# The Study of VFTO Distribution in the IOCT Insulation System Considering the Moisture and Frequency Dependence of Materials

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**For the precise calculation of the Very Fast Transient Overvoltage (VFTO) distribution of the Inverted-type Oil-immersed Current Transformer (IOCT) insulation system, the Frequency-domain Dielectric Spectroscopy (FDS) of the oil-immersed paper and semi-conductive paper at different moisture content has been measured. The data measured are fitted as a function of the frequency and the moisture content using the amendatory Cole-Cole model. Then the broadband MTL model of the insulation system is established considering the capacitive electrodes thin layer, and the distribution parameters take into account the moisture and frequency dependence. The impulse voltage is decomposed into a series of sinusoidal components by FFT, and the time-domain MTL equations are transformed into frequency-domain. Considering the particularity of the boundary conditions, the decomposed voltage column vector at the input end of each insulation layer is directly solved by the matrix transformation. Finally, the VFTO distribution of the total IOCT insulation system at different moisture content is obtained by taking the superimposed results into the solution equation of the MTL model.**

*Index Terms*—**Very fast transient overvoltage, insulation system inverted-type oil-immersed current transformer, moisture content.**

## I. INTRODUCTION

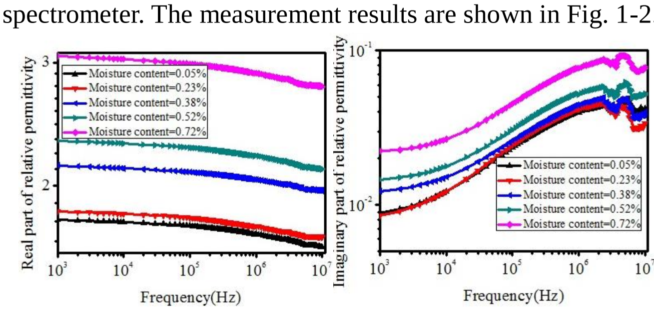
THE IOCT working in the outdoor is a series device used in high-speed railway traction network for measurement and protection purposes. During the IOCT operation, the moisture content of oil-paper insulation will increase due to the insulation aging degradation and the humid air attack, and the insulation performance of oil-paper deteriorates with the increase of the moisture content. In addition, there is a wide spectrum of harmonics in the traction network, especially for the VFTO impulse. The VFTO contains components from DC to tens of megahertz [1], and the dielectric characteristics of the insulation will drastically vary in such a wide frequency range. The leading wave of the VFTO is microsecond level. Such a steep voltage shock will result in a very non-uniform voltage distribution in the main insulation system, and the voltage gradient is very large. Therefore, it is important to study the VFTO distribution in the insulation system considering the moisture and frequency dependence of the dielectric properties for the IOCT safe operation.

The size of the lead portion of the IOCT insulation system is much larger than that of the ring portion. In addition, the capacitive electrodes thin layer of semi-conductive paper should be taken into account for more accurate VFTO distribution calculation. On account of that, the finite element model is no longer applicable. Therefore the equivalent circuit model of analytical method is established. The applicable frequency of classical lumped element equivalent circuit used for VFTO calculation is below 1MHz [2]. To overcome this deficiency, the multi-transmission line (MTL) model has been widely used [3-4]. But the previous studies mainly focused on the analysis of the transient response of power transformers and motor windings, and they did not take into account the relationship between the dielectric parameters of insulation with the moisture content and frequency.

In this paper, the FDS of the IOCT insulation system at different moisture content are measured, and the results are fitted as a function of moisture content and frequency using the amendatory Cole-Cole model, firstly. Then the broadband frequency-domain MTL model of the IOCT insulation system is established considering the semi-conductive capacitive electrodes based on the equivalent circuit model. Finally, the VFTO distribution of the IOCT insulation system at different moisture content is obtained.

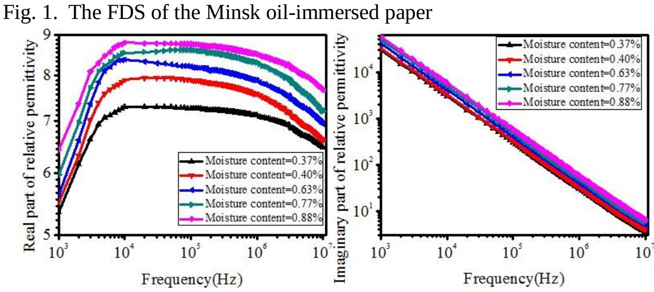
## II..THE MEASUREMENT AND FITTING OF THE FDS

The main insulation system of 330kV IOCT is consisted of the Minsk oil-immersed insulating paper layer and the German semi-conductive inserted electrodes (hereinafter referred to as insulation layer). The FDS of them at different moisture content were measured using the Alpha-A broadband dielectric spectrometer. The measurement results are shown in Fig. 1-2.




(a) The real part (b) The imaginary part

Fig. 1. The FDS of the Minsk oil-immersed paper




(a) The real part (b) The imaginary part

Fig. 2. The FDS of the German semi-conductive paper

The complex permittivity $\varepsilon^*$ is expressed as a function of angular frequency $\omega$ in the classical Debye relaxation model, but experimental results show that the Debye model is only consistent in dilute solutions and ferroelectric [5]. Therefore, the measured data are fitted using the amendatory double-relaxation Cole-Cole model considering DC conductance. The amendatory Cole-Cole model is shown in Fig. 3.

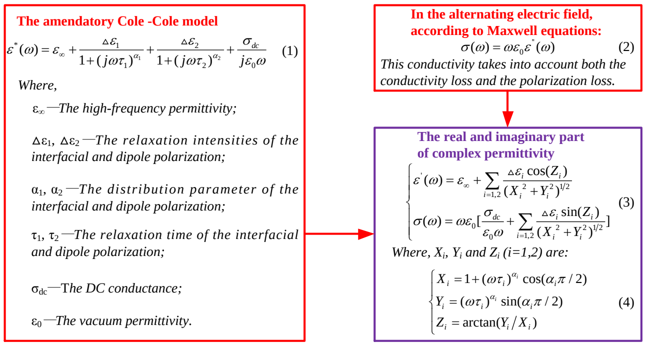



Fig. 3. The amendatory Cole-Cole model

The parameters of the model at different moisture content can be obtained using the least square method.

TABLE I THE FITTED PARAMETERS OF OIL-IMMERSED PAPER

| Moisture content (%) | $\varepsilon_\infty$ | $\Delta\varepsilon_1$ | $\Delta\varepsilon_2$ | $\alpha_1$ | $\alpha_2$ | $\tau_1$(s) | $\tau_2$(s) | $\sigma_{dc}$(ps/m) |
|---|---|---|---|---|---|---|---|---|
| 0.05 | 1.5 | 11 | 0.3 | 0.9 | 0.4 | 4000 | 0 | 71.3 |
| 0.23 | 1.6 | 11 | 0.2 | 0.9 | 0.4 | 4000 | 0 | 77.1 |
| 0.38 | 1.8 | 11 | 0.3 | 0.9 | 0.4 | 4000 | 0 | 83.9 |
| 0.52 | 1.9 | 11 | 0.4 | 0.9 | 0.4 | 4000 | 0 | 93.8 |
| 0.72 | 2.6 | 11 | 0.5 | 0.9 | 0.4 | 4000 | 0 | 221.3 |

TABLE II THE FITTED PARAMETERS OF SEMI-CONDUCTIVE PAPER

| Moisture content (%) | $\varepsilon_\infty$ | $\Delta\varepsilon_1$ | $\Delta\varepsilon_2$ | $\alpha_1$ | $\alpha_2$ | $\tau_1$(s) | $\tau_2$(s) | $\sigma_{dc}$(ps/m) |
|---|---|---|---|---|---|---|---|---|
| 0.37 | 6.4 | 1.5 | 0.7 | 0.8 | 1 | 3000 | 0 | 268.5 |
| 0.40 | 6.6 | 1.5 | 1.2 | 0.8 | 1 | 3000 | 0 | 290.4 |
| 0.63 | 6.8 | 1.5 | 1.2 | 0.8 | 1 | 3000 | 0 | 364.7 |
| 0.77 | 7.1 | 1.5 | 1.3 | 0.8 | 1 | 3000 | 0 | 440.8 |
| 0.88 | 7.6 | 1.5 | 1.1 | 0.8 | 1 | 3000 | 0 | 510.5 |

The two tables show that the variation of the parameters $\varepsilon_\infty$, $\Delta\varepsilon_2$, and $\sigma_{dc}$ is the most obvious and regular, while the others are constant. Thus, the former can be chosen as the characteristic parameter to represent the moisture content $m$ in the material. The fitted results are shown in Fig. 4.

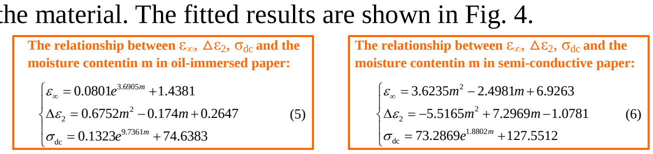



Fig. 4. The relationship between parameters and moisture content

Combining (2)-(6), the relative permittivity (real part, represent the capacitance characteristic) and conductivity (imaginary part, represent the resistance characteristic) can be expressed as the function of moisture content and frequency.

## III. THE ESTABLISHMENT OF MTL MODEL

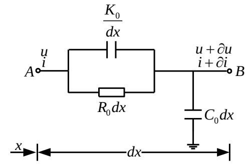
Assuming that:

(1)The distance of the ring portion from the ground is much larger than the radial dimension, and the radial dimension is much larger than the thickness of the insulation layer;

(2)Each insulation layer is uniform, i.e., the dielectric parameters of each insulation layer are equal everywhere along the thickness direction;

(3)Moisture content is not related to depth, i.e., the moisture content of every insulation layer is equal at the same time.

Considering the assumptions, the equivalent circuit diagram of the IOCT insulation system can be shown as in Fig. 5.




Where, $u, i$ are the voltage and current column vectors at the points $x$ of each layer;
$u+\partial u, i+\partial i$ are the voltage and current column vectors at points $x+dx$ of each layer;
$K_0, R_0$ and $C_0$ are the longitudinal capacitance, resistance and ground capacitance matrix of the unit insulation thickness, respectively.

Fig. 5. The equivalent circuit diagram of the IOCT insulation system

According to the equivalent circuit, the circuit equation of the insulation system is shown in the following (7):

$$\begin{cases} -\partial u = \dfrac{R_0(\omega,m)dx}{1+j\omega K_0(\omega,m)R_0(\omega,m)} \cdot i \\ -\partial i = j\omega C_0 dx \cdot u \end{cases} \tag{7}$$

For the power transformer windings and the IOCT insulation system, although the model and parameters of them are different, the essence of the VFTO distribution calculations is similar. Therefore, the MTL model of the IOCT insulation system is established to calculate the VFTO distribution at the different moisture content. The establishment and calculation of the MTL model are shown in Fig. 6.

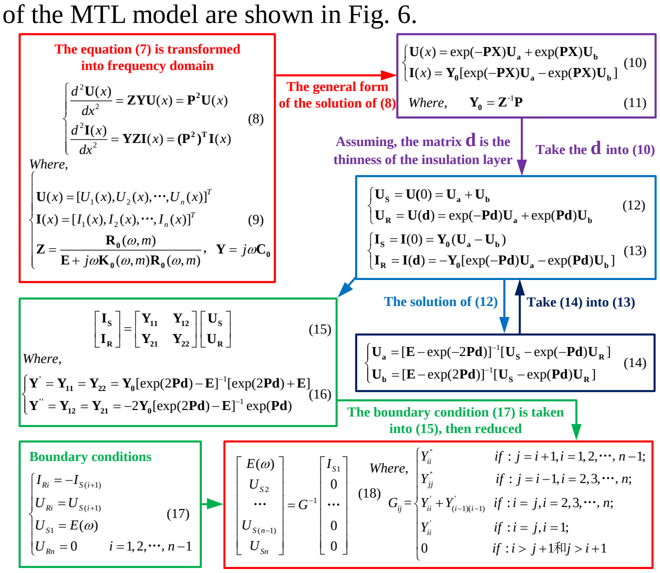



Fig. 6. The establishment and calculation of the MTL model

## IV. THE CALCULATION AND CONCLUSION

The standard chopped wave 1.2/50.0μs is used as impulse voltage, and the full-wave is truncated at 2.5μs. The calculations and conclusion will be shown in full paper. The results show that the method proposed in this paper is feasible for the study of the VFTO distribution of IOCT at different moisture content.

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