Research and Field Application of Oil-paper Insulation Material Aging State Based on FDS

LI Dandan¹, FAN Yongqiang², WANG Yaping², YUE Yonggang*², RENG Ming³

¹Training Center of Inner Mongolia power (Group) Co., Ltd., Hohhot 010080, China
²Inner Mongolia EHV Power Supply Bureau, Hohhot, Inner Mongolia, 010080, China
³State Key Laboratory of Electrical Insulation and Power Equipment, Xi’an Jiaotong University, Xi’an, Shaanxi, 710049, China

*Corresponding author’s e-mail: hvyue@163.com

Abstract: The effects of three factors, such as aging degree, water content and temperature, on the dielectric response characteristics of oil-paper insulating materials were studied by setting up a frequency-domain dielectric response experimental platform. In this paper, the frequency domain dielectric spectrum (FDS) test is carried out for the on-site transformer paper insulated casing, and it is found that the method is more abundant than the traditional power frequency dielectric loss method, which is less affected by the work frequency electromagnetic field, and can realize the nondestructive measurement of the aging state of the oil-grease insulation.

1. Introduction
For oil-immersed transformers and other power equipment, the insulation state directly determines the safe and stable operation of the power grid. With the increase of operating life, under the influence of many factors such as electricity, chemistry, mechanical force and temperature, the electrical performance of transformer oil-paper insulation will continuously decline. The electrical properties of transformer oil-paper insulation will continuously decline, which is manifested by breakdown voltage decline, dielectric loss and acid value increase, etc. The oil quality deterioration factors will produce a synergistic effect, and promote the accelerated development of aging.

According to the rules to determine the corresponding electrical parameters change state, the aging state of oil-paper insulation is evaluated in China by tests of different properties at present[1-3]. The main tests include dielectric loss at power frequency, insulation resistance, dissolved gas content in oil, furfural content, tensile strength (TS) and degree of polymerization (DP). The main reason for the deterioration of mechanical properties of insulating paper is the aging of cellulose insulating paper, the measured power frequency, pulse breakdown voltage strength and dielectric loss Angle of power frequency have little change in electrical properties. The dissolved contents of CO, CO₂ and furfural in the oil are all related to the degree of polymerization[4-5], which can indirectly reflect the mechanical properties of the insulation.

Although the tensile strength and the degree of polymerization can best reflect the aging degree of oil-paper insulation, it is difficult to measure. Therefore, the dielectric loss, capacitance, insulation resistance, dc leakage, dissolved gas analysis in oil (DGA), partial discharge and other test methods in the current regulations of China for the insulation aging assessment of large power equipment are often not true and effective to reflect the oil paper insulation state of transformers.
2. Development of oil-paper insulation aging detection technology

In recent years, some new methods for evaluating the insulation state of oil-paper based on dielectric response have been widely studied. Dielectric response refers to the polarization of the dielectric under the action of an electric field. The insulation aging of transformer and the change of moisture and impurities in the insulation will cause the change of the polarization process of oil paper insulation, and then cause the change of dielectric response characteristics. On the contrary, the change of dielectric response characteristic of transformer oil paper insulation corresponds to the change of transformer insulation state and insulation life. Therefore, the insulation state and insulation life of the transformer can be evaluated by measuring the dielectric response of the oil-paper insulation. Compared with the traditional chemical testing methods, the dielectric response methods are all electrical measurements, without complicated and expensive chemical instruments and reagents, and without collecting insulation samples, the testing method is simple, the testing process will not cause damage to the transformer insulation. Compared with the traditional electrical measurement methods such as insulation resistance, power frequency dielectric loss and capacitance, the dielectric response method has a richer information content, which can more accurately reflect the insulation defects and insulation degradation that are difficult to be reflected by the traditional method, thus more reliably evaluate the transformer life. Therefore, the testing method of transformer life evaluation based on dielectric response is expected to supplement or even replace the traditional testing method, which has a broad application prospect[6-7].

3. Oil-paper insulation experiment platform based on frequency domain dielectric spectroscopy

3.1. Frequency domain dielectric spectroscopy

Frequency domain dielectric spectroscopy (FDS) is used to evaluate the aging state of insulating materials by measuring the complex capacitance, dielectric loss factor and complex dielectric constant of the medium varying with frequency in the low-voltage sinusoidal alternating electric field[8]. FDS method measures the complex capacitance and dielectric loss spectrum of insulating medium from low frequency to high frequency through sweeping frequency measurement, such as sweeping frequency measurement from 1mHz to 1kHz, and analyzes and studies the change law of the curve. It can be said that FDS method is an extension of the conventional dielectric loss test method, and its measurement principle is shown in ‘figure 1’.

![Figure 1. Schematic diagram of measuring principle.](image_url)

The typical graph of FDS test is shown in ‘figure 2’. The horizontal axis is the frequency and the vertical axis is the dielectric loss coefficient. The whole curve is s-shaped. Different factors affect different parts of the FDS curve, for example, water affects the low frequency region and the high
frequency region. The transmissibility of oil affects the steeper middle part of the curve, while the geometry of the insulation affects the steeper "bulge" on the left.

![Graph showing the relation between dielectric loss and frequency]

**Figure 2. Relation curve between dielectric loss and frequency**

3.2. **Oil-paper insulation experiment platform**

The oil-paper insulation test platform as ‘figure 3’. The system mainly consists of high-voltage copper electrode, measuring electrode and protection electrode. The position of the measuring electrode and the protection electrode was fixed, and the high voltage electrode was fixed through the card slot to ensure that the position of the cardboard was fixed during the long-term dielectric response experiment. There are air valves and oil valves on the tank body, which can guarantee the vacuum oil immersion or vacuum gas injection. The experimental temperature can be changed by coating the tank with an heating belt. The temperature sensor and barometer can monitor the experimental conditions in real time. The experimental tank is connected with the experimental device by the high-temperature resistant coaxial cable. The coaxial cable contains two wire cores for connecting the measuring electrode and the high-voltage electrode respectively, and the shielding layer of the cable is connected with the protection electrode.
4. Experimental study on aging of oil-paper insulation material

4.1. Influence of aging
The insulating board was heated and aged at 120℃, and 5 samples with different aging degrees (0 days, 10 days, 31 days, 50 days and 75 days) were obtained. The complex capacitance $C^*$ and $\tan\delta$ frequency domain spectra of the samples were measured by FDS method, as shown in ‘figure 4’, ‘figure 5’ and ‘figure 6’.

Figure 4. $C^*$ frequency domain spectrum of samples with different aging degrees
As can be seen from ‘figure 4’, the real part C’ of the complex capacitance of the samples with different aging degrees increases gradually with the aging degree in the whole frequency band range of 10^{-3}~10^{3} Hz, and for the samples with the same aging degree, the real part C’ of the complex capacitance decreases continuously with the increase of frequency, and there is no coincidence in the samples with different aging degrees. As you can see from ‘figure 5’, for the different aging degree of the samples, after capacitance imaginary part C” within 10^{-3}~10^{0} Hz frequency range increases with aging degree is increasing gradually, and in the frequency range is greater than 10^{0} Hz is overlap phenomenon, for the same aging degree of the samples, after capacitance imaginary part C” within the frequency range is less than 10^{0} Hz decreases with frequency, the frequency range is more than 10^{0} Hz above change is not obvious, tend to be a straight and level. See from ‘figure 6’, the dielectric loss factor tanδ of oil-immersed insulation board within 10^{-3}~10^{3} Hz frequency range increases with aging degree of intensified, and in this range, the tanδ of the same sample decreases with the increase of frequency, in does not change significantly within 10^{0}~10^{3} Hz frequency range, the tanδ of samples with different aging degree overlap.

4.2. Influence of moisture

In addition to the FDS, which is affected by the aging degree of insulating paper, moisture is another important factor. The insulating paper with different moisture content was put into the insulating oil for a long time to stand still, and four test samples with different moisture content of 0.76%, 1.2%, 2.35% and 3.38% were obtained. The C* and tanδ frequency spectrum as shown in ‘figure7’, ‘figure 8’ and ‘figure 9’ were detected by FDS method.

As can be seen from ‘figure 7’, for samples with the same water content, the real part of the complex capacitance C’ gradually decreases with the increase of frequency in the frequency band range of 10^{-3}~10^{3} Hz, and the real part of the complex capacitance C’ of samples with different water
content in this range will continuously increase with the increase of water content, and the larger the water content of samples, the steeper the curve. When the frequency range is greater than 10Hz, the real part $C'$ of the complex capacitance does not change much into a horizontal line, and the real part $C'$ of the complex capacitance with different water contents overlaps. As you can see from ‘figure 8’, and after the change of capacitance imaginary part $C''$ similar to the real component and within $10^{-3} \sim 10^{0}$Hz frequency range of the imaginary part of the same water sample after capacitance $C''$ decreases with the increase of frequency, the frequency range of samples of different water content under the same frequency, complex capacitance imaginary part $C''$ increases with the increase of water content, while in the frequency range is greater than $10^{0}$Hz overlap phenomenon, the same water sample along with the increase of the frequency change is not big, straight and level. See from ‘figure 9’, the dielectric loss factor $\tan\delta$ of the same water sample within $10^{-3} \sim 10^{1}$Hz frequency range along with the increase of the frequency decreases, and samples of different water content under the same frequency dielectric loss factor $\tan\delta$ increases with the increase of water content, when more than $10^{1}$Hz frequency range, The $\tan\delta$ of the sample with the same water content did not change significantly with the frequency, while the $\tan\delta$ of the sample with different water content also overlapped.

![Figure 7. C’ frequency domain spectrum of samples with different water content](image)

![Figure 8. C” frequency domain spectrum of samples with different water content](image)
4.3. Influence of temperature
Temperature is another important factor that affects the spectrum of the dielectric. Especially in the northern region, the temperature difference between day and night and the harsh environment make the effect of temperature on the aging state of transformers more prominent. The complex capacitance and dielectric loss factor frequency domain spectrum of oil-paper insulating board with low water content without aging at 30°C, 50°C, 70°C and 90°C in 'figure 10', 'figure 11' and 'figure 12'.

Figure 9. Tanδ frequency domain spectrum of samples with different water content

Figure 10. C' frequency domain spectrum of samples with different temperature
As can be seen from ‘figure 10’, the real part $C^\prime$ of the complex capacitor gradually decreases with the increase of frequency in the frequency band range of $10^{-3}$~$10^{0}$Hz, and the real part $C^\prime$ of the complex capacitor increases with the increase of temperature in the same frequency range. The higher the temperature of the sample, the curve is steeper. When the frequency range is greater than $10^{0}$Hz, the real part $C^\prime$ of the complex capacitance does not change much into a horizontal line, and the real part $C^\prime$ of the complex capacitance with different water contents overlaps. As can be seen from the ‘figure 11’, the complex capacitance of imaginary part $C^\prime\prime$ decreases continuously with the increase of frequency, and under the same frequency, complex capacitance imaginary part $C^\prime\prime$ increases with the increase of temperature, see from ‘figure 12’, the dielectric loss factor $\tan\delta$ of sample decreases with the increase of frequency, under the same frequency, the dielectric loss factor $\tan\delta$ increases with the increase of water content, overlapping phenomenon occurring in the high frequency area.

5. Field test application of FDS
For the transformer bushing with good sealing, with the increase of operation life, the oil-paper composite insulation gradually ages under the action of thermal, electrical and chemical factors, resulting in the decline of insulation performance, thus affecting the safe and stable operation of the transformer. Therefore, the study on frequency domain dielectric property of oil-paper insulation of transformer bushing is of great significance to evaluate the insulation status of transformer as a whole. In order to further verify the effectiveness of the FDS method, 9 devices with different manufacturers,
voltage levels and operating life were selected, as shown in Table 1. At the same time, there is a positive correlation between operation life and equipment aging and water content.

Table 1: Selection of Transformer Bushing on Site

| Number | Voltage Level (kV) | Run Time (year) | Environment Temperature (°C) | The Upper Oil Temperature (°C) | Casing Temperature (°C) |
|--------|-------------------|-----------------|-------------------------------|-------------------------------|-------------------------|
| A      | 110               | 4               | 32.0                          | 42                            | 38.6                    |
| A      | 110               | 5               | 35.0                          | 50                            | 44.9                    |
| A      | 110               | 8               | 34.0                          | 42                            | 39.3                    |
| A      | 110               | 9               | 29.4                          | 46                            | 40.3                    |
| A      | 110               | 10              | 30.0                          | 44                            | 39.3                    |
| B      | 110               | 4               | 38.0                          | 49                            | 45.3                    |
| B      | 110               | 6               | 33.9                          | 40                            | 38.0                    |
| B      | 110               | 7               | 29.5                          | 36                            | 33.8                    |
| B      | 110               | 8               | 28.0                          | 35                            | 32.5                    |

The FDS test curves of 110kV bushing from different manufacturers are shown in ‘Figure 13’ and ‘Figure 14’. Although the same manufacturer produces the same batch of casing with the same voltage level, the capacitance varies. The tanδ-f curve in FDS characteristic is mainly compared here. It can be seen that the tanδ-f curve increases with the increase of the operating life, only in the high-frequency region (1kHz~5kHz) is not affected by the operating life. The FDS characteristic law of field casing is consistent with experimental results.

As the use time of the equipment increases, the cellulose long chain fracture gradually in the insulating paper, the DP value constantly decreases, and solid insulation became uneven, interstitial, insulation aging makes the paper generated polarity material such as organic acid, compound, water, which is more easily immerse the amorphous cellulose area, form a more abundant oiled paper, acid paper and other interface. With the increase of carrier concentration and mobility, the establishment of interlayer interface polarization is promoted and the strength of polarization is strengthened, which finally leads to the increase of equipment loss, and the increase of temperature rise in the operating state further aggravates the aging.

![Figure 13. The casing in A factory](image1)

![Figure 14. The casing in B factory](image2)
According to the FDS test, the dielectric loss factor $\tan \delta$ and capacitance $C$ of the above 110kV bushing operating frequency are calculated as shown in table 2 (A4 represents the bushing in A plant that has been running for 4 years, and so on). It is worth noting that the $\tan \delta$ of each casing under power frequency are not more than 0.7%, The capacitance variation is also within ±5% of the nameplate capacitance, indicating that the casing in traditional preventive test performance is good, not by power frequency test parameters to diagnose the assessment. However, it is obvious from the reference curve that the running state of each casing is very different. The capacitance of these casings hardly changes with the operating life of the equipment, and no curve is shown.

### Table 2. Frequency data of 110kV casing pipe of different manufacturers

| Number | Dielectric loss (%) | Capacitance (pF) |
|--------|---------------------|------------------|
| A4     | 0.226               | 364              |
| A5     | 0.310               | 291              |
| A8     | 0.360               | 338              |
| A9     | 0.370               | 302              |
| A10    | 0.484               | 304              |
| B8     | 0.305               | 312              |
| B4     | 0.311               | 284              |
| B6     | 0.334               | 311              |
| B7     | 0.451               | 314              |

It can be seen from table 2 that the power frequency dielectric loss gradually increases with the normal aging of the equipment as the operation life grows longer for the casing in plant A. For the casing in plant B, the power frequency dielectric loss is smaller when the casing has been running for 8 years and 4 years, and larger when the casing has been running for 6 years and 7 years.

### 6. conclusion

By setting up an experimental device for frequency domain dielectric response, the influence of aging degree, water content and temperature on the insulation state of oil paper insulation samples was analyzed, and the effectiveness of FDS in analyzing the insulation state of oil paper was verified. Through the analysis and research, the following conclusions are drawn:

1. Temperature, water content and aging degree have great influence on the dielectric response characteristics in frequency domain.

2. Compared with the traditional power frequency dielectric loss measurement method, the frequency-domain dielectric spectrum method contains more state information of the equipment and is less affected by the power frequency electromagnetic field.

3. The results of laboratory research and field test are basically the same, which can be popularized and applied on a large scale in the field, and the spectrum library of FDS can be established to assist the general test for comprehensive diagnosis.

### Reference

[1] Bao, Y., He, X.X., Zhang, M. (2017) Analysis of characteristic quantities in transformer life evaluation. J. Electroelectrics, 2:18-23.

[2] Yang, Q.P., Xue, W.D., Lan, Z.D. (2006) Research on insulation aging assessment of transformers.
J. Transformers, 5:1-5.

[3] Zhang, Q. (2015) Research on insulation state of high voltage bushing based on dielectric response method. D. Dalian university of technology.

[4] Jia, L.R., Liu, X. (2017) In the oil furfural analysis in the application of transformer life assessment. J. Journal of jiangxi electric power, 41 (2):9-12.

[5] Zhang, Y.X., Li, S.L. (2011) Variation law of polymerization degree of transformer insulating paper. J. High voltage technology, 37(10):2458-2463.

[6] Yang, L.J., Qi, C.L., Lu, Y.D. (2015) Characteristic parameters and evaluation methods of frequency domain dielectric spectrum for insulation state of transformer oil paper. J. Acta electrica technica sinica, 30(1):212-219.

[7] Chen, M.M., Wei, G., Liu, J. (2012) Effects of temperature and moisture on frequency-domain dielectric characteristics of oil-paper insulation system for transformers. J. Insulating materials, 45(1):57-61.

[8] Dong, M., Wang, L., Wu, X.Z. (2016) Research status and development of dielectric response detection technology for oil-paper insulation. J. High voltage technology, 42(4):1179-1189.