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Analysis of On-Load Tap-Changer Failures Based on Lightning Overvoltage

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Abstract. Transformer faults have now become a major cause of power system failures, with transformers being more susceptible to malfunctions in adverse weather conditions. This article takes the example of a fault in the on-load tap changer switch of a transformer caused by a localized overvoltage short circuit during severe thunderstorm weather. The author elaborates on three types of lightning-induced overvoltage, combining fault analysis with extensive on-site experimental data and comparisons with standard values to convincingly identify the fault causes. The article briefly discusses five types of overvoltage in neutral point ungrounded systems and, in conjunction with one of the transformer's crucial components, the on-load tap changer switch, provides a concise analysis of four main fault types associated with OLTC. Finally, the author traces the root cause of the fault, summarizes the findings, and presents effective recommendations to prevent similar incidents in the future.

Keywords. on-load tap-changer, lightning overvoltage, single-phase grounded short circuit, transformer failure

1. Introduction

With the gradual increase of people's demand for electric energy, the power system has ushered in the rapid development. As the most important electrical equipment in the power system, transformers play an important role in transforming different voltage levels. Whether in substations, power plants and other power generation and distribution sites, or on transmission lines such as towers, there are transformers of different voltage levels. On-load tap-changers (OLTC) are used to change the tap connection of the transformer windings, to realize the conversion between the taps in the transformer windings without interrupting the load current, and to change the number of turns in the windings to realize voltage regulation [1]. The OLTC is one of the few movable components inside the transformer, it is the core component of transformer voltage regulation and plays an important role in ensuring the voltage stability of the power system. However, the on-load tap-changer is also one of the components with frequent failures. It has been found that nearly 20% of the transformer failures are caused by the abnormal operation of the on-load tap-changer, which makes effective supervision of the on-load tap-changer and timely maintenance after a failure particularly important [2].

The common types of transformer faults are typically caused by internal malfunctions within the transformer itself or due to adverse environmental conditions such as lightning

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and thunderstorms[3]. In this paper, I focus on a transformer on-load tap-changer fault caused by lightning overvoltage, from the condition of the equipment, on-site observation and test data analysis, oil dissolved gas test and other aspects, to find out the cause of the fault and finally suggestions for accident handling and prevention. The paper analyzes several issues that arise from failures, such as transformer winding deformation and abnormal dissolved gas content in transformer oil, and summarizes the types of failures of on-load tap-changers. Since the on-load tap-changer has a higher failure rate compared with other components, it is necessary to conduct a detailed analysis of this failure, providing a reference for relevant practitioners to avoid such accidents as far as possible.

2. Failure process and statistics

On August 02, 2022, a power plant No. 1, No. 2, No. 3 and No. 4 generators were in normal operation, with a total unit load of 120 MW and No. 5 and No. 6 backpressure units in hot standby status, of which the No. 1 and No. 2 main transformers were running at 120 MW load; the No. 3 main transformer was running in no-load hot standby operation, No. 1 main transformer was running in neutral grounded operation, and the No. 2 and No. 3 main transformers were running in neutral ungrounded operation.

At 20:54 on August 02, the switch tripped, followed by the on-load switch heavy gas protection operation of No. 2 and No. 3 main transformers, and No. 3 and No. 4 generating units tripped, shedding load of 60 MW. On-site inspection found that the pressure release operation of on-load regulator tap-changer of No. 2 and No. 3 main transformers and oil leakage occurred. At present, No. 1 and No. 2 units are in operation, and No. 3, No. 4, No. 5 and No. 6 units are in standby mode.

2.1. Inspection of No. 2 main transformer

No. 2 main transformer body inspection, according to the inspection condition can be clearly found No. 2 main transformer on-load voltage regulator tap-changer burned, the bottom of the oil chamber is damaged and oil leakage.

Entering the No. 2 main transformer tank internal checker, it was found that the A and C two-phase high-voltage windings had obvious deformation, the on-load regulator tap-changer core a and b phase gap burnt, current limiting resistor burnt, and the bottom of the on-load regulator tap-changer oil compartment was damaged.

2.2. Inspection of No. 3 main transformer

After completing the No. 2 main transformer inspection, the No. 3 main transformer body was inspected and found to have a certain degree of damage to its on-load switch.

Into the No. 3 main transformer tank internal inspection, compared with the No. 2 main transformer, the No. 3 main transformer did not find A, B, C three-phase high-voltage windings have obvious deformation, tampering, loose situation. Winding ends neatly without tampering, no loosening, tap line and on-load connection terminals firmly.

The basic situation of No.2, No.3 transformer is shown in Figure 1.

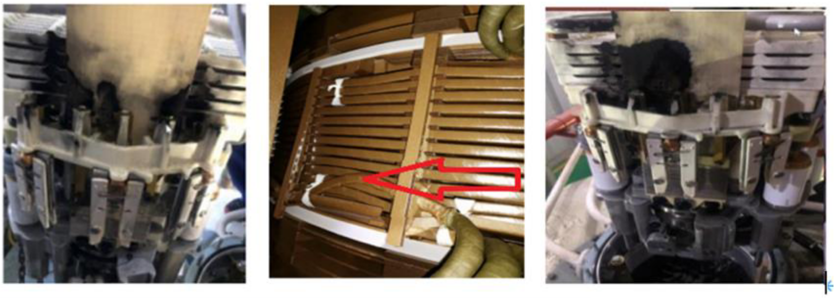

Figure 1. The basic situation of No.2, No.3 transformer

2.3. Chromatographic analysis of the main components of transformer oils

After the failure, the transformer oil of No. 2 and No. 3 main transformer body was sampled and analyzed respectively, as shown in Table 1.

Table 1. No. 2 and No. 3 main transformer oil assay results

Equipment Name	CO	CO_2	H_2	CH_4	C_2H_6	CH_{24}	C_2H_2	ΣC
No. 2 main transformer	558.70	6102.01	77.90	8.53	1.20	4.89	9.01	23.63
No. 3 main transformer	203.89	3341.13	59.28	18.60	4.33	22.62	38.97	84.52

Diagnosis is made based on the results of oleochemical experiments.104 TM-2008 Rogers Ratio Typical Failure Analysis of Power Transformers with Gases Dissolved in the Oil, as shown in Table 2[4] .

Table 2. Typical Faults as Identified by the Ratios of Various Gases (The table lists only some of the faults)

Case	Typical fault	C_2H_2/C_2H_4	CH_4/H_2	C_2H_4/CH_2
1	Partial discharge	Not significant	<0.1	<0.2
2	Discharge of low energy	>1	0.1-0.5	>1
3	Discharge of high energy	0.6-2.5	0.1-1	>2

Calculations according to this table give:

$$C_2H_2/C_2H_4 = 1.84$$
$$CH_4/H_2 = 0.109$$
$$C_2H_4/C_2H_6 = 7$$

It can be initially judged as a high-energy discharge and then analyzed according to the three-ratio method in the judgment guidelines, as shown in Tables 3,4[5] .

Table 3. IEC Triple Ratio Codes

Gas ratio range	Code for gas ratio		
	C_2H_2/C_2H_4	CH_4/H_2	C_2H_4/C_2H_6
<0.1	0	1	0
0.1-1	1	0	0
1-3	1	2	1
>3	2	2	2

Table 4. Types of faults for the IEC three-ratio method (partial faults)

Fault codes for ratios			Fault type
C_2H_2/C_2H_4	C_2H_4/H_2	C_2H_2/C_2H_6	
0	1	0	Partial discharge
1	0,1	0,1,2	Arc discharge
	2	0,1,2	Arc discharge and thermal fault
2	0,1	0,1,2	Low energy partial discharge
	2	0,1,2	Low energy discharge and thermal fault

According to the calculations, it was judged to be an arc discharge. The analysis concluded that the arc discharge from the on-load tap-changer was strong and that a portion of the acetylene was mixed into the main body of the transformer, resulting in an increase in the total hydrocarbon content of the body oil.

2.4. Recorder Checks

Information about the line and 2-unit recorders was viewed in Figure 2.

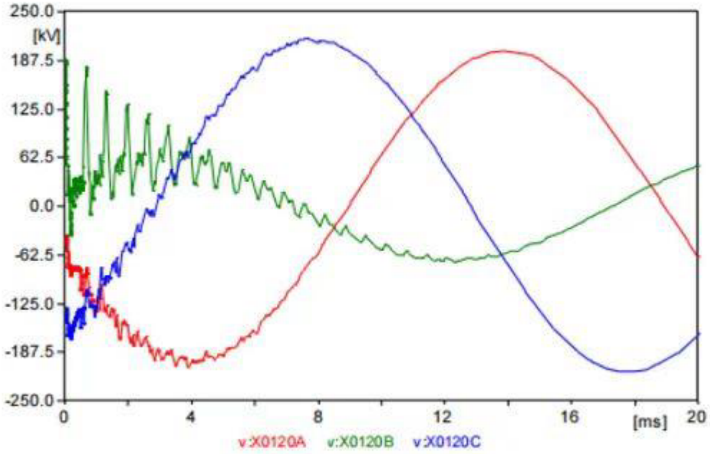

Figure 2. Waveform diagram of fault recording device $3U_0$ for power substation

Analyzed from Figure 2 waveform: grid 220kV line B phase and 110kV line B the same when the ground faults, 57ms after 110kv line C phase ground. After understanding the grid 220kV and 110kV with the tower, the day the power plant is located in the local climate for thunderstorms and windy weather analysis that the bad weather caused by external line ground faults [6].

3. Analysis and discussion

3.1. fault types of the OLTC.

3.1.1. Oil malfunction.

Insulating oils play an important role in electrical insulation, and phenomena such as arc discharges, which are so far still unavoidable, lead to oil failures in on-load tap-changers. Concentrations and combinations of gases like hydrogen (H2), carbon monoxide (CO), carbon dioxide (CO2), methane (CH4), acetylene (C2H2), ethylene (C2H4), ethane (C2H6), oxygen (O2), and water (H2O), and other gases, all of which can lead to varying degrees of failure [7]. The As the temperature of the insulating oil increases, some hydrocarbons such as methane, ethylene, acetylene, etc. can further carbonize the insulating oil and even the on-load tap-changer, which, if left unchecked, can lead to serious failures such as combustible gas explosions. Literature [8]. The fuzzy clustering algorithm is based on the reconstruction of the affiliation calculation method to effectively classify the insulating oil chromatographic data. Literature [9]. Based on the B-spline theory, this method effectively improves the limitation problem of the three-ratio method, and expands the research direction of OLTC oil chromatographic fault detection technology. The deterioration of the on-load tap-changer oil is also one of the important reasons for the contamination of transformer oil [10].

3.1.2. Mechanical breakdown

The on-load tap-changer has several mechanical components that are used to control the position of the taps, e.g. shunts. After a long period of use, these mechanical components are subject to wear and tear, aging, and other mechanical failure factors [11]. The most common faults in on-load tap-changers are the most common mechanical faults in on-load tap-changers are loose fasteners, abnormal torque, fatigue damage, and abnormal mechanical wear, which can lead to excessive resistance of the on-load tap-changer, damage to the contact system, and increased temperatures of some mechanical components. the OLTC's online mechanical diagnostics are constantly updated [12][13]. Literature[14] By synchronization, framing, and Fourier transform, represents the signal in the form of an energy matrix which can be used to differentiate between different conditions of OLTC and show the severity of the fault. Literature [15] A new strategy for mechanical fault diagnosis of OLTC with high recognition accuracy based on Hidden Markov Model (HMM) is proposed to achieve the diagnosis of mechanical faults by analyzing the power signal spectrum. Literature [16] A mechanical fault diagnosis model based on homologous heterogeneous data fusion with on-load pickup is proposed to make the OLTC mechanical fault diagnosis model applicable.

3.1.3. Electrical malfunction

When moisture is present in the transformer, the arc insulation effect of the insulating oil during tap changer operation is greatly reduced, causing conditions such as localized overheating and discharges due to external short circuits, arc discharges due to switching hysteresis or malfunction, and discharges due to degradation of the insulating oil or insufficient insulating material. These are all electrical faults, and the fault in this power plant is an electrical discharge [17].

There are already many ways to detect faults on the on-load regulator tap-changer in various ways, e.g. based on frequency, signal and vibration monitoring. Literature [18] Aiming at the problem of limited diagnostic accuracy of on-load tap-changer (OLTC), a new fault diagnosis method for oil-immersed on-load tap-changers is proposed, which combines the analysis of mechanical vibration signals of the contact pair and high-frequency current signals in order to improve the accuracy of OLTC fault diagnosis. To better focus on the use of frequency response analysis to diagnose the mechanical integrity of transformer on-load tap-changers, the literature [19] Two common tap changer faults were generated and four FRA test configurations were experimentally tested. Literature [20] The current status of research on equipment monitoring and fault diagnosis techniques is sorted out on the basis of various types of failure mechanisms of mechanical OLTCs.

4. Causes of Failure Discussion

4.1. Positioning the direction of accident finding

By accessing the fault recorder waveforms, relay protection action, according to Figure 3 process analysis and judgment, clearly indicate the direction of the accident is a single-phase grounding of the line to form a transient overvoltage, resulting in the gap action of the on-load tap-changer discharges and develops into a fault.

4.2. Traceability analysis of causes

4.2.1. Transformer Neutral Protection Gap Action Causes

No. 2 and No. 3 main transformer neutral point is not grounded operation, through the parallel neutral point of the lightning arrester and discharge protection gap together to complete the overvoltage protection function. The air distance of the protection gap is 268mm, the frequency discharge voltage is 3.8kV/cm26.8cm=102kV, the rated voltage of the lightning arrester is 144kV, the short-time frequency withstand voltage is 200kV, and the residual voltage is 320kV. the two main transformer neutral and high voltage side of the lightning arrester's action recorder shows the value of zero, which means that the arrester has not been acted on, and through the on-site video playback, it is found that the two main transformer neutral point discharge protection gap is not grounded. Through the field video playback found two main transformer neutral point discharge protection gap discharge phenomenon, indicating that in the transformer neutral point overvoltage invasion moment, the protection gap prior to the lightning arrester action. The reason is that the fault moment of neutral frequency zero sequence voltage is greater than 102kV, less than 200kV, so the transformer neutral protection gap action and lightning arrester did not act.

4.2.2. Causes of on-load tap-changer gap burnout

The on-load tap-changer gap burnout is because the gap discharge circuit (whose function is to protect against interstage overvoltage) is connected to the transformer neutral point. Since the neutral point of the main transformers No. 2 and No. 3 is operated in a way that it is not directly (via the discharge gap) grounded, which results in the suspension of the tap-changer gap, the on-load tap-changer gap discharge circuit is not effectively formed. The frequency voltage action value of the on-load tap-changer gap protection is 20 kV, and the voltage action value of the transformer neutral gap protection (impulse voltage or transient voltage) is 102 kV. When single-phase grounding occurs in the system, the transformer neutral potential rises, the on-load tap-changer gap protection is activated but the discharge circuit is not accessible, so that the overvoltage energy cannot be discharged and the on-load tap-changer gap discharges, and at the same time the gap discharges to the equalizing ring, resulting in The gap in the on-load tap-changer is discharged and the gap is also discharged to the voltage equalizing ring, resulting in burnout of the on-load regulator gap. Lightning overvoltage and single-phase grounded short circuits are the main cause of many accidents, as are overvoltage in the neutral point of the transformer[21] .

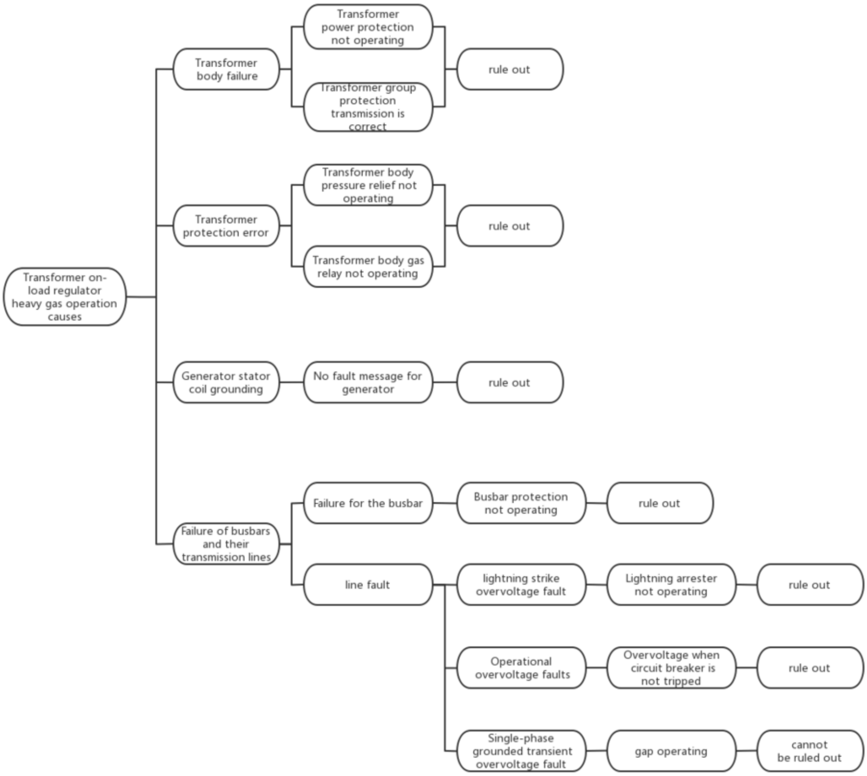

Figure 3. Flow chart of transformer fault analysis

5. Summary and recommendations

5.1. Conclusion

The relay protection of main transformers No. 2 and No. 3 of this 220 kV power plant was operating correctly, and the neutral gap of main transformers No. 2 and No. 3 was operating correctly. The on-load tap-changer was not designed properly or had original quality defects and did not withstand the overvoltage generated by the single-phase grounding fault of the external line, which led to the burnout of the on-load tap-changer gaps in the main transformers No. 2 and No. 3, which were operating without grounding.

5.2. Recommendation

1. For the two transformers with different damages, combined with the needs of production and power generation, the main transformer with less damage will be dismantled by the on-load tap-changer and changed to the fixed tap operation mode, and the other transformer will be returned to the factory for repair. According to the standard test, the main test items are DC resistance, ratio, winding deformation, dielectric loss, AC withstand voltage, local discharge test, etc., after passing the test, the power supply is put into standby.
2. It is recommended that the transformer manufacturer carry out the relevant accounting or modification work to ensure the safe and stable operation of the on-load tap-changer in the neutral ungrounded mode of operation and to prevent the occurrence of similar events.
3. The transformer manufacturer provides theoretical and simulation calculations for matching the on-load tap-changer to the transformer windings to ensure that the insulation margin meets the design requirements and to safeguard the improvement and enhancement of the resistance to short circuits and shocks.
4. Regularly check the parallel protection gap whether there is action, after the action should check whether the electrode surface is smooth, such as burn traces, it is recommended to use sandpaper to polish, such as the effect is not obvious should be replaced electrode. And each time after the action should check whether the parallel protection gap distance is within the required range, if not should be adjusted.
5. Multiple actions of the gap will cause fusion corrosion of the electrodes of the parallel protection gap, so the electrodes of the parallel protection gap should be made of fusion-resistant materials, such as tungsten steel and other materials.
6. To reduce the probability of faulty operation of gaps caused by transient overvoltage, closed protection gaps or controllable protection gaps may be considered for protection of the neutral point of the transformer.

5.3. Limitations and improvement

This paper focuses on the failure of OLCT (On-Load Tap Changer) under the condition of single-phase grounding short circuit caused by lightning overvoltage, which is only one of the many types of failures of the on-load tap-changer and has strong limitations. Meanwhile, this paper does not provide a specific analysis of the causes of transformer winding deformation and abnormal dissolved gas content in transformer oil, which will be further improved in subsequent experiments.

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