Application of Frequency Domain Dielectric Response Method in Intelligent Location of Oil Paper Insulation Bushing Damp Fault

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Abstract—Oil paper insulating bushing is widely used in 500 kV and above power transformers. In order to quantitatively study the influence of water content on the dielectric spectrum of oil paper insulated bushing, HN model was used to fit and analyze the dielectric spectrum parameters of oil paper insulated bushing with different water content. The experimental results show that HN model can be used to evaluate the wettability of oil paper insulation, but the evaluation range of wettability of oil paper bushing with complex insulation structure is not clear. The results show that the relaxation time constant decreases with the increase of water content, and has a linear relationship with the change of water content; the difference between high frequency dielectric constant and static dielectric constant increases with the increase of water content.

1. Introduction

Oil immersed bushing is an important accessory equipment of large transformer, and it is also the weakness of transformer insulation system. The long-term damp of oil immersed bushing will lead to serious fault of transformer, which will lead to serious accident of power system. The frequency domain analysis method of dielectric spectrum is used to study the dielectric spectrum of casing after being damped. The method can sensitively reflect the characteristic quantity of dielectric spectrum of the change of bushing's damp state, and evaluate the water content. According to the actual work and field operation of bushing with different voltage levels in power grid substation, the damping state of bushing is calculated and compared through software testing and verification. The evaluation results are basically consistent with the actual working conditions, which can be used as a reference for field evaluation.

2. Intelligent location of oil paper insulation sleeve damp fault

2.1. Construction of Havriliak-Negami model

The dielectric relaxation process is generally analyzed by model functions. The commonly used model functions include Debye equation, Kohl equation, Davidson Cole equation and havrlick nagmi equation, which can be combined to explain the dielectric relaxation process of polymer system. The relaxation process is calculated as follows:

$$\varepsilon^*(\omega) = \varepsilon_\infty + \frac{\varepsilon_0 - \varepsilon_\infty}{1 + (i\omega\tau)^\alpha}$$

(1)
\[ \varepsilon^*(\omega) = \varepsilon_\infty + \frac{\varepsilon_\infty - \varepsilon_s}{(1 + \omega \tau)^\beta} \]  

(2)

Where: \(0 \leq \alpha \leq 1\), \(0 \leq \beta \leq 1\), \(\alpha\) and \(\beta\) parameters related to the relaxation time distribution are expressed respectively; \(\omega\) represents the angular frequency of external electric field; \(\tau\) represents the relaxation time constant; \(\varepsilon_\infty\) represents the high frequency dielectric constant; \(\varepsilon_s\) is the static dielectric constant. The Havriliak-Negami model can be obtained by combining the above formula as follows:

\[ \varepsilon^*(\omega) = \varepsilon_\infty + \frac{\varepsilon_\infty - \varepsilon_s}{(1 + \omega \tau)^\beta} \]  

(3)

According to these changes, the real and imaginary parts of the complex relative permittivity \(\varepsilon^*(\omega)\) can be obtained as follows:

\[ \varepsilon' = \varepsilon_\infty + \frac{(\varepsilon_\infty - \varepsilon_s) \cos(\beta \theta)}{(1 + 2(\omega \tau)^{\alpha} \cos(\alpha \pi / 2) + (\omega \tau)^{2\alpha})^{\beta/2}} \]  

(4)

\[ \varepsilon'' = \frac{(\varepsilon_\infty - \varepsilon_s) \sin(-\beta \theta)}{(1 + 2(\omega \tau)^{\alpha} \cos(\alpha \pi / 2) + (\omega \tau)^{2\alpha})^{\beta/2}} \]  

(5)

Among them:

\[ \theta = \arctan \left( \frac{(\omega \tau)^{\alpha} \sin(\alpha \pi / 2)}{1 + (\omega \tau)^{\alpha} \cos(\alpha \pi / 2)} \right) \]  

(6)

By further combining FDS measurement technology, the traditional power frequency dielectric loss and capacitance measurement methods can be extended to low frequency and high frequency (e.g. from 0.1 mhz – 1 khz). The polarization and loss are reflected in a wider frequency domain. According to the formula, the complex capacitance \(C^*(\omega)\) of the dielectric is defined as \(Z(\omega)\), which represents the input impedance of the dielectric. The real capacitance and virtual capacitance of the complex capacitor are defined as \(C(\omega)\) and \(C''(\omega)\) respectively. \(\varepsilon'(\omega)\) is the complex permittivity \(\varepsilon^*(\omega)\) and imaginary part; \(A\) and \(w\) represent the distance and area of the test electrode, respectively. In the calculation formula \(Z(\omega)\) and \(C^*(\omega)\) is usually applied to the specimen by measuring voltage and current. The algorithm is as follows:

\[ Z(\omega) = \frac{1}{\omega C^*(\omega)} \]  

(7)

\[ C^*(\omega) = C'(\omega) - C''(\omega) = \frac{A}{w} \times \varepsilon^*(\omega) \]  

(8)

\[ \varepsilon^*(\omega) = C^*(\omega) - \varepsilon'(\omega) \]  

(9)

The imaginary and real parts of complex permittivity are defined as follows:

\[ \tan \delta(\omega) = \frac{\dot{C}'(\omega)}{\dot{C}'(\omega)} = \frac{\varepsilon''(\omega)}{\varepsilon'(\omega)} \]  

(10)

The model construction based on the above algorithm can better realize the accurate calculation of the abnormal value of high-quality insulation tubes affected by moisture, so as to locate.

2.2. Realization of intelligent location of oil paper insulation bushing damp fault

The dielectric response theory of oil paper insulation is also applicable to oil immersed power equipment, but the proportion of oil paper insulation in oil paper insulation is special and belongs to light oil equipment[1]. Compared with the oil immersed transformer and other power equipment, the main
The insulation of the shell has no support rod and oil gap, and its insulation structure is more clear, which can quantitatively evaluate the moisture performance of the shell[2]. The physical characteristics of insulator determine that its internal polarization in alternating electric field is difficult to respond to the change of electric field. From the polarization intensity $P(t)$ and field strength $E(t)$ determines the magnetic field density generated at both ends of the medium $D(t)$:

$$D(t) = \varepsilon_0 E(t) + P(t)$$  \hspace{2cm} (11)

Where $\varepsilon_0$ is the vacuum dielectric constant, the value range is $8.50 - 8.70$ SpF/m. Due to the different composition and structural characteristics of the medium, the polarization forms are different under the action of external electric field. Oil paper insulation has the following five polarization mechanisms, and their characteristics are shown in the table.

Dielectric polarization $P_n(t)$ can be expressed by the sum of instantaneous polarization, such as electron displacement, ion displacement $E$, the sum of polarization of bipolar rotation polarization and thermal ion relaxation polarization[3], while instantaneous polarization and relaxation polarization can be expressed by formula respectively.

$$P_n(t) = \varepsilon_0 (\varepsilon_r - 1) E(t)$$  \hspace{2cm} (12)

Therefore, $P(t)$ and $D(t)$ can be expressed as

$$P(t) = \varepsilon_0 (\varepsilon_r - 1) E(t) + \varepsilon_0 E_0 \int_0^t f(\tau) E(t-\tau) d\tau$$  \hspace{2cm} (13)

$$D(t) = \varepsilon_0 E_0 \left[ \left( \varepsilon_r - 1 \right) + 1 + \int_0^t f(\tau) d\tau \right]$$  \hspace{2cm} (14)

In view of the complexity of calculation and the anti-interference of the test, the dielectric response function is adopted $f(t)$ and external electric field $E(t)$ convolution method of a transforms the time domain signal into the frequency domain signal[4]. The Fourier transform of dielectric response function is as follows:

$$F[f(t)] = \chi(\omega) = \chi'(\omega) - \chi''(\omega) = \int_{-\infty}^{\infty} f(t) \exp(-j\omega t) dt$$  \hspace{2cm} (15)

The polarization coefficient is a complex function of polarization amplitude and phase of medium in AC electric field. The $\chi''(\omega)$ of the real part of the polarization coefficient is the polarization amplitude, and the $\chi'(\omega)$ of the imaginary part of the polarization coefficient is the hysteresis of the field phase by 90°. The polarization coefficient values are as follows:

$$\chi'(\omega) = \int_0^\infty f(t) \cos(\omega t) dt$$  \hspace{2cm} (16)

$$\chi''(\omega) = \int_0^\infty f(t) \sin(\omega t) dt$$  \hspace{2cm} (17)

There are:

$$F\left[ \int_{-\infty}^\infty f(\tau) E(t-\tau) d\tau \right] = \int_{-\infty}^\infty \exp(-j\omega t) \int_{-\infty}^\infty f(\tau) E(t-\tau) d\tau dt$$

$$= \int_{-\infty}^\infty f(\tau) \exp(-j\omega t) \left[ \int_{-\infty}^{\infty} \exp[-j\omega(t-\tau)] E(t-\tau) d\tau \right] dt$$

$$= \int_{-\infty}^\infty f(\tau) \exp(-j\omega t) \left[ \int_{-\infty}^{\infty} \exp[-j\omega(s)] E(s) ds \right] dt$$

$$= \int_{-\infty}^\infty f(\tau) \exp(-j\omega t) dt \left[ \int_{-\infty}^{\infty} \exp(-j\omega s) E(s) ds \right]$$

$$= \chi(\omega) E(\omega) = \left[ \chi'(\omega) - \chi''(\omega) \right] E(\omega)$$
The total current density of the medium consists of conduction current density and displacement current density. At this time, the alternating electric field makes the free charge move in one direction, thus producing conduction current, thus determining the displacement current.[5-7]

\[ J(t) = \sigma_0 E(t) + \frac{\partial D(t)}{\partial t} \] (19)

Further conversion of the above formula can be obtained as follows:

\[ J(\omega) = \sigma_0 \omega E(\omega) + \omega D(\omega) \] (20)

By substituting the above formula with Fourier transform, we can get the following results:

\[ J(\omega) = \left\{ \sigma_0 + \omega \varepsilon_0 \left[ \varepsilon_\prime(\omega) - 1 + \varepsilon_\prime(\omega) - \varepsilon_\prime(\omega) \right] \right\} E(\omega) \]

\[ = \omega \varepsilon_0 \left\{ 1 + \varepsilon_\prime(\omega) - \left[ \frac{\sigma_0}{\varepsilon_0 \omega} + \varepsilon_\prime(\omega) \right] \right\} E(\omega) \]

\[ = \omega \varepsilon_0 \left\{ \varepsilon_\prime(\omega) - \varepsilon_\prime(\omega) \right\} E(\omega) \] (21)

Where \( \varepsilon_\prime(\omega), \varepsilon_\prime(\omega) \) is the real and imaginary part of the complex permittivity. The real part represents the compatibility part of the total current, the imaginary part represents the dielectric constant of the medium, the imaginary part represents the resistance part, the imaginary part represents the total current, and the imaginary part represents the dielectric loss \( \sigma_0 \).

Based on the above steps, the real-time detection of oil paper insulation bushing damp fault can achieve more accurate and rapid fault intelligent location and ensure the accuracy of positioning.

3. Analysis of experimental results

Dry method and vacuum oil immersion method refer to 40.5 kV casing method, The casing type has good electrical performance. After the paper is cut off, the core is formed. By controlling the drying time and humidification method, five kinds of paper rolls with different moisture content are obtained. Finally, the shell model with different water content was obtained by rolling, assembling the mandrel and vacuum impregnating according to the design size. The frequency of the dielectric spectrum is measured by the idax300 frequency domain dielectric spectrum system of megaohm company. It is found that the peak value of its output current is 0~50 mA, the output voltage is at 0~200 V, the frequency range is 0.1 MHz~10 KHz. Capacitance test range: 10pF~100uF, measurement error: 0.5%+1pF. Dielectric loss measurement error:

\(<0.5\%+0.0001; 45~70Hz, C>100pF; <0.5\%+0.0002; 45~70Hz, C>300pF\)

Using idax300 frequency domain dielectric spectrum system, the frequency domain dielectric spectra of five different water content casing models were tested, and the frequency domain dielectric spectrum characteristics of different water content casing were analyzed, and the test data were fitted with HN model. The peak voltage of dielectric spectrum obtained by this method is 200 V, and the test frequency is shown as Fig.1.

![Figure 1 experimental test frequency](image)
The FDS characteristics of casing samples with different water content were analyzed by idax300 frequency domain dielectric spectroscopy. The capacitance data of average water content of five FDS type casings is shown as Fig.2.

![Figure 2 real part of complex capacitor](image)

The results show that with the increase of the average water content in the casing, \( 1 \text{mHz} \sim 10 \text{kHz} \). In the frequency range, the real part of the complex capacitor shows an obvious upward trend. The composite capacitance is expressed as follows:

\[
C'' = C_0 \left[ \varepsilon'(\omega) - \varepsilon''(\omega) \right] = C'(\omega) - C''(\omega)
\]  

(22)

Among them, \( C_0 \) is the geometric capacitance of the medium in vacuum. Coefficient of difference between complex permittivity and complex permittivity \( C_0 \). It is found that the dielectric response characteristic reflected by the complex capacitance energy is basically consistent with that of the complex capacitance energy. Then, the measured data of complex capacitance are fitted directly with HN model. The test data is fitted by the formula on the graph, the test value is represented by the discrete symbols in the graph, the continuous curve is fitted by the graph expression, and the numerical method is the nonlinear least square method. The objectives are:

\[
\min \sum_{i=1}^{n} \left[ (C'(\omega) - C''(\omega))^2 \right]
\]  

(23)

The parameters of HN model is shown as Table 5:

| Water Content | \( \tau \) |
|---------------|------------|
| 9.5%          | 2649.18\( \times 10^{-0.33M} \) |
| 4.5%          | 2649.18\( \times 10^{-0.33M} \) |
| 3.1%          | 2649.18\( \times 10^{-0.33M} \) |
| 1.4%          | 2649.18\( \times 10^{-0.33M} \) |
| 0.7%          | 2649.18\( \times 10^{-0.33M} \) |

The experimental results show that the high frequency dielectric constant \( \varepsilon_\infty \) increases slightly with the increase of M. The dielectric constant at high frequency is different from that at static state \( \varepsilon_S - \varepsilon_\infty \), \( \varepsilon_S - \varepsilon_\infty \) increased with the increase of water content. Shape parameter \( \alpha \), \( \beta \) was no obvious change with M. With the increase of the average water content of the bushing, the real part of the complex capacitor increases obviously in the frequency range of \( 1 \text{MHz} \sim 10 \text{kHz} \). The dielectric spectrum of oil paper insulating bushing with different moisture content was fitted by HN model to verify the research on dielectric spectrum of oil paper insulating sleeve by HN model. Relaxation time constant \( \tau \) The water content \( m \) decreases with the increase of water content \( m \), and satisfies the logarithmic linear relationship \( \varepsilon_\infty \) With the increase of M, the difference between high frequency and static permittivity increases slightly \( \varepsilon_S - \varepsilon_\infty \) The water content increases with the increase of water content. Shape parameters \( \alpha \), \( \beta \) was no obvious change with M.

4. Conclusion

In order to improve the accuracy and diagnosis method of bushing insulation moisture, the composition and structure of bushing defect products were analyzed, and the dielectric spectrum characteristics of bushing model wax were extracted. The research results can provide theoretical and experimental basis
for casing equipment manufacturing and operation diagnosis, and have important scientific significance and engineering application value to ensure the stable operation of power grid and make it become a reliable power system.

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