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Study on the Transfer Functions for Detecting Windings Displacement of Power Transformers with 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. 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. 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 were analyzed with correlation coefficients and spectrum deviations. In the analysis, the results depend on the types of transfer functions and the rising times of input voltages.

Keywords: Transformers, Windings, Displacement, Transfer function, Frequency response analysis (FRA), Impulse, Correlation coefficient, Spectrum deviation, Diagnosis

1. Introduction

In the power networks there are many power transformers, circuit breakers and various apparatuses. High short-circuit currents do damage to these power apparatuses. 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 measure-ments 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 the characteristics of these transfer functions were analyzed 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

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

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

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

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

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

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 developed 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 Fig. 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 are shown in Fig. 2. The connections could be changed to three phase(Y or Delta) or single phase.

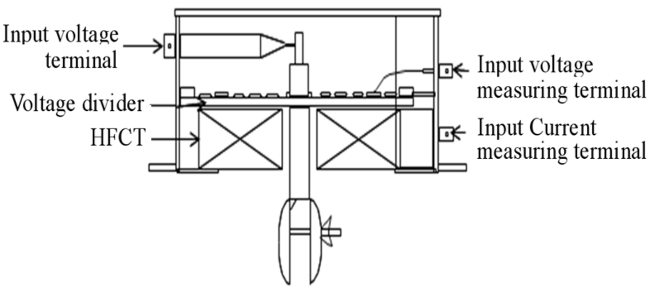
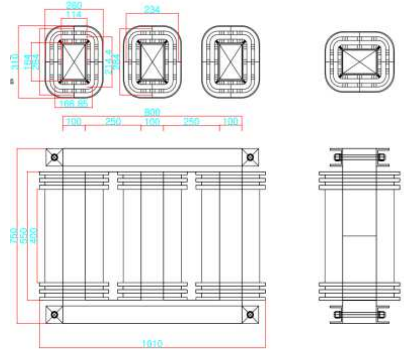


Fig. 1. Figure of input module

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 0.6μs), medium rising time(about 0.8μs) and long rising time (about 1μs) 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



(a) Design sheet

(b) Picture

Fig. 2. The design and picture of the model transformer

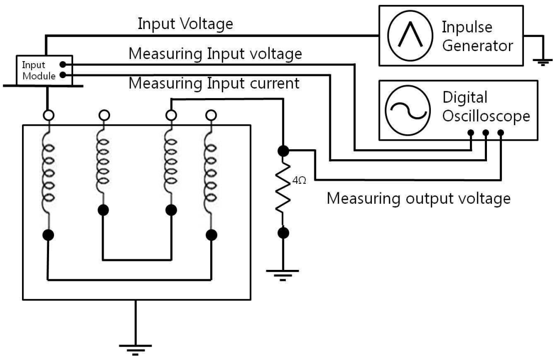
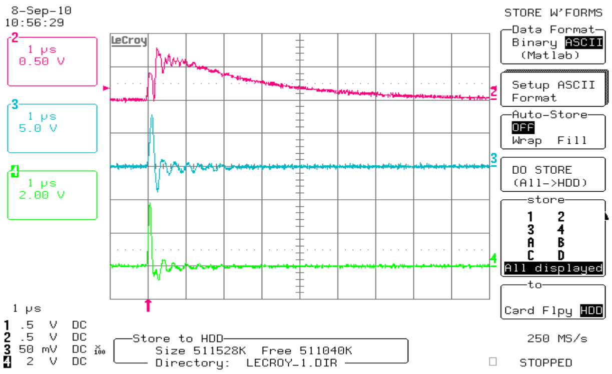


Fig. 3. Measuring Circuit in model transformer

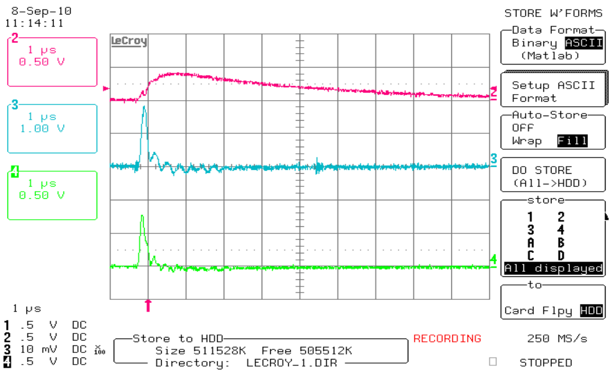
Fig. 4. The arrangement of windings in model transformer.

averaged from 50 measurements of voltage and current waves.

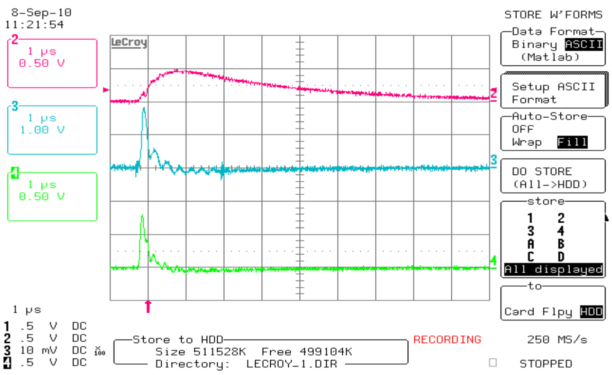
The model transformer was tested with single phase connection and testing circuit is shown in Fig. 3. The three testing conditions were controlled by arrangement of high voltage winding and Fig. 4 shows the normal arrangement and 48mm elevated windings. The first condition was the normal arrangement 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) Short rising time (y scales are 0.5V, 5V, 2V)



(b) Medium rising time (y scales are 0.5V, 1V, 0.5V)



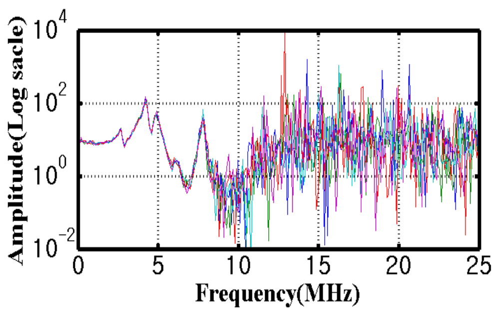
(c) Long rising time (y scales are 0.5V, 1V, 0.5V)

Fig. 5. The waves of input voltages, input currents, and their responses according to rising times of input voltages (One grid line of x scale corresponds to 1μs and that of y scales are in each figures).

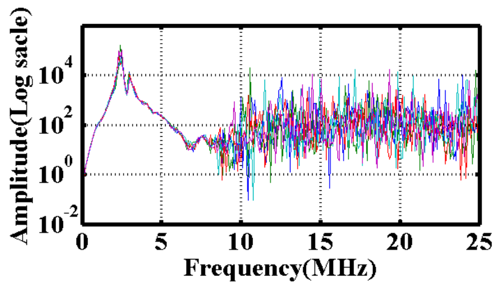
4. Experimental Results

When three types of input voltages were applied to model transformer, input voltages, input currents and output currents were measured as shown in Fig. 5. When the short rising time of input voltages are applied to the model transformer in normal testing condition, Fig. 6 shows TF1(ω), TF2(ω), and TF3(ω). And every transfer functions were plotted with 5 sets of 10 averaged data.

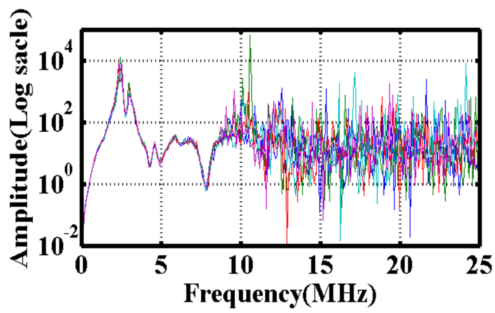
Fig. 7(a) shows TF1(ω), TF2(ω) and TF3(ω) transfer functions which were calculated on the measured data in the testing conditions of high voltage winding elevated 24mm from low voltage winding. Fig. 7(b) shows those of the high voltage winding elevated 48mm from low voltage winding. Every transfer functions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



(a) TF1(ω)

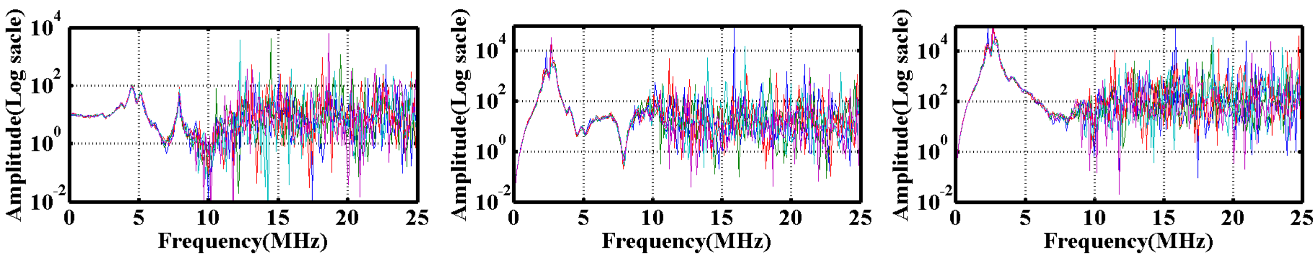


(b) TF2(ω)



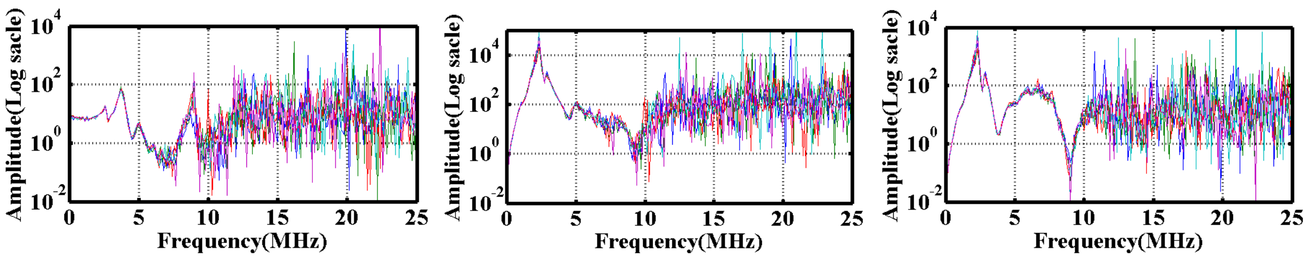
(c) TF3(ω)

Fig. 6. The estimated transfer functions in 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

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

5. Analysis of Experimental Results

To know the difference between transfer functions, the correlation coefficient was proposed as an indicator for comparing FRA traces by Xu, Fu and Li in [7].

Consider two sets of n numbers, xi=X{x1,x2, ... , xn} and yi=Y{y1, y2, ... , yn}. The correlation coefficient between these two sets of numbers is defined by Eq. (5).

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

The spectrum deviation was proposed as a statistical indicator for comparing FRA traces by Bak-Jenson and Mikkelsen in [5].

The spectrum deviation σ between X and Y is given by (6).

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

FFT results of Fig. 6 and Fig. 7 show that frequency ranges from DC to 25MHz. In the results, valid frequency range is less than 5MHz.

The correlation coefficients and spectrum deviations were calculated in comparing every 10 averaged FFT data with 50 averaged FFT one in this frequency range. Table 1-4 show correlation coefficients and spectrum deviations which have been calculated on transfer functions to the normal and the elevated windings arrangement.

Table 1 shows the results in normal arrangement of windings. The correlation coefficients of TF1(ω), TF2(ω), TF3(ω) transfer functions have near 1 value and the correlation coefficients in the short rising time waves have nearer 1 than those in the other rising times. The spectrum deviations of TF1(ω),TF2(ω), TF3(ω) transfer functions have near 0 value and the spectrum deviations in the short rising time waves have nearer 0 than those in the other rising times.

It is very important to know the range of these values in the same conditions. If the distributions of these values are assumed to be normal distribution, the values between upper value that is the sum of average value and 2 times of its standard deviation and lower value that is sum of average value and -2 times of its standard deviation exist in probability of 96.8%. Table 2 shows average, standard deviation, upper and lower values of table 1.

Table 3 shows the average and standard deviation values and upper and lower values whose correlation coefficients and spectrum deviations were acquired of comparing 10 averaged values of 24mm elevated high voltage winding with 50 averaged value of normal arrangement winding in TF1(ω) transfer functions.

Table 4 shows the average and standard deviation values and upper and lower values whose correlation coefficients

Table 1. Correlation coefficients and Spectrum Deviations in the normal arrangement of winding in the model transformer

(a) In the case of TF1(ω) transfer functions

RT	SRT		MRT		LRT	
	CC	SD(%)	CC	SD(%)	CC	SD(%)
1	0.999723	1.518672	0.992978	4.524918	0.992921	5.207102
2	0.999577	1.596394	0.994176	4.538124	0.994904	4.751207
3	0.999501	2.029411	0.994437	4.466887	0.992590	4.469365
4	0.999779	1.530681	0.994537	4.950882	0.992014	5.167771
5	0.999573	1.652706	0.995110	3.999805	0.992036	5.919840

(b) In the case of TF2(ω) transfer functions

RT	SRT		MRT		LRT	
	CC	SD(%)	CC	SD(%)	CC	SD(%)
1	0.999759	1.617685	0.998802	2.094159	0.998696	2.100624
2	0.999720	2.022976	0.999074	1.948727	0.998972	1.973767
3	0.999650	1.604632	0.998367	2.421129	0.999141	1.777853
4	0.999755	1.461946	0.998605	2.394832	0.999061	1.871625
5	0.999711	1.392104	0.999359	1.740883	0.999233	1.827277

(c) In the case of TF3(ω) transfer functions

RT	SRT		MRT		LRT	
	CC	SD(%)	CC	SD(%)	CC	SD(%)
1	0.999262	4.234050	0.983085	9.092176	0.984415	8.932218
2	0.998981	2.646113	0.986039	15.048820	0.987814	8.311859
3	0.998808	2.721174	0.986640	9.280073	0.982894	8.452164
4	0.999460	2.261024	0.985752	10.309277	0.980818	9.064375
5	0.998936	2.460454	0.987376	12.747602	0.980258	10.204327

Table 2. Averages, standard deviations, upper and lower values whose correlation coefficients and spectrum deviation are calculated on table 1.

(a) In the case of TF1(ω) transfer functions

RT	SRT		MRT		LRT	
	CC	SPD(%)	CC	SPD(%)	CC	SPD(%)
AV	0.999631	1.665573	0.994248	4.496123	0.992893	5.103057
SD(σ)	0.000115	0.210419	0.000787	0.337855	0.001187	0.549434
AV-2σ	0.999400	1.244734	0.992672	3.820413	0.990517	4.004189
AV+2σ	0.999862	2.086411	0.995823	5.171834	0.995269	6.201926

(b) In the case of TF2(ω) transfer functions

RT	SRT		MRT		LRT	
	CC	SPD(%)	CC	SPD(%)	CC	SPD(%)
AV	0.999719	1.619869	0.998841	2.119946	0.999021	1.910229
SD(σ)	4.38E-05	0.244718	0.000388	0.291523	0.000205	0.128629
AV-2σ	0.999631	1.130432	0.998064	1.536899	0.998609	1.652971
AV+2σ	0.999807	2.109306	0.999618	2.702993	0.999432	2.167487

(c) In the case of TF3(ω) transfer functions

RT	SRT		MRT		LRT	
	CC	SPD(%)	CC	SPD(%)	CC	SPD(%)
AV	0.999089	2.864563	0.985778	11.29558	0.983240	8.992989
SD(σ)	0.000265	0.786024	0.001629	2.553685	0.003048	0.747087
AV-2σ	0.998559	1.292514	0.982520	6.188219	0.977142	7.498814
AV+2σ	0.999620	4.436612	0.989037	16.40295	0.989337	10.48716

Table 3. Averages, standard deviations, upper and lower values of correlation coefficients and spectrum deviation compared of 10 averaged values of 24mm elevated high voltage winding with 50 averaged values of normal arrangement winding in TF1(ω) transfer functions.

RT	SRT		MRT		LRT	
	CC	SPD(%)	CC	SPD(%)	CC	SPD(%)
AV	0.992873	6.371175	0.988833	9.109833	0.989521	9.863568
SD(σ)	0.001072	0.900285	0.002471	0.631409	0.002110	0.440429
AV-2σ	0.990727	4.570605	0.983889	7.847014	0.985299	8.982709
AV+2σ	0.995018	8.171745	0.993776	10.37265	0.993742	10.744427

Table 4. Averages, standard deviations, upper and lower values of correlation coefficients and spectrum deviation compared of 10 averaged values of 48mm elevated high voltage winding comparing with 50 averaged values of normal arrangement winding in TF1(ω) transfer functions.

RT	SRT		MRT		LRT	
	CC	SPD(%)	CC	SPD(%)	CC	SPD(%)
AV	0.985551	16.501370	0.981875	13.924701	0.985792	12.316866
SD(σ)	0.001109	3.664225	0.003375	1.879496	0.001707	1.507921
AV-2σ	0.983331	9.172920	0.975124	10.165708	0.982378	9.301023
AV+2σ	0.987770	23.829821	0.988625	17.683693	0.989206	15.332708

and spectrum deviations were acquired of comparing 10 averaged values of 48mm elevated high voltage winding with 50 averaged value of normal arrangement winding in TF1(ω) transfer functions.

Fig. 8 and Fig. 9 show upper and lower values of TF1(ω), TF2(ω) and TF3(ω) transfer functions which were acquired in normal arrangement, 24mm and 48mm elevated windings applied with all rising time input voltages.

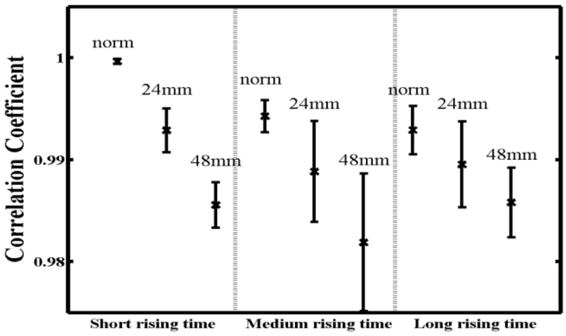
Fig. 8 shows that the range between upper and lower values of correlation coefficient in TF2(ω) transfer function did not overlap in all rising time of input voltage. The range between upper and lower values of correlation coefficient in TF1(ω) transfer function did not overlap in short rising time input voltages but overlapped in medium and long rising time input voltages. The characteristics of TF3(ω) transfer function were the same with the characteristics of TF1(ω) transfer function.

Fig. 9 shows that the range between upper and lower values of spectrum deviations in TF2(ω) transfer function did not overlap in all rising time of input voltages. The range between upper and lower values of spectrum deviations in TF1(ω) transfer function did not overlap in short and medium rising time input voltages but overlapped in long rising time input voltages. The characteristics of spectrum deviations ranges in TF3(ω) transfer function were identified between normal arrangement windings and elevated high voltage windings in short and long rising time input voltages but were not identified in medium rising time input voltages.

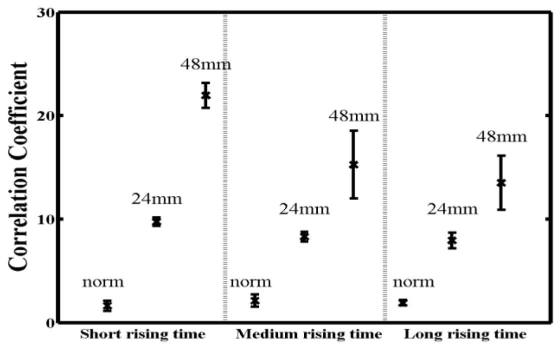
When three transfer functions were applied to diagnosis of winding displacement with correlation coefficient and spectrum deviation, TF2(ω) transfer function had higher ability to identify displacement than TF1(ω) and TF3(ω) transfer functions. The shorter rising time of input voltages were applied, the higher ability to diagnose displacement of transfer functions, spectrum deviations had higher ability to windings was obtained in transfer function. In TF1(ω) identify displacement of winding than correlation coefficient. In TF3(ω) transfer functions, correlation coefficient had higher ability to identify displacement of winding than spectrum deviations. Therefore the ability to resolve displacement of windings depended on types of transfer functions and the rising time of input voltages.

We compared the transfer functions of normal windings, 24mm elevated windings, 48mm elevated windings and the type-A windings. The type-A is a winding deformation of which some portion (10%) is axially displaced from the normal state windings.

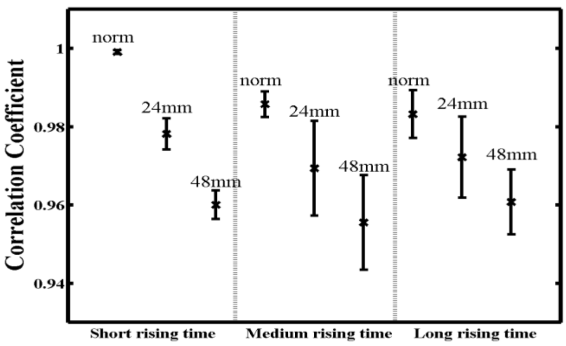
For detailed comparison, the small figures are nested for the frequency range from 4MHz to 6MHz. We could observe the change of the transfer functions in the peak position and amplitude between the normal state and the modified windings. The detailed explanation will be published later because of space limitation.



(a) In the case of TF1(ω) transfer functions

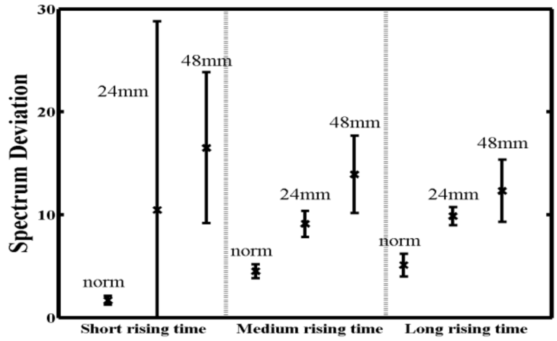


(b) In the case of TF2(ω) transfer functions

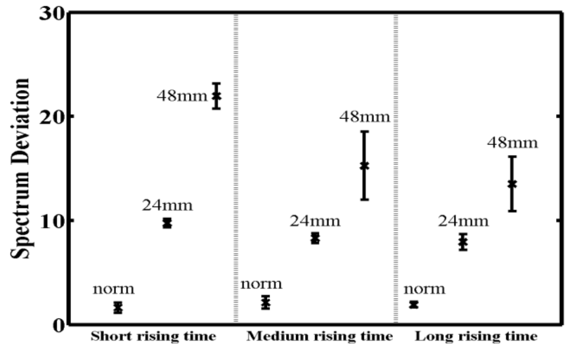


(c) In the case of TF3(ω) transfer functions

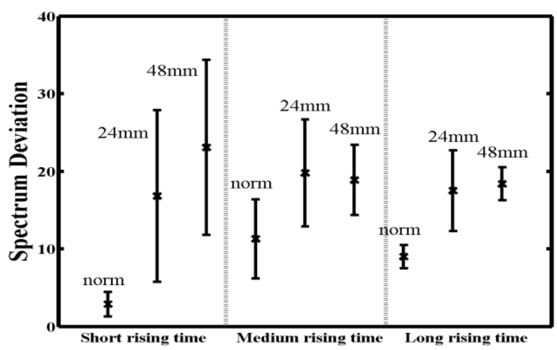
Fig. 8. The characteristics of correlation coefficient upper and lower values in normal, 24mm elevated and 48mm elevated windings.



(a) In the case of TF1(ω) transfer functions

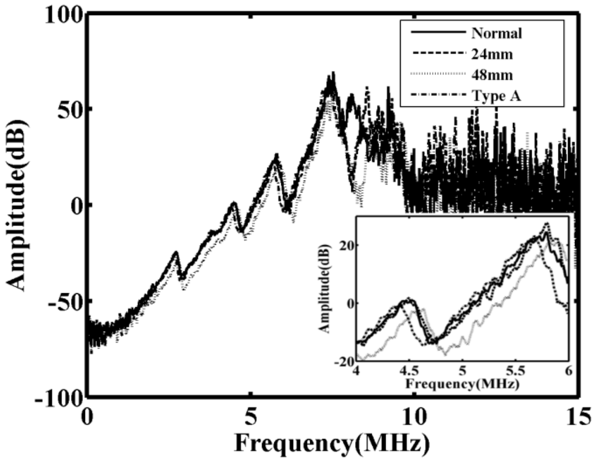


(b) In the case of TF2(ω) transfer functions

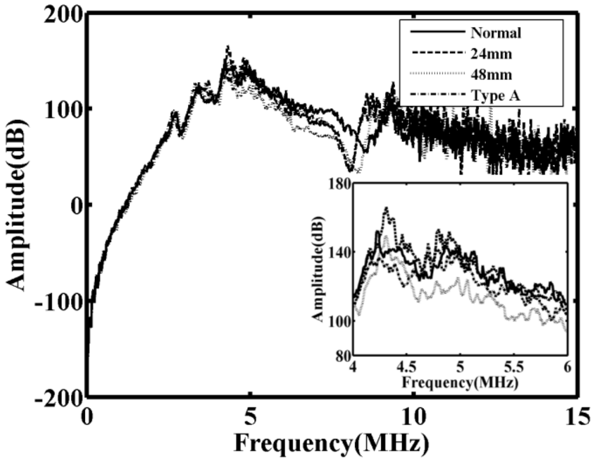


(c) In the case of TF3(ω) transfer functions

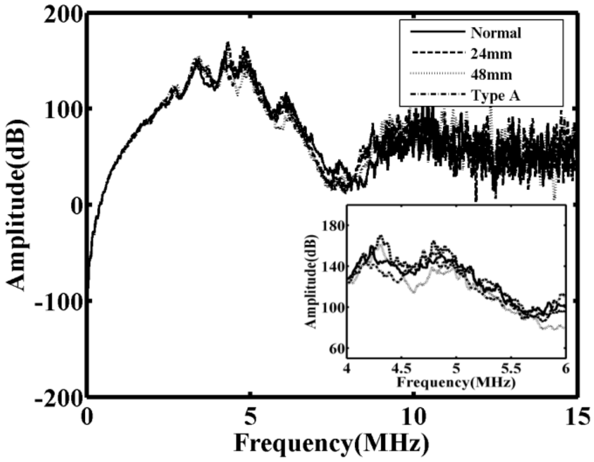
Fig. 9. The characteristics of spectrum deviation upper and lower values in normal, 24mm elevated and 48mm elevated windings



(a) TF1(ω)



(b) TF2(ω)



(c) TF2(ω)

Fig. 10. The estimated transfer functions in high voltage winding elevated 24mm, 48mm, and from low voltage winding

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, these transfer functions were analyzed with correlation coefficient and spectrum deviations. In this analysis, correlation coefficient and spectrum deviations have different values according to transfer functions and rising times of input voltages in the same testing condition. This analysis had different ability to diagnose the displacement of windings in three types transfer function. TF2(ω) transfer function had the best ability to diagnose the displacement of winding. The shorter rising time of input voltages were applied, the higher ability to diagnose displacement of windings in transfer functions were identified. The transfer function results of axially displaced windings are compared with normal and elevated windings. The suggested three transfer functions will be tested in another testing conditions and have to be analyzed in the next research.

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