The characteristics of transfer functions for detecting winding displacements by impulse method

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Abstract: The paper investigates three types of transfer function methods for detecting displacements of winding in a model transformer. To acquire these transfer functions, the measuring method of input voltage, current and its response is used in impulse method. Every 10 measurements of voltage and current waves were averaged from 50 measurements of voltage and current waves. These transfer functions were tested in normal, 24mm elevated and 48mm elevated windings conditions and features of correlation coefficient, spectrum deviation, absolute sum of logarithmic error and max-min error in these transfer functions were analyzed with artificial neural network. In the analysis, the regression values become higher as the composition number increases. But in the case of TF2(ω), the all feature composition showed worse result than the two or three features compositions..

1 INTRODUCTION

In the power networks there are many power transformers, circuit breaks and various apparatus. High short-circuit currents do damage to these power apparatus. In the power transformers, these currents cause deformation and displacement of transformer windings due to mechanical forces. Such deformation do not necessarily lead to an immediate failure of transformer, but its ability to withstand mechanical and dielectric stresses may be strongly reduced. To ensure a sufficient ability to withstand short circuits modern diagnostic methods should identify such pre-damaged power transformers.

Representative diagnostic methods are the reactance measurement and FRA(Frequency Response Analysis). The reactance measurement is not usually applicable for detecting winding displacements at power transformers already in service. The main reason is that displacements have only a very small effect on the reactance of the winding in concern [1], [2].

FRA is a powerful diagnostic technique to detect winding displacements. It consists of measuring transfer functions of transformer windings over the wide range of frequencies and comparing the result of these measurements with a reference set. There are two ways of injecting the signal of wide range frequencies necessary, either by injecting an impulse into the winding or by making a frequency sweep using a sinusoidal signal.

The main advantage of the impulse response method over the swept frequency method is a shorter measurement time but does not equal or nearly equal, accuracy and precision across the whole measurement range [3], [4]. The accuracy and precision in FFT results are limited by sampling time and acquired data numbers. However impulse response method has the room for developing diagnostic technologies.

Therefore to overcome these problems three type transfer functions which were calculated with input voltage, input current and its response were suggested and features of correlation coefficient, spectrum deviation, absolute sum of logarithmic error and max-min error in these transfer functions were analyzed with artificial neural network in this paper.

2 TRANSFER FUNCTION METHOD

The transfer function (TF) is an approximation to the Fourier transformed impulse response H(ω). It is calculated as the quotient of an applied input signal X(ω) and its response Y(ω) in frequency domain according to

$$\mathrm{H}(\omega) = \frac{\mathrm{Y}(\omega)}{\mathrm{X}(\omega)} \tag{1}$$

For this investigation, X(ω) and Y(ω) have been determined by a Fourier transformation of an applied low voltage impulse x(t) and its response y(t) [2], [5].

When input voltage V(t), current I(t) and its response R(t) are measured, three types of transfer functions could be suggested. These transfer functions are as follows

$$\mathrm{TF1}(\omega) = \frac{\mathrm{R}(\omega)}{\mathrm{V}(\omega)} \tag{2}$$

$$\mathrm{TF2}(\omega) = \frac{\mathrm{R}(\omega)}{\mathrm{I}(\omega)} \tag{3}$$

$$\mathrm{TF3}(\omega) = \frac{\mathrm{I}(\omega)}{\mathrm{V}(\omega)} \qquad (4)$$

TF1(ω) is a transfer function which consists of input voltage V(ω) and its response R(ω). TF2(ω) is a transfer function which consists of input current I(ω) and its response R(ω). TF3(ω) is a transfer function(admittance) which consists of input voltage V(ω) and current I(ω) that is a response of V(ω).

3 EXPERIMENTAL METHOD

3.1 Experimental equipment

To acquire high signal to noise ratio, the impulse charging voltages (Maximum charging voltage 4kV) were applied with 1 kV. As input voltage is applied, input current and output current (voltage) were measured and three type transfer functions could be acquired. The input module that consists of a voltage divider to measure the input voltage and a high frequency current transformer (CT) to measure input current were designed in our laboratory. The voltage divider is less than 10% errors in the range of from DC to 10MHz. The bandwidth of the high frequency CT is 20MHz (CT Pearson 2100). The output currents were transformed into output voltages with 4 ohm resister. The input module is shown in **Figure 1** [6]. The voltages and currents were measured with a digital oscilloscope (Wavepro 960, LeCroy Co.).

The model transformer which consists of three legs core, high voltage windings and low voltage windings was used in our experiment. The size and picture of model transformer is shown in **Figure 2**. The connections could be changed to three phase(Y or Delta) or single phase.

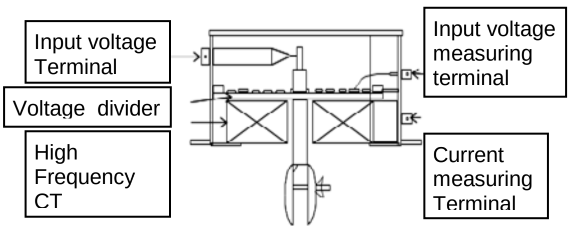
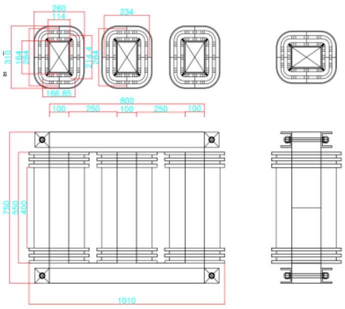


Figure 1: Figure of input module

3.2 Experimental Method

To diagnose displacement of windings, the impulse input voltages was applied to the model transformer through a input module. The applied impulse voltages had three rising times, which were short rising time(less than 0.6 μs), medium rising time(about 0.8 μs) and long rising time(about 1 μs) in front waves. The input voltages were applied to the terminals of transformers through a input module. The input voltages were applied to 50 times in one testing condition. Input voltages, input currents and output currents were measured with a digital oscilloscope. Every 10 measurements of voltage and current waves were averaged from 50 measurements of voltage and current waves.

The model transformer was tested with single phase connection and testing circuit is shown in **Figure 3**. The three testing conditions were controlled by arrangement of high voltage winding and **Figure 4** shows the normal arrangement and 48mm elevated windings. The first condition was the normal arrangement of windings. The second one was high voltage winding elevated 24mm from low voltage winding and third one was high voltage winding elevated 48mm from low voltage winding.



(a) Design sheet

(b) Picture

Figure 2: The design and picture of the model transformer

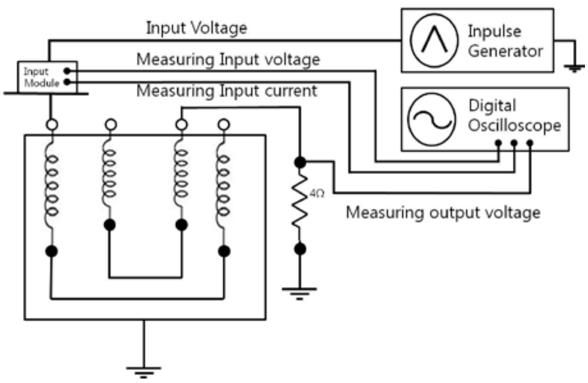


Figure 3: Measuring Circuit in model transformer

4 EXPERIMENTAL RESULTS

When input voltages were applied to model transformer, input voltages, input currents and output currents were measured as shown in **Figure 5**. **Figure 6** shows TF1(ω), TF2(ω), and TF3(ω). And every transfer functions were plotted with 5 sets of 10 averaged data.

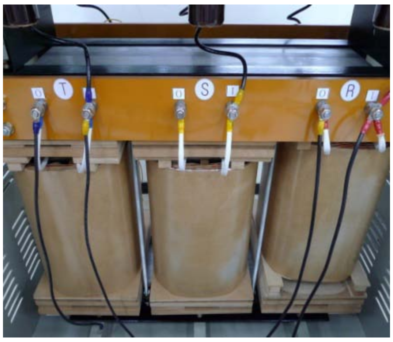


Figure 4: The arrangement of windings in model transformer.

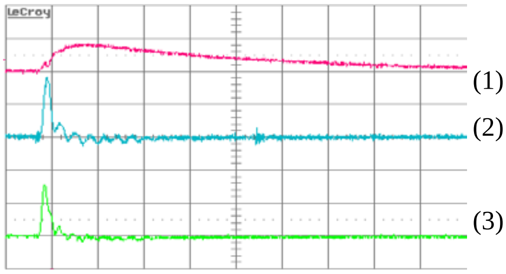
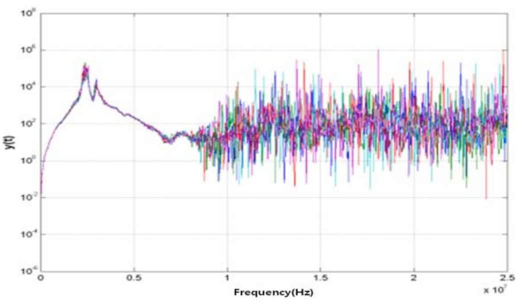
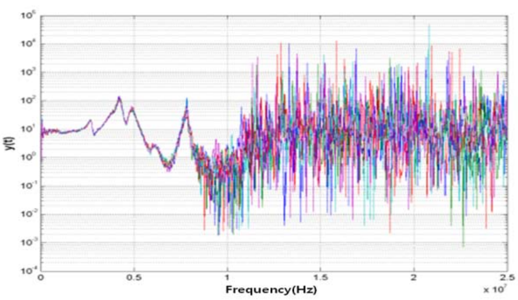


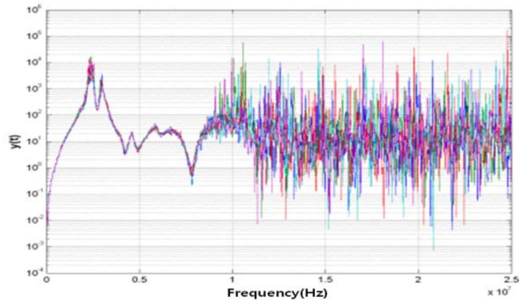
Figure 5: The waves of input voltages(1), input currents(2), and their responses(3)



(a)TF1(ω)



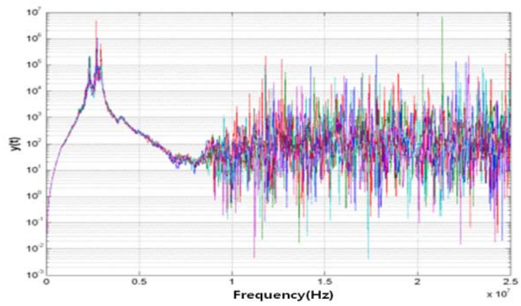
(b) TF2(ω)



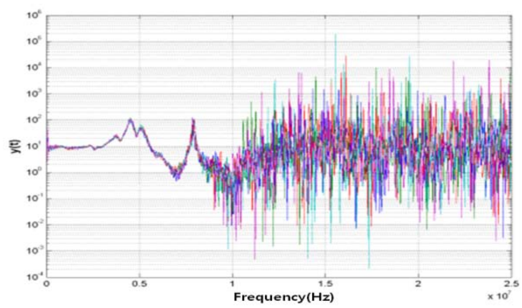
(c) TF3(ω)

Figure 6: The estimated transfer functions in normal winding arrangement.

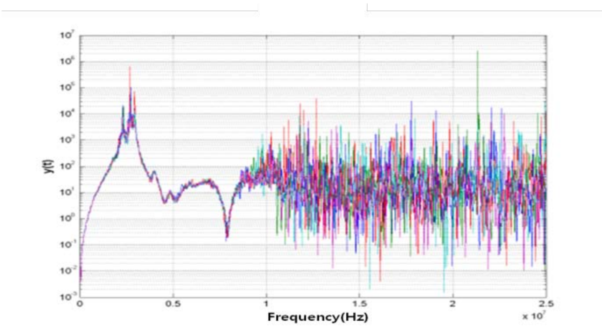
Figure 7(a) shows TF1(ω), TF2(ω) and TF3(ω) transfer functions which were calculated on the measured data in the testing conditions of high voltage winding elevated 24 ㎜ from low voltage winding. **Figure 7**(b) shows those of the high voltage winding elevated 48 ㎜ from low voltage winding. Every transfer functions show small differences between 24 ㎜ elevated winding and normal winding arrangement. But there are big differences between 48 ㎜ elevated winding and normal winding arrangement.



TF1(ω)

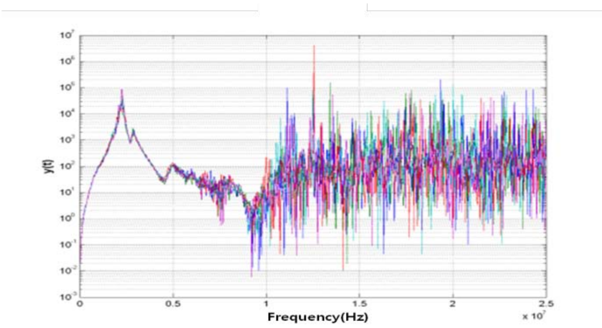


TF2(ω)

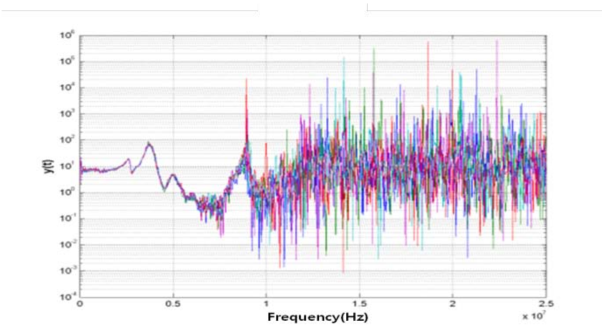


TF3(ω)

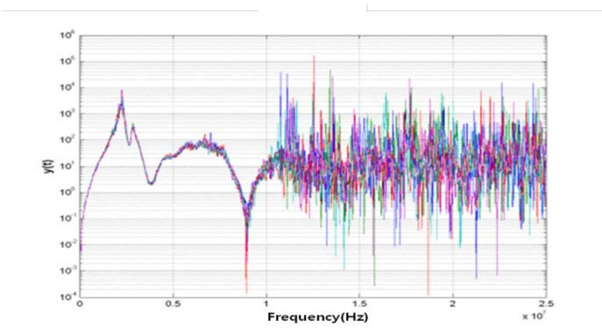
(a) High voltage winding elevated 24mm from low voltage winding



TF1(ω)



TF2(ω)



TF3(ω)

(b) High voltage winding elevated 48mm from low voltage winding

Figure 7: The estimated transfer functions in high voltage winding elevated 24mm and 48mm from low voltage winding

5 . CLASSIFICATION BY NEURAL NETWORK LEARNING

In order to calssify the movement of the coils, we have used artificial neural network (ANN) algorithm. Using backpropagation algorithm we have tried to classify the features extracted from the above transfer functions. The extracted features are the correlation coefficients (CC) proposed by Xu, Fu, and Li in [7], spectrum deviation (SD) by Bak Jenson and Mikkelsen in [5], absolute sum of logarithmic error (ASLE) and max-min error (MM) by J. R Secue and E. Mombello [8]. These features are obtained by the equations below.

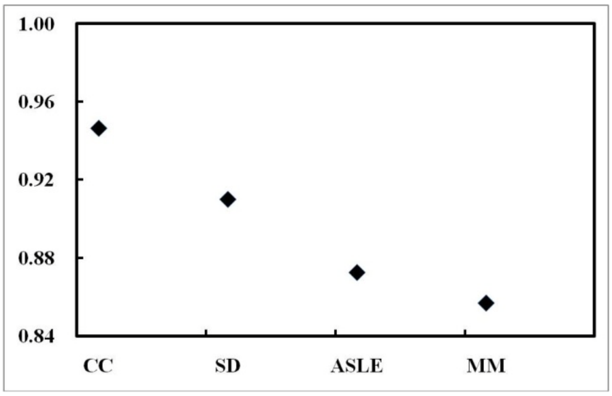
$$CC = \sum_{x=i}^{n} x_i\, y_i \Big/ \sqrt{\sum_{x=i}^{n} x_i^2 \sum_{y=i}^{n} y_i^2} \quad (5)$$

$$SD = \frac{1}{n}\sum_{i=1}^{n} \sqrt{\left(\left[\frac{x_i-(x_i+y_i)/2}{(x_i+y_i)/2}\right]^2 + \left[\frac{y-(x_i+y_i)/2}{(x_i+y_i)/2}\right]^2\right)} \quad (6)$$

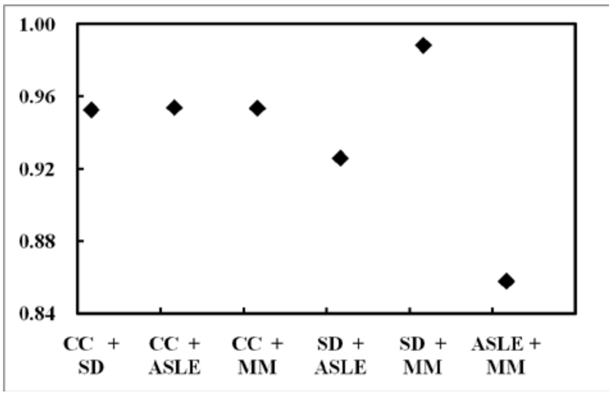
$$ASLE = \frac{\sum_{i=1}^{n} |20\log_{10} y_i - 20\log_{10} x_i|}{N} \quad (7)$$

$$MM = \frac{\sum_{i=1}^{N} \min\,(x_i, y_i)}{\sum_{i=1}^{N} \max\,(x_i, y_i)} \quad (8)$$

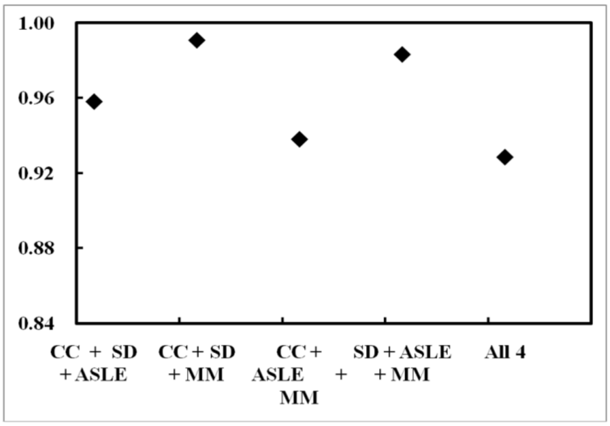
The four features are extracted from the three transfer functions and used for the classification algorithm. The results are compared using average regression values of the features. The regression values of every one feautres and compositions of all features are calculated and compared for the three transfer functions. The compositions of features of TF2(ω) are shown in **Figure 8**. The closer to 1, the better the learning and classification. **Figure 8**(a) is one extracted feature and CC is the closest to 1. **Figure 8**(b) is two compositions of features and SD+MM is the closest to 1. And **Figure 8**(c) is three and all compositions of features and CC+SD+MM is the closest to 1. In order to estimate TF1(ω), TF2(ω) and TF3(ω), the average regression values with composition numbers of features are used and shown in **Figure 9**.



(a)



(b)



(c)

Figure 8: The optimized average regression values of (a) one extracted feature, (b) two compositions, (c) three and all 4 compositions of TF2(ω) parameters.

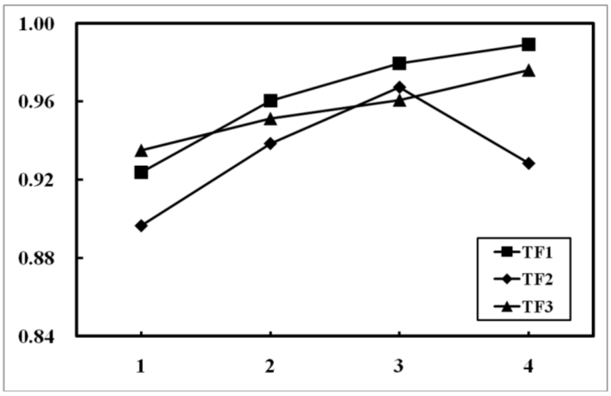


Figure 9: The optimized average regression values of all the transfer functions with the composition numbers. The X axis is the number of compositions used in ANN algorithm.

As shown in the figure, the regression values becomes higher as the composition number increases. But in the case of TF2(ω), the all feature composition showed worse result than the two or three features compositions. It means that there is an optimized features exist for a given transfer function.

6 CONCLUSION

We have discussed the characteristics of three types of transfer functions (TF1(ω), TF2(ω), TF3(ω)) based on the measurement of input voltage, current and its response. To diagnose the displacement of windings in model transformer, features of CC, SD, ASLE and MM in these transfer functions were analyzed with artificial neural network. In this analysis, the regression values have different values according to the composition of features. In this result the regression values become higher as the composition number increases. But in the case of TF2(ω), the all feature composition showed worse result than the two or three features compositions. Therefore this analysis method will be tested in another testing conditions and have to be developed in the next research.

7 REFERENCES

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