Research on Pressure-based Detection Technology for Partial Overheat Insulation Defect of Oil-less Power Equipment

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Abstract. Pressure monitoring technology is the current state monitoring research hotspot of oil-less power equipment. Aiming at the lack of pressure change characteristics caused by overheating insulation defect of oil-less power equipment, this paper studies the pressure change characteristics of 110kV oil-immersed power transformer under local overheating insulation defect. Overheating defect belongs to the low temperature overheating, temperature rise gradient is 50 °C. Analysis of the experimental results indicates that pressure change trends show exponential, in the initial stage, the pressure increased sharply, then it increased slowly, and finally it tended to be stable; the increase of pressure in 50 hours ranged from 1kPa to 3kPa, and the pressure increase was obvious, which indicated that the online monitoring of local overheating insulation defects of the casing could be achieved by pressure monitoring technology, and finally the casing pressure change law was analyzed theoretically.

Keywords: Oil-immersed power equipment; localized over-heading insulation defects; pressure variation characteristics.

1. Introduction

Due to the structural characteristics of oil-less power equipment such as current transformer, voltage transformer and high-voltage bushing, the current operation and maintenance supervision mainly relies on inspection of oil level, infrared temperature measurement, ultraviolet detection, high-voltage test, oil chromatogram detection, etc., but the common problem of the above methods is poor timeliness, unable to timely and accurately reflect the internal insulation status of equipment[1-4]. The on-line monitoring methods such as pulse current method and dielectric loss method need to be reformed, which reduces the reliability of equipment grounding and improves the risk of equipment failure; in addition, field operation experience shows that when dissolved gas in oil of oil less equipment increases, the dielectric loss growth is not obvious, so it has not been widely promoted and applied in power system[5-8].
In recent years, the proportion of oil less equipment failure rate in the total fault rate of all equipment in the substation has increased, which has attracted the attention of the power sector and scholars at home and abroad. Therefore, some scholars have proposed the online monitoring technology of less-oil equipment based on pressure[9-11]. The insulating oil in oil less equipment is a kind of mineral oil obtained by distillation and refining of natural oil. When there is a discharge or overheating fault in the equipment, characteristic gases such as H2, CH4, C2H4 will be produced[12-14]. The generated gas is either dissolved in the oil or released to the oil surface. Due to the sealing structure of the less oil equipment, the gas on the oil surface gradually accumulates, and the gas pressure increases, which acts on the liquid insulating oil, resulting in the gradual increase of oil pressure. Therefore, it can be considered to realize the online monitoring of partial discharge and overheating insulation defects in the oil less equipment by obtaining the change of oil pressure.

Our research group[9] studied the relationship between PD and pressure, and the effectiveness of pressure monitoring is proved. However, the pressure variation characteristics of less oil equipment under overheating defect is not studied. Short circuit between iron chips, multi-point grounding, poor contact of winding and tap changer will cause local overheating of oil less equipment[4, 15, 16]. During the development of overheating defects, the temperature around the defects increases, the aging of insulation materials accelerates, and the formation of holes and impurity bridges will eventually lead to serious discharge faults. It is of great significance to diagnose overheating defects in time to avoid overheat and discharge faults. Temperature is the most important characterization of overheating defects. Therefore, this paper mainly studies the pressure variation characteristics of low oil equipment under five overheating temperatures of 100 °C, 150 °C, 200 °C, 250 °C and 300 °C, so as to provide laboratory data for fault diagnosis of low oil equipment based on pressure.

2. Experiment

2.1. Principle of pressure detection

In hydrostatics mechanics, Pascal's law[17, 18] states that the pressure increase at any point in an incompressible stationary fluid caused by an external force is instantaneously transmitted to all points of the stationary fluid. It can be seen that inside the transformer, at any point in the oil at high h, the oil pressure at the bottom is

\[ P = P_{\text{external}} + \rho gh \]  

Where \( \rho \) is the density of insulating oil, \( g \) is the acceleration of gravity, and \( h \) is the height of oil level. If the external pressure \( P_{\text{external}} \) changes to \( P_{\text{external}} + \Delta P \), as long as the liquid remains in its original static state, the pressure at any point in the liquid will change by the same magnitude. That is, in the transformer, the pressure exerted on the insulating oil will be transmitted to each point at the same time. For any point at any height \( h \), the pressure is

\[ P' = (P_{\text{external}} + \Delta P) + \rho gh \]  

Therefore, the pressure change at any point of the liquid can reflect the change of the internal pressure of the equipment. Therefore, the pressure sensor is installed at the oil drain valve at the bottom of the equipment, and a tee is installed to facilitate oil sampling during actual operation. The installation of pressure sensor and measuring circuit are shown in Fig 1.

![Fig.1 Pressure sensor installation diagram and pressure detection circuit](image)
Oil immersed CT is a metal sealed structure, and its pressure change is affected by the following three factors: 1) sealing performance of equipment; 2) ambient temperature; 3) partial discharge. In order to eliminate the interference of other factors, the air tightness experiment was carried out before the experiment. The insulating oil in the test sample is drained from the oil drain valve, and then filled with pure $N_2$ to make the internal pressure of the equipment increase by 10.22kpa from atmospheric pressure, and the expander expands from 5.9cm in free state to 15.5cm. After standing for 10 days (240 hours), the pressure change is very small, the fluctuation is not more than 0.3kpa, and there is no sharp change of pressure in a short time. The results are shown in Fig. 2.

![Fig.2 Pressure curve of tightness test](image)

**Fig.2** Pressure curve of tightness test

### 2.2. Experiment subject
The experiment subject used in the experiment is 110kV vertical current transformer. Its structure diagram is shown in Figure 3. The primary winding is a "U" type structure. The primary winding extends vertically from the top of the sample into the bottom oil tank. The high-voltage end and the low-voltage end are insulated with porcelain bushing. The main winding and the secondary winding are wrapped with paper insulation. A corrugated metal expander, pb330-nx12, with a diameter of 330mm, is installed on the top of the experiment subject. The whole experiment subject is filled with 25# insulating oil. An oil discharge drain valve is arranged at the bottom of the oil tank. The ambient temperature is room temperature (25°C), and the ambient humidity is (60%).

![Fig.3 vertical CT structure diagram](image)

1. Rain cover; 2. Expander; 3. Primary terminal; 4. Series and parallel terminal; 5. Porcelain sleeve; 6. Secondary terminal; 7. Oil discharge valve; 8. Ground terminal

**Fig.3** vertical CT structure diagram

### 2.3. Partial Overheat Simulation System
Temperature is the most important characteristic of overheat defect. In fault simulation, the temperature of fault point should be controlled accurately. In modern control theory, the commonly used control methods are P, PI and PID control method. PID control method is widely used in industrial production because of its strong tracking ability and good anti-interference performance.
In order to achieve the effect of accurate temperature control, this paper uses the temperature controller based on PID control. Solid-state relay is chosen to control output. Compared with the traditional relay, solid state relay adopts semiconductor structure to realize contactless switch, which has the advantages of fast breaking and no mechanical loss. The real objects of temperature controller and solid state relay is shown in Fig. 4.

PID control is a typical feedback control, that is, according to the actual temperature of the measuring point, the breaking time and frequency of the current are controlled to realize temperature control. In application, the accuracy of temperature measurement at fault point is very important. In order to ensure the accuracy of temperature measurement, we integrate the temperature sensor into the heating resistance to ensure that the measured temperature is the temperature of the fault point.

Temperature sensor can be divided into resistance temperature detector (RTD) and thermocouple sensor according to material. RTD sensors have high sensitivity, high accuracy, fast response to temperature and small size, but thermistor is a resistive device, any current source will cause heat on it due to power, power is equal to the product of current square and resistance, so a small current source should be ok. Also, RTDs have a small measurable temperature range and are generally the choice for high precision measurements at low temperatures. However, in oil-immersed power equipment, the normal operating temperature is about 100°C, and the temperature of overheating failure is higher than this, up to hundreds of degrees Celsius, therefore, in this paper, a thermocouple sensor is chosen to achieve the measurement of the overheating temperature. Ultimately, the integrated RTD and temperature sensors are shown in Figure 5(a). The red thick wire is the input and output of the heating rod, the white thin wire is the input and output of the temperature sensor, and the diameter of the heating part is 4mm and the length is 40mm.

Current transformer as a measuring device, there is a secondary junction panel installed on its main tank, during normal use, the secondary winding is fixed on the inside of the junction panel, according to different measurement needs, from the outside of the junction panel leads to the control room. As the experiment does not need to measure the current, therefore the heating rod can be installed on the inside of the secondary terminal block, and the outside is connected to the temperature control system, and the installed object is shown in Figure 5(b).
2.4. Experiment content
According to their severity, the overheating faults of oil paper insulation equipment can be divided into four types: mild overheating (below 150℃), low-temperature overheating (150-300℃), medium-temperature overheating (300-700℃) and high-temperature overheating (generally higher than 700℃)[19-21]. According to China “GB 1208-2016 current transformer national standard”, the temperature rise of oil immersed current transformer under normal operation of all levels shall not exceed 60℃. For CT installed outdoors, the range of environmental temperature required is 5 ~ 40℃, and the maximum operating temperature of CT is 85℃ when the room temperature is 25℃. The insulation will deteriorate when the operation temperature is greater than 85℃. When the actual operating temperature is greater than 85℃, the insulation paper will deteriorate, and eventually cause damage to the internal insulation structure of the device over time. According to the temperature change law of faults and hot spots in the CT, this article sets the overheating temperature at 100℃ and above, and the temperature interval is set at 50℃. In practice, high temperature fault is difficult to simulate, because the volume of the heating rod is affected by the power. The greater the power, the larger the volume of the heating rod, the larger the surface area, and the faster cooling speed. In addition, with the excellent heat dissipation performance of insulating oil, the temperature is quickly transmitted to all parts, so it is difficult to achieve local high temperature. At the same time, theoretically, the higher the temperature of hot spot is, the higher the rate of expansion and yield of insulating oil is, and the greater the degree of pressure change is. If the pressure change under low temperature overheating fault can be detected, the online monitoring based on pressure under high temperature fault is also feasible.

Therefore, considering the feasibility of the experiment, this paper mainly studies the pressure variation characteristics under mild overheating and low temperature overheating faults.

3. Result analysis

3.1. Pressure change characteristics under mild overheating
Figure 6 shows the pressure variation curve and its fitting curve within 50 hours of heating time at fault temperature of 100℃ and 150℃. It can be seen that the pressure has an obvious upward trend in the whole heating process. In the first 10 hours of the failure, the internal pressure of the equipment rises sharply, and then the slope gradually decreases. After 20 hours, it increases at a very slow speed. Through data fitting, it is found that exponential fitting is the best way to fit the pressure at two overheating temperatures, which indicates that the pressure increases exponentially with time under overheating fault.

![Fig.6 Pressure versus time curve under mild overheating](image)

It can be seen from Figure 6 that due to the fluctuation of the measured pressure, the maximum pressure value in the whole experiment process does not necessarily appear at t=50h. In order to more accurately compare the characteristics of pressure change at various temperatures, this paper defines the maximum increment of pressure (the difference between the maximum value and the initial value) in the experimental process as α, and the maximum pressure value is β. The values of α and β at various
temperatures are listed in Table 1. When the superheating temperature is 100°C, the pressure increases by 1.33kPa within 50 hours, and when the superheating temperature is 150°C, the pressure increases by 1.65kPa within 50 hours. This shows that the amplitude of pressure rise increases with the increase of superheat temperature. It can be seen from Fig. 6 that the pressure rise rate also increases. But on the whole, the pressure increment is small, no more than 2kPa.

| Hot spot temperature (°C) | α (kPa) | β (kPa) |
|---------------------------|---------|---------|
| 100                       | 1.33    | 122.74  |
| 150                       | 1.65    | 123.08  |

3.2. Pressure change characteristics under low overheating

Figure 7 shows the pressure change curves at 200°C, 250°C and 300°C. It can be seen that the pressure change trend is basically the same as that of mild overheating: at the initial stage of the fault (about 10 hours), the internal pressure of the test object rises sharply, and then rises at a very slow speed.

![Fig.7 Pressure versus time curve under low temperature overheating](image)

Similarly, the values of α and β at various temperatures are calculated, and the results are shown in Table 2. When the overheating temperature is 200°C, the pressure in 50 hours increases by 2.01kPa; when the superheating temperature is 250°C, the pressure increases by 2.51kPa within 50 hours; when the superheating temperature is 300°C, the pressure increases by 2.70kPa within 50 hours. With the increase of the hot spot temperature, the amplitude and rate of pressure rise increase, and the change rule is consistent with that of mild overheating.

| Hot spot temperature (°C) | α (kPa) | β (kPa) |
|---------------------------|---------|---------|
| 200                       | 2.01    | 123.44  |
| 250                       | 2.51    | 123.94  |
| 300                       | 2.70    | 124.13  |

This is because the higher the hot spot temperature is, the more energy is released into the insulating oil paper. On the one hand, the temperature of the fault hot spot makes the surrounding insulating oil temperature rise and thermal expansion through heat conduction. The heating time is the same. The higher the temperature of the hot spot is, the higher the temperature rise of the nearby insulating oil is, the larger the temperature range is, and the greater the pressure change is; on the other hand, the more insulation oil decomposition caused by overheating is, the more fault gases appear.
Table 3 Difference between $\alpha$ values of adjacent temperatures

| Hot spot temperature (℃) | Difference between $\alpha$ values (kPa) |
|--------------------------|------------------------------------------|
| 100-150                  | 0.32                                     |
| 150-200                  | 0.37                                     |
| 200-250                  | 0.50                                     |
| 250-300                  | 0.19                                     |

Table 3 shows the difference of $\alpha$ value between two adjacent temperatures. It can be seen that the maximum change of pressure is only a few hundred pa per 50℃ for 50 hours when the overheat temperature increases by 50℃.

At the end of the experiment, it was found that the internal pressure of the equipment continued to drop after the heating rod power was turned off. After the power was turned off for 3 hours, the internal pressure was even less than 120kPa, far less than the initial pressure of 121.4kpa, that is, negative pressure appeared in the equipment. After the experiment is over, open the top vent valve and find that the pressure instantly increases to a normal value, while the oil level drops, and then the pressure remains stable. After the overheat fault was removed, the pressure change was shown in Fig. 8.

After removing the fault, the pressure drop is understandable because the oil temperature gradually returns to room temperature and the insulating oil shrinks as it cools. However, because the ambient temperature remains unchanged before and after the experiment, even if the insulating oil shrinks, there should be no negative pressure when new gas is produced.

In order to find out the reason for this phenomenon, the author took out the heating rod after the experiment, and found that a large number of coking particles of insulating oil were attached on the surface of the heating rod, as shown in Fig. 9. This shows that in the process of forming oil coke, a large amount of insulating oil cracking reaction occurs, resulting in the reduction of total oil volume, and the
volume of generated oil coke is smaller than that of insulating oil, and a larger gas space is formed at the top of the equipment. If there is less fault gas generated, negative pressure will appear.

3.3. Differential analysis of pressure change between discharge defect and overheating defect

The previous experimental studies by our research group [9] showed that the pressure change caused by discharging defects is continuously increasing and is approximately linearly increasing under constant pressure conditions. In this paper, it is found that the pressure change caused by overheating fault is only drastic in the initial stage, after which the change is very slow or even remains basically unchanged, which indicates that the pressure change law is significantly different between overheating fault and discharge fault. By reviewing the literature and theoretical analysis, it is believed that the formation of the phenomenon has the following three reasons.

1) Under the condition of discharge defects, with the increase of voltage loading time, the equipment defects gradually deteriorate, and the gas generated gradually increases. However, the overheat defects are controlled by PID control, which is always controlled at the same defect degree without deterioration. Therefore, the pressure changes slowly in the middle and later stages of the experiment.

2) In the initial stage of overheating fault, the oil temperature inside the oil less equipment will rise, the dissolved gas in the oil will be separated out, and the insulating oil will be heated and expanded. With the increase of oil temperature, the oil-less equipment will emit more heat to the environment. Finally, it will gradually reach the balance of heating and heat dissipation, and the oil temperature will no longer rise. At this time, the internal pressure rise of the equipment is completely caused by the decomposition of insulating oil.

3) The literature indicates [22,23] that the cracking coking process of oil can be divided into an initial coking stage and a steady-state coking stage. At the beginning of the reaction, the coking rate is higher and more fault gas is produced, but as the cracking coking reaction proceeds, the surface of the heating rod is gradually passivated by the carbon layer and the coking rate gradually decreases, and finally the fault gas produced tends to a stable value.

4. Conclusions

1) The pressure changes caused by mild and low-temperature overheating defects are small, and the maximum increments during the experiment are 1.33kPa, 1.65kPa, 2.01kPa, 2.51kPa, 2.70kPa, respectively;

2) The pressure rises sharply during the first 10 hours of overheating defects, slowly during 10-20 hours, and remains essentially constant after 20 hours.

3) When the temperature of the hot spot increases by 50 °C, the maximum pressure increase range is several hundred Pa.

4) There are three reasons for the exponential change in pressure caused by the overheating defect: the overheating defect does not deteriorate under PID control; the initial increase in oil temperature causes the insulating oil to expand, and the original dissolved gas in the oil will be separated out; as the insulating oil cracks, the surface of the heating rod is gradually covered by a carbon layer, and the cracking rate decreases.

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