmental factors can affect the operation of electrical equipment. Therefore, in the diagnosis of electrical equipment faults, it is necessary to take the environmental factors of the electrical equipment into consideration, fully analyze whether they will affect the operation of electrical equipment, and carry out targeted tests. In this way, the fault problems can be found and solved quickly, and the normal production and operation of the substation can be maintained.

VI. SUBTOTAL

Q6

In general, this paper primarily analyzes in detail the testing methods of transformer winding deformation and insulation strength, such as frequency response, low-voltage impedance, and capacitance method used for testing winding deformation, and also the insulating oil analysis and three-ratio method used for testing winding insulation strength. Second, fault diagnosis rules for the circuit breaker, lightning arrester, capacitor, high-voltage electrical appliances such as power cable insulation, have been made. With respect to the requirements of each high-voltage equipment and electrical insulation fault diagnosis, the winding deformation and lightning are the two actual cases analyzed. In case one, the abnormal problem of winding DC resistance data was found by using the handover test method, and the fault type and specific location were determined by using the diagnosis test and the disassembly test respectively. In the second case, the chromatographic analysis of the main transformer #2 was carried out, and the fact that the total hydrocarbon and hydrogen dissolved in oil were continuously increasing was noticed. Secondly, the fault nature of main transformer #2 was determined by using the ratio-of-three method, and then the problem of transformer internal power generation was confirmed by using the characteristic gas method. Thirdly, the reason for the #2 main transformer fault problem was found through the hanging cover experiment, that is, it is caused by lightning intrusion when differential protection had not started. Finally, the optimization strategies of high-voltage equipment fault test items are given, such as adding online detection system and developing live detection items, and fully considering the influence of environmental factors on high-voltage equipment, etc. Although this paper has carried out an in-depth study on the detection methods of transformer winding deformation and insulation strength, and put forward targeted solutions for different fault problems, the research has certain limitations. It has not discussed all kinds of common fault problems. In the future research work, faults due to too much load, ice arcing fault, power failures, insulator surface subsidence caused by the fault, the aspects such as research and ongoing refinement to improve the power equipment fault diagnosis system, improving the efficiency and accuracy of the equipment fault diagnosis, and development of the whole power system in the direction of security and stability, could be areas of focus.

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REFERENCES

1. Y. Zhou, "Short circuit fault analysis and preventive countermeasure analysis of 10kV high voltage equipment," *Electr. World*, vol. 2020, no. 12, pp. 74–75, 2020.
2. R. M. Wang, X. N. Zhang, Y. Meng and L. Yang, "Research on automatic fault monitoring of high voltage production equipment in power system," *Commun. Power Source Tech.*, vol. 37, no. 10, pp. 12–14, 2020.
3. J. Lu and Y. Wang, "Research on automatic electrical fault monitoring of high voltage production equipment in power system," *Autom. Instrum.*, vol. 2019, no. 7, pp. 66–69, 2019.
4. X. X. Dai, "Analysis of high voltage distribution equipment fault and countermeasures," *Shandong Ind. Tech.*, vol. 2019, no. 10, p. 210, 2019.
5. J. L. Dong, "Research on common faults of high voltage switching electrical equipment and treatment measures," *Low Carbon World*, vol. 2018, no. 10, pp. 137–138, 2018.
6. D. Y. Li, "Analysis and solutions of abnormal detection of high voltage electrical equipment," *Commun. Power Sources Technol.*, vol. 37, no. 4, pp. 90–91, 2020.
7. D. W. Shi, Z. X. Wang, Q. B. Mao, D. Liu, S. F. Liu and X. Z. Gong, "Study on frequency response analysis of transformer winding deformation under 500kV bus electromagnetic interference," *Transformer*, vol. 57, no. 8, pp. 49–51, 2020.
8. Y. M. Liu and L. H. Zhu, "Comprehensive diagnosis method of transformer winding deformation based on low voltage impedance and winding capacity," *New Ind.*, vol. 10, no. 2, pp. 1–5, 2020.
9. Z. Y. Zhou, Q. Liu, H. Liu, X. X. Liu and X. K. Zhang, "Frequency response analysis method for interference detection of power transformer winding deformation," *Electrotech. Eng.*, vol. 2021, no. 7, pp. 76–78, 2021.
10. Y. X. Li, "Application of oil chromatography in fault detection of power transformer," *Electr. Tech.*, vol. 50, no. 1, pp. 138–139, 2021.

Zhumao Lu has received the master's degree. He is working in State Grid Shanxi Electric Power Research Institute of SEPC. He is interested in research and application of high voltage outage test and live detection and research and application of substation operation and maintenance management technology.

Tao Jin has received the master's degree. He is working in State Grid Shanxi Electric Power Research Institute of SEPC. He is interested in research and application of safety control technology for substation operation and maintenance.

Yaning Zhao has received the master's degree. He is working in State Grid Shanxi Electric Power Research Institute of SEPC. He is interested in high voltage and insulation technology and power equipment testing technology.