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Based on Energy Ratio Curve Locating Partial Discharge in Single Phase Transformer Winding

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Abstract: - Based on multi-conductor transmission lines (MTLs) theory, a model of partial discharge pulse propagating in single phase transformer is established. The distributed parameters of transformer winding MTLs model are calculated, and the scattering parameter measuring method is applied to validate this MTLs model. Then energy ratio curve can be simulating calculated by MTLs model or measured by test. When the discharge location is far away HV terminal and close earth terminal, energy ratio curve descend with a logarithmic relationship, which is partial discharge location criterion. Three different transformer windings test results show the validity of energy ratio curve method.

Key-Words: - Partial discharge, Multi-conductor transmission lines(MTLs), Transformer winding, Fault location, Energy ratio

1 Introduction

Partial discharge (PD) pulse propagation course from discharge location inner transformer to the measure terminals will appear signal distorted, signal decaying, waveform distortion and time delay, etc. It is important to study the propagation process of discharge pulse along the transformer windings which has important value for transformer partial discharge detection.

R.E.James have equaled the transformer winding as a capacitive network in 1977[1], but this method is only valid over a limited frequency range and mainly for the interleaved winding. But for continuous type windings or others, these frequency bands are very narrow or not exist at all. At present, it is studying mainly for setting up lump parameter model [2, 3] of PD propagation in transformer winding with frequency variation parameter. But the lump parameter unit method has the upper limit frequency. PD itself includes abundant frequency composition, experimental study shows, discharge energy in transformer oil concentrate on within several tens MHz mainly [4], therefore, the lump parameter model is unavailable in high frequency range.

In recent years, based on multi-conductor transmission lines (MTLs) theory, a new model of partial discharge pulse propagating in single winding is established. S.N.Hettiwatte and Z.D.Wang have preliminary set up the MTLs model of PD pulse propagation along the continuous type winding [5]. The calculation result indicates that the transfer functions of winding represent the message of PD orientation.

In this paper, based on multi-conductor transmission lines (MTLs) theory, a model of partial discharge pulse propagating in single phase transformer is established. Together with the real winding structure, the current transfer functions of sectional transformer winding are calculated. Energy ratio value of partial discharge in different transformer winding location also are simulating calculated, which used for PD location in transformer winding.

2 MTLs Model of Transformer Winding

2.1 MTLs Models of Different Transformer Windings

In the progress of PD pulse propagation along the transformer winding, the winding itself is considered as a single input multiple output (SIMO) system, where the input is the PD signal and the outputs are the current signals at the measuring terminals. Every turn of the windings may be looked as a transmission line [5], as shown in Fig.1, and the transmission line equations are:

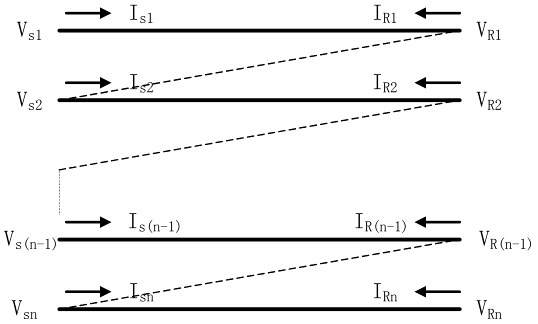


Fig.1 Multi-conductor transmission line model

$$\begin{aligned} \frac{d^2\mathbf{V}(z)}{dz^2} &= \mathbf{ZYV}(z) = \mathbf{P}^2\mathbf{V}(z) \\ \frac{d^2\mathbf{I}(z)}{dz^2} &= \mathbf{YZI}(z) = \mathbf{P}_t^2\mathbf{I}(z) \end{aligned} \qquad (1)$$

Where impedance matrix $\boldsymbol{Z}=\boldsymbol{R}+j\omega\boldsymbol{L}$， admittance matrix $\boldsymbol{Y}=\boldsymbol{G}+j\omega\boldsymbol{C}$ and $\boldsymbol{P}^2=\boldsymbol{ZY}$, $\boldsymbol{P}_t^2=\boldsymbol{YZ}$.

When the distributing parameter is related to frequency， it is more convenient to adopt the frequency field analysis[6]. Since $\boldsymbol{Z}$ and $\boldsymbol{Y}$ in equation (1) are both full matrix, the decoupling calculating amount is very large. In order to simplify the calculation of these equations, the mode transformation method is generally taken[7]. Transform $\boldsymbol{P}^2$ or $\boldsymbol{P}_t^2$ into diagonal matrix so as to realize equation (1) decoupling.

If a MTLs system is made up of n-conductor lines, the $\boldsymbol{T}_V$ and $\boldsymbol{T}_I$ are its mode voltage transformation matrix and mode current transformation matrix respectively, $\boldsymbol{V}^m=\boldsymbol{T}_V^{-1}\boldsymbol{V}$ is mode voltage, $\boldsymbol{I}^m=\boldsymbol{T}_I^{-1}\boldsymbol{I}$ is mode current，and $\boldsymbol{T}_I=\boldsymbol{T}_V^{-1T}$, so the waveform equations of mode voltage can be shown as:

$$\frac{d^2}{dz^2}\mathbf{V}^m(z) = \mathbf{T}_V^{-1}\mathbf{ZYT}_V\mathbf{V}^m(z) = \begin{bmatrix} r_1 & & & & \\ & \ddots & & & \\ & & r_k & & \\ & & & \ddots & \\ & & & & r_n \end{bmatrix} \begin{bmatrix} \mathbf{V}_1^m(z) \\ \vdots \\ \mathbf{V}_k^m(z) \\ \vdots \\ \mathbf{V}_n^m(z) \end{bmatrix} \qquad (2)$$

$$\frac{d^2}{dz^2}\mathbf{I}^m(z) = \mathbf{T}_I^{-1}\mathbf{ZYT}_I\mathbf{I}^m(z) = \begin{bmatrix} r_1 & & & & \\ & \ddots & & & \\ & & r_k & & \\ & & & \ddots & \\ & & & & r_n \end{bmatrix} \begin{bmatrix} \mathbf{I}_1^m(z) \\ \vdots \\ \mathbf{I}_k^m(z) \\ \vdots \\ \mathbf{I}_n^m(z) \end{bmatrix} \qquad (3)$$

The solution of superposition type wave equation of the incident and reflection wave is:

$$\begin{aligned} V_{m(j)}(z) &= V_{m(j)}^{+}e^{-r_j z} + V_{m(j)}^{-}e^{r_j z} \\ I_{m(j)}(z) &= I_{m(j)}^{+}e^{-r_j z} - I_{m(j)}^{-}e^{r_j z} \end{aligned} \qquad (4)$$

With boundary conditions x=0 and x=l, the relations between voltage and current terminal conditions of MTLs are as following

$$\begin{bmatrix} \mathbf{I}_S \\ \mathbf{I}_R \end{bmatrix} = \begin{bmatrix} \mathbf{A} & -\mathbf{B} \\ -\mathbf{B} & \mathbf{A} \end{bmatrix} \begin{bmatrix} \mathbf{V}_S \\ \mathbf{V}_R \end{bmatrix} \qquad (5)$$

Where:

$$\boldsymbol{A} = \boldsymbol{Y}_C\boldsymbol{T}_V Coth(\boldsymbol{r}l)(\boldsymbol{T}_V)^{-1} = \boldsymbol{Y}\boldsymbol{T}_V\boldsymbol{r}Coth(\boldsymbol{r}l)(\boldsymbol{T}_V)^{-1}$$

$$\boldsymbol{B} = \boldsymbol{Y}_C\boldsymbol{T}_V Cosech(\boldsymbol{r}l)(\boldsymbol{T}_V)^{-1} = \boldsymbol{Y}\boldsymbol{T}_V\boldsymbol{r}Cosech(\boldsymbol{r}l)(\boldsymbol{T}_V)^{-1}$$

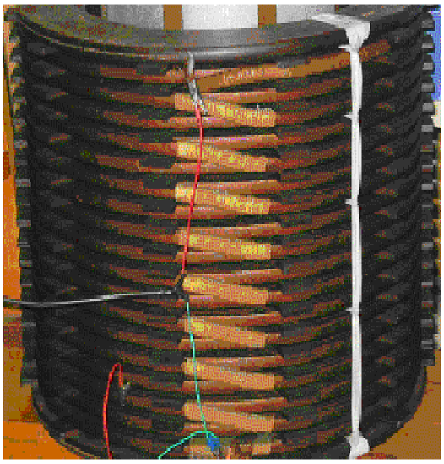


Fig.2 180 turns single winding

180 turns single winding is shown in Fig.2 its height is 560mm, its inside diameter and outside diameter are respectively 240mm and 360mm. This winding has 18 sections, and every section is 10 turns, sum to 180 turns, so its MTLs model can be expressed as following:

$$\begin{bmatrix} \mathbf{I}_S|_{180\times1} \\ \mathbf{I}_R|_{180\times1} \end{bmatrix} = \begin{bmatrix} \mathbf{A} & -\mathbf{B} \\ -\mathbf{B} & \mathbf{A} \end{bmatrix} \begin{bmatrix} \mathbf{V}_S|_{180\times1} \\ \mathbf{V}_R|_{180\times1} \end{bmatrix} \qquad (6)$$

Fig.3 400kV transformer high voltage winding

High voltage winding of 400kV transformer OSFPSZ-2400/400 is shown in Fig.3. Its height is 2307mm, and its inside diameter and outside diameter are respectively 1650mm and 1962mm. This winding has 56 sections, sum to 973 turns current conductors and 59 turns shielding conductors, so its MTLs model can be expressed as following:

$$\begin{bmatrix} \mathbf{I}_S\big|_{(973+59)\times 1} \\ \mathbf{I}_R\big|_{(973+59)\times 1} \end{bmatrix} = \begin{bmatrix} \mathbf{A} & -\mathbf{B} \\ -\mathbf{B} & \mathbf{A} \end{bmatrix} \begin{bmatrix} \mathbf{V}_S\big|_{(973+59)\times 1} \\ \mathbf{V}_R\big|_{(973+59)\times 1} \end{bmatrix} \tag{7}$$

Fig 4 500kV transformer high voltage winding

High voltage winding of 500kV transformer ODFPSZ-250000/500 is shown in Fig.4. Its height is 2315mm, and its inside diameter and outside diameter are respectively 2009mm and 2450mm, This winding has 54 sections, sum to 461 turns current conductors and 53 turns shielding conductors, so its MTLs model can be expressed as following:

$$\begin{bmatrix} \mathbf{I}_S\big|_{(461+53)\times 1} \\ \mathbf{I}_R\big|_{(461+53)\times 1} \end{bmatrix} = \begin{bmatrix} \mathbf{A} & -\mathbf{B} \\ -\mathbf{B} & \mathbf{A} \end{bmatrix} \begin{bmatrix} \mathbf{V}_S\big|_{(461+53)\times 1} \\ \mathbf{V}_R\big|_{(461+53)\times 1} \end{bmatrix} \tag{8}$$

2.2 Transformer Winding MTLs Model's Parameters

It is important to calculate the capacitance parameter matrix of MTLs [8]. At present it often use equivalent model of parallel plate capacitance, this method neglects border effect among conductors and has some certain approximately. In this paper, using finite element method to calculate the static electric field distribution and using electric field power to calculate capacitance may avoid this limitation [9].

With the m-conductors, we study the k_{th}

$$\begin{aligned} q_k &= C_{k1}U_{k1} + C_{k2}U_{k2} + \cdots + C_{k,k-1}U_{k,k-1} \\ &\quad + C_{k0}U_{k0} + \cdots + C_{km}U_{km} \end{aligned} \tag{9}$$

Where C_{ij} ($i{\neq}j$, i, j=0…m) is mutual capacitance among conductors. Not considering the dielectric vary with frequency, the mutual capacitance has relation to the dielectric constant and conductor form, relative position rather than conductor voltage. U_k= 1V, when other conductors are grounded, the static electric field power is:

$$\begin{aligned} W_{ek} &= \frac{1}{2} q_k U_k \\ &= \frac{1}{2}\left(C_{k1} + C_{k2} + \cdots + C_{k,k-1} + C_{k0} + C_{k,k+1} + \cdots + C_{km}\right) \end{aligned} \tag{10}$$

Using finite element software to calculate the electrostatic field distribution and electric field power can get the sum of mutual capacitance between conductor k and other conductors. According to which, adopting different voltage way to the conductor, the linear equations of mutual capacitance can be get, decouple these equations the capacitance matrix is obtained.

Other parameters $\boldsymbol{R}$, $\boldsymbol{L}$, $\boldsymbol{G}$ result from the relationship among the parameters. The conductor inductance of transformer winding MTLs model is made up with two parts. One part is $\boldsymbol{L}_n$, which is produced by outer magnetic line of winding conductor, the other part is interior inductance $\boldsymbol{L}_i$ as a result of high frequency Kelvin effect enter into conductor. Considering skin effect under high frequency, the resistance matrix is shown as:

$$\mathbf{R}_S = \frac{1}{2\left(d_1 + d_2\right)} \sqrt{\frac{\pi f u}{\sigma}} \mathbf{E} \tag{11}$$

Where μ is magnetic permeability of conductor, d_1 and d_2 are sectional size of the conductor, σ is conductivity. Considering the capacitance loss, it looks capacitance among windings as the resistance and capacitance parallel branch, then $\mathbf{G} = 2\pi f \mathbf{C} \tan\delta$.

2.3 Validity of Transformer Winding MTLs Model

Use Agilent 4395 network/spectrum/resistance analyzer to measure the scattering parameter of a 400kV single phase transformer winding [10], which is shown in Fig.5. The reference resistance is 50Ω. The measuring and simulating current transfer functions I_{pd}/I_{end} are shown in Fig.6.

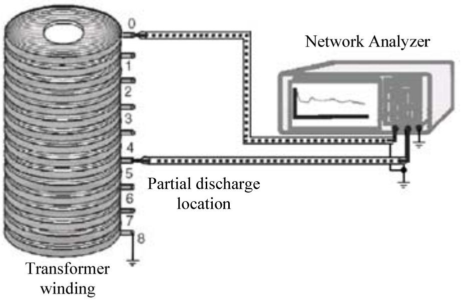
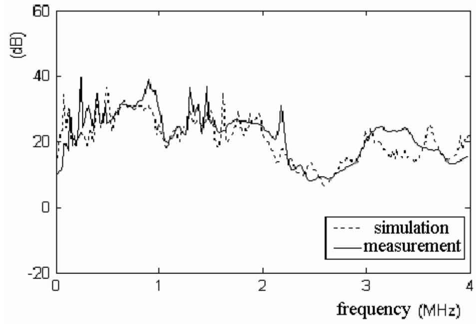


Fig.5 Scattering parameters measuring system

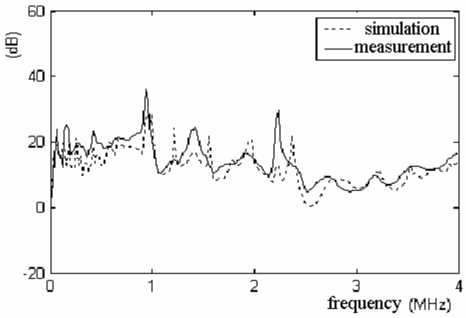
Compare the measuring and simulating results of different location current transfer function in Fig.5 and Fig.6, their waveforms of measurement and simulation are relatively close. In order to realize quantitative analyzes, correlation coefficient is applied. It is defined as follows:

$$R(x,y)=\left|\sum_i x_i y_i\right| \Big/ \left(\sum_i x_i^2 \sum_i y_i^2\right)^{\frac{1}{2}} \qquad (12)$$

Table 1 has given the results of 400kV transformer winding correlation coefficient, where the elements in diagonal are the most great, which indicate that the measuring and simulating results of the same discharge location have the best relativity. This result has also indicated that the model and its analytical method can well reflect the reality propagation characteristic of partial discharge pulse along the transformer winding.



(a) 24 section



(b) 40 section

Fig.6 Current transfer function I_{pd}/I_{end} at different locations of 400kV winding

Table 1 Correlation coefficients of 400kV transformer winding

Sim. (section)	Mea. (section)					
	8	16	24	32	40	48
8	**0.856**	0.823	0.768	0.749	0.755	0.707
16	0.798	**0.863**	0.748	0.770	0.765	0.724
24	0.783	0.812	**0.843**	0.737	0.774	0.741
32	0.778	0.772	0.821	**0.845**	0.789	0.762
40	0.771	0.789	0.751	0.744	**0.822**	0.775
48	0.634	0.715	0.732	0.694	0.693	**0.860**

3 Energy Ratio Curve Location

There exits a relationship between energy ratio curve and partial discharge location. With the increase of the distance between partial discharge source and measuring terminal (HV terminal or earth terminal), the energy of terminal measuring signal is decrease.

E_{hv} and E_{end} are measuring discharge energy of HV terminal and earth terminal, and are defined as following.

$$\begin{aligned} E_{hv} &= \int \left|i_{hv}(t)\right|^2 dt = \int \left|i_{hv}(j\omega)\right|^2 d\omega \\ E_{end} &= \int \left|i_{end}(t)\right|^2 dt = \int \left|i_{end}(j\omega)\right|^2 d\omega \end{aligned} \qquad (13)$$

Then the energy-ratio curve can be expressed as $E_{hv}/E_{end}\big|_{f\in(f_1,f_2)}$, when the partial discharge location is farer away HV port, the energy-ratio value is smaller. f_1 and f_2 are lower limiting frequency and upper limiting frequency respectively. Based on two sides, the frequency range is selected. One side is the power spectrum distribution of original discharge signal itself, the power spectrum distributions of typical discharge signals are usually under several tens MHz. On the other side, under the selected frequency range, the transformer winding MTLs model is effective. Part 2.3 show the validity of Transformer Winding MTLs Model under frequency range from 100 kHz to 4 MHz. So lower limiting frequency is 100 kHz and upper limiting frequency is 4 MHz, and the energy-ratio curve can be expressed as

$$E_{hv}/E_{end}\Big|_{f\in(100kHz,4MHz)} \qquad (14)$$

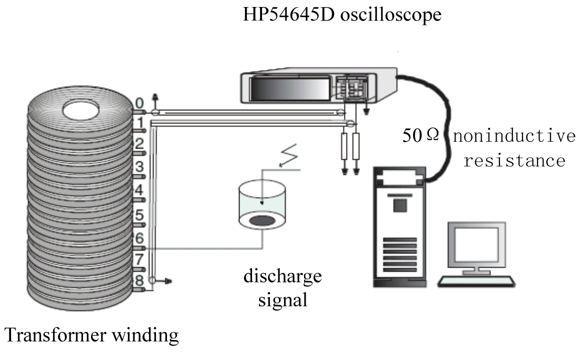


Fig.7 Energy ratio curve test system

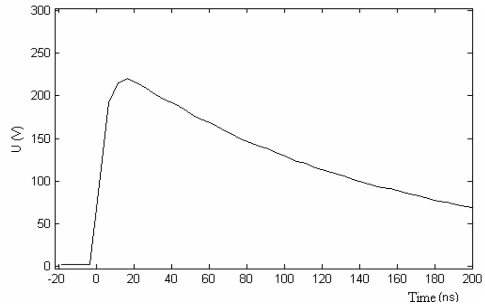


Fig.8 High voltage discharge pulse

Fig.7 gives out the energy ratio curve test system of partial discharge in transformer winding, and this is a test method. High voltage discharge pulse is shown in Fig.8. At the same time, the energy ratio curve can be gotten by MTLs model simulating calculation which is afforded in upper part 2, and this is a simulating method. Then the test and simulating energy ratio curves of different transformer windings are shown from Fig.9 to Fig.11. The test results are shown in real line and the simulating results is shown in dotted line.

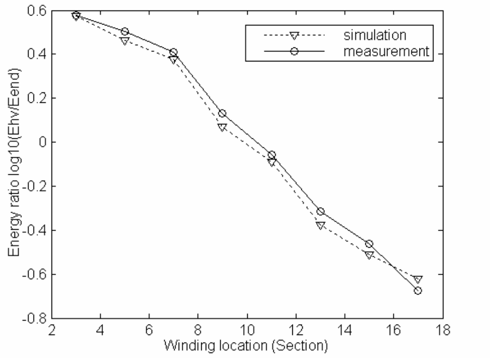


Fig.9 Energy ratio curve of 180 turn winding

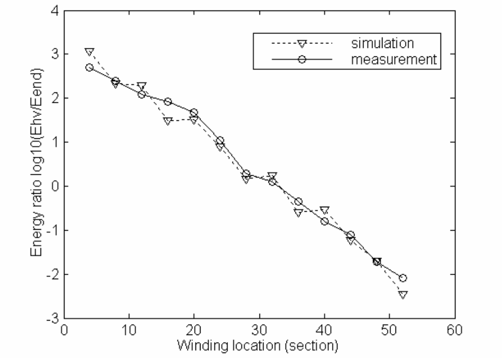


Fig.10 Energy ratio curve of 400kV high voltage winding

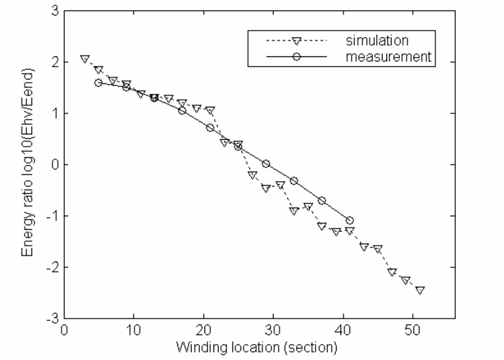


Fig.11 Energy ratio curve of 500kV high voltage winding

From the simulating and measuring results of discharge energy ratio curve in Fig.9, Fig.10 and Fig.11, several useful conclusions can be drawn.

(1) There are two methods to get energy ratio curve of partial discharge in transformer winding, one is simulating calculation and the other is test method. They can be regard as the locating criterion and the beforehand knowledge of partial discharge in transformer winding. When partial discharge happens in transformer winding, the HV terminal and earth terminal measurement can be done, and energy ratio value $E_{\mathrm{hv}}/E_{\mathrm{end}}$ is acquired, then compare to the beforehand simulating or measuring locating criterion, the partial discharge source can be located.

(2) There is a change rule between partial discharge location and energy ratio curve $E_{hv}/E_{end}\big|_{f\in(100kHz,4MHz)}$. When the discharge location is far away HV terminal and close earth terminal, energy ratio curve is descend with a logarithmic relationship.

(3) From Fig.9 to Fig.11, the simulating and measuring results of energy ratio curve are consistency. If the simulating energy ratio curve is regard as the locating criterion, every measuring energy ratio value is regard as a real discharge in transformer winding, and then the maximal discharge location error is the maximal transverse distance

between simulation and measurement which appear in Fig.9, Fig.10 and Fig.11. The height location error and relative error of three different transformer windings are shown in table 2. The maximal relative error is no more than 5%.

Table 2 Partial discharge location error based on energy ratio curve

Transformer winding type	Winding height (mm)	Height location error (mm)	Relative error (%)
180 turns	560	26.43	4.72
400kV HV	2307	102.9	4.46
500kV HV	2315	104.4	4.45

4 Conclusion

Based on the MTLs theory, a model of partial discharge pulse propagating in single phase transformer winding is established. Sectional transfer functions between winding terminal and partial location are obtained, then energy ratio curve can be simulating calculated.

Partial discharge location depends on energy ratio value of the terminal discharge response signals in the frequency from 100 kHz to 400 MHz. the relationship between energy ratio and location is described by energy ratio curve. Three different transformer windings test results show the validity of energy ratio curve method.

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