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Uncertainty Analysis of Insulating Oil Dielectric Dissipation Factor and Volume Resistivity Testers

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Abstract

Based on JJF 1618-2017"Calibration Specification for Insulating Oil Dielectric Dissipation Factor and Volume Resistivity Testers", this paper introduces the insulating oil dielectric dissipation factor and volume resistivity testers. Then we analyze the measurement models and evaluate the uncertainty of the sources of measuring errors of voltage, capacitance, dielectric dissipation factor, volume resistivity and temperature of the insulating oil dielectric dissipation factor and volume resistivity testers in detail. Each uncertainty is evaluated with both class A and class B of the standard uncertainty.

Keywords

Insulating Oil Dielectric Dissipation Factor and Volume Resistivity Testers; Measurement Model; Uncertainty.

1. Introduction

Insulating oil is an important part of the high voltage electrical equipment insulation whose quality affects the safety of the devices and the power network[1]. For example, the insulating oil in the transformer has good insulation as liquid medium, which fills the gap in the transformer to ensure that there's no air inside the shell. It enhances insulation strength with a moisture-proof effect[2]. The insulating oil dielectric dissipation factor and volume resistivity tester combines the dielectric loss factor test which has been used in the quality analysis of transformer oil in China and the volume resistivity test used in many imported equipments[3].

2. Organization of the Text

Section 1 intrudes the insulating oil dielectric dissipation factor and volume resistivity tester.

Section 2 intrudes the organization of the text.

Section 3 intrudes the measurement basis and the environmental conditions.

Section 4 intrudes the measuring objects and the measurement standards used.

Section 5 intrudes the measurement models and analyzes the uncertainty.

3. Measurement Basis and Environmental Conditions

3.1 Measurement Basis

JJF 1618-2017"Calibration Specification for Insulating Oil Dielectric Dissipation Factor and Volume Resistivity Testers"(JJF 1618-2017 for short below).

3.2 Environmental Conditions

Temperature:(20±5)℃

Humidity:≤60%RH

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4. Measurement Standards

4.1 Measuring Objects

The specific calibration items of the insulating oil dielectric dissipation factor and volume resistivity tester are in Table 1.

Table 1. The specific calibration items of the oil dielectric dissipation factor and volume resistivity tester

Specific calibration item	Measuring range
high voltage power dupply	(0.1~5)kV
capacitance	100pF
dielectric dissipation factor	0~0.1
volume resistivity	$1\times10^{6}\Omega\cdot m$~$1\times10^{12}\Omega\cdot m$
temperature	(0~120)℃

4.2 High Voltage Power Supply

Based on 7.2.5 in JJF 1618-2017, set insulating oil dielectric dissipation factor and volume resistivity tester to the voltage to be measured and launch it. After the voltage is stabilized, measure the voltage with the high voltage meter. The difference between the indicated value of the insulating oil dielectric dissipation factor and volume resistivity tester and the high voltage meter is the indicating error of the voltage.

4.3 Capacitance and Dielectric Dissipation Factor

Based on 7.2.1 and 7.2.2 in JJF 1618-2017, connect the insulating oil dielectric dissipation factor and volume resistivity tester and the high voltage dielectric loss factor standard. Measure the capacitance and dielectric dissipation factor under the condition of no heating and no refueling. The differences between the indicated values of the insulating oil dielectric dissipation factor and volume resistivity tester and the high voltage dielectric loss factor standard are the indicating errors of the capacitance and dielectric dissipation factor.

4.4 Volume Resistivity

Based on 7.2.3 in JJF 1618-2017, connect the insulating oil dielectric dissipation factor and volume resistivity tester and the megohm meter verification device. Measure the volume resistivity under the condition of no heating and no refueling. The difference between the indicated value of the insulating oil dielectric dissipation factor and volume resistivity tester and the megohm meter verification device is the indicating error of the volume resistivity.

4.5 Temperature

Based on 7.2.4 in JJF 1618-2017, heat the oil in the insulating oil dielectric dissipation factor and volume resistivity tester to the temperature to be measured. Measure the temperature of the oil in the oil cup with the standard thermometer after the oil temperature is stable. The difference between the indicated value of the insulating oil dielectric dissipation factor and volume resistivity tester and the standard thermometer is the indicating errors of the temperature.

4.6 Measurement Standard Devices

Main measuring standard equipment involves: high voltage meter, high voltage dielectric loss factor standard, megohm meter verification device, standard thermometer. For specific parameters, see Table 2.

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Table 2. Standard devices

No.	Device	Measuring range	MPE
1	high voltage meter	(0.1~10)kV	±1%
2	high voltage dielectric loss factor standard	capacitance: 97.3pF, loss factor:0~0.1	capacitance: ±0.2%Cx±0.5pF, loss factor:±(0.2%D+0.0001)
3	megohm meter verification device	100Ω~10MΩ 10MΩ~100MΩ 100MΩ~1GΩ 1GΩ~1TΩ	±0.2% ±0.5% ±1% ±2%
4	standard thermometer	(-80~300)℃	±0.05℃

5. Measurement Models and Uncertainty Analysis

5.1 Measurement Models

5.1.1 Measurement Model of Voltage Indication Error of the Insulating Oil Dielectric Dissipation Factor and Volume Resistivity Tester

$$\Delta U = U_x - U_N \tag{1}$$

ΔU -- voltage indication error, kV;

U_X -- voltage indication of the insulating oil dielectric dissipation factor and volume resistivity tester, kV;

U_N -- voltage standard value, kV.

5.1.2 Measurement Model of Capacitance Indication Error of the Insulating Oil Dielectric Dissipation Factor and Volume Resistivity Tester

$$\Delta C = C_x - C_N \tag{2}$$

ΔC -- capacitance indication error, pF;

C_X -- capacitance indication of the insulating oil dielectric dissipation factor and volume resistivity tester, pF;

C_N -- capacitance standard value, pF.

5.1.3 Measurement Model of Dielectric Dissipation Factor Indication Error of the Insulating Oil Dielectric Dissipation Factor and Volume Resistivity Tester

$$\Delta D = D_x - D_N \tag{3}$$

ΔD -- dielectric dissipation factor indication error;

D_X -- dielectric dissipation factor indication of the insulating oil dielectric dissipation factor and volume resistivity tester;

D_N -- dielectric dissipation factor standard value.

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5.1.4 Measurement Model of Volume Resistivity Indication Error of the Insulating Oil Dielectric Dissipation Factor and Volume Resistivity Tester

$$\Delta\rho = \rho_x - \rho_N \tag{4}$$

$\Delta\rho$ -- volume resistivity indication error, Ω·m;

ρ_X -- volume resistivity indication of the insulating oil dielectric dissipation factor and volume resistivity tester, Ω·m;

ρ_N -- volume resistivity standard value, Ω·m.

5.1.5 Measurement Model of Temperature Indication Error of the Insulating Oil Dielectric Dissipation Factor and Volume Resistivity Tester

$$\Delta t = t_x - t_N \tag{5}$$

Δt -- temperature indication error, ℃;

t_X -- temperature indication of the insulating oil dielectric dissipation factor and volume resistivity tester, ℃;

t_N -- temperature standard value, ℃.

5.2 Uncertainty Propagation Formula

Voltage for example, U_X is independent from U_N, the uncertainty propagation formula is derived from the mathematical model [5]:

$$u_c^2 = c_1^2 u_X^2 + c_2^2 u_N^2 \tag{6}$$

coefficients of sensitivity:

$$c_1 = \frac{\partial \Delta U}{\partial U_X} = 1 \tag{7}$$

$$c_2 = \frac{\partial \Delta U}{\partial U_N} = -1 \tag{8}$$

The coefficients of sensitivity of capacitance, dielectric dissipation factor, volume resistivity and temperature can be gotten in the same manner.

5.3 Standard Uncertainty Assessment

5.3.1 Standard Uncertainty Assessment of Voltage

The component of standard uncertainty introduced by measurement repeatability is evaluated by class A of standard uncertainty.

Voltage 10kV for example, calibrate the voltage of the insulating oil dielectric dissipation factor and volume resistivity tester measured with the high voltage meter independently for 10 times, then read and record the indicated values.

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Table 3. Measuring Result

NO.	1	2	3	4	5
measured value (kV)	1.01	1.01	1.02	1.02	1.01
NO.	6	7	8	9	10
measured value (kV)	1.02	1.02	1.02	1.01	1.01

Average value is:

$$\overline{U} = \frac{1}{n}\sum_{i=1}^{n} U_i = 1.015kV \tag{9}$$

Experimental standard deviation from a single measurement is:

$$s = \sqrt{\frac{\sum_{i=1}^{n}(U_i - \overline{U})^2}{n-1}} = 0.0053kV \tag{10}$$

$$u_1 = \frac{s}{\overline{U}} \times 100\% = 0.519\% \tag{11}$$

The standard uncertainty component introduced by the accuracy of the standard is evaluated by class B of the standard uncertainty.

The degree of accuracy of the high voltage meter is ±1%, we get an uncertainty component estimated by uniform distribution:

$$u_2 = \frac{1\%}{\sqrt{3}} = 0.577\% \tag{12}$$

The combined standard uncertainty of voltage is:

$$u_c(V) = \sqrt{c_1^2 u_1^2 + c_2^2 u_2^2} = 0.78\% \tag{13}$$

5.3.2 Standard Uncertainty Assessment of Capacitance

Table 4. Measuring Result

NO.	1	2	3	4	5
measured value (pF)	97.31	97.33	97.35	97.33	97.36
NO.	6	7	8	9	10
measured value (pF)	97.35	97.32	97.34	97.31	97.32

The component of standard uncertainty introduced by measurement repeatability is evaluated by class A of standard uncertainty.

Capacitance 97.3pF for example, calibrate the capacitance of the insulating oil dielectric dissipation factor and volume resistivity tester measured with the high voltage dielectric loss factor standard independently for 10 times, then read and record the indicated values.

Average value is:

$$\overline{C} = \frac{1}{n}\sum_{i=1}^{n} C_i = 97.332pF \tag{14}$$

Experimental standard deviation from a single measurement is:

$$s = \sqrt{\frac{\sum_{i=1}^{n}(C_i - \overline{C})^2}{n-1}} = 0.0175pF \tag{15}$$

$$u_1 = s = 0.0175pF \tag{16}$$

The standard uncertainty component introduced by the accuracy of the standard is evaluated by class B of the standard uncertainty.

The nominal value of the high voltage dielectric loss factor standard is 97.3pF and its degree of accuracy of is ±0.2%Cx±0.5pF, we get an uncertainty component estimated by uniform distribution:

$$u_2 = \frac{0.2\% \times 97.3pF + 0.5pF}{\sqrt{3}} = 0.401pF \tag{17}$$

The combined standard uncertainty of capacitance is:

$$u_c(C) = \frac{\sqrt{c_1^2 u_1^2 + c_2^2 u_2^2}}{\overline{C}} = 0.42\% \tag{18}$$

5.3.3 Standard Uncertainty Assessment of Dielectric Dissipation Factor

The component of standard uncertainty introduced by measurement repeatability is evaluated by class A of standard uncertainty.

Dielectric dissipation factor 0.01(1%)for example, calibrate the dielectric dissipation factor of the insulating oil dielectric dissipation factor and volume resistivity tester measured with the high voltage dielectric loss factor standard independently for 10 times, then read and record the indicated values.

Table 5. Measuring Result

NO.	1	2	3	4	5
measured value (%)	1.001	1.002	1.001	1.002	1.003
NO.	6	7	8	9	10
measured value (%)	1.002	1.003	1.002	1.001	1.001

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Average value is:

$$\overline{D}=\frac{1}{n}\sum_{i=1}^{n}D_i=1.0018\%=0.010018 \tag{19}$$

Experimental standard deviation from a single measurement is:

$$s=\sqrt{\frac{\sum_{i=1}^{n}(D_i-\overline{D})^2}{n-1}}=0.0000079 \tag{20}$$

$$u_1=s=0.0000079 \tag{21}$$

The standard uncertainty component introduced by the accuracy of the standard is evaluated by class B of the standard uncertainty.

The nominal value of the high voltage dielectric loss factor standard is 0.01 and its degree of accuracy of is ±(0.2%D+0.0001), we get an uncertainty component estimated by uniform distribution:

$$u_2=\frac{0.2\%\times 0.01+0.0001}{\sqrt{3}}=0.000069 \tag{22}$$

The combined standard uncertainty of dielectric dissipation factor is:

$$u_c(D)=\sqrt{c_1^2u_1^2+c_2^2u_2^2}=0.00007 \tag{23}$$

5.3.4 Standard Uncertainty Assessment of Volume Resistivity

The component of standard uncertainty introduced by measurement repeatability is evaluated by class A of standard uncertainty.

Volume resistivity 6.76×107Ω·m for example, calibrate the volume resistivity of the insulating oil dielectric dissipation factor and volume resistivity tester measured with the megohm meter verification device independently for 10 times, then read and record the indicated values.

Table 6. Measuring Result

NO.	1	2	3	4	5
measured value (Ω·m)	6.79×10^7	6.82×10^7	6.85×10^7	6.83×10^7	6.76×10^7
NO.	6	7	8	9	10
measured value (Ω·m)	6.73×10^7	6.75×10^7	6.78×10^7	6.82×10^7	6.78×10^7

Average value is:

$$\overline{\rho}=\frac{1}{n}\sum_{i=1}^{n}\rho_i=6.791\times10^7\,\Omega\cdot\mathrm{m} \tag{24}$$

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Experimental standard deviation from a single measurement is:

$$s = \sqrt{\frac{\sum_{i=1}^{n}(\rho_i - \overline{\rho})^2}{n-1}} = 0.03843 \times 10^7 \Omega \cdot \text{m} \tag{25}$$

$$u_1 = s = 0.0384 \times 10^7 \Omega \cdot \text{m} \tag{26}$$

The standard uncertainty component introduced by the accuracy of the standard is evaluated by class B of the standard uncertainty.

Conversion formula of volume resistivity and insulation resistance is:

$$\rho = 0.113 C_0 R \tag{27}$$

ρ --volume resistivity of the insulating oil, Ω·m;

C_0 -- empty cup capacitance of oil cup, pF;

R -- insulation resistance of the insulating oil, Ω.

As the empty cup capacitance of oil cup is constant, the standard uncertainty component introduced by the accuracy of the standard is related with resistance. The degree of accuracy of the megohm meter verification device is ±0.5%, we get an uncertainty component estimated by uniform distribution:

$$u_2 = \frac{0.5\% \times 6.791 \times 10^7 \Omega \cdot m}{\sqrt{3}} = 0.0196 \times 10^7 \Omega \cdot m \tag{28}$$

The combined standard uncertainty of volume resistivity is:

$$u_c(\rho) = \frac{\sqrt{c_1^2 u_1^2 + c_2^2 u_2^2}}{\overline{\rho}} = \frac{0.044 \times 10^7 \Omega \cdot m}{6.791 \times 10^7 \Omega \cdot m} = 0.7\% \tag{29}$$

5.3.5 Standard Uncertainty Assessment of Temperature

The component of standard uncertainty introduced by measurement repeatability is evaluated by class A of standard uncertainty.

Temperature 50℃ for example, calibrate the temperature of the oil of the insulating oil dielectric dissipation factor and volume resistivity tester measured with the standard thermometer independently for 10 times, then read and record the indicated values.

Table 7. Measuring Result

NO.	1	2	3	4	5
measured value (℃)	50.01	50.02	50.03	50.04	50.03
NO.	6	7	8	9	10
measured value (℃)	50.04	50.03	50.04	50.03	50.02

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Average value is:

$$\overline{T} = \frac{1}{n}\sum_{i=1}^{n} T_i = 50.029℃ \tag{30}$$

Experimental standard deviation from a single measurement is:

$$s = \sqrt{\frac{\sum_{i=1}^{n}(T_i - \overline{T})^2}{n-1}} = 0.0099℃ \tag{31}$$

$$u_1 = s = 0.0099℃ \tag{32}$$

The standard uncertainty component introduced by the accuracy of the standard is evaluated by class B of the standard uncertainty.

The degree of accuracy of standard thermometer is ±0.05℃, we get an uncertainty component estimated by uniform distribution:

$$u_2 = \frac{0.05℃}{\sqrt{3}} = 0.0289℃ \tag{33}$$

The combined standard uncertainty of temperature is:

$$u_c(T) = \sqrt{c_1^2 u_1^2 + c_2^2 u_2^2} = 0.031℃ \tag{34}$$

5.4 Extended Uncertainty Assessment

Set the coverage factor k=2, then the extended uncertainty:

voltage 1 kV

$$U_{rel}(V) = k \times u_c(V) = 1.6\% \tag{35}$$

capacitance 97.3 pF

$$U_{rel}(C) = k \times u_c(C) = 1.0\% \tag{36}$$

dielectric dissipation factor 0.01

$$U(D) = k \times u_c(D) = 0.00015 \tag{37}$$

volume resistivity $6.76 \times 10^7\, \Omega \cdot m$

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$$U_{rel}(\rho) = k \times u_c(\rho) = 1.5\% \tag{38}$$

temperature 50℃

$$U(T) = k \times u_c(T) = 0.07℃ \tag{39}$$

6. Conclusion

In this paper, we analyze the measurement models of the insulating oil dielectric dissipation factor and volume resistivity tester and calculate the coefficients of sensitivity of the uncertainty propagation formula. Then we evaluate the uncertainty of the sources of measuring errors of voltage, capacitance, dielectric dissipation factor, volume resistivity and temperature by class A and class B of the standard uncertainty and get the extended uncertainty values.

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