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

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SUMMARY

Since 2018, four vacuum load tap changer (LTC) failures have occurred both on converter transformer and power transformer in Southern China Grid (CSG), which made a significant impact on the safe operation of the power grid. Based on the four vacuum LTC failures, this paper firstly summarizes the fault features and causes. It is concluded that foreign matters, insufficient clamping force of auxiliary contact and unsuccessful operation of mechanism are the main reasons for the failures of vacuum LTC. By analysing the recorded fault signals, it is found that the action time of pressure relief devices (PRD) is important to protect tap changers and transformer from fire. Based on the statistics, the transformer does not catch fire as the action time of PRD is less than 14ms, while the action time gets longer such as more than 58ms, fire is caused. Oil flow relay protection plays an insignificant role in the internal fault of the tap changers, the action time of which delays the differential protection and PRD. Besides, the three-phase current imbalance rate is proposed as an indicator of fault in tap changers according to the analysis of fault wave recordings, a threshold of 10% could be used as the warning value. After that, we carry out a fault simulation with FEM tools and reproduce one of the failures progresses successfully. Moreover, we investigate the distributions of acetylene concentration statistically from a population of 1247 VRS tap changers. The 90% accumulative probability method given in IEC 60599 and the upper outlier limits method recommended by IEEE Std C57.139 are employed to calculate the caution value of acetylene. Results indicate that the caution value of acetylene of vacuum tap changers is dynamic, showing a positive relation to the operation counts of tap changers. The caution limit of acetylene of vacuum tap changers is quite dependent on the design of manufacturers. However, little connections are found with voltage levels and service time. The effectiveness of caution limit of acetylene is verified with extra cases. Results show that DGA test cannot cover all the scope of defect patterns of vacuum tap changers. It is effective to detect defects like insufficient clamping force of auxiliary contact or poor connections, while abnormality of mechanisms and foreign matters in the oil chamber could not be warned by DGA. At last, we propose a number of operation and maintenance, design and test suggestions for vacuum tap changers for the reference of power grid and manufacturers. Especially, it is strongly suggested that demands on the arc interrupting ability of auxiliary contacts should be taken into consideration by IEC standard. This paper is expected to provide useful reference for power companies and manufacturers.

KEYWORDS

Vacuum tap changers; failures; acetylene; fire; maintenance suggestions

1 INTRODUCTION

Load tap changers (LTC) are the key components of transformers to regulate voltage. At present, different types of LTC are used worldwide. Based on the design structure and arcing interrupt principle, a classification of LTC is summarized and indicated in Table 1 by CIGRE [1].

Table 1 Classification scheme for LTCs

A	Arc-breaking in oil for breaking/making load current
V	Vacuum interrupters for breaking/making load current
R	Bridging current through resistors (Resistor type)
X	Bridging current through reactance (Reactor type)
S	Divert switch and Tap selector in different oil compartments (Separate)
C	Divert switch and Tap selector in the same oil compartment (Combined)

In China, a large majority of LTCs in operation are of the arc breaking in oil and vacuum interrupter bridging through resistors for the voltage above 110kV transformers, as indicated in Table 1 as ARS and VRS. Compared with ARS LTCs, VRS has been widely used in converter transformers due to its larger breaking capacity. Meanwhile, the application of VRS is also increasing in power transformers due to the advantage of less maintenance as the arc is interrupted in vacuum bottles.

However, with the accumulation of application experience of VRS, some shortcomings have been exposed in service. First of all, compared with ARS, the insulation gap of the main contact of VRS is commonly shorter. Once there are contaminants in the divert switch chamber, the breakdown risk of VRS is much higher. Secondly, the diverting time of VRS is usually longer than ARS, which results in a longer heating of transition resistor. Therefore, dissipating heat measures such as increasing the volume of the divert switch chamber or installing extra radiators have to be considered. Moreover, it is generally believed that VRS does not produce any combustible gases like acetylene in normal operation because arcing is confined in vacuum interrupters. But operation service experience shows that acetylene is generated even in normal conditions due to the current division effect caused by the auxiliary contact branch. However, few literature on the gas generation of vacuum tap changers have been found so far and little experience could be referred to.

Since 2018, four vacuum LTC failures have occurred both on converter transformer and power transformer in southern China, which made a significant impact on the safe operation of the power grid. Based on the four vacuum LTC failures, this paper firstly summarizes the fault features and causes and analyses the fault current features. After that, we carry out a fault simulation with FEM tools and reproduce one of the failures progresses. Besides, we also investigate the acetylene distribution characteristics of vacuum tap changers statistically. At last, we propose a number of operation and maintenance suggestions for vacuum tap changers. This paper is expected to provide useful reference for power companies and manufacturers.

2 FAILURE DISCUSSIONS

Basic information of the four failures of vacuum LTCs are listed in Table 2. Besides, other two vacuum LTCs failures for ±800kV converter transformers in other regions are also included.

Table 2 Basic information of failure vacuum tap changers

No.	Voltage	Service time	Failure features
Failure-1	±800kV	1 Year	Fault occurs 9 seconds after diverting. Top cover is torn and oil is spout.
Failure-2	±800kV	9 Year	Fault occurs during diverting. Top cover is torn and oil is spout.
Failure-3	220kV	4 Year	Fault occurs during diverting. Top cover is torn and oil is spout. Causing fire.
Failure-4	220kV	2 Year	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.

According to Table 2, four failures occur after diverting and two failures occurs during diverting. In term of results, two failures cause fire. After a long period of fault analysis, simulations and test verification, 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 bottle 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.

To investigate the causes of different fault consequences, protection actions of six failures are summarised in Table 3, where the protection parameters are defined as follows and visualized in Fig. 1 for easy understanding.

t_0-time of fault current appears; Δt-total failure time; Δt_1-three-phase current imbalance rate start to increase; 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.

Table 3 Protection actions of six vacuum tap changer failures

Cases	Δt	Δt_1	Δt_2	Δt_3	Δt_4	Δt_5	Fire
Failure-1	79ms	-27ms	7ms	44ms	14ms	55ms	No
Failure-2	67ms	-51ms	—	44ms	13ms	—	No
Failure-3	80.6ms	-17.5ms	23.5ms	48.5ms	63.5ms	75.5ms	Yes
Failure-4	70.8ms	-17.4ms	6ms	26ms	6ms	78ms	No
Failure-5	Appx.61ms	—	—	28ms	—	57ms	No
Failure-6	Appx.70ms	—	—	21ms	58ms	91ms	Yes

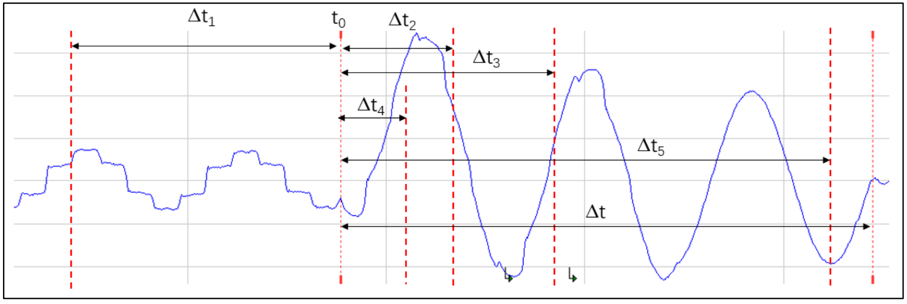


Fig. 1 Definition of protection parameters as the example of failure 2

The three phase-current imbalance rate ΔI_u is defined as:

$$\Delta I_u = \frac{|\max_{i=A,B,C}\{I_{irms}\} - min_{j=A,B,C}\{I_{jrms}\}|}{(I_{Arms}+I_{Brms}+I_{Crms})/3} \qquad (1)$$

where I_{Arms}, I_{Brms} and I_{Crms} are the RMS value of three phase current.

From Table 3, it can be seen that the action time of the pressure relief device is the parameter for determining whether the transformer is on fire. As the action time of pressure relief device of tap changer is less than 14ms, transformer does not catch fire, such as failure 1, failure 2 and failure 4, while as the action time gets longer such as more than 58ms, transformers get fires, as the example of failure 3 and failure 6. Additionally, it is shown that the oil flow relay protection plays an insignificant role in the internal fault of tap changers. All oil flow relay protection lag behind differential and pressure relief protection. Even one is found to operate after the fault current has been cut by circuit breaker, such as failure 4.

During the analysis of the fault current wave-forms of the four vacuum tap changer failures, it is found that the three-phase current imbalance rate could be used as an indicator of pre-failures before fault current appears. With equation (1), the variation of three-phase current imbalance rate ΔI_u with failure time is plotted in Fig. 2~Fig. 3, in which the protection time parameters in Table 3 are all labelled.

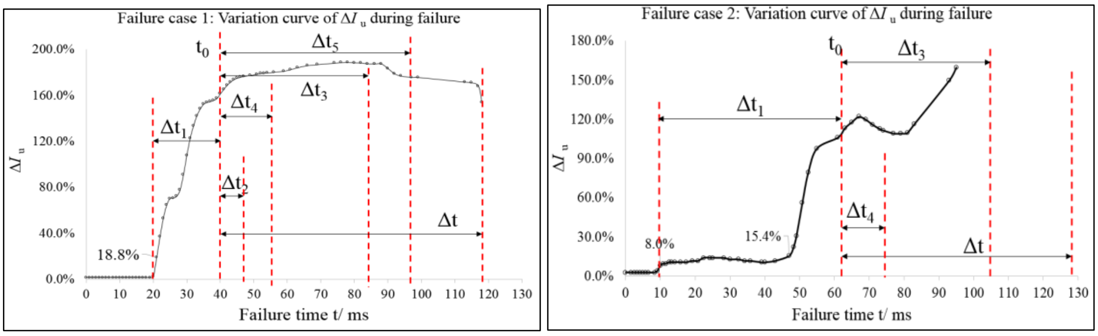


Fig. 2 variation curve of ΔIu of failure case 1 and case 2

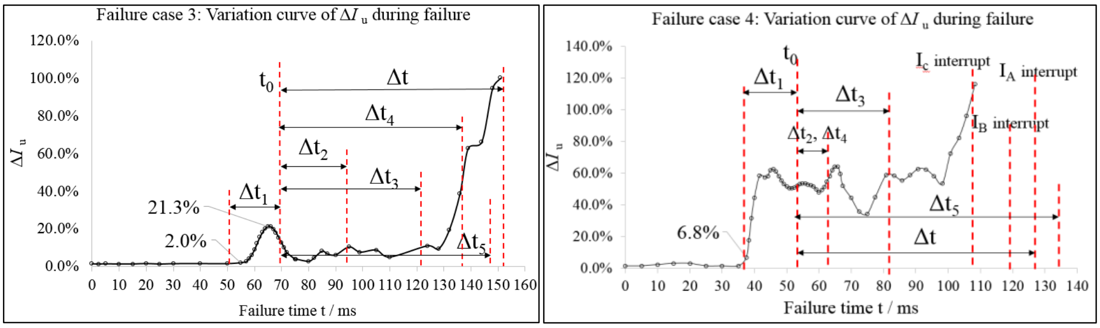


Fig. 3 Variation curve of ΔIu of failure case 3 and case 4

From Fig. 2~Fig. 3, it can be seen that the activation and operation time of differential protection delays the time that fault current appears, which results in a longer fault duration. However, the three-phase current imbalance rate increases apparently before fault current appears, which could be used as an early warning of tap changer failures. According to the results from Fig. 2~Fig. 3, a threshold value of 10% of three-phase current imbalance rate could be used as an indicator of inter fault of tap changers.

3 FEM SIMULATION

In this section, a field-circuit FEM model is established to simulate the fault process of failure case 1.

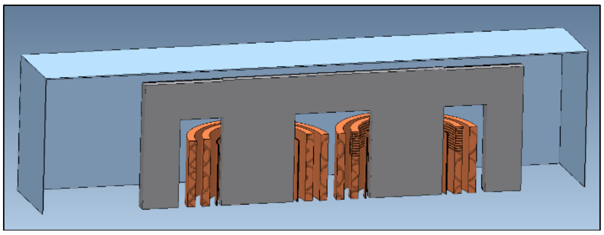


Fig. 4 1/4 3D simulation model of converter transformer

By collecting the iron core, winding and tank geometry parameters of the converter transformer from manufacture, a 1/4 3D simplified model is constructed to save computation source. The rated power of the single-phase converter transformer is 248600kVA. The rated voltage of the grid side is 525/√3kV and the step voltage is 1.25%. This single-phase converter transformer has two parallel windings. The arrangement from the core is regulating, grid side, and valve side winding. To simulate the fault process, the top part of the right-hand grid winding is expressed as 10 segments of windings, each of them indicates 2 disks. This is done to simulate inner short circuit progress due to the melting or breakdown between disks. Besides, the regulating winding is divided into three segments to simulate three-step voltage regulation. The material of the iron core is set to be nonlinear and magnetic isotropy. The tank material is Q235. Impedance boundary condition is applied to the tank for the reason of the eddy current effect.

According to the recorded waveform before failure, the RMS voltage and load current at the grid side is 320.4kV and 95A. The phase angle of the grid side voltage leads current 0.9ms which is equal to 16.2°. The load current at the valve side can then be obtained as 189.84A with the turn's ratio of 1.9977. By tuning the load impedance at valve side Z_{load}, the load current before failure at both sides can then be satisfied, where Z_{load}=213+57jΩ.

In order to simulate the short circuit of winding disk by disk, 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. In our model, the resistance at the short circuit fault point of winding is also considered. Generally, the fault resistance ranges from 100~10000μΩ. In this model, 10000μΩ is selected for each segment of grid winding and regulating winding, while 4.5Ω is configured for the remaining part of grid winding at right-hand due to the long short circuit path.

The constructed circuit is shown in Fig. 5.

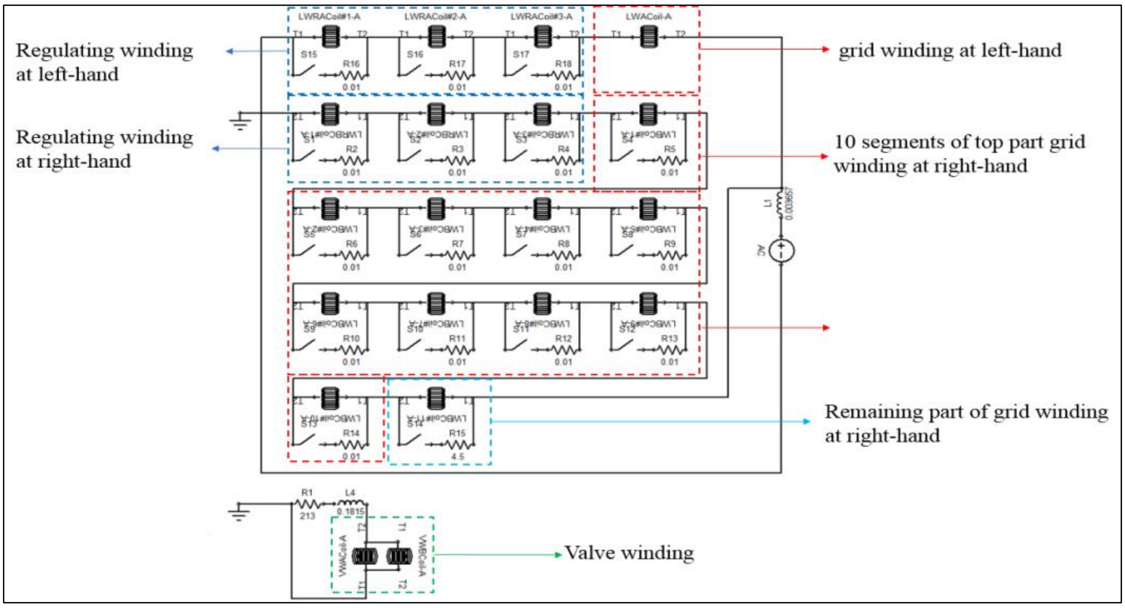


Fig. 5 Sketch map of simulation circuit

According to our test, the fault current can be reproduced appropriately according to the switching sequence set as Table 4.

Table 4 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

The 3D transient solver is applied and the simulation step is set as 0.2ms. Before making switch S1, a period of 20ms is calculated to make the transformer state stable. After that, making the switch as the sequence shown in Table 4. The simulation result is shown in Fig. 6, 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 the extra short circuit of winding according to our simulation.

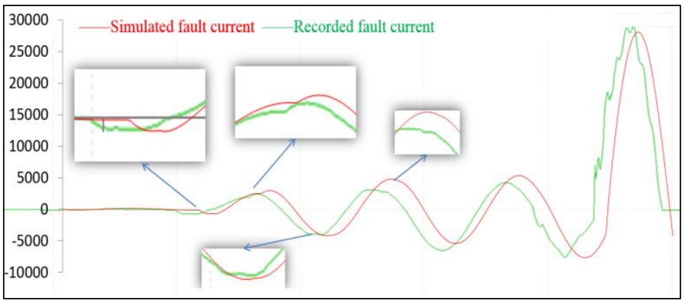


Fig. 6 Comparison of simulation fault current and recorded fault current

4 ANALYSIS OF DGA DATA SET OF VACUUM TAP CHANGERS

Different from ARS LTCs, VRS LTCs is designed to extinguish arc in vacuum bottles. In other words, combustible gases, especially acetylene, will not be produced in diverting switch compartment. However, not all load current goes through the main contact of vacuum tap changers in the stable state. A small faction of load current will be diverted to the parallel auxiliary branch because of the branch resistance. Generally, the diverting proportion of load current is different from manufacturers due to the difference of contact structure design, contact material, clamping force of contact spring and so on. Therefore, under the shunt effect of parallel auxiliary branch resistance, a recovery voltage will be applied on the main contact when the diverting operation initiates and sparking or arcing in oil takes place. In this way, acetylene is produced after a certain amount of normal operations. Besides, the auxiliary contacts, usually immersed in the oil compartment, are designed to work without taking load current. But for some reasons like the mechanism of vacuum bottle jammed, auxiliary contacts have to operate to break current. In this situation, acetylene is also produced. What's worse, if the auxiliary contacts have no capability of breaking arc in oil, a short circuit between taps would be resulted. Therefore, it is quite necessary to investigate the gas production mechanisms of vacuum tap changers, and a guidance for distinguishing the normal and abnormal VRS LTC conditions is expected.

An appropriate option to evaluate the condition of VRS LTC is the DGA test. CIGRE and IEC recommend the use of 90% typical values as a starting point, beyond which more attention should be given. By definition, 90% typical values are cumulative percentile values. Apart from that, IEEE recommends upper outlier limits as caution values. The calculation method can be found in [2]-[3]. According to the IEC and IEEE methods, the acetylene distribution is studied in this paper by collecting the DGA results of a total number of 1247 vacuum tap changers with the voltage of transformers above 35kV. Fig. 7 illustrates the total distribution of acetylene. It can be seen that 84.3% of VRS LTCs are less than 1ppm, and 1.9% exceed 50ppm.

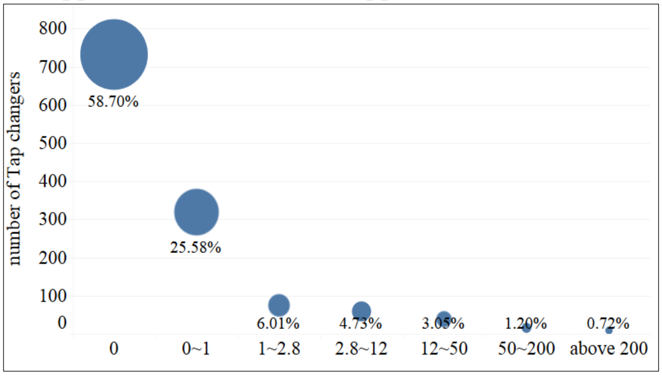


Fig. 7 Acetylene concentration distribution

The 90% and 95% typical value of acetylene is 2.8ppm and 12ppm respectively. The upper limit according to IEEE [3] is also obtained as 1.22ppm. All of the three caution limits (CL) are summarized in Table 5. Also, caution limits of hydrogen and heating gas (HG) which is the sum of CH_4, C_2H_4, and C_2H_6 are indicated for reference as well.

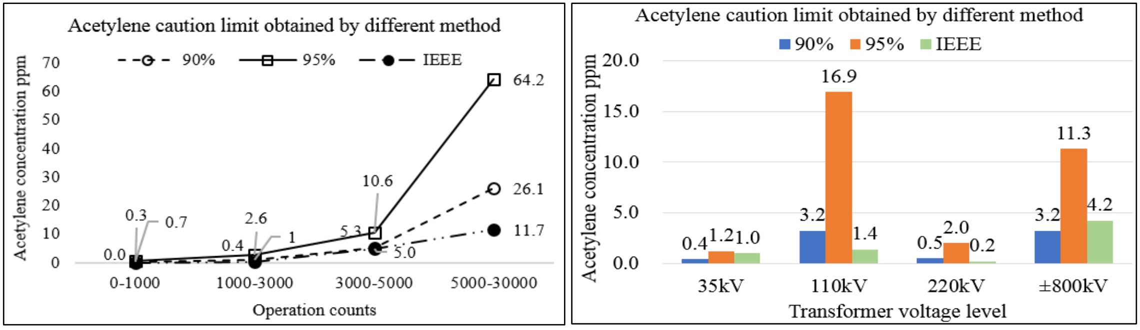
Table 5 Caution limits of acetylene with different methods

	$CL_{90\%}$	$CL_{95\%}$	CL_{IEEE}

C_2H_2	2.8	12.0	1.22
H_2	190	370	353
HG	186	257	351

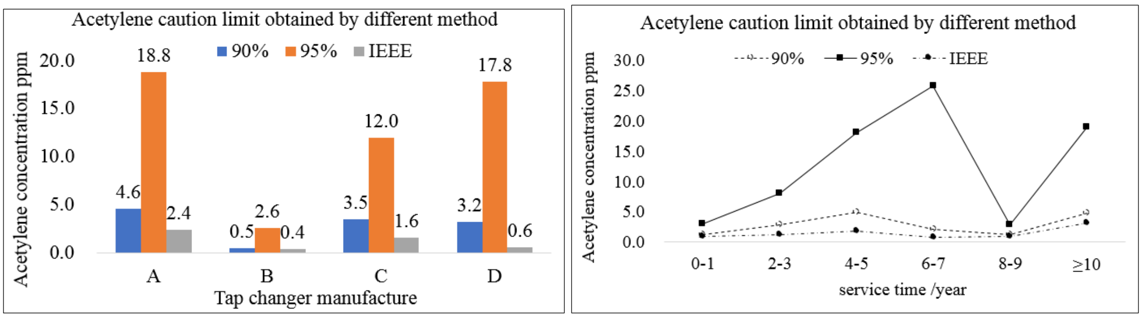
Especially, the dependence of acetylene on operation counts, voltage levels, manufacturers and service years are investigated as follows.

The variation of caution limits of acetylene with operation counts is illustrated in Fig. 8(a). Both the IEC and IEEE methods show a positive correlation between the caution limit of acetylene and operation counts. Also, it is shown that the caution value increases significantly after 5000 operation counts. Therefore, operation counts should be considered when evaluating the condition of vacuum tap changers.



(a) Operation count

(b) Voltage level



(c) Manufacture

(d) Service time

Fig. 8 Variation of caution limits of acetylene

Caution limits of acetylene for different voltage levels are shown in Fig. 8(b), however no dependence on transformer voltage levels has been found. Caution limits of acetylene for different manufacturers are shown in Fig. 8(c). As mentioned above, the caution values for manufacturers are quite different due to their unique design. Caution limits of acetylene varying with service time are shown in Fig. 8(d). Similarly, few dependencies are found.

In summary, Acetylene caution limits for different factors are listed in Table 6.

Table 6 Acetylene caution limit for different dimensions

factors	value	$CL_{90\%}$	$CL_{95\%}$	CL_{IEEE}
Operation counts	0-1000	0.3	0.7	0.0
	1000-3000	1	2.6	0.4
	3000-5000	5.3	10.6	5.0
	5000-30000	26.1	64.2	11.7
Voltage	35kV	0.4	1.2	1.0
	110kV	3.2	16.9	1.4
	220kV	0.5	2.0	0.2
	±800kV	3.2	11.3	4.2
Manufacturers	A	4.6	18.8	2.4
	B	0.5	2.6	0.4
	C	3.5	12.0	1.6
	D	3.2	17.8	0.6
Service years	0-1	1.2	3.0	1.0
	2-3	2.8	8.1	1.2
	4-5	5.0	18.0	1.8

	6-7	2.2	25.8	0.8
	8-9	1.2	2.8	1.0
	≥10	4.8	19.0	3.2
Total		2.8	12.0	1.22

To apply the caution limits in Table 6, different weights are assumed for each dimension. The weight of manufacturers is set as 0.5 considering the importance of design. The weight of operation counts is set as 0.3 due to the positive relevance with acetylene. At last, the weights of voltage and service year are both set to be 0.1, respectively.

To verify the caution limit of acetylene in Table 6, four vacuum tap changers are taken out from service and inspected. The basic information and the field test of acetylene are shown in Table 7.

Table 7 Basic information of verification cases

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

Based on the information and weights of different dimensions, the caution limits can be obtained for each case.

According to Table 7, the test acetylene of four cases all exceeds the 90% typical value and the upper limit value recommended by IEEE. After inspection, 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.

However, the cover scope of the caution limits in Table 6 is quite dependent on the defect or failure patterns of vacuum tap changers. Table 8 shows the basic information of failure 2 and failure 4 and the test results of acetylene before failures. It can be seen that the tap changers are in normal conditions as the field results are all below the caution limits obtained by different methods.

Table 8 Basic information of failure 2 and failure 4

No.	Vendors	Service time	Voltage	Counts	Acetylene	CL-90%	CL-95%	CL-IEEE
Failure 2	B	9a	±800kV	60347	0.7	8.5	22.0	4.2
Failure 4	C	2a	220kV	3654	0.4	3.7	10.2	2.4

As mentioned above, failure 2 and failure 4 are caused by the failure of vacuum interrupter mechanisms and contaminant in the oil compartment. Therefore, in terms of the condition evaluation of vacuum tap changers, defects such as long-term arcing in oil resulted from the auxiliary contacts due to the lack of clamping force or poor connections caused by loosened bolts could be detected by DGA test. On the contrary, DGA is less effective for defects like abnormality of mechanisms and foreign matters in the oil chamber, and other test methods are expected.

5 MAINTENANCE SUGGESTIONS

(1) Auxiliary contacts shall have the arc extinguishing ability in oil. According to surveys, not all the tap changer manufacturers' products meet this demand. Once the vacuum bottle is abnormal and unable to operate, auxiliary contacts have to interrupt the arc in oil inevitably. A short circuit between taps will occur if arc exists continuously. Therefore, it is strongly suggested that demands on the arc interrupting ability of auxiliary contacts should be taken into consideration by IEC standard, also including test requirements.

(2) According to the failures caused by contaminant, vacuum tap changer and transformer manufacturers and power companies should pay special attention to inspection and focus on inspections and quality improvement during the manufacturing, transportation, and installation due to the smaller insulation gap between main contacts.

(3) Vacuum tap changers shall carry out DGA tests regularly to track the variation trend of DGA results. If necessary, it is recommended to install a DGA online monitoring device. Besides, it is also suggested that vacuum tap changers should be equipped with Buchholz delay to pre-warning.

(4) The oil pump for vacuum tap changer is not suggested. On the one hand, DGA information will be lost. On the other hand, oil flow will be stronger under the effect of the oil pump, enhancing the movement of contaminant and increasing the short circuit probability. However, if the oil pump is cancelled, the heat dissipation capacity of the vacuum tap changers should be further optimized by manufacturers due to the cooling problems. Moreover, time intervals between voltage regulations should be considered by power companies in case of overheating, especially for converter transformers.

(5) From the point of fire protection, the mechanical strength of the top cover of vacuum tap changers should be strengthened. It is suggested to carry out the arcing test in the oil chamber of the vacuum tap changers to verify the mechanical strength of the top cover, which can provide a reference for the structure design and optimization.

(6) The fast and correct action of pressure relief devices is very important for the protection of internal fault of vacuum tap changers, which is the key factor to protect tap changers 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.

6 CONCLUSIONS

(1) Foreign matters, the insufficient clamping force of auxiliary contact and unsuccessful operation of mechanism are the main reasons for the above four failures of vacuum tap changer.

(2) The action time of pressure relief devices is important to protect tap changers and transformer from fire. Based on the statistics of six tap changer failures above, the transformer does not catch fire as the action time of pressure relief device of tap changer is less than 14ms, while the action time gets longer such as more than 58ms, transformers get fires. Oil flow relay protection plays an insignificant role in the internal fault of the tap changers.

(3) Three-phase current imbalance rate is a potential protection option for tap changers, a threshold value of 10% of three-phase current imbalance rate could be an indicator of fault in tap changers.

(4) The field-circuit coupling method is a useful way to analyse the internal short circuit fault development process of transformers, a fault process is reproduced successfully in this paper.

(5) The caution limit of acetylene of vacuum tap changer is investigated and proposed according to data analysis. Results show that the caution value of acetylene is positively related to the operation counts of tap changers. The caution limit of acetylene of vacuum tap changers is quite dependent on the design of manufacturers. In maintenance, manufacturers should be distinguished.

(6) DGA test cannot cover all the scope of defect patterns of vacuum tap changers. It is effective to detect defects like an insufficient clamping force of auxiliary contact or poor connections, while abnormality of mechanisms and foreign matters in the oil chamber could not be warned by DGA.

(7) Suggestions and quality improvement measures are proposed for the design, manufacturing, test, transportation, and installation of vacuum tap changers for the reference of power grid and manufacturers.

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