

Temperature Segment Compensation Method of Dissipation Factor for Insulation Diagnosis in Converter Transformer Bushing

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This work was supported in part by the Natural Science Foundation of Beijing under Grant 3214062, in part by the Scientific Research Project of Beijing Municipal Education Commission under Grant KM202111417004, and in part by the Premium Funding Project for Academic Human Resources Development in Beijing Union University under Grant BPHR2020BZ02 and Grant BPHR2020DZ03.


ABSTRACT Temperature compensation occupies a significant function in the insulation condition evaluation of converter transformer bushings based on the Frequency Domain Spectroscopy (FDS), which could influence the accuracy of its insulation diagnosis. In order to accurately obtain the variation law of FDS at different temperature, a Resin Impregnated Paper (RIP) insulation bushing for converter transformer was designed by the equivalence of maximum electric field, coaxial cylinder structure and RIP materials. The increment law of dielectric parameters both dissipation factor and capacitance at wideband frequency (1mHz ~ 10kHz) was measured for a quality RIP insulation samples at the temperature from 30°C to 100°C. 1) Under the uniform temperature, it was found that the value of dissipation factor was rising with the frequency from 10 Hz to 0.001Hz, while the tendency was reversed at the frequency from 100Hz to 10kHz. 2) The minimum value of $\tan\delta$ from 0.001Hz to 10kHz could be driven to higher frequency moving (10Hz to 10kHz) by the action of temperature rising 30°C to 100°C. 3) The effect of temperature on the lower frequency 0.001Hz ~ 1Hz $\tan\delta$ of RIP insulation closely conformed to the index law of Arrhenius equation, while it was in accordance with the linear decrease at higher frequency 1kHz ~ 10kHz. The effect of temperature on dissipation factor could be eliminated by curve segment shifting based the experiment equation, which it at 0.001Hz dissipation factor could be eliminated by curve shifting based the index equation originated Arrhenius equation. The method is beneficial to eliminate the influence of temperature on the dielectric spectroscopy test results, and then to eliminate the influence of temperature on the dielectric spectroscopy diagnosis of RIP bushings.

INDEX TERMS Converter transformer, resin-impregnated paper insulation, frequency domain spectroscopy (FDS), temperature, dissipation factor, fault diagnosis.

I. INTRODUCTION

As the most complex, expensive and enormous equipment in the HVDC transmission system, the quality of insulation in converter transformer has become a constraint critical factor of the construction and operation of the current transmission project [1], [2]. The insulation type of resin-impregnated paper (RIP) are widely used in valve side bushing of converter transformer, because of its stable electrical performance, light

weight, explosion-proof flame retardant and other advantages. The resin-impregnated paper (RIP) bushing in the converter transformer is the key equipment for the valve side winding to external connection in ultra-high voltage (UHV) converter stations [3], [4]. It would be a feasible scheme that RIP bushings could at least a partial substitute for the oil-impregnated paper bushings in converter transformer for avoiding exposure of oil leakage, fire and explosion. However, in recent years, the insulation faults of RIP bushing in converter transformers have occurred frequently [5], which would pose a serious threat to the safety operation of

The associate editor coordinating the review of this manuscript and approving it for publication was Guillaume Parent .

power grid. It became the focus issues that accurately diagnosed the insulation status of RIP bushings. According to CIGRE group A2/B4.28 [6], insulation failure of the valve side winding and bushings in the converter transformer accounted for 65% of the total failure, which is mainly caused by the insulation damage such as flashovers the surface and dielectric breakdown. From the operation report of the State Grid Corporation of China [7], the failure of the converter valve side bushing accounted for 16.7% of all HVDC equipment failures, which was one of highest fault ratio equipment to cause converter valve lock-up or other insulation failures in converter stations. Thus, it is of great importance to reduce the failure rate of the RIP bushings and improve the reliability of the RIP insulation bushing equipment in the converter transformer. Especially, a new defect detection method for the defect earlier stage of RIP insulation has become a hot research topic, which maybe realize the early diagnosis of RIP bushings defects, and establish the evaluation methods and maintenance strategies of the RIP bushings in operation.

Frequency domain spectroscopy (FDS) is an important method for detecting the insulation status of resin-impregnated paper insulation in converter transformers. It is an important insulation aging detection and moisture evaluation method with good engineering application prospects [8], [9]. Temperature has an important influence on the dielectric spectroscopy response characteristics of RIP bushings, which restricts the application of the dielectric spectroscopy technology to diagnose the insulation state of converter transformer bushing [10], [11]. The shape of the FDS curve in oil-paper insulating has a strong dependence on temperature [12]. A “Master Curve” of FDS can be formed by shifting FDS curves at different temperatures for oil-impregnated paper insulation [13], [14]. The method of temperature compensation occupies a significant function in the insulation condition evaluation of Resin Impregnated Paper (RIP) insulation based on the Frequency Domain Spectroscopy (FDS). At present, the influence of temperature on the dielectric spectroscopy of oil-paper insulation is relatively enough, while it is not clear the formula from oil-paper insulation whether suitable to RIP insulation [15], [16]. In order to accurately obtain the variation law of wideband frequency dissipation factor at different temperature, a RIP insulation bushing was designed by the equivalence of electric field. The increment law of dielectric parameters both dissipation factor and capacitance at wideband frequency (1mHz ~ 10kHz) was measured for a drying RIP insulation samples at the temperature from 30°C to 100°C. It is of great urgency to establish a more accurate, universal and practical temperature normalization method, to eliminate the influence of temperature on the diagnostic accuracy of the bushing dielectric spectroscopy. Thus, achieving a better temperature shifting method for FDS and polarization current technology for diagnosing the insulation status of converter transformer bushings could ensure the accuracy of FDS assessment of the insulation status of RIP insulation bushings, and improve the application of FDS in the field evaluation of power equipment.

II. RIP MODEL DESIGN AND TEST SETUP

A. RIP INSULATION BUSHING DESIGN

The main insulation of a RIP insulation bushing is the capacitance core as the center of the aluminum rod for winding multilayer wrinkle paper and aluminum foil, then through epoxy resin vacuum casting, piecewise curing process. The principle of consistency including maximum electric field and coaxial cylinder structure and RIP materials was adopted with the valve side of converter transformer RIP bushings. A RIP insulation bushing was produced by a famous RIP bushing manufacturer with a rated voltage of ± 25 kV. The structure design and sample of a RIP insulation bushing is shown in Figure 1. The RIP bushing capacitance core is equipped with 5 layers of equalized aluminum foil plates, where R_0 and L_0 are 45mm and 300mm, other size respectively shown in table 1.

The capacitor core is rolled with crepe paper and aluminum foil electrode, after vacuum drying, it is impregnated and cured with fully degassed epoxy resin. To achieve the same electric field strength on the model as the actual DC bushing electric field strength, the electric field is calculated using the bushing electric field calculation method. The maximum radial field strength E_a of RIP bushing is 3.97kV/mm. The maximum axial field strength E_r is 0.56 kV/mm. The capacitance core with crepe paper was processed by the core winding machine, while the drying process and casting production process were the same as the actual resin-impregnated paper capacities bushing. The consistency of electric field, coaxial cylinder structure, RIP materials and processing technology were designed and adopted for a good-quality RIP bushing insulation as the valve side of converter transformer RIP bushings.

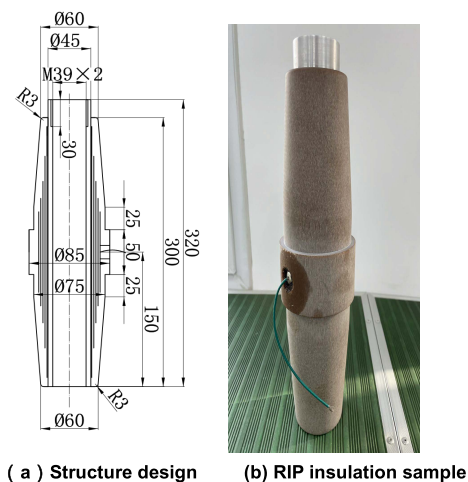


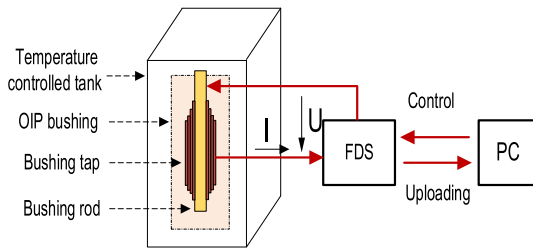
FIGURE 1. Structure design and sample of a RIP insulation bushing.

B. TEMPERATURE CONTROL FOR FDS MEASUREMENT

The connection diagram of FDS and polarization current measurement at controlled temperature is presented at figure2, which included mainly FDS device, temperature

TABLE 1. Structure size of resin-impregnated paper insulation.

Foil layers	Thickness (mm)	Upper bench (mm)	Bottom bench (mm)	Foil length (mm)	D (mm)
1	1	30	10	250	45
2	2.2	33	33	214	51.4
3	2.2	28	28	158	55.8
4	2.2	19	19	120	60.2
5	2.2	15	15	90	64.6



(a) Principle connection diagram

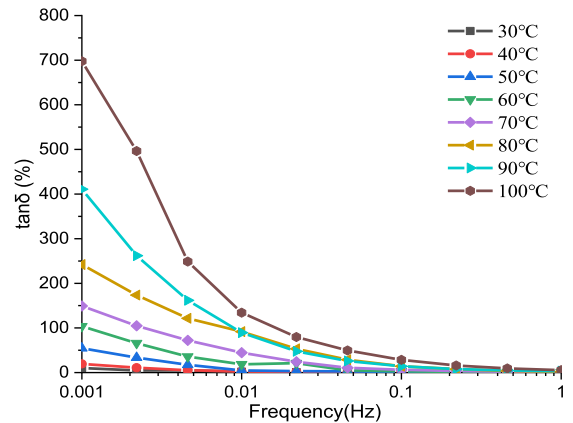


(b) Pictorial wiring diagram

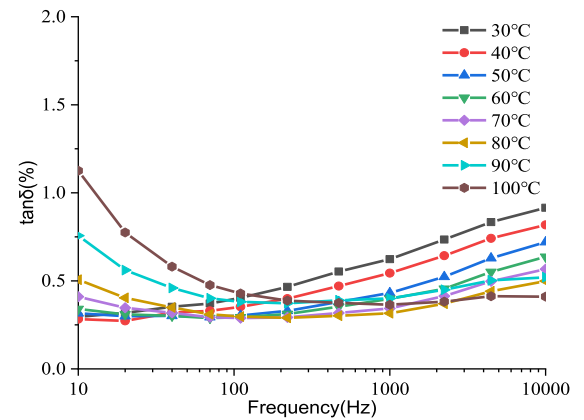
FIGURE 2. Connection diagram of FDS and polarization current measurement at controlled temperature.

controlled tank and assorted computer. In order to control precisely temperature on the risen-impregnated paper bushing, one precision temperature test oven chamber of WGL-65B with temperature resolution 0.1 °C was used as shown in figure 2(b). FDS and polarization current for the RIP bushing was adopted at the same time when the sample was applied to the setting temperature in oven chamber. The voltage peak value of 200V was applied for the FDS and polarization current measurement of main insulation between the bushing center rod and end-screen leading wire by the heat resisting insulated wire. The temperature was setting successively as 30°C, 40°C, 50°C, 60°C, 70 °C, 80 °C, 90 °C and 100 °C. The dissipation factor ($\tan\delta$) for the RIP sample was measured at the frequency from 0.001Hz to 10kHz at the setting temperature. Following closely, the polarization current at 0-1000s was detected at the same temperature as FDS.

The frequency domain dielectric spectroscopy test voltages of different frequencies were applied to the guide rod of



(a) Dissipation factor with temperatures at low frequency



(b) Dissipation factor with temperatures at mid-high frequency

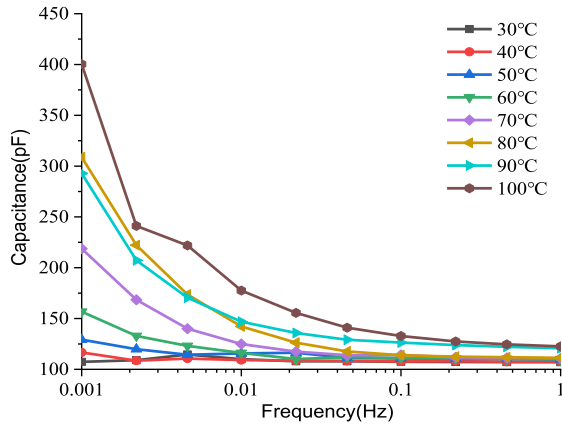
FIGURE 3. Dissipation factor–frequency relationship for a quality RIP insulation under different temperatures.

the bushing, while the response current could be obtained from the end screen of the bushing. The FDS information from 1mHz ~ 10kHz is obtained through the comparison and calculation of FDS device.

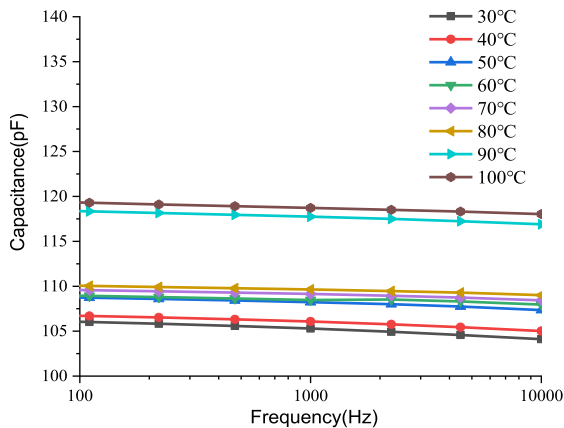
III. DISSIPATION FACTOR AND FREQUENCY RELATIONSHIP OF RIP INSULATION UNDER DIFFERENT TEMPERATURES

A. DISSIPATION FACTOR UNDER DIFFERENT TEMPERATURE

The dissipation factor from 0.001Hz to 10kHz is a key parameter for the diagnosis of moisture and aging insulation for converter transformer bushing. As shown in the Figure 3, under different temperatures (30°C ~ 100°C), the value of dissipation factor for a good-quality RIP insulation was incremental with the frequency from 1 Hz to 0.001Hz. The value of dissipation factor displayed closely the tendency of “U” curve with the frequency from 10Hz to 10kHz under the action of identical temperature (30°C ~ 100°C). As a result, the value of $\tan\delta$ at 0.001Hz was the maximum one at all measured frequency range (0.001Hz ~ 10kHz) under the same temperature 30°C ~ 100°C. The minimum value of $\tan\delta$ for a good-quality RIP insulation appeared at a special



(a) Capacitance-Frequency with temperatures at low frequency



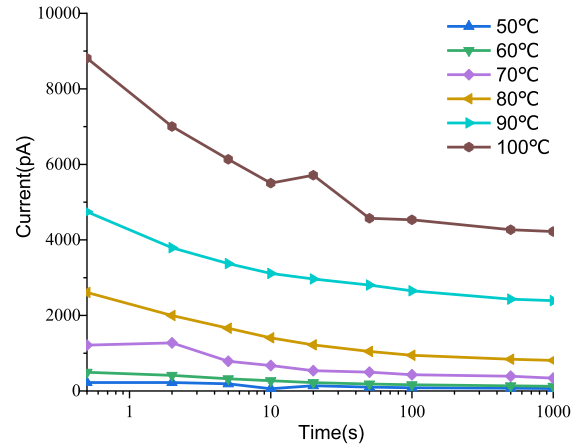
(b) Capacitance-Frequency with temperatures at high frequency

FIGURE 4. Complex capacitance–Frequency relationship of RIP insulation under different temperatures.

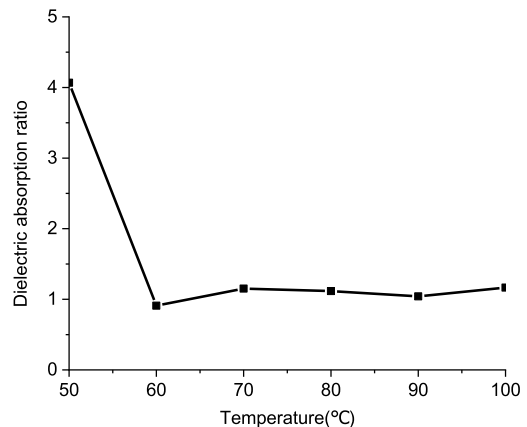
frequency point among the frequency from 10kHz to 0.001kHz, which changed with the temperature varied. The value of $\tan\delta$ for a good RIP would go up from the special point frequency to 10kHz under the same temperature 30°C ~ 100°C.

B. COMPLEX CAPACITANCE-FREQUENCY CHARACTERISTICS UNDER DIFFERENT TEMPERATURE

As presented in the Figure 4(a), under different temperatures (30°C ~ 100°C), the value of complex capacitance real part (complex capacitance) for a good-quality RIP insulation was incremental with the frequency from 1 Hz to 0.001Hz. The value of complex capacitance displayed closely linear downswing with the frequency from 10Hz to 10kHz under the action of identical temperature (30°C ~ 100°C), as exhibited in the Figure 4(b). As a result, the value of capacitance at 0.001Hz was the maximum one at all measured frequency range (0.001Hz ~ 10kHz) under the same temperature 30°C ~ 100°C. The minimum value of capacitance for a good-quality RIP insulation appeared at the maximum measured frequency 10kHz, where no changed with temperature varied. The value of capacitance for a good RIP would almost



(a) Polarization current



(b) Absorption ratio

FIGURE 5. Polarization current of RIP bushing under different temperature.

grow up at the frequency from 10kHz to 0.001kHz under the same temperature 30°C ~ 100°C.

C. POLARIZATION CURRENT CHARACTERISTIC UNDER DIFFERENT TEMPERATURE

As presented in the Figure 5(a), under different temperatures (50°C ~ 100°C), the value of polarization current (current) for a good-quality RIP insulation was closely exponential falling with the applied voltage time from 0 to 1000s. The value of current for a good-quality RIP insulation was 10pA with the applied voltage time 1000s under the temperatures 30°C ~ 40°C. The value of current was closely stable at 500s under the action of identical temperature (30°C ~ 100°C). As a result, the value of current at 500s was the maximum one at all measured frequency range (0.001Hz ~ 10kHz) under the same temperature 30°C ~ 100°C. The minimum value of current for a good-quality RIP insulation appeared at 1000s and stable at 500s with temperature varied. As presented in the Figure 5(b), the value of dielectric absorption ratio is in close proximity to one stable value under the temperature from 60°C to 100°C. The phenomenon of dielectric absorption ratio is non-significant for a well RIP bushing under high temperature.

IV. DISSIPATION FACTOR AND TEMPERATURE RELATIONSHIP OF RIP INSULATION UNDER DIFFERENT FREQUENCY

A. DISSIPATION FACTOR UNDER DIFFERENT TEMPERATURE

As presented in the Figure 6, test temperature of FDS for RIP insulation has different effects on the dissipation factor and capacitance curve at different frequency band (0.001Hz ~ 1Hz, 40Hz ~ 470Hz and 1kHz ~ 10kHz). The temperature of RIP model rises from room temperature 30°C to 100°C by the temperature controlled tank. The low-frequency tanδ (1mHz ~ 1Hz) of the RIP model shows an increasing trend, where the low-frequency tanδ of 1mHz increases from 10.1% to 697.6%. When the temperature rises from 30°C to 100°C, the dielectric loss tangent value in the frequency range of 40Hz, 70Hz, 110Hz, 220Hz, 470Hz all presents a U-shaped curve, which is neither linear nor exponential.

In the FDS diagnosis of oil-impregnated paper bushing in a certain temperature range, the dielectric response curve can be measured under different temperature conditions. The standard curve can be formed by curve shifting at different frequencies. However, the law of curve shifting for RIP bushing needs to revise anew by experimental evaluation.

As presented in the Figure 7(a), during the entire temperature rise process, the 1mHz low-frequency tanδ shows a good exponential growth trend. The fitting result of tanδ_{0.001Hz} is shown as Function 1.

$$\tan \delta_{0.001\text{Hz}} = 4.37 \exp(T/19.7) - 5 \quad (1)$$

The effect of temperature on 0.001Hz tanδ of RIP insulation closely conformed to the index law of Arrhenius equation. The effect of temperature on 0.001Hz dissipation factor could be eliminated by curve shifting based the index equation originated Arrhenius equation.

As presented in the Figure 7(b), when the temperature rises from 30°C to 100°C, the dissipation factor at higher frequency 1kHz ~ 10kHz for the bushing model shows a downward trend, while its value at 10kHz drops from 0.91% to 0.41%.

The effect of temperature on FDS curve is not amazingly consistent between the lower frequency(0.001Hz ~ 0.1Hz) and higher frequency (1kHz ~ 10kHz). At the action of higher frequency AC voltage, the contribution of particle movement on dielectric loss would be weakened by the combined action both temperature and AC electric field at higher frequency, which lead to the domain wall motion not following AC electric field at higher frequency.

Temperature is an important external factor that affects the dielectric response of risen-impregnated paper insulation. By studying the dielectric response of risen-impregnated paper insulation under different temperature conditions, the temperature dependent characteristics of different microscopic particle motions in the dielectric relaxation process can be obtained as presented from figure 7. Generally, the

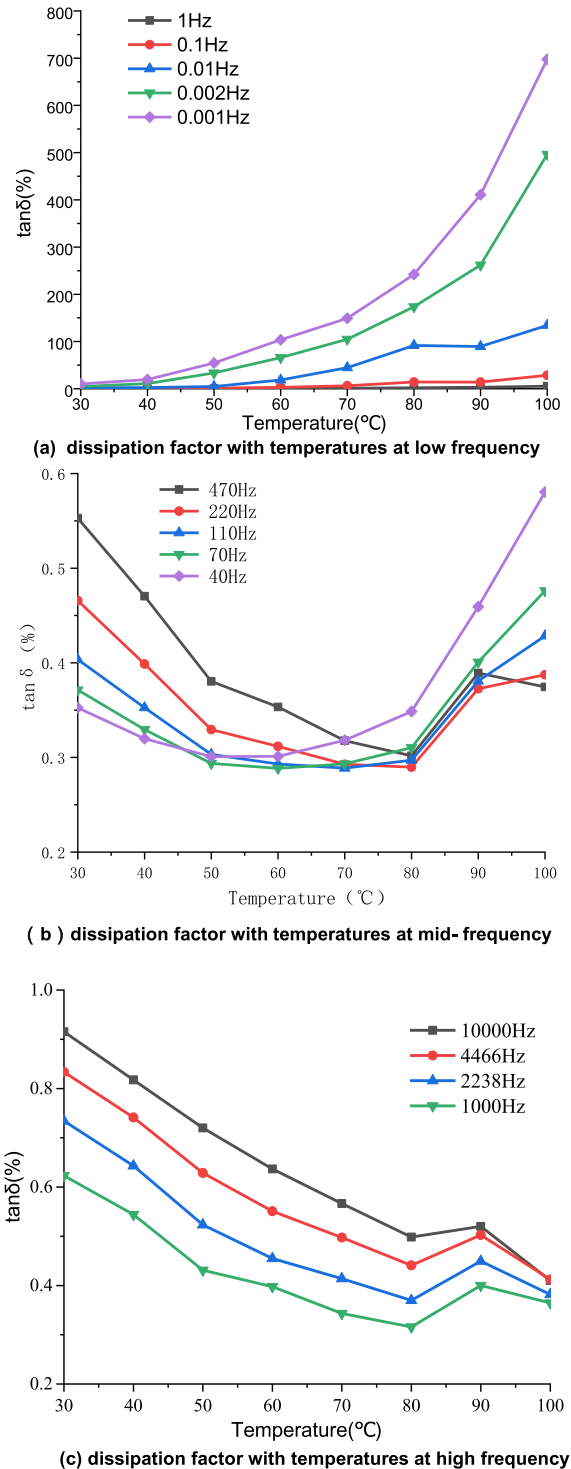


FIGURE 6. Dissipation factor –temperatures relationship of RIP insulation under different frequency.

function of curve shifting was different from the lower frequency 0.001Hz to 1Hz and higher frequency 1kHz to 10kHz. If only the tanδ curve was shifting by one function at all frequency, the obtained curve may be inaccurate. Temperature segment shifting of dissipation factor of converter transformer bushings can eliminate the effect of temperature so

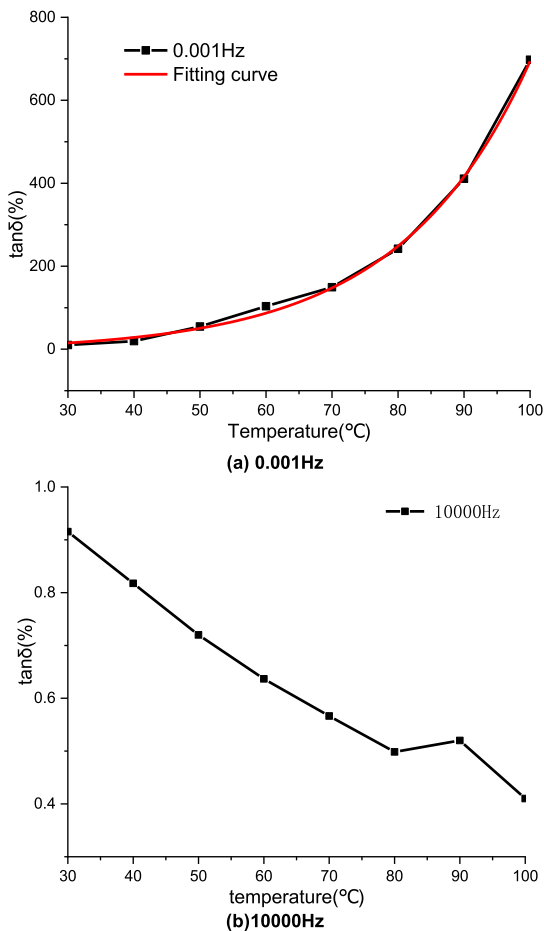


FIGURE 7. Fitting curve of high frequency and lower frequency $\tan\delta$.

that the result of FDS diagnosis only reflects on the condition of insulation aging or moisture content.

V. CONCLUSION

This paper describes an experimental method to eliminate the effect of temperature on frequency dielectric response and polarization current in converter transformer bushings. It provides a new design method of equivalent model for converter transformer bushings, based on maximum electric field and coaxial cylinder structure and RIP materials. The experiments of frequency domain response with temperatures verify that the difference laws that temperature for dissipation factor at lower frequency (0.001Hz \sim 1Hz) and higher frequency (1Hz \sim 10kHz). A temperature mathematical model of 0.001Hz $\tan\delta$ is presented for accuracy diagnosis of bushing based on Arrhenius equation.

1) The influence of lower frequency of the dissipation factors for drying RIP insulation is larger than its at mid-high frequency under 30°C \sim 100°C. Under the uniform temperature, the value of dissipation factor was rising with the frequency from 10 Hz to 0.001Hz, while the tendency was reversed at the frequency from 100Hz to 10kHz.

2) The minimum value of $\tan\delta$ appears at a wide range frequency from 10Hz to 10kHz, and its shifting from 10Hz to 10kHz with the temperature rising from 30°C to 100°C. The minimum value of $\tan\delta$ from 0.001Hz to 10kHz could be driven to higher frequency moving by the action of temperature rising.

3) The effect of temperature on the lower frequency 0.001Hz \sim 1Hz $\tan\delta$ of RIP insulation closely conformed to the index law of Arrhenius equation, while it was in accordance with the linear decrease at higher frequency 1kHz \sim 10kHz. The effect of temperature on dissipation factor could be eliminated by curve segment shifting based the experiment equation. The method is beneficial to eliminate the influence of temperature on the dielectric spectroscopy test results, and then to eliminate the influence of temperature on the dielectric spectroscopy diagnosis of RIP bushings.

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