U.P.B. Sci. Bull., Series D, Vol. 75, Iss. 1, 2013 ISSN 1454-2358

APPLIED RESEARCH ON MEASURING WATER CONTENT OF NO.10 AVIATION HYDRAULIC OIL USED IN SF_6 CIRCUIT BREAKERS VIA CONDUCTIVITY METHOD

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This study conducted a triple-factor experiment of temperature, water content and conductivity to determine the basic parameter used in inferring the water content of No.10 aviation hydraulic oil (AHO 10) in SF_6 circuit breakers. The impacts of temperature and water content on the conductivity of AHO 10 samples were discussed; AHO 10 samples from many SF_6 circuit breakers were analyzed too. In accordance with the characteristics of AHO 10, this study proposed a preliminary method to infer the water content of AHO 10 samples via conductivity, and applied this method to analyze practical AHO 10 samples.

Keywords: aviation hydraulic oil; SF_6 circuit breaker; conductivity; water content; parameters research.

1. Introduction

The SF_6 high-voltage circuit breaker, as one of the key equipment of electrical power systems, is responsible for power system protection; the performance of the breaker directly affects the security, and stable operation of a power system. According to statistics, operating mechanism failure accounts for 43.5% of failure of breakers [1] while hydraulic operating mechanism failure even accounts for 80% of failures of SF_6 circuit breakers [2]. The contamination of hydraulic oil is identified as the major factor causing failure of hydraulic systems, premature wear or damage of hydraulic components, and contributes 70% to 80% to loss due to failure of hydraulic systems [3]. Thus, it can be concluded that the contamination of hydraulic oil, including contamination by water, has become the major source of failures of hydraulic systems. Water content in the hydraulic oil of a hydraulic system reduces the lubrication capacity of the hydraulic oil, resulting in the premature wear of the hydraulic system. Water combining chemically with sulfur or chlorine in the hydraulic oil may produce sulfuric acid or hydrochloric acid, causing corrosion of metallic materials. Water contacting surface of metals including iron may lead to numerous tiny anodes and cathodes causing electrochemical corrosion, rust and even perforation in case of serious rust. Water also accelerates the oxidative deterioration of hydraulic oil, thus shortening the service life of hydraulic oil.

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Differing from hydraulic systems of engineering machinery, the hydraulic system of the high voltage circuit breaker is a manipulation mechanism of low operating frequency and high reliability. The hydraulic system is in a state of preparedness for operation for a prolonged time and it must operate with 100% reliability once the power system fails. This special mode of operation requires that the management and maintenance staff of the circuit breaker not only regularly check the appearance of the hydraulic system to recognize and identify potential failures and problems, but also determine the degree of the contamination of the hydraulic oil and decide whether the hydraulic oil should be filtered or changed, thus ensuring the reliability of the hydraulic system of the high voltage circuit breaker. Therefore, developing hydraulic-oil-contamination testing technologies and standards fitting for the hydraulic system of the special high voltage circuit breaker is of significance for ensuring its reliable operation.

Major methods for measuring water content in hydraulic oil include the electrical conductivity method, micro-water detectors for hydraulic oil, photoacoustic spectroscopy [4] as well as some experience-based detection methods [5]. The electrical conductivity method has been under increased attention and research of scholars since it is rapid and easy and can reveal the degrees of other types of contamination in hydraulic oil [6, 7]. According to the author’s actual experience, different types of hydraulic oil, even the same type of hydraulic oil from different manufacturers or various production lots of the same manufacture, have a big difference in electrical conductivity. Therefore, it is necessary to research on the conductivity-water content behavior of AHO 10 used in the SF_6 circuit breaker.

2. Experiment method

2.1. Experimental apparatus and reagents

The experimental apparatus and reagents included a set of YX1154B oil conductivity meter (developed by Guangzhou Electric Apparatus Research Institute), thermometers, a thermostat, and magnetic stirrers as well as No.10 aviation hydraulic oil (produced by Pinggao Electric Co., Ltd.).

2.2. Experimental methods

The first step was to make simulated samples of water-contaminated hydraulic oil. Water (tap water) in different volume fraction (0%, 0.01%, 0.05%, 0.1% and 0.2%) was added into five reagent bottles of new hydraulic oil respectively. Then, the samples were stirred with magnetic stirrers for more than two hours to completely dissolve or emulsify the water in order to simulate actual oil samples. The bottles were tightly sealed during stirring so as to avoid water evaporation and other impurities into the samples affecting the experimental accuracy. When the samples were made, they were kept still for 24 hours to observe if there was demulsification. If demulsification occurred, samples were re-prepared with an increased stirring time. Then the samples and the conductivity meter were put into the thermostat; the samples were tightly sealed to prevent water evaporation. When the oil sample without water (the sample added with 0% water) reached the specified temperature of 10 to 35℃, whose temperature was measured by a thermometer, conductivity of all samples was measured.

3. Experimental results and discussion

3.1. States of water in the oil samples

AHO 10 is a kind of light oil in which water has a low solubility. Low content of water is able to completely dissolve into an oil sample, and the sample is clear and transparent. When water content exceeds its solubility in an oil sample, the sample is turbid due the formation of a water-in-oil emulsion. Water's solubility in AHO 10 goes up with increased temperature. Table 1 lists the existing states of water in the samples with different water contents at various temperatures. The experiment found that the states of water in the samples influenced the conductivity of the samples, which is discussed later.

Table 1

Existing states of water in the samples with different water contents at various temperatures

T/℃	Existing states of water (at various water contents)				
	0%	0.01%	0.05%	0.1%	0.2%
10	D	D	E	E	E
15	D	D	E	E	E
20	D	D	ST	E	E
25	D	D	ST	E	E
30	D	D	D	E	E
35	D	D	D	E	E

Note:
D denotes that water is dissolved in oil samples;
E denotes that water is in an emulsified state in oil samples;
ST denotes that oil samples are slightly turbid.

It can be seen from Table 1 that the water content of 0.05% is the critical point for water's existence state in the oil samples. The oil samples with water content of less than 0.05% are clear and clean with totally dissolved water while the oil samples with water content higher than 0.05% are turbid with emulsified water. The temperature of 25℃ marks the cutoff point for the state of the oil sample with 0.05% water content: With the rise of temperature, the sample changes to a dissolved and clear state from an emulsified and turgid state.

3.2. Conductivity of oil samples of different water contents at a fixed temperature

Table 2 gives the conductivity data of the oil samples at various temperatures. Figure 1 displays the conductivity-water content curves at different temperatures.

Table 2

Conductivity of the oil samples of different water contents at various temperatures

T/℃	K/pS·m^{-1}(at various water contents)				
	0%	0.01%	0.05%	0.1%	0.2%
10	0.67	2.45	1.53	0.85	1.1
15	0.97	2.67	2.02	1.16	1.39
20	1.21	3.03	2.92	1.49	1.76
25	1.7	3.28	4.71	2.02	2.31
30	2.33	3.87	8.05	2.8	3.11
35	3.15	4.36	11.9	3.92	4.3

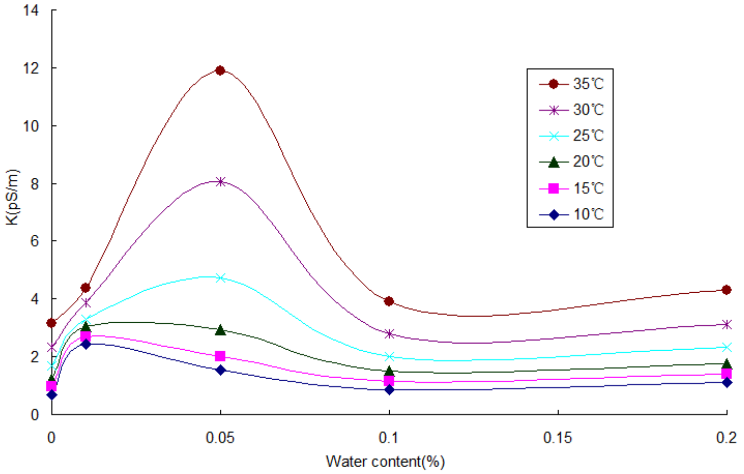

Fig. 1 Water content's impact on conductivity at various temperatures

It can be seen from the six curves in Fig. 1 that there is a conductivity peak for the samples with various water contents at a fixed temperature. The water content corresponding to the conductivity peak gradually increases from 0.01% to 0.05% as the temperature increases. It's inferred from the data in Table 1 that the conductivity peak corresponds to the critical point of water-content for emulsification. When the water is completely dissolved in an oil sample with low water content, the dissolved water contributes considerably to enhance the conductivity of the oil sample. When the oil sample with increased water content is in an emulsified state, it can be seen from the experiment data that emulsification represses the enhancement of the sample conductivity. Although the emulsified samples conductivities rise with increased water content, emulsification reduces the conductivities of the emulsified samples in general. As the temperature goes up, the solubility of water in the oil gradually increases, which causes that the water content enabling emulsification becomes higher, as shown in Figure 1 where the peak of a conductivity curve is gradually moving towards higher water content.

In addition, it can be seen from Table 2: the ratio between the conductivity of the sample with 0.05% water content and that with 0.05% water content is 2.77 while 0.05% is the warning value for water content in hydraulic oil [8]. This ratio can be used as a reference when the degree of contamination of hydraulic oil is determined by the increase in hydraulic oil conductivity.

3.3. Conductivity of the oil sample with fixed water content at varied temperatures

The equation below describes the relation between the electrical conductivity and temperature of light oil at a common temperature (0℃ to 40℃) [9]:

$$lgK_{t1}=N(t_1-t_2)+lgK_{t2} \tag{1}$$

where:

K_{t1} is the conductivity of oil sample at temperature t_1, unit $pS\cdot m^{-1}$;

K_{t2} is the conductivity of oil sample at temperature t_2, unit $pS\cdot m^{-1}$;

N is the temperature-conductivity coefficient;

It can be seen that the logarithm of the sample conductivity is linear with temperature. Define $C=lgK_{t2}-Nt_2$, then Eq.(1) can be written as:

$$lgK=Nt+C \tag{2}$$

If the values of N and C are fixed, the conductivity of a sample at an arbitrary temperature can be calculated by Eq.(2) if the sample conductivity at a specific temperature is obtained. Nevertheless, determining the values of N and C requires the conductivities of the sample at two different temperatures, which causes inconvenience in practice. Therefore, it is expected that reliable empirical values can be given to N so as to simplify measurement in practice.

The logarithmic curves for the conductivities of the samples against temperature are plotted with data in Table 1 and displayed in Fig. 2.

Linear fitting of the five curves in Fig. 2 generates the following five equations:

$$\begin{aligned} lgK_{0\%} &=0.02657t-0.43264 \\ lgK_{0.01\%} &=0.01011t-0.27917 \\ lgK_{0.05\%} &=0.03693t-0.22936 \\ lgK_{0.1\%} &=0.02628t-0.33923 \\ lgK_{0.2\%} &=0.02359t-0.21075 \end{aligned}$$

where:

$K_{0\%}$, $K_{0.01\%}$, $K_{0.05\%}$, $K_{0.1\%}$ and $K_{0.2\%}$ denote the conductivities of the five samples with water contents of 0%, 0.01%, 0.05%, 0.1% and 0.2% respectively. Since the goodness of fit for these five fitting equations are all over 0.99, lgK is linearly related with *t*, thus validating the experiment data.

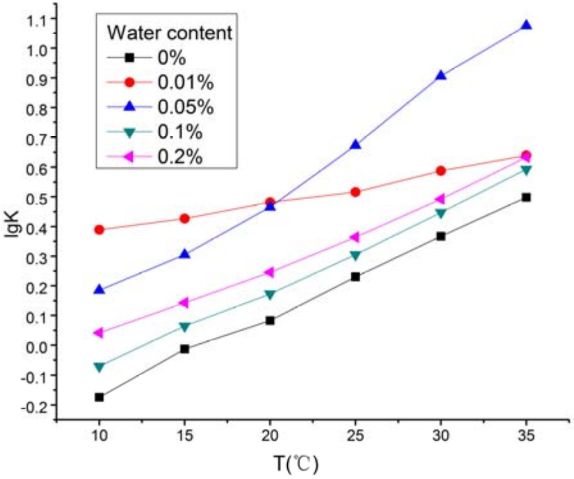

Fig. 2 Temperature's impact on conductivity at varied water content

The five equations also determine the values of N for the samples. Excepting $N_{0.01\%}$=0.01011 and $N_{0.05\%}$=0.03693, $N_{0\%}$, $N_{0.1\%}$ and $N_{0.2\%}$ only have small difference, which means that the values of N for the emulsified samples have minor disparity with that of the sample without water, and that totally dissolved water in oil samples reduce the value of N while the critical water content of emulsification-total dissolution at a temperature range increases the value of N.

3.4. Preliminary method for inferring water content in an oil sample via conductivity

Since the relation between the conductivity of a sample and the temperature varies with water content, it is impossible to obtain the water content of the sample by calculating the sample conductivity at a specified temperature with the sample conductivity at a certain measured temperature. The temperature must be fixed when the water content of the sample is calculated via conductivity measurement. As mentioned earlier in Section 3.2, the sample with 0.05% water content has the highest conductivities among the five samples at the temperature is 25℃, about 2.77 times of the conductivity of the sample without water.

The temperature of 25℃ happens to be the critical temperature when the sample of 0.05% water content transforms from the emulsified state to the completely dissolved state. In other words, oil samples with water content higher than 0.05% should be in an emulsified state at 25℃. Therefore, the following steps can be taken to determine the water content of a sample in practice:

(1) Determine whether the water content of an oil sample is higher than 0.05% by observing the sample state in terms of turbidity at 25℃; if the oil sample is in an emulsified state, no conductivity test is required to confirm that the water content of an oil sample is higher than 0.05%, and follow-up treatment proceeds directly;

(2) If the oil sample is clear and clean, measure its conductivity of 25℃, and calculate the ration between the 25℃ conductivity measured and that of the water-free oil sample. If this ratio is greater than or equal to 2.77 (other pollutants in an oil sample may cause increased water solubility [6, 7] and lead to a ratio higher than 2.77), then the oil sample has reached the water-content warning value of 0.05%, dewatering should be done.

3.5. Overall assessment of practical hydraulic oil

On the basis of research with simulated oil samples, the authors measured the conductivities of AHO 10 in a great number of SF_6 circuit breakers owned by a branch of State Grid Corporation of China. There were 81 oil samples studied excluding the samples in an emulsified state at 25 ℃. Fig. 3 gives the conductivities of the 81 samples at 25℃, K_{25}, in solid columns.

In addition, the authors also received two new AHO10 samples that had not been used from the branch. Their conductivities at 25℃ were 57PS/m and 1.7PS/m respectively. It can be seen that new AHO 10 produced in various lots and batches varies widely in conductivities due to differences in additives or transportation and storage conditions. Obviously, if 1.7PS/m is taken as the conductivity of a water-free sample at 25℃, the rate of oil samples that have water content exceeding the warning value divorces from reality.

Thus, new AHO 10 in various batches cannot be randomly used as the water-free sample in determining water content via conductivity. In fact, in real-life applications, the conductivity data of new hydraulic oil used are missing. Therefore, the authors conducted dewatering treatment on the 81 oil samples, with the goal of analyzing the similarities and differences between using conductivities of dewatered samples and 57PS/m as the conductivity of the water-free sample to infer water contents of the samples.

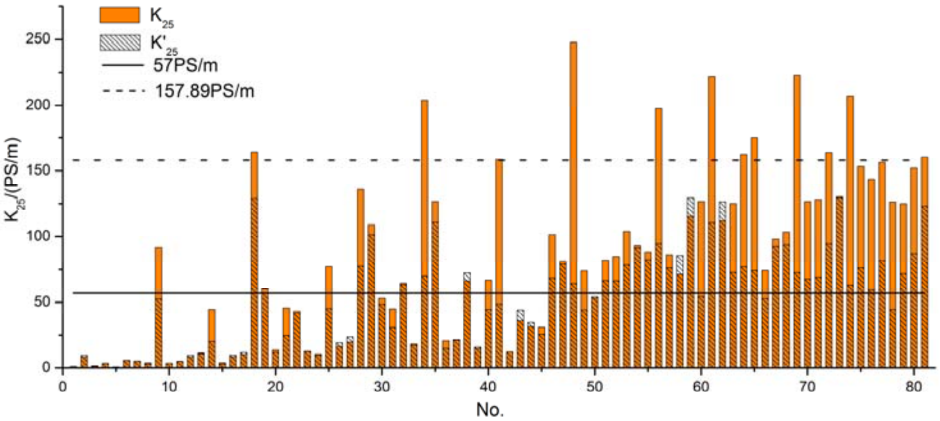

Fig. 3 Conductivities of the selected oil samples at 25℃ before and after dewatering

Dewatering steps were as follows:

1) Put the oil sample in a drying oven to dry it at 80℃ for 24 hours.

2) Take out the sample and put it immediately into a vacuum container, and deair the container for one hour to remove residual water.

3) Measure the conductivity of the sample at 25℃ after dewatering, namely K'_{25}, when it was cooled to 25℃. The hollow slashed columns in Figure 3 depict the conductivities for the samples after dewatering, K'_{25}.

Figure 4 shows the ratio of the conductivities of a sample before and after dewatering, K_{25}/K'_{25}.

It can be seen from Fig. 3 and Fig. 4 that 68 samples (84%) have a decrease in conductivity after dewatering and that some samples even have considerable drop. Nevertheless, 13 samples (16%) have an increased conductivity after dewatering. The reason behind increased conductivity may be that the dewater treatment may enhance the contribution of factors including particles impurities and aging-induced impurities in promoting up conductivity since these factors and water content both serve to boost conductivity [6, 7]. It is worth noting that the conductivity rises of the 16 samples are not significant with all K_{25}/K'_{25} over 0.8. Therefore, it can be concluded that conductivity increase of AHO 10 in circuit breakers is closely related to the water content, and that the impact of dewatering on samples conductivity is basically limited in changing water content.

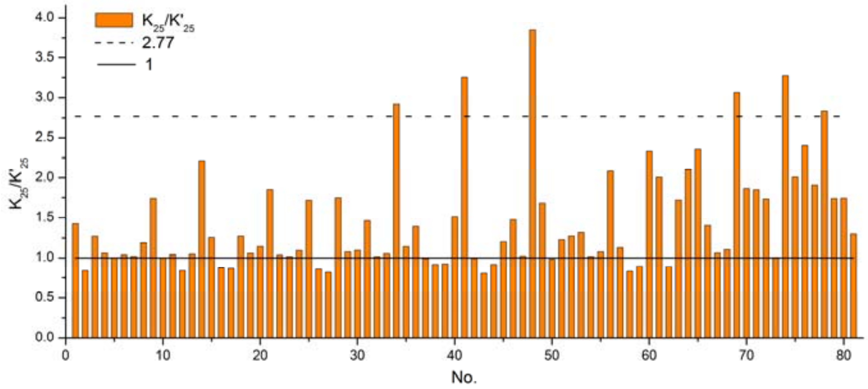

Fig. 4 The ratio of the conductivities of a sample at 25℃ before and after dewatering

Thus, the conductivity of dewatered samples can be used as the data basis to infer water content.

It can be found by comparing Fig. 3 and Fig. 4:

1) If the conductivity of new oil at 25℃, 57 PS/m, (the solid line in Figure 3), is taken as the basis data and the first criterion that the conductivity of an oil sample exceeds 2.77 times of the basis data (157.89 PS/m, the dashed line in Figure 3) is applied to judge that the oil sample has a water content no less than the critical warning value of 0.05%, then there are 12 samples meeting this criterion (their numberings are 18, 34, 41, 48, 56, 61, 64, 65, 69, 72, 74 and 81).

2) If the conductivity of the dewatered oil sample at 25℃ is taken as the basis data and the second criterion that the conductivity of an oil sample exceeds 2.77 times of the basis data (the dashed line in Fig. 4) is applied to judge that the oil sample has a water content no less than the critical warning value of 0.05%, then there are 6 samples meeting this criterion (their numberings are 34, 41, 48, 69, 74 and 78).

There are only 5 samples judged as having a water content exceeding the critical warning value by both of the two criteria mentioned above. No.78 sample’s water content falls below the warning value judged by the first criterion while its water content exceeds the warning value by the second criterion. It can be inferred that the remaining 7 samples of the 12 samples have high new-oil conductivity or high degree of other type of contamination, and that No.78 have low new-oil conductivity or low degree of other type of contamination, which accounts for the judgment results by the two criteria. The above analysis further proves that only the conductivity of dewatered oil samples at 25℃ can be taken as the basis data to inter water content in practical applications.

4. Conclusions

1) The conductivity of AHO 10 has close ties with its water content and the existence state of water in it. Dissolved water in it contributes significantly to boost its conductivity while emulsification inhibits its conductivity enhancement. Whether water in it is totally dissolved or emulsified, the increase of water conditions in it steps up the conductivity of AHO 10 samples. The conductivity of the samples varies with water content yet has a peak when the temperature is fixed. The peak conductivity corresponds to the water-content critical point of emulsification under different temperatures.

2) AHO 10 has a unique conductivity-water content behavior, which shows that different types of hydraulic oil have varied conductivity-water content relationship [6, 7, 10].

3) This study proposes a preliminary method to infer water content of oil samples via conductivity in accordance with the characteristics of AHO 10.

4) Based on the measurement and analysis of 81 clear AHO 10 samples from a great number of SF_6 circuit breakers of a power grid system, this study proposes that only the criteria that the conductivity ratio of an oil sample at 25℃ before and after dewatering, namely K_{25}/K'_{25}, is no less than 2.77 can be used to ascertain that the sample has reached the water-content critical warning value.

REFERENCES

[1] *S. Zhong, L. Lv, Y.A. Luo, J.T. Luo* - Monitoring on hydraulic mechanism of circuit-breaker based on expert system - Sich. Electr. Power Technol. 30 (2007), 62-64

[2] *J. Liu* - Analysis on the comment defects of circuit breakers series LW6 - Fuj. Electr. Power Electr. Eng. 23 (2003), 57-59

[3] *C.Y. Yao, J.Y. Zhao, Q.S. Zhang, Y.Q. Wang* - Research on contamination monitoring technology in hydraulic fluid - Lubr. Eng. 10 (2006), 196-199

[4] *N.S. Foster, J.E. Amonette, T. Autrey, J.T. Ho* - Detection of trace levels of water in oil by photoacoustic spectroscopy – Sensor. Actuat. B-Chem. 77 (2001), 620-624

[5] *China Petroleum and Chemical Corporation* - GB/T 7631.2—2003 Lubricants, industrial oils and related products (class L)—Classification—Part 2: Family H (Hydraulic systems) - Standards Press of China, Beijing, China, 2005

[6] *S.Z. Wang, H.R. Fu, S. Tan* - Investigation on rapid contamination analysis of in-use hydraulic fluid by electrical conductivity - Appl. Sci. Technol. 12 (2006), 54-56

[7] *A. W. Stannett* - The conductivity of hydrocarbon transformer oil containing water and solid conducting particles - Br. J. Appl. Phys. 2 (1951), 110-114

[8] *S.Q. He, S.Q. Xie* - Degradation of hydraulic oil in vehicles and the preventive measures - Hoist. Convey. Mach. 3 (2003), 37-39

[9] *The State Economic and Trade Commission of the People's Republic of China* - GB 6950—2001 Safe rest conductivity of light fuel oil - Standards Press of China, Beijing, China, 2001

[10] *F. Bordi, C. Cametti, S.H. Chen, J. Rouch, F. Sciortino, P. Tartagalia* - The static electrical conductivity of water-in-oil microemulsions below percolation threshold - Physica A 231 (1996), 161-167