2016 Electrical Insulation Conference (EIC), Montréal, Qc, Canada, 19 - 22 June 2016

Study on Aging Degree and Moisture Content Assessment Methods of oil-paper in Transformer based on FDS

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***Abstract*—In order to apply frequency-domain dielectric spectroscopy (FDS) in nondestructive diagnosis of transformer insulation status more effectively, the frequency domain dielectric response test platform of oil- paper insulation was set up and complex permittivity of oiled paper samples with different aging degree and moisture content were tested. The test results were analyzed and the analysis results show that real permittivity and imaginary permittivity increase with the decrease of DP (degree of polymerization) in low frequency stage while they stay unchanged in high frequency stage; the increase of moisture content in oiled paper would increase the real permittivity before 10^2Hz and imaginary permittivity during the whole testing frequency stage; Along with the increase of the water content, the imaginary part curve shows the right shift trend. This paper proposes to use the "Equivalent decrease amplitude" of imaginary permittivity as mapping feature quantity of DP to evaluate the situation of oiled paper, then fit the relationship formula between moisture content and the real permittivity at frequency of 10^{-4}Hz. With this support the paper present the moisture content measurement method based on frequency domain dielectric characteristics which apply to different aging degree oiled papers.**

Keywords—oil-paper insulation; FDS; degree of polymerization; moisture; equivalent decline extent

I. INTRODUCTION

Oil-paper insulation as a large power transformer main insulation system, subjected to stress the role of temperature, moisture, oxygen, acid, electric field, mechanical force, etc, in the long run and the aging process, resulting in its mechanical properties and insulation performance[1,2]. Which water can be considered lead to insulation aging "the second largest killer" (thermal stress is considered to be the number one killer)[3], cause serious damage of insulation paper mechanical strength and electrical strength. The study shows that the mechanical life of the insulation paper will decrease rapidly with the increase of moisture content, and the thermal aging rate will increase exponentially[4]. Water is the catalyst of the chemical degradation reaction of oil, paper cellulose and other polymer materials, and the irreversible accelerating effect on the degradation of the material.

Thus, the moisture content of oil paper insulation system assessment is an important link in transformer fault diagnosis. In recent years, with the rapid development of measurement and control technology, the dielectric response technology has been gradually applied to nondestructive condition assessment of transformer oil paper insulation. The dielectric response method for transformer fault diagnosis is mainly the response voltage method (RVM), the polarization depolarization current method (PDC) and the frequency domain dielectric spectroscopy (FDS). Among them, FDS has the advantages of rich information, narrow bandwidth and strong anti-interference ability, which is more suitable for field measurement [5, 6]. Numerous studies have demonstrated the frequency domain dielectric spectra characteristic quantity (complex permittivity, dielectric loss factor, etc.) curve can reflect the state aging oil-paper insulation system[7-9]. However, these studies are based on new oil and new transformer insulating paper is an experimental basis, it does not apply to aging assessment of transformer moisture content. Therefore, how to identify the aging and water their of oil paper insulation FDS characteristics, and puts forward the applicable in different aging condition of oil paper moisture content assessment method has more practical significance.

This paper was prepared with different water content in oil paper sample different degrees of aging and its FDS test, analyze the impact of the aging degree of insulation and moisture content of the paper to its dielectric characteristics in the frequency domain, and from the polarization characteristics of the insulating paper and aging mechanism analyzes the causes of this effect. Finally, one for different aging oil impregnated paper moisture content evaluation methods.

II. EXPERIMENTAL DESIGN

A. Experimental Materials

The specific information of the experimental material is shown in table 1.

Tab 1 Detail information of experimental materials

Experimental materials	Material specifications	Moisture content/%	Degree of polymerization	Place of Origin

Insulating paper	0.3mm thick kraft paper	6.5	1190	Leshan paper mill
Insulating oil	25# naphthenic oil	17.9×10^{-4}	–	Karamay

B. Experimental Procedure

In order to improve the accuracy of the test results, the following treatment is carried out first: The insulating paper is cut into a circular board with a radius of about 11cm, and then a plurality of pieces of cut layer insulation paper are pressed into a circular insulating paper with a thickness of about 1mm. The compacted insulating paper samples were dried at 90℃ /50Pa environment 60 hours to a moisture content of less than 0.1%. Mineral oil after vacuum degassing at 40℃/50Pa dried to a moisture content of about 10ug/g.

In order to obtain the insulating paper samples with different degree of polymerization, the above mentioned insulation paper is placed in the aging box for the equivalent thermal aging of different temperature and time, the specific process is shown in Table 2. To improve the measurement accuracy, three samples of the same equivalent aging of insulating paper for measuring degree of polymerization, and take the average value as the final polymerization equivalent aging degree. Each equivalent aging treatment process after the completion of the insulating paper in mineral oil in standing for 48 hours, an insulation paper aging after the majority of the product exists in the insulating oil, to reduce the aging products (mainly acid) influence the test results.

Table.2 Pre-conditional process of paper with different DP

Degree of polymerization	Process flow
1292	At 25℃ vacuum oiled
735	100℃/50Pa/20d
420	140℃/50Pa/20d
215	150℃/50Pa/40d

After aging the equivalent of each obtained after polymerization of the insulating paper sufficiently dried natural moisture absorption of moisture content of 1%, 2%, 3% and 4% of the insulating paper samples, which was placed in the drying good insulating oil apparatus shown in Fig. 1, left to stand for 48 hours at 60 ℃ environment, until the water reached a steady state after greaseproof paper in between the measurement of the moisture content of the insulating paper and FDS test.

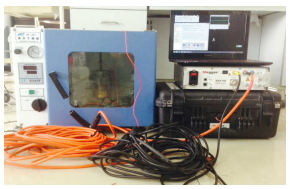


Fig.1 Device of FDS

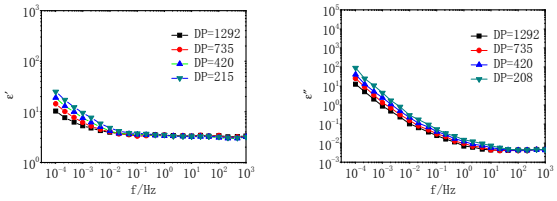
In this paper, FDS test instruments produced by the United States Megger insulation diagnostic analyzer IDAX300, its frequency range is 0.1mHz to 10kHz. FDS oil-paper insulation test device test system shown in Figure 1. Not the elimination of environmental temperature and humidity affect the test results, the figure oil-paper insulation system is placed in the aging tank, aging tank vacuum environment, temperature set to 60℃.

III. Experimental Results Analysis

A. Effect of the Degree of Polymerization of the Insulating Paper FDS Characteristics

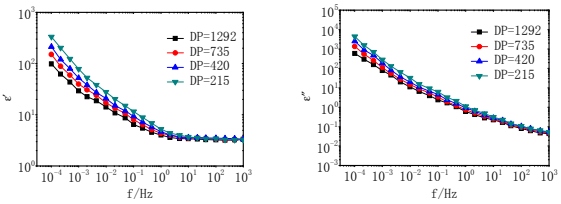
Figure 2 and figure 3 for moisture content of 1% and 3%, respectively, the degree of polymerization of the composite dielectric constant test curve(Moisture content of the test curve with similar laws 2% and 4%, in order to save space is omitted here).

Oil-paper insulation system polarization system at low frequencies, at high frequency is determined by the interfacial polarization dominated by the steering polarization. From Figure 2 and figure 3, we can see that both the real and imaginary parts of the complex dielectric constant decrease with the increase of frequency, and remain unchanged in the high frequency region. This is because in the low frequency domain, oil paper insulation system more polarization process can be completed, with increasing frequency, polarization process some for a longer period of time, such as the interlayer interfacial polarization and space charge polarization gradually catch up with the speed of electric field changes, so that the complex dielectric constant decreases.



a) real part b) imaginary part

Fig.2 Complex permittivity of paper with different DP and 1% moisture content



a) real part b) imaginary part

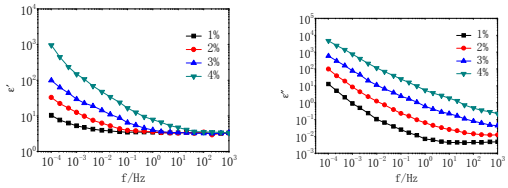
Fig.3 Complex permittivity of paper with different DP and 3% moisture content

As you can see from figure, when the insulating paper moisture content is the same, complex the real part and the imaginary part of the dielectric constant in the low frequency band with degree of polymerization decreases, increased in frequency slightly, increases can be ignored, and polymerization degree is small, the complex dielectric constant real part and the imaginary part of the dotted line in the low-frequency range from low frequency to high frequency decreased more steeply. This is consistent with the conclusions of the literature[10]. This is because the polarization system dominated by the low frequency insulation interface polarization. As the degree of polymerization of the insulating paper continuously reduce thermal aging, thermal stress not

only the crystalline regions of cellulose into amorphous regions, but also non-crystalline structure is more evacuation zone. Weakened interaction between cellulose molecules, more intrusive insulation paper insulating oil molecules into contact with the cellulose molecules, forming more oil-paper interface, the degree of polarization oilpaper interface enhancements, greaseproof paper interfacial polarization loss also increased, therefore complex the dielectric constant of the real and imaginary parts of the increase in the low frequency region.

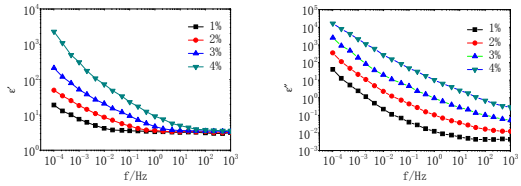
B. Evaluation of Moisture Content of Insulating Paper With Different Degree of Polymerization

Figure 4 and figure 5 for polymerization of 1292 and 420 different moisture content of insulation paper complex permittivity measurement curve (for the degree of polymerization of 735 and 215 to have similar rules, in order to save space this article will not repeat them). As can be seen from the figure, when the same degree of polymerization of the insulating paper, the real part of the complex dielectric constant with increasing moisture content increases in the frequency range below 10^2Hz. This is because the water molecules are polar molecules, will participate in the process of oil-paper insulation of the polarization, the greater the moisture content of insulating paper, the polarization of the



a) real part b) imaginary part

Fig.4 Complex permittivity of paper with DP 1292 and different moisture content



a) real part b) imaginary part

Fig.5 Complex permittivity of paper with DP 420 and different moisture content

Table 3 Decline extent and equivalent decrease amplitude of imaginary part curve

DP/moisture content	1%	2%	3%	4%	Average (equivalent to decrease)
1292	34.4578	34.4646	34.4184	34.4684	34.4629
735	40.8722	40.9845	40.8478	41.1091	40.9534
420	45.1156	45.0176	45.1224	44.9424	45.0495
215	47.8546	47.7752	47.8168	48.0670	47.8784

polar molecules involved in the stronger polarization. In addition, with the increase of the water content, the imaginary part of the complex permittivity increases in the whole test frequency domain, and the ε″ curves show the trend to the right. This is because the moisture content of the paper insulation not only increases the loss of oil paper interface, and oil paper insulation conductivity also increases with moisture content increasing, the conductance loss increases.

In order to explore the method of evaluating the moisture content of insulation paper in frequency domain, it is necessary to seek the characteristics of the degree of polymerization degree of insulation paper from the complex dielectric constant curve. As can be seen from Figure 2 and Figure 3, the moisture content of the insulating paper is the same, with the decrease of the degree of polymerization of the insulating paper, the real and imaginary parts of the complex permittivity of the curve and its downward trend in the low frequency band becomes steep. As can be seen from Figures 4 and 5, the same degree of polymerization of the insulating paper, the imaginary part of the complex permittivity curve with the moisture content increases were pan right trend, and by observing the imaginary part of the curve shows that the moisture content under four basic parallel can be speculated that if the decline in the same uniform coordinate system. Therefore, this paper proposes the use of the complex dielectric constant imaginary part curve in before 10^2Hz frequency range equivalent decreased amplitude "as the insulating paper polymerization degree and maximum 10^3 corresponding homogeneous coordinate X axis of the minimum value 0 and the maximum value of 70, complex dielectric constant curve of the imaginary part of the in decline in uniform coordinate system is as an equivalent decrease value. Figure 4(b) of the imaginary part of each curve 10^{-4}Hz in homogeneous coordinates of corresponding value as the moisture content condition of decline, we can obtain the polymerization degree of 1292 four kinds of moisture content under the curve of the imaginary part of the in homogeneous coordinates of the decline, take four kinds of moisture content curve of the imaginary part of the decline of the average as the polymerization degree corresponding equivalent decline "minus 10^2Hz falsely corresponds to the value. In accordance with this method obtained different polymerization degree of different water content of oil impregnated paper imaginary part curve in the transformed coordinate system decrease values and equivalent decrease in value as shown in Table 3. From table 3 it can be seen that the same polymerization under the condition of different water content of oil paper imaginary part curve in the transformed coordinates decreased at almost the same rate and each polymerization degree equivalent declines and decrease of the degree of polymerization, which with the previous speculating results.

Figure 6 is the relationship between the equivalent decrease amplitude and the degree of insulation paper:

$$y = 50.339 - 0.0124x \quad (1)$$

Wherein, y is an equivalent decrease value, x is the corresponding value of the degree of polymerization. Goodness of fit is 0.99788, goodness of fit is very high, and so you can use this formula to the aging state of the insulating paper assessed.

In order to evaluate the different aging degree of insulation paper moisture content, this paper selects 10^{-4} Hz ε′ as the moisture content of the frequency domain dielectric characteristics evaluation. Figure 7 shows the relationship between the moisture content of the insulation paper and the characteristic frequency ε′ of four kinds of aging degree. As shown in Figure 7, the different aging degree of insulation

paper moisture content and ε′ in the presence of 10^{-4} (2) as shown in the functional relationship:

$$y_{mc} = B + A\exp(-x/t) \tag{2}$$

Wherein, y_{mc} represents the moisture content of insulating paper, x represents the value of ε′ 10^{-4}Hz characteristic frequency at which the fitting parameters are shown in Table 4. From the data in the table, with the decrease of the degree of polymerization of insulating paper moisture content and frequency domain characteristics of the dielectric function of the amount of the goodness of fit showed a downward trend, indicating more serious aging oil impregnated paper, its special mechanism of the polarization complex, affecting their frequency domain dielectric properties of factors more. As can

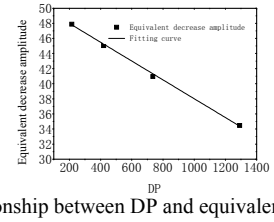


Fig.6 Relationship between DP and equivalent decline extent

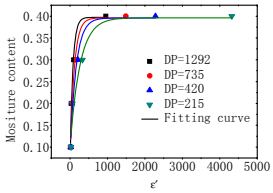


Fig.7 Relationship between moisture and Characteristic Parameters

Table 4 Fitting parameters of moisture and papers with different aging dgree

DP	B	A	t	R^2
1292	0.39732	-0.33178	73.7576	0.97419
735	0.39600	-0.31575	112.3202	0.94355
420	0.39594	-0.30889	161.4093	0.93415
215	0.39629	-0.29529	264.0576	0.86508

be seen from the data in the table, when the degree of polymerization of insulating paper dropped to 215, the goodness of fit is less than 0.9, otherwise the aging state of goodness of fit is high, the actual operation of transformer insulating paper degree of polymerization of not less than 500 , so it can fit function for the series different levels of moisture content of aging insulating paper for evaluation.

Summing up the above, the evaluation of different aging degree when the moisture content of oil impregnated paper, can be fitted by the relationship between the degree of polymerization of insulating paper and the "equivalent decline" of oil impregnated paper obtained the degree of polymerization, and then depending on the degree of polymerization of Oil paper moisture content and frequency domain dielectric characteristic quantities of the moisture content of the fitting relationship evaluated.

IV. Conclusion

1) The polymerization degree of change is mainly affected in the low frequency domain dielectric properties of oil immersed paper. When the polymerization degree different, the same moisture content, with insulating paper reduce the degree of polymerization, the real part and the imaginary part of the dielectric constant at low frequency was increased, almost unchanged in the high frequency and real part and imaginary part in low frequency band from low frequency to high frequency decreased with polymerization degree drop low become steeper.

2) When the moisture content is the same, the polymerization degree at the same time, complex dielectric constant ε′ in 10^2Hz following frequency range with insulation paper moisture content increases and increases, complex dielectric constant imaginary part ε″ in the test frequency range with insulation paper moisture content increased and increased and ε″ curve presented rightward shift of the trend.

3) Proposed use of "equivalent decline" as insulating paper aging mapping feature quantity obtained with a degree of polymerization of insulating paper relationship, you can use the aging of oil impregnated paper test to assess. Also fit the different polymerization degree of insulation paper characteristic ε′ frequency 10^{-4}Hz values as a function of moisture content, and then explore suitable for different aging degree of oil paper moisture content assessment methods.

References

[1] Supramaniam G K, Hussien Z F, Aizam M. Application of frequency domain spectroscopy(FDS) in assessing dryness and ageing state of transformer insulation systems[C]. IEEE International Conference on Power and Energy, Johor Baharu， Malaysia: IEEE, pp. 55-61, 2008.

[2] Emsley A M, Xiao X, Heywood R J, et al. Degradation of cellulosic on aging in oil[J]. IEEE Proceedings-Science, Measurement and Technology, 2000, vol. 147, pp. 115-119.

[3] Fofana I, Wasserberg V, Borsi H, et al. Challenge of mixed insulating liquids for use in high-voltage transformers. Investigations of mixed liquid impregnated paper insulation[J]. IEEE Transactions on Electrical Insulation Magazine, 2002, vol. 18, pp. 5-16.

[4] ZHOU Lijun, LI Xianlang, WANG Xiaojian, et al. Status assessment of oil-paper insulation based on recovery voltage method[J]. High Voltage Engineering, 2014, vol. 40, pp. 489-496.

[5] Sonerud B, Bengtsson T, Blennow J, et al. Dielectric response measurements utilizing semi-square voltage waveforms[J]. IEEE Transactions on Dielectrics and Electrical Insulation, 2008, vol. 15, pp. 920-926.

[6] Duan Zongchao Wu Guangnin, Gao Bo, et al. Study of Linkage Effects Between Degree of Polymerization and Frequency Domain Dielectric Spectroscopy Characteristics of Oil-Paper Insulation[J]. Power System Technology, 2014, vol. 38, pp. 2881-2887.

[7] Amir Abbas Shayegani, Hossein Mohseni, Hossein Borsi , et al. Diagnostics of power transformers with dielectric response measurements[C]. IEEE International Power System Conference, Columbus, United States, 2005, pp. 1-8.

[8] D. Linhjell, L. Lundgaard, U. Gafvert. Dielectric response of mineral oil impregnated cellulose and the impact of aging[J]. IEEE Transactions on Dielectrics and Electrical Insulation, 2007, vol. 14, pp. 156-169.

[9] Yang Lijun, Hao Jian, Liao Ruijin, et.al. Frequency-Domain Dielectric Characteristic Parameter and Moisture Content Assessment Methods Study on Frequency-Domain Dielectric Spectroscopy of Oil-Paper Insulation for Transformers. Transactions of China Electrotechnical Society, 2013, vol. 28, pp. 59-66.

[10] Amir Abbas Shayegani, Hossein Mohseni, Hossein Borsi , et al . Diagnostics of power transformers with dielectric response measurements[C]. IEEE International Power System Conference, Columbus, United States, 2005, pp. 1-8.