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POWER TRANSFORMERS AND REACTORS

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Investigations on Vacuum Tap Changer Failures of Converter Transformers and Maintenance Suggestions

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Motivation

- Since 2018, four vacuum load tap changer (VLTC) failures have occurred both on converter transformer and power transformer in Southern China Grid (CSG). However, few literature on the maintenance of VLTC have been found so far and little experience could be referred to.
- It is hoped that our research could provide useful reference to the design, test and maintenance of VLTC.

Brief introduction

- Based on the four VLTC failures, this paper firstly summarizes the fault features and causes. Foreign matters, insufficient clamping force of auxiliary contact and unsuccessful operation of mechanism are the main reasons for VLTC failures.
- By analyzing the recorded fault current signals, the relationship between transformer fire and protection time is obtained.
- We also reproduce one of the VLTC failures successfully by establishing a field-circuit FEM model.
- Based on the DGA results of a population of 1247 VLTCs, the distribution and caution limit (CL) of acetylene are studied statistically with 90% accumulative probability method given in IEC 60599 and the upper outlier limits method recommended by IEEE Std C57.139.
- Finally, we propose a number of maintenance, design and test suggestions for VLTC for the reference of power grid and manufacturers. Especially, it is strongly suggested that the arc interrupting ability of auxiliary contacts of VLTC should be taken into consideration by IEC standard.

Failure discussions

- Basic information of the four failures of vacuum LTCs are listed in Table 1. Besides, other two vacuum LTCs failures of ±800kV converter transformers in other regions are also included.
- Four failures occurred after diverting and two failures occurred during diverting. In terms of results, two failures cause fire. After a long period of fault analysis, simulations and test verifications, reasons for the initiation of failures are determined.
- Failure 1: After diverting, **contaminants** in the oil compartment, due to the effect of oil pump, flow to the gap between the main moving contact and fixed contact, which is only 18 mm long, resulting in the oil gap breakdown.
- Failure 2: **Mechanism of vacuum interrupter fails to operate** and causes the auxiliary contact to operate under load current conditions. As the auxiliary contact is not designed to interrupt arc in oil, short circuit between taps are finally resulted.
- Failure 3: The clamping spring of the auxiliary contact is not assembled accordingly, which leads to the **auxiliary contact loose due to the insufficient clamping force**. Although the auxiliary contact of this type of tap changer is capable of extinguishing arc in oil, the erosion of the auxiliary contact is aggravated during the long-term operation, which eventually leads to arcing and short circuit between taps.
- Failure 4: After diverting, **contaminants** in the oil compartment flow to the gap between the main moving contact and fixed contact which is only 26 mm long and leads to the oil gap breakdown.

Table.1 Information of failures

No.	Voltage	Failure features
Failure-1	±800kV	Fault occurs 9 seconds after diverting. Top cover is torn and oil is spout.
Failure-2	±800kV	Fault occurs during diverting. Top cover is torn and oil is spout.
Failure-3	220kV	Fault occurs during diverting. Top cover is torn and oil is spout. **Causing fire**.
Failure-4	220kV	Fault occurs 0.5 seconds after diverting. Top cover is torn and oil is spout.
Failure-5	±800kV	Fault occurs 13 seconds after diverting. Top cover is torn and oil is spout
Failure-6	±800kV	Fault occurs 10 seconds after diverting. Top cover is torn and oil is spout. **Causing fire**.

Fault current and protection analysis

- Table 2 shows the protection actions of VLTC failures. It can be seen that the action time of the pressure relief device (PRD) is the key parameter for determining whether the transformer is on fire. As the action time of PRD of VLTC is **less than 14ms**, transformer does not catch fire. While as the action time gets longer such as **more than 58ms**, transformers get fire.
- It is also shown that the oil flow relay protection plays an insignificant role in the internal fault of VLTC. All oil flow relay protection lag behind differential and pressure relief protection.

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Table.2 Protection actions of vacuum tap changer failures

Cases	Δt-total fault duration	Δt_2-differential protection activates	Δt_3-differential protection operates	Δt_4-pressure relief device of tap changer operates	Δt_5-oil flow relay of tap changer operates	Fire
Failure-1	79ms	7ms	44ms	14ms	55ms	No
Failure-2	67ms	—	44ms	13ms	—	No
Failure-3	80.6ms	23.5ms	48.5ms	63.5ms	75.5ms	Yes
Failure-4	70.8ms	6ms	26ms	6ms	78ms	No
Failure-5	Appx.61ms	—	28ms	—	57ms	No
Failure-6	Appx.70ms	—	21ms	58ms	91ms	Yes

FEM simulation

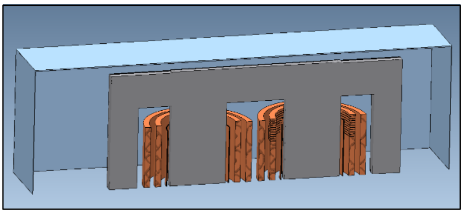

Fig. 2 1/4 3D simulation model of converter transformer of failure 1

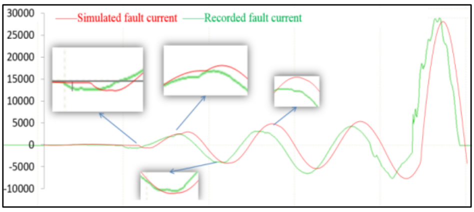

Fig. 4 Simulation fault current and recorded fault current

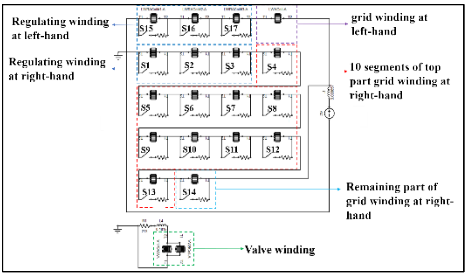

Fig. 3 Simulation circuit settings

Table.3 Switching sequence

switch	Closing time (ms)	switch	Closing time (ms)
S1/S15	21.8/23.8	S8	81.2
S2/S16	31.6	S9	82.2
S3/S17	42.6/53.6	S10	83.2
S4	77.2	S11	84.2
S5	78.2	S12	85.2
S6	79.2	S13	86.2
S7	80.2	S14	86.4

- To save computation source, a 1/4 3D symmetry model is constructed by real geometry. The regulating winding is divided into three segments to simulate three-step voltage regulation.
- The load impedance at valve side is tuned to (213+57j)Ω to match the voltage and load current of grid side and valve side.
- To simulate the short-circuit of windings disk by disk, the top part of the right-hand grid winding is expressed as 10 segments of sub-windings, each segment includes 2 disks. Besides, each segment of winding is in parallel with a switch. By controlling the operation time of each switch, the dynamic short-circuit process of wingdings can be achieved.
- The resistance at the short-circuit point of winding is also considered, set by 0.01Ω. For the remaining part of grid winding at right-hand, the resistance is set by 4.5Ω to simulate the long short-circuit arc.
- The simulation step is set as 0.2ms. Before switching on S1, a period of 20ms is calculated to make the transformer stable.
- The simulation result is shown in Fig. 4, it can be seen that the calculated fault current is in a good agreement with the recorded ones. Especially, the oscillations of fault current are reproduced successfully, which can be explained as extra short-circuit of windings according to our simulation.

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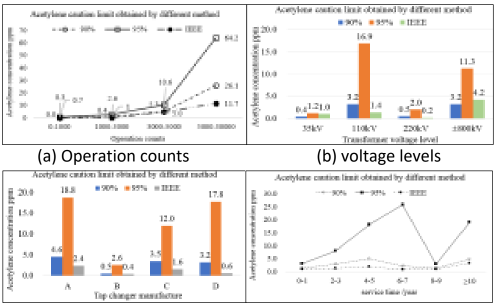
DGA of VLTCs



(a) Operation counts (b) voltage levels

(c) Manufactures (d) Service time

Fig. 5 distribution of caution limit of acetylene

- Caution value of acetylene is positively related to the operation counts of VLTCs, and quite dependent on the design of manufacturers. While little connections are found with voltage levels and service time.
- To apply the caution limits, different weights are assumed for each dimension. Manufacturer, operation counts, Voltage and service year is set as 0.5, 0.3, 0.1 and 0.1 , respectively.
- The effectiveness of caution limit of acetylene is verified with case1-case 4 in Table 4. It is found that auxiliary contacts have arcing marks for case 1 and case 4 due to the decrease of the clamping force of contacts spring. For case 2 and case 3, arcing marks are found on the transient resistor and the outer surface of vacuum bottle due to the loosen bolts, which reduces the insulation distance.
- Acetylene of failure 2 and failure 4 are all below the caution limits, which means DGA is less effective for defects like abnormality of mechanisms and foreign matters.

Table.4 Verifications of caution limit of acetylene

No.	Vendors	Voltage	Service time	Counts	Acetylene	CL-90%	CL-95%	CL-IEEE
Case 1	C	110kV	6a	/	3.1	3.1	13.9	1.4
Case 2	D	220kV	2a	1557	21.3	2.2	10.69	0.56
Case 3	A	110kV	11a	/	2431	3.9	16.59	2.03
Case 4	C	110kV	4a	/	19.8	3.4	13.1	1.5
Failure 2	B	±800kV	9a	60347	0.7	8.5	22.0	4.2
Failure 4	C	220kV	2a	3654	0.4	3.7	10.2	2.4

Maintenance suggestions

- **Auxiliary contacts shall have the arc extinguishing ability in oil**. Once the vacuum interrupter is unable to operate, auxiliary contacts have to interrupt the arc in oil inevitably. It is suggested that arc interrupting ability of auxiliary contacts should be taken into consideration by IEC standard, also including test requirements.
- Manufacturers and power companies should **pay special attention to the invasion of foreign matters** during manufacturing, transportation, and installation.
- **Vacuum tap changers shall carry out DGA tests regularly**. If necessary, DGA online monitoring device and Buchholz relay are potential options for pre-warning.
- From the point of fire protection, the mechanical strength of the top cover of VLTC should be strengthened. **It is suggested to carry out the arcing test in the oil chamber of VLTC** to verify the mechanical strength of the top cover.
- The fast and correct action of PRD is very important to protect VLTC and transformer from fire. It is suggested **to explore the application of a new type of pressure relief device** combining pressure relief valve and explosion-proof film.

Conclusion

- Foreign matters, insufficient clamping force of auxiliary contact and unsuccessful operation of mechanism are the main reasons for VLTC failures.
- The action time of PRD is important to protect tap changers and transformer from fire. Oil flow relay protection plays an insignificant role in the internal fault protection of VLTC.
- The field-circuit coupling method is a useful way to analyze the internal short circuit fault of transformers, a fault progress is reproduced successfully in this paper.
- Caution limit of acetylene is positively related to the operation counts of VLTC, and quite dependent on the design of manufacturers.
- DGA test cannot cover all the scope of defect patterns of VLTC. Abnormality of mechanisms and foreign matters in the oil chamber could not be warned.
- Suggestions and quality improvement measures are proposed for the reference of power grid and manufacturers.