Study on Influence of Pressure on Water Saturation Solubility in Insulation Oil

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Abstract. The running condition of negative pressure is existed in the metal expander of oil-immersed inverter-type current transformer, which affects the internal water distribution in oil-paper of the current transformer. Thus, we carried out tests to measure water saturation solubility in insulation oil on different oil samples under different pressures and temperatures, and found that the water saturation solubility in oil would decrease with the increase of vacuum degree, resulting in water transferring from oil to paper or suspending in oil. According to these results, we introduced a shifting factor \( n \) related to pressure to establish a mathematical expression involving pressure in expander, temperature, and water saturation solubility in oil by Arrhenius equation. Based on previous studies, we took the acid value in oil, temperature and pressure as an evaluation system to comprehensively evaluate the water saturation solubility in insulation oil, and the influence law of the multiple factors was obtained. The water content and the insulation condition of oil-paper insulation of the oil-immersed inverter-type current transformer could be evaluated more accurately by using the results mentioned above.

1. Introduction

The current transformer is an important equipment to connect the primary and secondary systems of the power grid, which is used for electric energy measuring as well as monitoring and protecting the primary equipment. The oil-immersed inverter-type current transformer has been widely used in power grid in recent years due to its advantages of small size, less oil and copper consumption, lightweight, strong dynamic thermal stability and so on. However, with the expansion of the application, products of different manufacturers’ malfunctions like exploding or expanding header. These kinds of failure occur probably due to the reason that the manufacturers design the metal expander without considering that the products may run in the environment of large temperature difference. In areas with large temperature difference between day and night, negative pressure is easy to form inside the expander, which may lead to the reduction of oil-paper insulation strength of the current transformer. As the influence mechanism of negative pressure on oil-paper insulation is unknown, this reason has not been confirmed. Currently, researchers have been focused on fault statistics, fault operating condition investigation and fault case analysis of oil-immersed inverter-type current transformers to solve the problem. They have analyzed the typical faults in the process of operation and proposed that the quality of the oil-immersed inverter-type current transformer should be improved in the design and manufacture stage, instead of paying attention to the failure mechanism.
of the current transformer [1]. Researchers have been studying on the failure mechanism of oil-paper insulation for transformers, including the influence of water, temperature, partial discharge and other factors except for pressure [2]. However, for the oil-immersed inverter-type current transformer, of which the running condition of negative pressure is existed, the influence of pressure on oil-paper insulation has not been studied at home and abroad. The water saturation solubility in oil is an important parameter to evaluate the insulation performance of oil-paper insulation system. In this paper, the water saturation solubility in oil under different pressures and temperatures was obtained. The influence of water on insulation properties of oil was studied. Exploratory work was done on the failure mechanism of oil-paper insulation under different pressures for oil-immersed inverter-type current transformer.

2. Water absorption property of oil-paper insulation

2.1. Water Solubility of Insulation Oil

Insulation oil for instrument transformers is the product of fractionation of petroleum. Its main components are alkanes, cycloalkanes and a small amount of aromatic compounds. Insulation oil of the instrument transformer will absorb water from the environment during the manufacturing, assembling and actual operation, and water will generate in the aging process of oil-paper insulation. The internal temperature rise in the running process of instrument transformers makes great influence on the water solubility of oil. Water is existed in insulation oil mainly in the following three forms:

2.1.1. Dissolved water. It’s mainly the water evenly distributed in insulation oil in the form of imperceptible granular. Because water that can be dissolved in new insulation oil is very little, the insulation performance of oil will not be significantly reduced by dissolved water.

2.1.2. Suspended water. It’s mainly the water generated by aging and cracking of oil-paper insulation. When the water dissolved in the oil reaches saturation, it will form an oil-repellent mist with the oil. Transferring of this form of water will exacerbate the oil flow electrification on the oil-paper insulation interface and seriously reduce its insulation performance.

2.1.3. Deposited water. It is mainly due to the poor sealing of the instrument transformer which makes external water invade. Since the density of water is higher than that of oil, water will accumulate and deposit at the bottom of the insulation oil. This form water is far away from the high electric field, so it has little influence on the insulation performance of oil.

In a word, the water saturation solubility of insulation oil is of great significance to its insulation performance.

2.2. Water adsorption of insulation paper

Insulation paper for instrument transformers is mainly composed of cellulose. Cellulose is linear polymer composed of \( \beta \)-D-glucopyranosyl \( (\text{C}_6\text{H}_{10}\text{O}_5) \) bonded by 1-4-\( \beta \)-glycosides [3]. Adsorption of water molecules for cellulose mainly includes the following three ways:

2.2.1. Specific surface area. It refers to the total area of cellulose per unit mass. The size of the specific surface area of cellulose directly shows its adsorption capacity, which is the most important index to measure the adsorption capacity. The larger the specific surface area of cellulose, the greater the surface energy, and the stronger the adsorption capacity for water molecules.

2.2.2. Crystallinity. Whether aged or not, cellulose is made of a two-phase system including both crystalline region and amorphous region. Cellulose macromolecules in crystalline region are arranged so closely that water molecules are difficult to enter, while amorphous region is the opposite. Therefore, the lower the crystallinity of cellulose, the stronger its water adsorption capacity. In
addition, in the amorphous region, the larger the gap, the less smooth the surface, and the stronger the adsorption for water molecules.

2.2.3. Hydrophilic groups. Common hydrophilic groups includes hydroxyl group (-OH), carboxyl group (-COOH-) and amino group (-NH₂), among which hydroxyl group is the hydrophilic group in cellulose. Hydroxyl groups can form strong bonds with water molecules, so the more hydrophilic groups of cellulose, the stronger the adsorption capacity of cellulose for water molecules.

3. Test principle of water saturation solubility in oil

3.1. Test principle of water saturation solubility in oil
Researchers as R B Kaufman et al. of GE [5] and Y Du et al. of the Massachusetts Institute of Technology [6] have shown that at the same temperature, the relative humidity of insulation oil and of environment are equal when water reaches balance between them. The relative humidity of insulation oil is the ratio of water content in oil and water saturation solubility in oil at the same temperature, as shown in formula (1).

\[
\%R.H = \frac{W_o}{W_s} \times 100\%
\]  

(1)

In formula (1), \%R.H is the relative humidity of insulation oil, which is equal to the relative humidity in the environment at equilibrium. \(W_o\) is the water content in oil, in mg/L. \(W_s\) is the water saturation solubility in oil, in mg/L.

Formula (2) can be obtained by transforming formula (1).

\[
W_o = W_s \times \%R.H
\]  

(2)

3.2. Principle of humidity source preparation
In order to obtain the water saturation solubility in oil under different pressures, tests need to be carried out in a closed space. In this paper, a seal vessel was used to form a closed space. In order to meet the different humidity requirements in the test, it is necessary to control the environmental humidity in the seal vessel, so the humidity source in the seal vessel was prepared [7].

The humidity source was made of the mixture solution of water and glycerol. The humidity source, whose mixing ratio of water and glycerol is given by ANSI/ASTM D 5032-2011, was used to preliminarily control the humidity range in the seal vessel. Temperature and humidity were monitored in real-time by the temperature and humidity probes inside the seal vessel, and observed and recorded by the LCD digital display temperature and humidity meter. Continuous vacuum pumping was needed to keep the negative pressure condition required in the test, which would take away the moisture in the seal vessel and reduce the environmental humidity. Thus, the mixing ratio of water and glycerol given by ANSI/ASTM D 5032-2011 should be calibrated according to the humidity data recorded by the temperature and humidity meter to achieve the target humidity.

When the target humidity was high, the insulation oil was taken out of the seal vessel. The method of external humidifying was used to accelerate the rate of reaching the target humidity. And then the insulation oil was put into the seal vessel environment for water balance.

4. Test Method and Device

4.1. Test materials and pretreatment
The oil used in the test was 45# naphthenic base mineral insulation oil produced by Karamay oilfield of Xinjiang.
In order to avoid the influence of the initial water content of oil on the test results, the insulation oil was pretreated as follows: the insulation oil had been vacuum dried in a vacuum drying oven under the temperature of 313.15K and the vacuum degree of 50Pa until the water content in the oil was less than 10mg/L, and then kept in sealed preserving condition.

4.2. Test flow
(1) Place the 250mL beaker containing oil sample in a 2L seal vessel. The temperature, humidity and pressure in the seal vessel should be controlled simultaneously.
(2) Control the humidity in the seal vessel through the mixture solution of water and glycerol, the mixing ratio of which is referred to ANSI/ASTM D 5032-2011. Calibrate and adjust the mixing ratio through the temperature and humidity meter.
(3) Place the seal vessel in the thermostat. Control the temperature from 273.15K to 333.15K with an interval of 10K.
(4) The pressure in the seal vessel was controlled by the external vacuum pump, and the test pressure condition was ensured by timely vacuum extraction as required. The test vacuum degrees were adjusted to be 0, -0.01MPa, -0.02 MPa, -0.05MPa and -0.1MPa.
(5) Adjust the humidity in the seal vessel to 40% by the mixture solution of water and glycerol, control the temperature in the seal vessel at 273.15K and the vacuum degree at 0. Record the parameters until the temperature, pressure and humidity were all stable. Use the coulometric method to measure the water content in the insulation oil in accordance with GB/T 7600-2014. Then adjust the humidity in the seal vessel to 60% and 80%, and repeat the process above.
(6) Set the temperature and pressure in the seal vessel to the values in (3) and (4) respectively, and repeat the test process in (5).

![Figure 1. Experimental flow chart.](image-url)
5. Analysis of test results

5.1. Variation law of water saturation solubility in oil

The water saturation solubility in oil of instrument transformers is an important parameter to evaluate the water distribution for oil-paper insulation. According to the Arrhenius equation, the relationship between water saturation solubility in oil and temperature is shown as follows:

\[ W_2 = 10^{A - \frac{B}{T}} \]  

In formula (3), \( T \) is the absolute temperature. \( A \) and \( B \) are the correlation coefficients, which are related to the composition and chemical properties of insulation oil. In formula (3), only the influence of temperature is considered on the water saturation solubility in oil, and other factors are not considered.
And temperature at different pressures.

By fitting the measured points in figure 3 (a) according to formula (3), the corresponding values of $A$, $B$ and the goodness of fit $R^2$ under different pressures were obtained, as shown in table 1.

| Number | Vacuum degree/MPa | $A$   | $B$   | $R^2$     |
|--------|-------------------|-------|-------|-----------|
| 1      | 0                 | 6.77  | 1466  | 0.99833   |
| 2      | -0.01             | 6.60  | 1417  | 0.99525   |
| 3      | -0.02             | 6.48  | 1386  | 0.98868   |
| 4      | -0.05             | 6.16  | 1296  | 0.98764   |
| 5      | -0.1              | 6.17  | 1309  | 0.99266   |

In order to obtain the general law of the influence of pressure on the water saturation solubility in oil, logarithm the left and right sides of formula (3), formula (4) and the curve shown in figure 3 (b) were obtained.

$$\lg W_s = A - \frac{B}{T}$$

(4)

It could be seen from figure 3 (b) that the remaining four curves could be obtained by shifting the curve of water saturation solubility in oil and temperature under the normal pressure (i.e., the vacuum degree is 0). Therefore, the shifting factor $n$ related to pressure could be introduced into formula (4), as shown in formula (5):

$$\begin{cases} 
\lg W_s = A - \frac{B}{T} + nP \\
W_s = 10^{A - \frac{B}{T} + nP}
\end{cases}$$

(5)

In formula (5), $P$ is the vacuum degree, in MPa. Parameters $A=6.7727$, $B=1466.07$, the shifting factor $n=1.7711$, and the goodness of fit $R^2=0.9894$ were obtained by fitting with least square method. That is, the relationship of water saturation solubility in oil, temperature and pressure was obtained. Figure 3 shows the relationship of water saturation solubility in oil, temperature and pressure. Figure 3 (a) shows the relationship between water saturation solubility in insulation oil and temperature. It can be seen that the water saturation solubility in oil decreases under negative pressure, and this trend becomes more and more obvious with the increase of temperature and vacuum degree. When the water saturation solubility in oil decreases, the dissolved water in oil precipitates out, resulting in forming into suspended water in oil or precipitating out to the insulation paper.

As for the suspended water in oil, on the one hand, it will form an oil-repellent mist with the oil. Transferring of this form of water will exacerbate the oil flow electrification on the oil-paper insulation interface and seriously reduce its insulation performance. On the other hand, according to the small bridge breakdown theory of the engineering liquid dielectric, water is arranged along the electric field direction and forms into an impurity bridge. Due to the dielectric constant of water is greater than that of oil, the formation of Impurity Bridge leading into increased conductivity, increased leakage current and the exothermic bridge. Then, the oil and water partially boil and vaporize, leading into the formation of Gas Bridge. Due to that the electric field intensity is inversely proportional to the relative dielectric constant, the electric field intensity in the gas is much greater than in the oil, the gas bridge breakdown as well as the oil. Thus, the increase of suspended water in oil will reduce the breakdown strength of insulation oil.

Transferring of water from oil to insulation paper will accelerate the hydrolytic aging of insulation paper and reduce the insulation strength of oil-paper insulation. Due to the small size, water molecules
will first infiltrate into the polymer molecules in the amorphous region of cellulose. Water molecules react with the 1-4-β-glycosidic bond between two adjacent glucose rings of cellulose, which are very sensitive to hydrogen ions. When the polymer is separated into two parts, two hydroxyl groups are formed at the same time. With the deepening of aging, the crystalline region of cellulose will gradually change into amorphous region. Aging of insulation paper leads to evacuation of porous of insulation paper, reduction of cellulose diameter and length, reduction of cellulose crystallinity, reduction of polymerization degree, and generation of moisture, organic acids, furan compounds and other aging products.

Figure 4 shows the corresponding relationship between water saturation solubility in oil and pressure at different temperatures.

![Figure 4. Influence of negative pressure on water saturation in oil.](image)

5.2. Further discussion on factors influencing water saturation solubility in oil

Researchers at home and abroad have studied on the water distribution in oil-paper insulation system, and also studied on the factors influencing the water saturation solubility in oil. The influence law of acid value in oil and temperature on the water saturation solubility in oil has been obtained [8]:

\[
\begin{aligned}
\log W_s &= A - \frac{B}{T} + mA_c \\
W_s &= 10^{A - \frac{B}{T} + mA_c}
\end{aligned}
\]  

In formula (6), \(A_c\) is the acid value in oil, in mg KOH/g.

However, for the oil-immersed inverter-type current transformer, the running condition of negative pressure is existed in the metal expander, the results concluded in [8] will not be universal. The influence factors become more complex, and the factor of pressure which also affects water saturation solubility in oil cannot be ignored. Thus, the important factor of pressure shall be introduced into the key influence factors of water saturation solubility in oil. The water saturation solubility in insulation oil shall be comprehensively evaluated though three key factors including the acid value in oil, temperature and pressure. The influence law are shown in formula (5) and formula (6) respectively.

6. Conclusion

(1) According to the Arrhenius equation, the shifting factor \(n\) related to pressure was introduced to establish a mathematical expression involving pressure in expander, temperature, and water saturation solubility in oil. The water saturation solubility in oil decreases with the increase of vacuum degree, that is, with the increase of negative pressure.
(2) The water saturation solubility in oil of instrument transformers is an important parameter to evaluate the water distribution for oil-paper insulation. In previous studies, factors as the acid value in oil and temperature have been researched. In this paper, we found that the pressure also has a great influence on water saturation solubility in oil. The factor of pressure shall be introduced into the study of oil-paper insulation evaluation for the oil-immersed inverter-type current transformer. We took the acid value in oil, temperature and pressure as an evaluation system to comprehensively evaluate the water saturation solubility in oil, which has important guiding significance for solving the practical engineering problems of the oil-immersed inverter-type current transformer.

(3) In the future, the influence of pressure and temperature on the gas saturation solubility characteristics of insulation oil can be further studied. Combining the gas saturation solubility characteristics with the water saturation characteristics of oil, the influence of pressure and temperature on insulation characteristic of oil can be obtained.

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