# Study on Failure Diagnosis of Power Transformer Using FRA

Takahiro Sano[a]
*Transformer Design Department, Japan AE Power Systems Corporation, Numazu-shi, Shizuoka, 410-0865, Japan*

Katsunori Miyagi
*Research & Development Department, Japan AE Power Systems Corporation, Hitachi-shi, Ibaraki, 316-8501, Japan*

[a]E-mail : sano-takahiro@mb.jaeps.com

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As the average usage period of transformers increases, it is becoming increasingly necessary to know the internal condition of transformers. It is therefore critically important to establish monitoring and diagnostic techniques that can perform transformer condition assessment. Frequency response analysis, generally known as FRA, is one of the technologies to diagnose transformers. Using case studies, this paper presents the effectiveness of FRA as measurements for detecting transformer failures. This paper introduces the fact that FRA waveforms have useful information about diagnosis of failure on core earths and winding shield, and that the condition outside transformers can affect frequency response characteristics.

*Keywords* : Transformers, Frequency response, Fault diagnosis, Resonance

## 1. INTRODUCTION

FRA has been studied as a method for diagnosing from outside deformation and loose contacts inside transformers[1,2]. However, transformer diagnostic testing by FRA is relatively new, and at the moment, its guidelines are under consideration by CIGRE (SC A2) WG. In this paper, experiments were conducted on aged power transformers as test objects with simulated-failure. The results of these experiments found that the comparison of frequency response characteristics for individual phases was effective as a method of FRA on transformers for diagnosis. Also, the comparison to simulations suggested the possibility of pinpointing the failed part by FRA measurement.

## 2. PRINCIPLES AND MEASUREMENT EXAMPLE

### 2.1 Failure detection principles

The impedance $Z$ of the transformer is a combined value mainly of the winding components (resistances, leakage reactances and capacitances) and the excitation components (conductance, susceptance and capacitance). The inductive ($L$) and capacitive ($C$) components are responsible for the transient and resonance, which occurs at a given frequency when the inductive reactance balances the capacitive reactance. Where the resonant frequency $fr$ then is generally expressed by the equation (1).

$$fr = \frac{1}{2\pi\sqrt{LC}} \tag{1}$$

There are two types of the resonances; parallel and series resonance. The parallel resonance is related to the parallel connection of the capacitance and inductance and has high impedance. On the contrary, the series resonance is related to the series connection, has very low impedance.

In addition, resonances can also occur locally between sections and turns of the windings. These resonances can be affected by changes of $L$ or $C$ that take place locally. FRA, which performs measurement over a wide frequency range, is capable of detecting many resonance points. Therefore, it is possible to estimate the locations of local changes that could not be detected through conventional diagnostic techniques.

### 2.2 Test conditions and circuits

There are two ways of FRA measurement on a two-winding transformer from the HV side: one with the low-voltage side of the transformer in Fig. 1a open-circuited, and the other with the low-voltage side of transformer in Fig. 1b short-circuited. During an open-circuit test, the excitation components and winding components are in series, so the excitation components dominate the circuit, and the winding resistance and leakage reactance are negligible at low frequency. The other, during a short-circuit test, the phenomenon is reversed, with the opposite winding components in parallel. The excitation components become negligible compared to the short-circuited winding resistance and leakage reactance.

The measurement system is shown in Fig. 2. The input impedance of the measuring equipment is 1 M ohm, and Table 1 shows the characteristics of the measurement cables. A sinusoidal wave that automatically made a frequency sweep at 100 Hz to 1 MHz was applied to the high voltage terminal, and then the impedance $Z$ of the transformer was calculated from $V/I$. Where the sweep resolution was set to 400 steps/sweep (100 steps/div), and the applied voltage was set to 10 Vpeak.

### 2.3 FRA measurement example (baseline measurement)

The waveforms by which we attempted to make comparison of individual phases with respect to FRA measurements on a normal three-phase transformer (220 kV, 120 MVA) are shown in Fig. 3 and 4 in the case of open- and short-circuit respectively. The first peak frequency (200 to 300 Hz) in Fig. 3 (open-circuit test) is lower than the first peak frequency (approx. 4 kHz) in Fig. 4 (short-circuit test). It can be supposed that compared to the leakage reactances of windings, the susceptance of excitation was so great that the frequency was dropped according to the equation (1).

From the comparison of frequency response characteristics in the cases of open- and short- circuit, the following two characteristics can be recognized:

1) In the open-circuit test, over a range of 100 Hz to 1 kHz, the characteristics of the impedance of V phase are shifted to lower frequencies compared to those of the other phases (U, W).
2) In the short-circuit test, the waveforms of the three phases were nearly identical to each other.

As shown in Fig. 5, for the core structure, V phase is located in the center of the three-leg core and its magnetic path is longer than the paths of the other phases. As the susceptance value is proportional to the length of a magnetic path, the susceptance value of V phase becomes smaller than the values of U and W phases. In

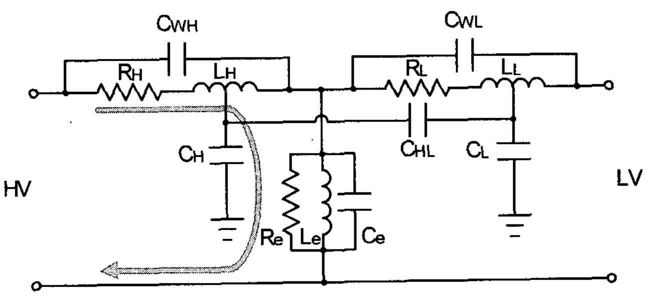


Fig. 1a. Simplified equivalent circuit for open-circuit test.

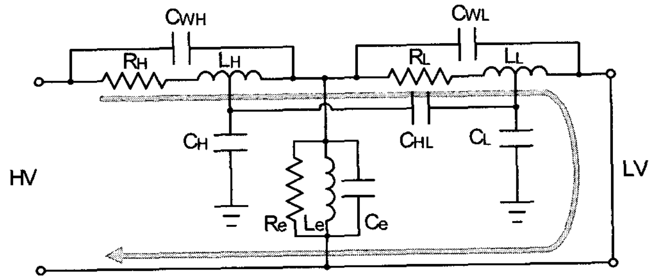


Fig. 1b. Simplified equivalent circuit for short-circuit test.

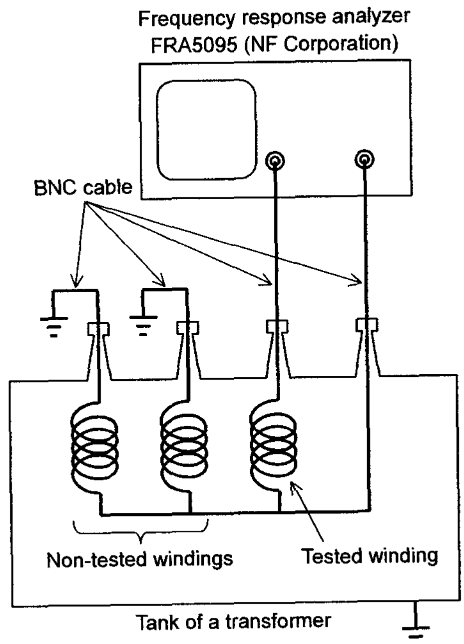


Fig. 2. FRA measurement system of a three-phase transformer.

Table 1. Characteristics of measurement cable.

| Name | 3D-2V BNC cable |
|---|---|
| Characteristic impedance | 50 Ω |
| Length | 12m |

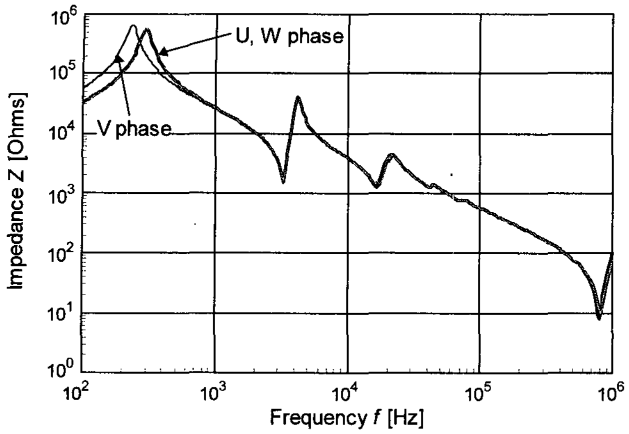


Fig. 3. FRA measurement example for the open-circuit test of a normal three-phase transformer(220 kV, 120 MVA).

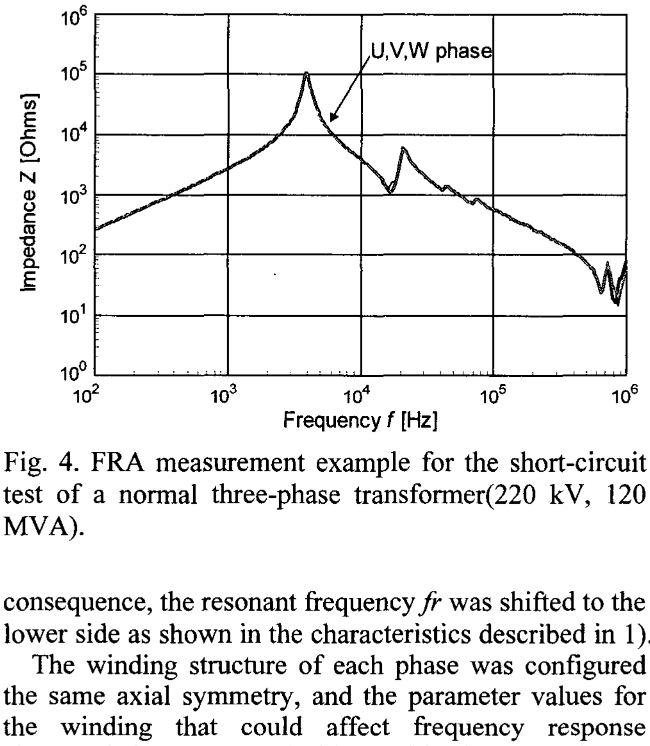


Fig. 4. FRA measurement example for the short-circuit test of a normal three-phase transformer(220 kV, 120 MVA).

consequence, the resonant frequency $fr$ was shifted to the lower side as shown in the characteristics described in 1).

The winding structure of each phase was configured the same axial symmetry, and the parameter values for the winding that could affect frequency response characteristics were nearly identical in the three phases. In addition, it can be judged that the characteristics described in 2) could be obtained because they were free from the influence of the above-mentioned magnetic circuit.

As shown above, for a normal transformer, the measured FRA waveforms show different characteristics in the open-circuit test depending on the structures of individual phases.

## 3. DIAGNOSING FAILURES (CASE STUDIES)

### 3.1 Case 1: Diagnosis of double core earths (open-circuit test)

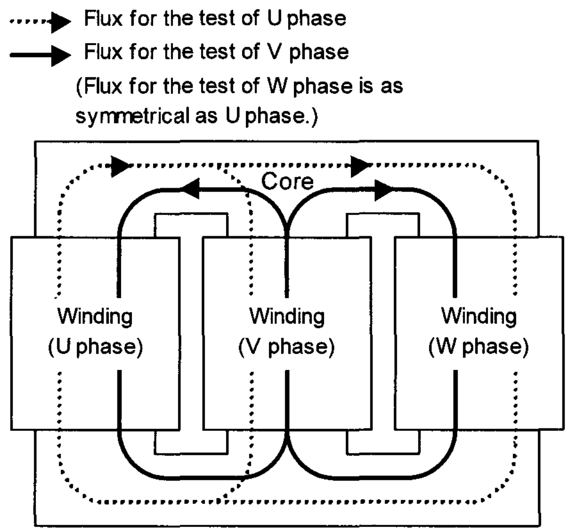


Fig. 5. The flow of flux in the case of the open-circuit test.

If the internal structure materials of the transformer including the core are multiple-earthed, local overheating can occur owing to circulating currents. We selected a three-phase power transformer (230 kV, 150 MVA) to be used in the case study on double core earths. Frequency response characteristics about the core can be tested through the open-circuit test.

Here, an investigation was made by comparing the case of normal core earth and the case of simulated double core earths. As a typical example of FRA measurements results, Fig. 6 shows the comparison of FRA waveforms from the HV side (U phase). The above comparison shows that differences in frequency response characteristics between normal core earth and double core earths are apparent in a lower frequency range (100 Hz to 1 kHz), whereas there are no significant differences in other frequency range (1 kHz to 1 MHz).

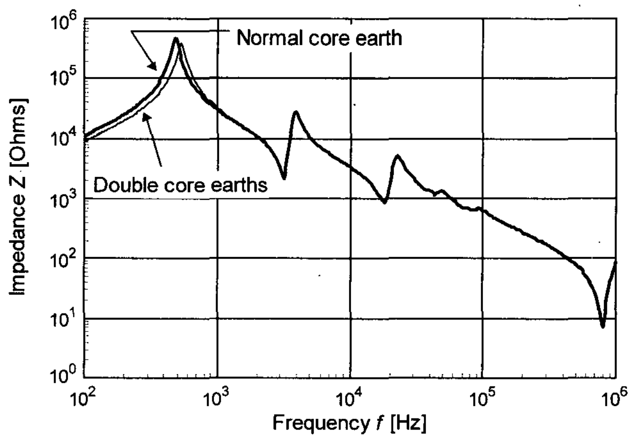


Fig. 6. FRA measurement result for the open-circuit test of a three-phase transformer(230 kV, 150 MVA).

In addition, the frequency response characteristics were discovered to be such that the first resonance frequency was higher in the case of double core earths than normal core earth, and the impedance of the former is smaller than the latter. The reason for the above seems to be that the core was partially short-circuited owing to double earths, which lowered excitation inductance and resulted in *fr* increase according to the equation (1).

### 3.2 Case 2: Diagnosis on lead wire breaks in electrostatic shields (short-circuit test)

We selected a three-phase power transformer (147 kV, 150 MVA) as a model for the diagnosis of lead wire breaks in electrostatic shields. This transformer is characterized by the electrostatic shield with ground potential installed between high-voltage primary winding and tap winding to prevent over-voltage when power surges strike the transformer-windings.

Here, an investigation was made on the assumption that the earth lead wire to the electrostatic shield was broken. Because frequency response characteristics about windings can be diagnosed through the short-circuit test, comparison and investigation of frequency response characteristics were performed between normal connection of the lead wire and simulated disconnection of the lead wire.

Figure 7 shows the FRA measurement results in case the disconnection of the lead wire of W phase only was simulated while the lead wires of U phase and V phase were connected. As a result, we could recognize the following:

1) The first resonant frequency of W phase is higher by approximately 26 % than those of the other two phases.

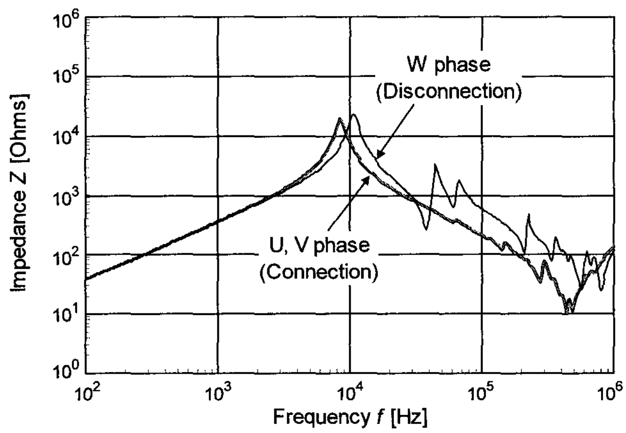


Fig. 7. FRA measurement result for the short-circuit test of a three-phase transformer(147 kV, 150 MVA).

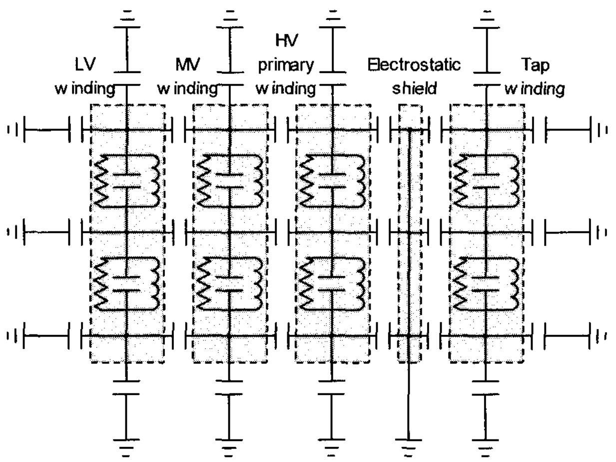


Fig. 8. Equivalent circuit of three-winding transformer windings for EMTP (single phase model).

2) The impedance of W phase at the first resonant frequency is higher than the impedance of the other two phases.
3) Differences in the characteristics of impedance are more significant at high frequencies than those at the first resonant frequency.
4) The characteristics of the impedance in a frequency range of 3 kHz or below are identical for the three phases.

The results of FRA measurement indicated that changes were significant in a relatively high frequency range of 10 kHz or over, so there is a possibility of applying a lumped parameter model of the transformer-windings shown in Fig. 8. For EMTP models simulated in cases both with and without lead wire connection, Fig. 9 shows the results of respective calculations obtained using the "Frequency Scan" function of EMTP. From the

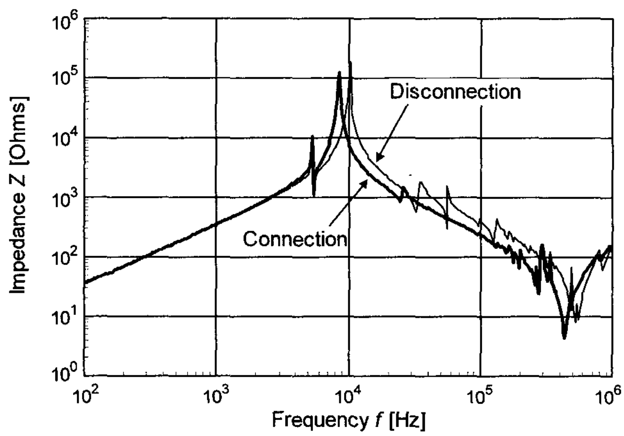


Fig. 9. FRA simulation result for the short-circuit test of a three-phase transformer(147 kV, 150 MVA).

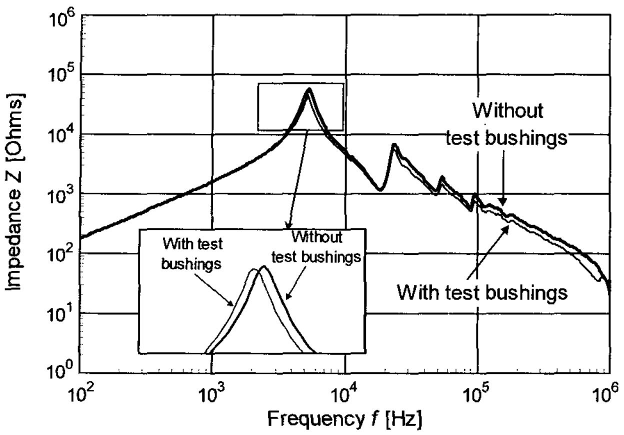


Fig. 10. FRA measurement result for the short-circuit test of a three-phase transformer(110 kV, 40 MVA).

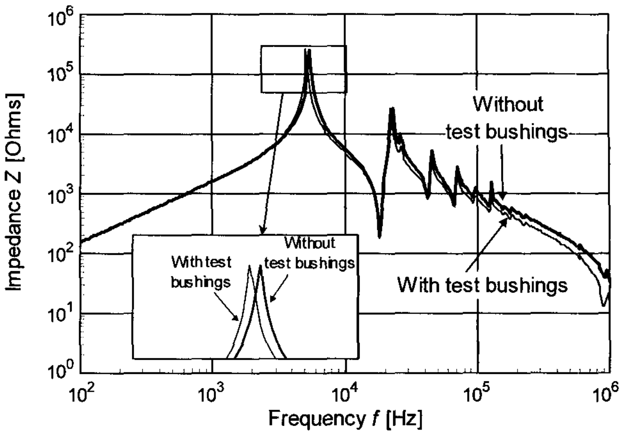


Fig. 11. FRA simulation result for the short-circuit test of a three-phase transformer(110 kV, 40 MVA).

above, we could find similar features in the actual FRA measurements and the simulation results.

If the applicability of the simulation model can be confirmed, it will be possible, for example, to simulate frequency response characteristics by assuming the damaged part – the test technique that can be used for diagnosis such as identification of damaged part through comparison to FRA measurements results.

### 3.3 Case 3: Influence of factors outside the transformer (short-circuit test)

FRA measurements aim to diagnose damage to the transformer from outside by detecting a few differences in the waveforms that show frequency response characteristics. Should these a few differences be affected by external condition, failure diagnosis could not be performed with accuracy. The external condition includes, for example, measurement cables, power cables and bushings.

To investigate the influence of external factors, measurements were made on a normal three-phase power transformer (110 kV, 40 MVA) with and without test bushings. FRA measurements at the factory test were made assuming the case with test bushings, and FRA measurements at the on-site test were made assuming the case without test bushings. These measurements were made through the short-circuit test, and the FRA measurements results are shown in Fig. 10.

Table 2. Capacitance to ground of the transformer (measurement result).

| Condition | Capacitance to ground |
|---|---|
| With test bushings | 4100 pF / phase |
| Without test bushings | 3500 pF / phase |

These results found that the resonant frequency was reduced by approximately 7 % in the case with test bushings compared to the resonant frequency in the case without test bushings. In addition, Fig. 11 shows the results of EMTP simulation performed in cases with and without test bushings. We obtained the characteristics identical to those obtained through actual measurements, too.

Supposedly, these were caused by the capacitance of test bushings added to the capacitance to ground of the transformer, whereby $fr$ was reduced according to the equation (1). Table 2 shows the comparison with respect to capacitance to ground of the transformer in cases with and without test bushings. In the case with test bushings, from the equation (1), $fr$ decreases by approximately 8 % proportionately with $1/\sqrt{C}$. This value is nearly identical to the value obtained from the results of FRA measurement, so the differences in the above results are found to be attributable to the existence of test bushings only. As is presented above, because frequency response characteristics could be affected by the condition outside the transformer, much precaution is required when performing measurement.

## 4. CONCLUSION

It could be seen that if the transformer core was double-earthed, excitation admittance changed, causing frequency response characteristics to change accordingly. It could also be seen that if the lead wire of the electrostatic shield was broken, the capacitance between high-voltage primary winding and tap winding changed and caused frequency response characteristics to change significantly.

These findings suggest the possibility of transformer diagnosis from outside by FRA measurements. In addition, the influence of the conditions outside transformers could also been recognized over frequency response characteristics, so it is necessary to consider their influence at the time of diagnosis.

It was found that the characteristics similar to those of actually measured FRA waveforms could be obtained also in simulation. Particularly, it was confirmed that the location of damaged part could be estimated if examinations is performed by comparing the frequency response characteristics of three phases, and comparing between measurement and simulation characteristics.

## 5. FUTURE SUBJECT

Should the capacitance or inductance inside the transformer change partially, changes to frequency response characteristics could become very small. The overall feature of the frequency response characteristics from these measurements and simulations are in agreement, whereas there can be seen many differences in detailed parts. It will be necessary in the future to establish a simulation technique that can cope with a few changes.

FRA measurement helps to determine impedances over a range from high to low frequencies with relative ease. However, there is influence from the measurement system in a high frequency range, so precaution is required at the time of actual measurement. In the present study, it was confirmed that the differences of frequency response characteristics became apparent depending on cases with and without test bushings. It will be therefore necessary in the future to determine other parameters of the measurement system that may affect frequency response characteristics and to establish a measurement technique for minimizing the influence from the measurement system.

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