Study of the Dielectric Properties of Condenser Material Used in SF6 Insulated RIP Bushing

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Abstract. All In the frequency range of $10^1$–$10^6$Hz and the temperature range of -100–200℃, the experimental dielectric spectrum of the condenser material used in UHVDC RIP bushing has been measured by Novocontrol broadband dielectric spectroscopy. The measured data has been fitted applied to nonlinear numerical calculation of the Havriliak-Negami (HN) equation, by which the characteristic parameters of HN mathematical model have been got. The studies show that the genetic algorithm combining with the least-square curve fitting method can ensure the uniqueness and accuracy of the fitting parameters. In the frequency range of $10^1$–$10^6$Hz and the temperature range of -40–60℃, $\beta$ relaxation process mainly takes place in the condenser material. In temperature range of 70–150℃, $\alpha$ and $\beta$ relaxation processes can be observed. In the temperature range of 160–200℃, the $\alpha$ relaxation and DC conduction processes are obvious. The DC conductivity and relaxation time have significant temperature dependence which can be fitted well with Arrhenius equation.

1. Introduction
At present, a large number of dry-type DC bushing have been used in the construction of UHVDC transmission lines in China. Its operation status directly determines the safety and the stability of transmission lines [1]. Therefore, it is of great significance to monitor and evaluate the performance of dry-type bushing in actual operation. The most commonly used nondestructive monitoring method for dry bushing is the dielectric spectrum measurement, which mainly depends on the accurate measurement of dielectric properties of epoxy impregnated paper composites for dry bushing cores, and the post-processing of the measured results to extract the characteristic parameters characterizing the properties of materials.

The breakdown characteristics and space charge distribution of epoxy/crepe paper composites were studied in literature [2]. The space charge distribution characteristics of the pure epoxy near glass transition temperature $T_g$ were analyzed in literature [3]. However, few literatures specifically measured and fitted the dielectric properties of epoxy impregnated paper for UHVDC dry bushing cores. Based on this, samples of epoxy impregnated paper composite for dry bushing were prepared and observed by polarization and scanning electron microscopy. It was found that there were obvious interfaces between the epoxy resin and the wrinkle paper, which could cause the polarization effect of Maxwell-Wagner interface and lead to the complexity of dielectric properties of sub-composites [4]. The glass transition temperature ($T_g$) of core composites was obtained by DSC measurement, which can provide the basis for determining the test temperature range in subsequent dielectric spectroscopy measurements. At the same time, non-linear numerical fitting method combining genetic algorithm and least squares is proposed. The approximate values of fitting parameters are obtained by genetic
algorithm, and then the fitting parameters are solved accurately by least squares method. This method can ensure the uniqueness and accuracy of fitting parameters. Furthermore, the frequency spectrum and the temperature spectrum characteristics of the core material were measured by Novocontrol broadband dielectric spectrometer in the range of $10^{-1}$-10$^6$ Hz and -100-200$^\circ$C. The results show that in the frequency range of $10^{-1}$-10$^6$ Hz, the relaxation process is the main one in the temperature range of -40-60$^\circ$C, and the relaxation process is also found in the temperature range of 70-150$^\circ$C. The relaxation and the DC conductivity processes are remarkable in the temperature range of 160-200$^\circ$C. Based on improved Havriliak-Negami (HN) equation and the non-linear numerical calculation, the measured data are fitted to obtain characteristic parameters of the dielectric spectrum mathematical model. The results show that both the DC conductivity and the relaxation polarization time have remarkable temperature dependence, which conform to the Arrhenius formula. In the laboratory environment, the dielectric spectrum fitting method of UHV dry DC bushing core material is studied and its characteristic parameters are obtained, which provides the effective method for understanding the dielectric properties of dry bushing core, and can guide the condition monitoring and performance evaluation of dry bushing in actual operation[5-7].

### 2. Formatting Modified HN Model and Characteristic Parameters

The complex permittivity of the epoxy impregnated paper composites under Havriliak-Negami (HN) model function can be expressed as formula (1):

$$\varepsilon^\ast_{HN}(\omega) = \varepsilon_\infty + \frac{\Delta \varepsilon}{(1 + i\omega\tau_{HN})^\beta}$$  \hspace{1cm} (1)

Formula (1) $\varepsilon_\infty$ is the optical frequency relative permittivity $\Delta \varepsilon = \varepsilon_s - \varepsilon_\infty$, and $\varepsilon_s$ is the static relative permittivity, $\tau_{HN}$ is the relaxation polarization time under HN model, and $\beta, \gamma$ is the distribution parameter of the relaxation time. In addition, $\varepsilon^\ast_{HN}$ and $\varepsilon^\ast_s$, the real part and the imaginary part of the complex permittivity [8]:

$$\varepsilon^\ast_{HN} = r(\omega)\cos[\gamma\psi(\omega)]\Delta \varepsilon + \varepsilon_\infty \hspace{1cm} (2)$$

$$\varepsilon^\ast_s = r(\omega)\sin[\gamma\psi(\omega)]\Delta \varepsilon \hspace{1cm} (3)$$

Among them:

$$r(\omega) = [1 + 2(\omega\tau_{HN})^\beta \cos(\beta\pi/2) + (\omega\tau_{HN})^{2\beta}]^{-\gamma/2} \hspace{1cm} (4)$$

$$\psi(\omega) = \arctan\{\sin(\beta\pi/2)/[(\omega\tau_{HN})^{\beta} + \cos(\beta\pi/2)]\} \hspace{1cm} (5)$$

Therefore, there are five characteristic parameters in single HN model function $\varepsilon_\infty, \Delta \varepsilon, \tau_{HN}, \beta, \gamma$. Based on the experimental data of broadband dielectric spectroscopy, the specific values of the above five characteristic parameters can be fitted, and the frequency point $\omega_p$ of the peak value $\varepsilon^\ast_{HN}$ can be calculated by formula (6):

$$\omega_p = (1/\tau_{HN})[\sin((\beta\pi)/(2+2\gamma))]^{1/\beta}[\sin((\beta\gamma\pi)/(2+2\gamma))]^{-1/\beta} \hspace{1cm} (6)$$

When the testing temperature is lower than the glass transition temperature $T_g$ of the dry bushing core material, the dielectric properties of the material can be generally characterized by (1) ~ (6) formula. When the testing temperature is higher than $T_g$, the DC conductivity process of the material is remarkable, and the formula (7) should be introduced into the formula (3):

$$\varepsilon^\ast = \sigma_0/(2\pi f \varepsilon_\infty) \hspace{1cm} (7)$$

Among them, the characteristic parameters of DC conductivity are vacuum dielectric constant and $f$ is test frequency. For the DC dry bushing core composites, the HN model mentioned above needs to be further revised to (8)~(9) form due to combined effect of electrode polarization and Maxwell-Wagner interface polarization at temperatures higher than $T_g$.

$$\varepsilon^\ast = r(\omega)\cos[\gamma\psi(\omega)]\Delta \varepsilon + \varepsilon_\infty + A\omega^{-n} \hspace{1cm} (8)$$

$$\varepsilon^\ast = r(\omega)\sin[\gamma\psi(\omega)]\Delta \varepsilon + \sigma_0 f(ie_\infty/\omega^\ast) \hspace{1cm} (9)$$
A. N and s are the characteristic parameters to characterize the high temperature polarization process. For composites with complex dielectric properties, the polynomial HN equation can be introduced to characterize several independent relaxation polarization processes. As shown in Formula (10):

$$\varepsilon_{HN}^*(\omega) = \varepsilon_n + \sum_{i=1}^{m} \frac{\Delta \varepsilon_i}{(1 + (i\omega \tau_{HN_i})^{\beta_i})^{\gamma_i}} + \frac{\sigma_0}{i\varepsilon_0 \omega^s}$$

(10)

These two relaxation processes are commonly referred to as relaxations. The relaxation time constants and distribution parameters of two processes are sum, respectively. Formula (11) can be transformed to obtain the real and imaginary expressions of the dielectric polarizability, taking into account that:

$$(i)^a = (e^{i\pi/2})^a = \cos((\alpha \pi)/2) + i \sin((\alpha \pi)/2)$$

(11)

Substitute the above formula to get:

$$\chi^*(\omega) = \left[\varepsilon_n + \frac{\chi_i[1 + (\omega \tau)^n \cos \frac{n\pi}{2}]}{1 + 2(\omega \tau)^n \cos \frac{n\pi}{2} + (\omega \tau)^{2n}} + \frac{\xi \cos \frac{\gamma \pi}{2}}{\varepsilon_0 \omega^s} \right]$$

(12)

Within the test range of $10^{-4}$-$10^4$Hz, the dielectric response characteristics of pure epoxy and epoxy impregnated paper can usually be described by the modified Cole-Cole model with the single or two relaxation processes. If the single relaxation process is used, the seven parameters of $P_1$-$P_7$ can be obtained. For the model of double relaxation time constant, 10 parameters of $P_1$-$P_{10}$ can be obtained, of which $P_8$-$P_{10}$ represents the relaxation process.

3. Test Results and Analysis

Figure 1 (a) is microscopic observation result of wrinkle paper in bushing core. Cellulose is evenly distributed in the same direction, and coarse cellulose and fine cellulose are alternately arranged in wrinkle paper. Figure 1 (b) shows that for epoxy impregnated paper composites, wrinkle paper is tightly adhered to pure epoxy, and the structure can ensure mechanical toughness of dry bushing core.

![Figure 1 Micro-structure of specimen](image)

(a) Crepe paper (b) Section

The electrodes used in the breakdown test are copper, and the surface of the electrodes is polished. The thickness of the prepared sample includes 0.25mm, 1.08mm and 2.69mm. The step-up speed in the breakdown test is 4kV.s$^{-1}$. The test results are shown in Figure 2. The breakdown test data are processed and analyzed by the Wei-bull distribution function with two parameters [8]. According to Wei-bull probability and statistics theory, the breakdown probability of the epoxy impregnated paper under electric field $E$ is as follows:
In the formula $E$, the breakdown field strength/$kV.mm^{-1}$, breakdown field strength when breakdown probability is 63.2%, i.e. the scale parameter/$kV.mm^{-1}$, and the shape parameter are used.

$$F(E; \alpha, \beta) = 1 - \exp\left\{-\left(\frac{E}{\alpha}\right)^\beta\right\} = 0.632 \quad (13)$$

In the formula $E$, the breakdown field strength/$kV.mm^{-1}$, breakdown field strength when breakdown probability is 63.2%, i.e. the scale parameter/$kV.mm^{-1}$, and the shape parameter are used.

Figure 2 Relationship between breakdown field strength and thickness of the sample
Using the laser thermal conductivity analyzer and the thermal expansion analyzer to measure thermal performance parameters of epoxy impregnated paper materials for failure bushing is shown in Figure 3.

(a) The Relation between Thermal Conductivity and Thermal Capacity with Temperature
(b) Thermal Expansion Curve of Epoxy Immersed Paper Material

Figure 3 (a) shows that thermal conductivity of epoxy impregnated paper material is about $0.463W/(m \cdot ^\circ C)$ at room temperature of $25^\circ C$. The orderly arrangement of cellulose in wrinkle paper is beneficial to the heat flux transmission. The thermal conductivity of epoxy impregnated paper material increases first and then decreases in the temperature range of 25-150$^\circ C$, and the maximum value appears near 125$^\circ C$. This indicates that the temperature of the converter bushing core should be
controlled in the range of 25-125°C in actual operation. At this time, the thermal conductivity of the material has the "negative feedback" effect. With the slight increase in degree, the thermal conductivity increases, the thermal conductivity of material increases, and the temperature decreases. If the operating temperature of material exceeds 125°C, the heat inside the core is difficult to derive effectively due to the decrease of thermal conductivity, which is not conducive to the safe operation of the bushing. The thermal capacity of epoxy impregnated paper materials is kept between 1.5 and 2.5 J/(g°C) in the temperature range of 25-150°C. Figure 3 (b) shows that thermal expansion coefficient of epoxy impregnated paper increases slowly in the temperature range of 30-150°C, then increases abruptly. The inflection point of this change is near 130°C, which indicates that the cellulose structure of corrugated paper inside the epoxy impregnated paper material has the buffer effect on the thermal stress. In actual operation, the deformation of the core caused by thermal stress is relatively small in the temperature range of 30-120°C. If the temperature exceeds 130°C, the insulation defects such as cracking of epoxy impregnated paper material will occur in the core due to the long-term effect of thermal stress.

Routine test of bushing core is usually carried out at room temperature (20°C). For the actual bushing operation, the hottest temperature inside the core is about 90°C. To illustrate the change of dielectric properties of the insulating material of bushing core at 150°C, the dielectric spectrum test results in frequency domain at 20°C, 90°C and 150°C are listed as shown in Figure 4.

![Image](a) Real Frequency Domain Dielectric Spectra of Dielectric Constants

![Image](b) Imaginary part frequency domain dielectric spectroscopy of dielectric constant

Figure 4 shows that the dielectric spectrum in frequency domain varies significantly with temperature. The real part of dielectric constant decreases with the increase of frequency \( f \) at 20°C and 90°C. The reason is that the real part of dielectric constant of main insulating material of SF6 gas insulating bushing can be expressed as follows:
It can be seen from formula (15) that displacement polarization and relaxation polarization can be established in low frequency region (1), so the real part of dielectric constant tends to be equal. The real part of the number shows the decreasing trend. For the epoxy sample, the sum value decreases first and then increases with the increase of frequency, because the tangent value of loss angle can be expressed as follows:

\[
\tan \delta = \left[ \frac{1}{\omega \varepsilon_0} + (\varepsilon_r - \varepsilon_\infty) \frac{\omega \tau}{1 + \omega^2 \tau^2} \right] \left( \frac{1}{\omega \varepsilon_0} + (\varepsilon_r - \varepsilon_\infty) \frac{\omega \tau}{1 + \omega^2 \tau^2} \right) \tag{15}
\]

The formula is dielectric conductivity, relaxation polarization time constant, static dielectric constant and optical frequency dielectric constant. It can be seen from formula (16) that with the increase of the frequency of alternating electric field, the polarization lag electric field changes, and the relaxation polarization can not be fully established, so the loss caused within the week decreases, making the sum value of the epoxy insulation sample decrease with increase of the frequency. In the high frequency region, the relaxation polarization is also less than that. The sum value increases with the increase of frequency because of the increase of the number of cycles per-second, which increases the dielectric loss. It can also be seen from Figure 4 that the values of each parameter are higher than those of the other two temperatures at 150°C, and the imaginary part of dielectric constant and the tangent value of loss angle increase sharply at low frequencies (<1Hz). The main reasons for this phenomenon are as follows: (1) glass transition of epoxy resin has exceeded that of epoxy resin at 150°C. At temperature \( T_g \), the dielectric is in the high elastic state, the polar groups and chains in macro-molecules can be oriented along electric field direction, and the dipole polarizes in the high elastic state, so the dielectric constant and the tangent value of the loss angle increase significantly; (2) the dielectric conductivity increases significantly at high temperature, and the Formula(15) shows that the term will be in the low frequency condition.

4. Temperature Translation Characteristics

The frequency dependence of dielectric spectra of epoxy impregnated paper composites was fitted at the specific temperature. At the same time, temperature is closely related to the dielectric spectra: the dielectric spectra of materials have characteristics of temperature translation during the continuous change of temperature. The dielectric spectrum data at five temperatures are fitted and plotted in Figure 5 with temperature range of 160 ~200°C as an example and the temperature interval of 10°C. At high temperatures and low frequencies, the real part of dielectric constant shows an upward trend, which can not be fitted with theoretical curve, mainly due to existence of electrode polarization. All of them exhibit the characteristics of temperature translation, that is they tend to move to high frequency region. At the same time, with the increase of temperature, the conductivity polarization intensifies and the loss peak of polarization moves to the high frequency region. The main reason is that the relaxation time is approximately exponential to the temperature \( T \). With the increase of \( T \), the characteristic frequency \( f_c \) moves to high frequency direction. Temperature translation characteristics of Cole-Cole diagram are shown in Figure 5. It can be seen that if the temperature is further increased, the relaxation time is very small and polarization is established quickly, the relaxation polarization loss can be kept up with the change of electric field, so that the relaxation polarization loss is small and negligible, and conductivity loss increases rapidly with the increase of temperature.
Temperature dependence of dielectric spectra of epoxy impregnated paper composites was analyzed. The temperature spectra of the epoxy impregnated paper composites were plotted in Figure 6 at the frequency of 50 Hz in the temperature range of -10 ~200°C. The figure shows that the real part of the dielectric constant is basically unchanged in the temperature range of -100~130°C. It rises sharply after 130°C, and the peak D appears near 188 ℃. The imaginary part has two peaks A and B in the temperature range of -100 to 200°C, near -25℃ and 170℃, respectively, and the lowest value C near 110℃. The reason why the peak B of imaginary part lags behind the peak D of real part is that although the polarization is established rapidly in high temperature region, it does not mean that the polarization has been fully established. Only when the temperature rises to make the polarization fully established can the maximum be reached.

5. Summary
In this paper, the spectrum and temperature spectrum curves of UHVDC dry bushing core material are measured and fitted. The conclusions are as follows:
(1) The uniqueness and accuracy of the fitting parameters can be guaranteed by the genetic algorithm combined with least squares curve fitting method, and the binomial Havriliak-Negami (HN) equation with 11 parameters can be well fitted.

(2) The measured data are fitted by the improved HN equation. The measured and fitted data are in good agreement with each other at 20℃ and 170℃. From the low temperature to high temperature, the polarization peaks appear in turn, and after 160℃, the remarkable process of DC conductivity polarization is observed.

(3) The dielectric spectra of the core material are strongly dependent on frequency and temperature, and obvious temperature translation characteristics are found in the high temperature range of 160~200℃. Meanwhile, the DC conductivity and relaxation polarization time of the core material have significant temperature dependence, which basically conform to Arrhenius formula.

(4) The dielectric properties of single sample of the bushing core material are studied in this paper. The next step is to measure the spectrum and temperature spectrum curve of the actual bushing core, summarize difference and relationship between the two, and apply the conclusion to the evaluation and monitoring of the insulation state of the dry bushing.

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