EXPERIMENTAL AND X-Y MODEL SIMULATION INVESTIGATION ON THE FREQUENCY DOMAIN DIELECTRIC SPECTROSCOPY OF OIL-PAPER INSULATION SYSTEM

Xianping Zhao[1], Zhiqin Ma[2*], Ruijin liao[2], Yaolong Wang[1], Guochao Qian[1]
[1]Yunnan Electric Power Research Institute(Group)Co.Ltd.; Kunming 650051;China
[2]State Key Laboratory of Power Transmission Equipment & System Security and New Technology (Chongqing University), Shapingba District, Chongqing 400044, China
*Email: mzhqcqu@163.com

Abstract: To assess the condition of oil paper insulation using the X-Y model simulation, a model transformer with the alternative geometry structure has been designed. Equivalence between X-Y model simulation and field frequency domain spectroscopy measurement is verified in this paper. Then the influences of geometric structure, oil conductivity, water content of pressboard and aging condition on the frequency domain spectroscopy results of oil-paper insulation system are investigated respectively. Results show that a "hump" is visible in the frequency spectroscopy of tanδ when the oil conductivity is higher. The frequency where the maximum value of the "hump" appears shifts to higher value with the increment of oil conductivity, but the maximum tanδ values are the same. The frequency of the maximum value of the "hump" also shifts to higher with the increment of X or Y value of the insulation structure, meanwhile the amplitude of the "hump" decreases. The frequency range influenced by water content of pressboard is related to oil conductivity. With the degradation of oil paper insulation, the frequency spectroscopy of tanδ shifts to higher frequency. A new method using X-Y model simulation to assess the ageing condition of transformer insulation is optimistic.

1 INTRODUCTION

Power transformers are most expensive and vital equipments in electric power transmission and distribution systems. The inner insulation system of oil-impregnated transformers predominantly determines their operation life[1]. Therefore, precise and complete understanding the condition of oil paper insulation system becomes especially important.

Conventional diagnostic methods, such as the dissolved gas-in-oil analysis (DGA), furan analysis, and degree of polymerization (DP) analysis have been widely used to test the condition of oil-paper insulation in transformer[2-4]. However, due to various defects of these techniques, more and more scholors and engineers are focusing their attentions on researching new non-destructive and precise diagnostic methods. Techniques based on dielectric relaxation methods such as Return Voltage Measurement (RVM), Polarization & Depolarization Current (PDC) and Frequency Domain Spectroscopy (FDS) measurements have been introduced to assess the insulation condition of power transformers since the 1990s[5-7]. Among them, FDS is more suitable for field measurement and promising to determine moisture content and aging of the oil-paper insulation more correctly[8].

The X-Y model not only relates directly to the construction of transformer insulation, but also being widely used for the diagnostics of transformer insulation. In this paper investigation combined X-Y model simulation with transformer experimental model which supports main insulation structure modification is carried out on the frequency domain spectroscopy characteristics of transformer oil-paper insulation system. Equivalence between X-Y model simulation and field FDS measurement of model transformer is verified. And the influences of geometric structure, oil DC conductivity, water content of pressboard and aging condition on the FDS results of oil-paper insulation system are investigated.

2 THEORY OF X-Y MODEL

The transformer main insulation, consisting of cylindrical pressboard barriers in series with oil ducts and spacers (Fig 1), is represented as shown in Fig 2. The X and Y values can be obtained from construction drawings and usually lie in the interval 10%–50%[9].

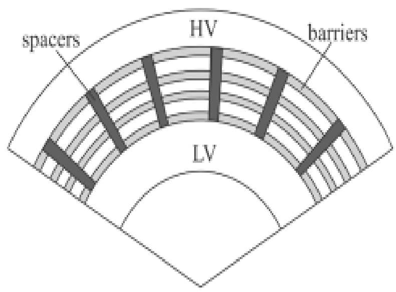


Fig 1: Section of main insulation in a core-type transformer.

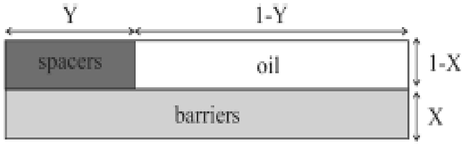


Fig 2: X-Y representation of transformer main insulation.

When the materials properties and the geometry have been chosen the composite response is calculated numerically. In frequency domain the response of the insulation module can be expressed in a simple formula[10]:

$$\varepsilon^*_{tot}(\omega) = \frac{1-Y}{\dfrac{1-X}{\varepsilon^*_{oil}(\omega)} + \dfrac{X}{\varepsilon^*_{PB}(\omega)}} + Y * \varepsilon^*_{PB}(\omega) \quad (1)$$

$$\varepsilon^*_{oil}(\omega) = 2.2 - j\frac{\sigma(T)}{\varepsilon_0 \omega} \quad (2)$$

The complex permittivity $\varepsilon^*_{PB}(\omega)$ can be taken from the database created from laboratory measurements. The complex permittivity of oil is simply described by DC conductivity and a constant real permittivity. By finding the best fit between X-Y model simulation and measurement, the condition of field measured transformers can be estimated.

3 FDS EXPERIMENT

Pressboard samples used for FDS measurement by Novocontrol Concept 80 Broadband Dielectric Spectroscopy equipment have a thickness of 2mm and a diameter of 20mm. The measuring voltage is 1V (RMS), and measuring frequency range is 10mHz~1kHz.

To verify the equivalence between X-Y model simulation and field FDS measurement, a model transformer is designed. The setup of the transformer is shown in figure 3. The main insulation is built according to figure 1. 4 layers of cylindrical pressboard tube of 2~3mm in thickness and 8 rectangular spacers distributed equality on the circles between pressboard tubes or between HV/LV winding and pressboard tube are completely impregnated in tranformer oil. These oil and paper mixture make up the main insulation of the model transforemer. It is worth mentioning that the spacers and barriers of transformer main insulation can be easily embed or removed to simulate different insulation structures. Additionally, the HV/LV winding is composed of 18 pancake coils in series, with 10 turns of paper-covered copper conductors in each coil. The dielectric responder DIRANA is used for FDS measurement of the model transformer. The measuring frequency range is 1mHz~1kHz, and the peak value of measuring voltage is 100V. The temperature of the experiment is 18 ^{o}C ~20^{o}C.

Fig 3: Model transformer with alternative geometric structure of main insulation

4 RESULTS AND ANALYSIS

4.1 Equivalence analysis between X-Y model simulation and field FDS measurement,

The X-Y model does not only tell FDS characteristics of oil and paper apart, but also take the influences of temperature and geometry into account. Therefore, the X-Y model is being widely used for the diagnostic of transformer insulation by researchers. However, the premise of this work is that results of X-Y model simulation and field FDS measurement of the object are identical.

Considering that the FDS measuring apparatus Novocontrol Concept 80 Broadband Dielectric Spectroscopy is only suitable for small samples, while DIRANA is not limited by the dimensions. But DIRANA normalizes the complex permittivity to ε_∞. For the sake of comparing the results of X-Y model simulation and field FDS measurement, DIRANA is used for measuring FDS of the model transformer and Concept 80 Broadband Dielectric Spectroscopy measuring the pressboard of the transformer main insulation.

The model transformer is stayed at room temperature for 1month to get moisture equilibrium between oil and pressboard. 6 pieces of pressboard with the same diameter of 20mm is respectively cut from each terminal and middle of the inner and outer pressboard tube. The FDS of pressboard is measurement by Concept 80 Broadband Dielectric Spectroscopy, and then average value of the FDS of pressboard is achieved. Oil DC conductivity taken from the model is measured at 20^{o}C according to DL/T 421-91[13]. The geomtry structure of the model transformer is: X=0.2, Y=0.15. According to formula(1) and (2), complex permittivity of the model transformer is calculated meanwhile tanδ can be obtained. For comparison, tanδ of the model transformer measured by DIRANA is shown in figure 4. It is clearly that FDS curve of the model transformer calculated from X-Y model simulation agrees with the measured one.

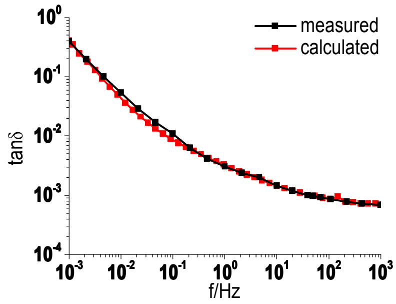


Fig 4: Comparison between simulation curve of X-Y model and onsite measured curve of transformer model

As FDS of oil is depend on its conductivity according formula (2) and FDS of pressboard under different condition can be measurement in the laboratory, it is easy to form various combinations of frequency domain spectroscopy corresponding to different oil paper conditions by X-Y model. When using FDS to diagnose the condition of transformer, it is just need to find out the best one close to field measured result. Therefore, X-Y model can be used to diagnose the operation condition of transformers. In the next section of this paper, FDS of pressboard under different conditions is measured by Concept 80 Broadband Dielectric Spectroscopy and used for X-Y model simulation. Factors such as geometry, water content of pressboard, oil conductivity and aging will be taken into account to investigate the effect on FDS characteristics of oil paper insulation .

4.2 X-Y model simulation analysis of oil paper insulation system

4.2.1 Influence of geometry As is shown in figure 5 and figure 6, tanδ of oil paper system with different oil conductivities and geometry is analysed by X-Y model simulation. When the oil conductivity is lower (σ =0.01pS/m), tanδ spectroscopy of oil paper insulation system increases with the X or Y value. When the oil conductivity is higher (σ =10pS/m), a “hump” is visible in the tanδ spectroscopy at lower frequency range. The frequency of the maximum value of the “hump” shifts to higher with the increment of X or Y value of the insulation structure, meanwhile the amplitude of the “hump” decreases. Additionally, there is a cross point around 4Hz for different geometry of oil paper insulation system and the frequency of the cross point will increase with oil conductivity. By analysing relationship between the frequency of cross point and oil conductivity, it can be found that they meet the following equation: $lgf=1.434*lg\sigma-0.8588$ with the fitness $R^2=0.9997$.

4.2.2 Influence of oil conductivity Oil conductivity has great affect on the frequency spectroscopy of tanδ. With the geometry of oil paper system fixed

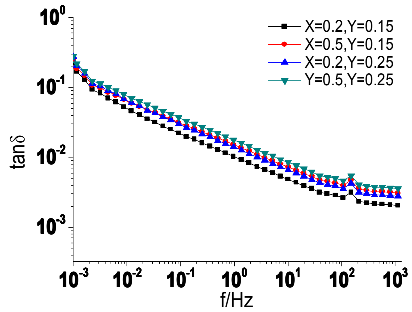


Fig 5: Influence of geometry on dissipation factor spectroscopy of oil paper insulation system with the lower conductivity oil(σ =0.01pS/m) .

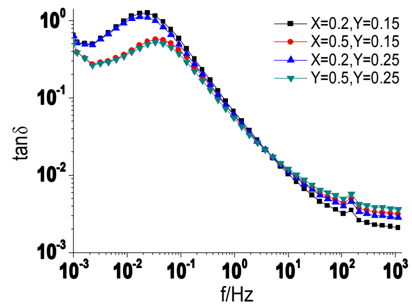


Fig 6: Influence of geometry on dissipation factor spectroscopy of oil paper insulation system with the higher conductivity oil (σ =10pS/m).

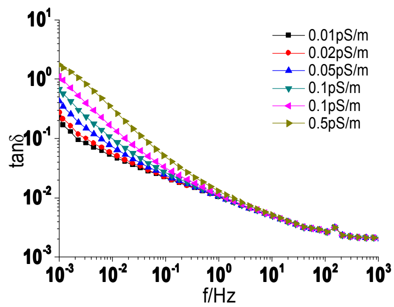


Fig 7: Influence of oil conductivity on dissipation factor spectroscopy of oil paper insulation system with the lower conductivity oil.

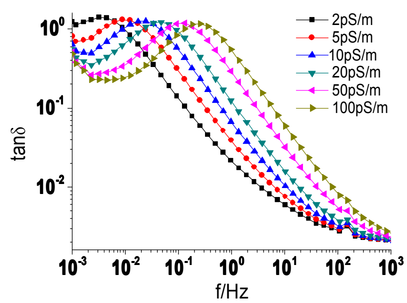


Fig 8: Influence of oil conductivity on dissipation factor spectroscopy of oil paper insulation system with the higher conductivity oil.

at X=0.2, Y=0.15, the influence of oil conductivity is shown in figure 7 and figure 8. when the oil conductivity is lower than 1pS/m, the tanδ values increase with oil conductivity at the frequency range 10^{-3}Hz~10^{0}Hz. Otherwise, when oil conductivity is higher than 1pS/m, the frequency where the maximum value of the "hump" appears shifts to higher value, but the maximum tanδ values are the same. After comparing the frequency data of the maximum value of the "hump" with the corrsponding oil conductivity, one equation can be obtained: $lgf=1.128*lg\sigma-2.815$ with the fitness $R^2=0.997$.

4.2.3 Influence of water content of pressboard Complex permittivity spectroscopy of original pressboard with different water content: 0.3523%, 1.7865%, 3.025% is measured by Novocontrol Concept 80 Broadband Dielectric Spectroscopy. As we can see from figure 9, both real and imaginary part of complex permittivity increases with water content of the pressboard. Given that the geometry of the oil paper insulation system is X=0.2 and Y=0.15, frequency spectroscopy of tanδ can be achieved using X-Y model simulation. As is shown in figure 10, the tanδ values increase obviously with water content of pressboard when the oil conductivity is lower (σ =0.01pS/m). In figure 11, the influence of water content only embodies in the frequency range 10^{-2}~10^{-1}Hz and 10^{1}~10^{3}Hz when the oil conductivity is higher (σ =100pS/m). However, in the frequency around 1Hz, the tanδ values are the same when the water contents of pressboard are different. That is because the influence of water content is covered by oil conductivity. so we can draw a conclusion that the frequency range influenced by water content of pressboard is relate to oil conductivity.

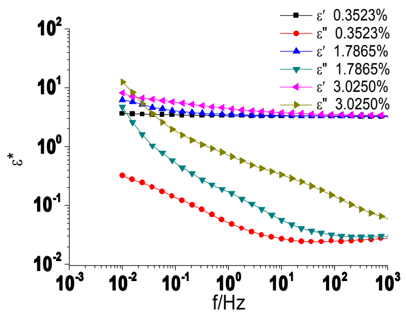


Fig 9: Complex permittivity spectroscopy of insulation pressboard with different water content.

4.2.4 Influence of aging The accelerated thermal aging experiment of oil-paper insulation is performed at 130°C to get oil-paper insulation samples with different aging states. The pre-treatment of the samples are similar to [11]. The initial water content of pressboard is 0.3205% (<0.5%), and mineral oil less than 10ppm. Frequency domain spectroscopy of oil impregnated pressboard with different aging time is measured

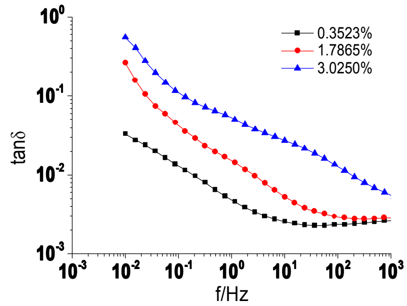


Fig 10: Dissipation factor spectroscopy of oil paper insulation with different water content with the lower conductivity oil (σ =0.01pS/m).

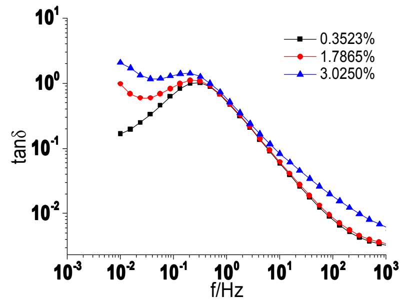


Fig 11: Dissipation factor spectroscopy of oil paper insulation with different water content with the higher conductivity oil (σ =100pS/m).

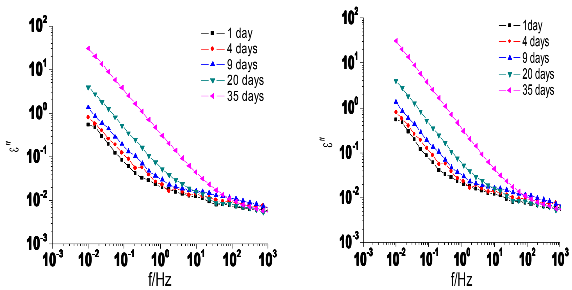
by Novocontrol Concept 80 Broadband Dielectric Spectroscopy. As it is present in figure 12, both real part and imaginary part of complex permittivity increase with aging time in lower frequency range. Considering that water content has a great effect on frequency domain spectroscopy, and it is hardly to distinguish the influence of water content from aging on the FDS results[14].DL32 Karl Fischer Titration is used to measure the water content of aged pressboard. As is shown in table 1, the water contents show no significant difference. It is believe that the diversity of frequency domain spectroscopy at lower frequency range is not come from water content, but aging by-products and cellulose degradation.

Aged oil DC conductivity is measured at 90°C according to DL421-91[13]. Since the aged pressboard samples were measured at 20 °C, it is necessary to convert the conductivity at 90 °C into 20 °C to simulate the influence of aging on FDS results. Arrhenius equation can perfectly describe the variation of Oil DC conductivity with temperature[15]:

$$\sigma_{oil} = \sigma_0 \exp(-\frac{E_a}{R_m T}) \quad (3)$$

Where: E_a is activation energy, R_m is universal gas constant ($8.31 J\cdot mol^{-1}\cdot K^{-1}$), T is the measuring temperature (K). Given that E_a equals to 0.7eV[15], the calculated oil DC conductivities at 20 °C are shown in table 1. With the geometry structure assumed to be X=0.2 and Y=0.15, FDS results of this oil paper system is achieved by X-Y model simulation. It can be obviously seen from figure 13 that frequency spectroscopy of tanδ shifts to higher frequency with aging time.

In figure 12 and 13, the frequency domain spectroscopy is different from each other with different aging condition. Therefore, frequency domain spectroscopy of pressboard in lower frequency band can be used to evaluation the aging condition of oil paper insulation. When using XY model to evaluate the aging status of field transformers, frequency domain spectroscopy of the transformer oil paper system can be measured and the water content of main insulation can be evaluated by DIRANA correctly[16]. Oil DC conductivity can be measured according to DL/T 421-91 or IEC 247 onsite, and then the frequency domain spectroscopy of pressboard can be calculated according to XY model. By comparing the frequency domain spectroscopy of pressboard based on XY model simulation with the group frequency spectroscopies from laboratory database which have the same water content with the measured transformer. The best close one has the same aging status with the field transformer. Therefore, a new way of transformer aging status diagnosis by FDS is provided.



(a) (b)

Fig 12: Complex permittivity spectroscopy of oil impregnated pressboard with different aging level at 130˚C. （a） ε′ -f (b) ε″ -f

Tab 1: Water content and oil conductivity of aged samples with different aging level at 130˚C

Aging days	Water content	Oil conductivity (90℃)	Oil conductivity (20℃)
1	0.3205%	6.99 pS/m	0.033 pS/m
4	0.4184%	9.04 pS/m	0.043 pS/m
9	0.5582%	19.62 pS/m	0.094 pS/m
20	0.5227%	90.5 pS/m	0.43 pS/m
35	0.3925%	191.94 pS/m	0.92 pS/m

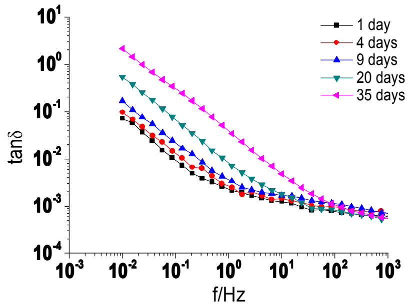


Fig 13: Dissipation factor spectroscopy of oil paper insulation with different aging level.

5 CONCLUSION

In this paper investigation combined X-Y model simulation with a model transformer which supports main insulation structure modification is carried out on the frequency domain spectroscopy characteristics of transformer oil-paper insulation system. Equivalence between X-Y model simulation and field FDS measurement of the model transformer is verified. And the influences of geometry, oil DC conductivity, water content of pressboard and aging on the FDS results of oil-paper insulation system are investigated. The following conclusions may be drawn from the research.

The primary differences between the influence of oil DC conductivity and geometry on the frequency spectroscopy of tanδ lie in that: when the oil conductivity is higher, the frequency where the maximum value of the “hump” appears shifts to higher value with the increment of oil DC conductivity, but the maximum tanδ values are the same; The frequency of the maximum value of the “hump” also shifts to higher with the increment of X or Y value, meanwhile the amplitude of the “hump” decreases; There is a cross in the higher frequency part of the frequency spectroscopy of tanδ with the alteration of X or Y value.

The frequency range influenced by water content of pressboard is relate to oil conductivity: when oil conductivity is higher, the influence of water content only embodies in the frequency range 10^{-2}~10^{-1}Hz and 10^{1}~10^{3}Hz; when oil conductivity is lower, water content influence the total frequency of 10^{-3}~10^{3}Hz.

With the degradation of oil paper insulation, the frequency spectroscopy of tanδ shifts to higher frequency. FDS method based on X-Y model simulation to assess the ageing condition of transformer insulation is optimistic.

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