Diagnostic Frequency Response Analysis (FRA) Techniques for Faults in Transformers

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Abstract

When power transformers are operated for many years, it becomes necessary to grasp their internal conditions in order to confirm how viable they are in order to prevent malfunction in advance. It is very important to establish diagnostic technologies to check inner conditions effectively. A method of Frequency Response Analysis (FRA) has been researched as a new approach to discover any deformation of the inner assembly of a transformer and any malfunctions such as contact defect by the external diagnosis[1]-[5]. Such an approach contains, however, some unclear aspects including phenomena and diagnostic approach. Although an FRA measurement method is specified in IEC60076-18[6], it is intended mainly for users as a guideline for macroscopic diagnosis. It is, therefore, generally difficult to perform detailed diagnosis to identify the abnormal parts.

Under such technical circumstances, we investigated the applicability of FRA through actual measurements and analysis. For this purpose, we adopted two fault models for aged transformers; grounding lead wire disconnection in the electrostatic shield (Case 1) and double grounding in the core (Case 2). In Case 1, we confirmed that it is possible to locate a faulty section through a 3-phase comparison and analytical comparison of FRA characteristics, even though initial data was lost and not available. As a result, the effectiveness of FRA measurements was proven in regard to fault diagnosis on winding systems. In Case 2, we confirmed that diagnosis by comparison is possible with the use of initial data of FRA characteristics in a low-frequency domain. This implies that FRA measurements by external diagnosis on transformer cores are still effective.

1 Preface

During a high economic growth period, demand for electric power in Japan was suddenly expanded. Accordingly, oil-immersed transformers and such electrical facilities were manufactured in a large quantity. Meanwhile the expected design life of a transformer is generally 30 years. Most transformers, however, are operated for more than 30 years after manufacture. In fact, even at present, many of these transformers are still in practical operation. It is anticipated that such aged transformers will be increased further in the future. Consequently, it is then necessary to take adequate measures for maintenance and management.

As such, a new approach of Frequency Response Analysis (FRA) has been recently attracting wider attention. This technology is used so that deformation, poor contact, and other faults occurring inside the transformer can be diagnosed from the outside. There are some methods to locate a faulty part, such as a model-based experiment to simulate a fault, or an examination by simulation. These methods, however, involve many unclear points of identifying the situation. In order to confirm the applicability of FRA diagnosis on aged transformers and establish this diagnostic approach, we investigated the FRA approach by setting up two typical fault models for aged transformers; i.e. lead wire disconnection in the electrostatic shield and double grounding in the core, as introduced in this paper.

2 Principle of FRA and Measuring Method

2.1 Principle of FRA

Impedance Z of a transformer is mainly a synthesis of winding impedance and phase-to-ground electrostatic capacitance. Impedance Z causes resonance at a certain frequency, and this resonance frequency is generally given by Expression (1) below.

$$fr = \frac{1}{2\pi\sqrt{LC}} \quad \cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots (1)$$

Where, $L =$ inductance and $C =$ electrostatic capacitance.

fr and Z are changed along with a change in L or C. While the Z-f characteristic is measured by changing the frequency f widely, presence of any internal fault can be identified according to the presence of waveform variations upon the occurrence of a fault based on normal characteristic waveforms for comparison. Between winding sections and between turns, there is a domain where value fr is high. For ordinary diagnostic practice, it is generally difficult to detect any partial deformation and displacement. In the case of FRA approach, however, such faults can be detected.

2.2 Measuring Circuit

Fig. 1 shows a simplified equivalent circuit of a transformer. In the case of FRA measurements attempted from the HV side of a typical two-winding transformer, two kinds of circuiting can be considered; i.e. LV terminals under short-circuited condition as shown in (a) and those under open condition as shown in (b). In the short-circuited state, there are winding components and exciting components present under parallel condition and the effect of a winding component is predominant in this case. While in the open state, these two components are aligned in series and the effect of an exciting component is predominant in the domain of low frequencies. In other words, the short-circuited state is suitable for diagnosis on a fault in the winding system and the open state is suitable for diagnosis on a fault in an iron core.

2.3 Measuring Method

Fig. 2 shows a FRA measurement system for 3-phase transformers. An auto-scanned sinusoidal waveform (10V peak) at a frequency of 100Hz to

(a) Short circuit

(b) Open circuit

C_{WH}, C_{WL}: Inter-section capacitance C_H, C_L: Capacitance to ground
C_{HL}: Inter-winding capacitance R_H, R_L: Winding resistance
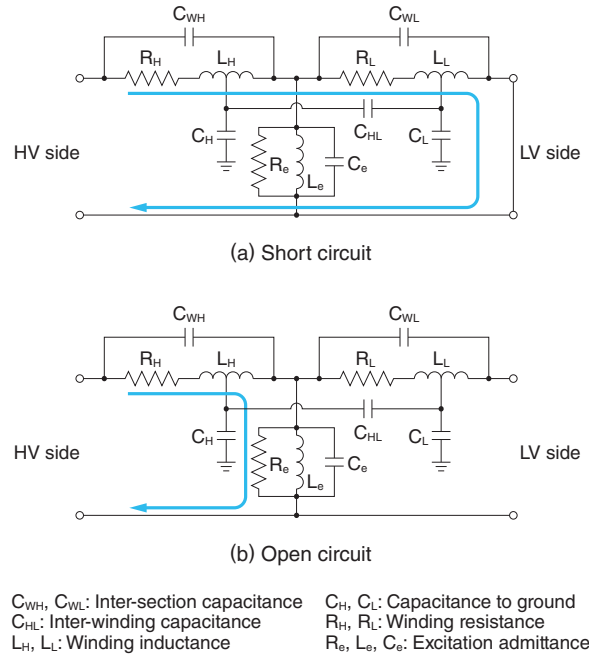L_H, L_L: Winding inductance R_e, L_e, C_e: Excitation admittance

Fig. 1 Simplified Equivalent Circuit of a Transformer

The short circuit is suitable for locating a fault in the winding system and the open circuit is effective to diagnose the core system.
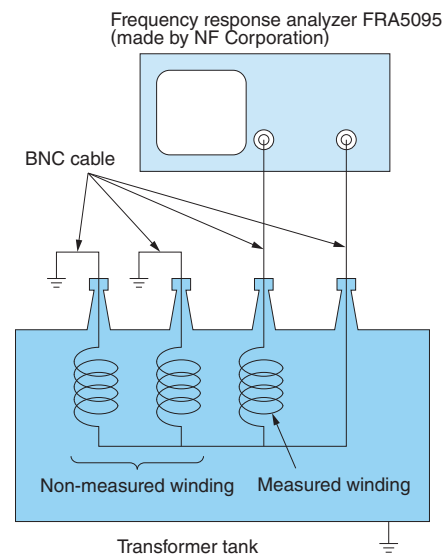

Fig. 2 FRA Measurement System for 3-Phase Transformers

Transformer terminal voltage and current are used to calculate transformer impedance from which frequency characteristics of impedance are defined.

1MHz is applied to the HV terminal and transformer impedance Z is calculated from transformer terminal voltage V and current I. In so doing, we obtain frequency characteristics of impedance.

3 Diagnostic Method

3.1 Comparison with Initial Data

When a fault occurs, obtained data are compared with the initial FRA data obtained under normal condition (at the time of factory test). This is the most typical approach to diagnose the presence of any fault occurring inside the transformer.

3.2 3-Phase Comparison

In a normal 3-phase transformer, values L and C in the respective phases are almost identical with each other. Therefore, FRA characteristics in each phase of a short circuit are likewise almost equal to each other. This is an approach to diagnose the FRA characteristics in each phase through comparison on the assumption that at least one phase is normal. If any apparent difference is found in the FRA data in each phase, it is possible to conclude that there is a fault in one or two phases.

3.3 Comparison with the Simulation Data

In the FRA approach, a domain of comparatively high frequencies is regarded as a target. It is, therefore, possible to use an equivalent circuit as shown in **Fig. 3** generally applied to surge analysis. When a possible faulty part is anticipated in advance and simulation is forwarded, it is possible to grasp changes in frequency characteristics of *fr* and *Z*. Both a faulty phase and a faulty part can be diag-

nosed by making a comparison between actually measured waveform and simulated waveform.

3.4 Selection of Diagnostic Method

If initial data are available, diagnosis by comparison should be carried out. It is only in the past few years that FRA measurements have become very popular. This method cannot be used for transformers manufactured more than ten years ago because initial data are not available. Consequently, for any faults caused in winding systems of aged transformers, a diagnostic approach by 3-phase comparison and comparison with the simulation data is generally adopted.

For a 3-phase transformer with a three-leg core, the magnetic path length in the middle phase is shorter than other phases. Diagnosis, therefore, by a 3-phase comparison is impossible to carry out. It is presently difficult to make FRA diagnosis on faults in core systems of aged transformers.

4 Diagnostic Examinations

4.1 Diagnosis on Grounding Lead Wire Disconnection in the Electrostatic Shield
4.1.1 Contents of Diagnosis

A 3-phase power transformer (154kV, 150MVA) was selected as a typical model to undergo diagnostic study. A feature of this transformer is that an electrostatic shield is allocated between the HV winding and the tap winding as shown in **Fig. 4**, intended for the suppression of an overvoltage to be caused at the time of an ingress of lightning surges. An investigation was carried out on the assumption
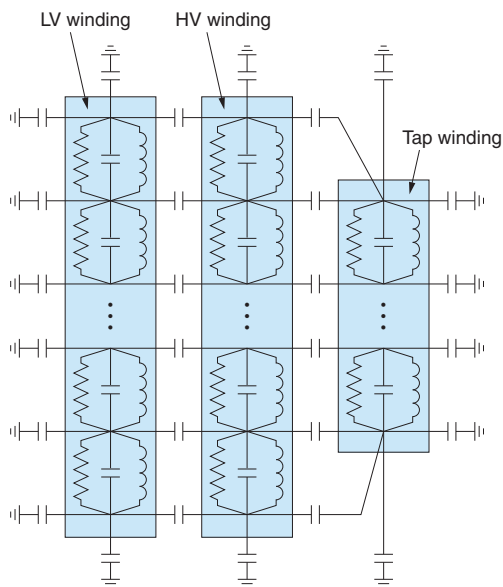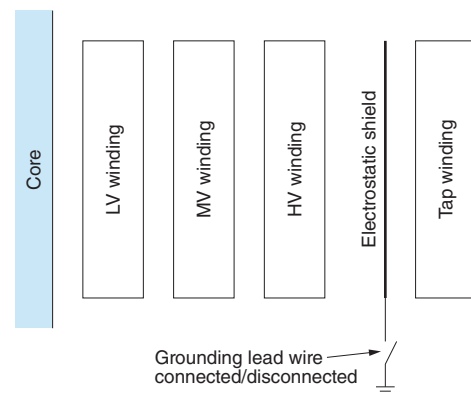
LV winding HV winding Tap winding

Fig. 3 Example of Transformer Winding Equivalent Circuit for Simulation (Single-Phase Model)

An equivalent circuit for surge analysis has been applied to FRA analysis.

Core, LV winding, MV winding, HV winding, Electrostatic shield, Tap winding

Grounding lead wire connected/disconnected

Fig. 4 Winding Structure and Circuit Conditions of a Grounding Lead Wire Disconnection Model for the Electrostatic Shield

It is assumed that the grounding lead wire of the electrostatic shield is connected (normal) and disconnected (faulty).

that the grounding lead wire of this electrostatic shield was disconnected.

4.1.2 Result of Measurement

Fig. 5 shows the result of FRA measurements in the case of a short circuit where the grounding lead wire in only Phase W was disconnected while grounding lead wires in Phases U and V were left connected (grounded). As a result, the following features were observed:

（1） The first fr value in Phase W is higher than the fr values in two other phases.

（2） Value Z of the first fr value in Phase W seems to have increased compared with the values in two other phases.

（3） Compared with the first fr value, there is a great difference in Z on high-frequency side.

（4） Impedance Z in the domain of frequencies at 3kHz or lower is identical with that of the other in all three phases.
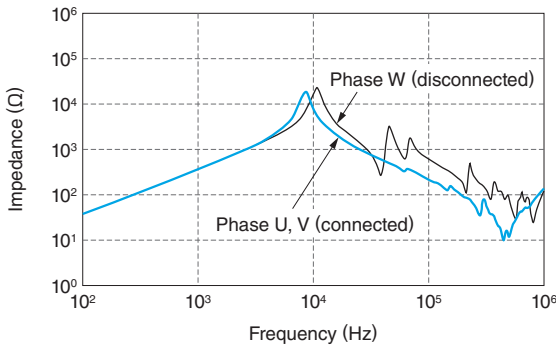
Difference in waveform can be perceived between phase U, phase V, and phase W.
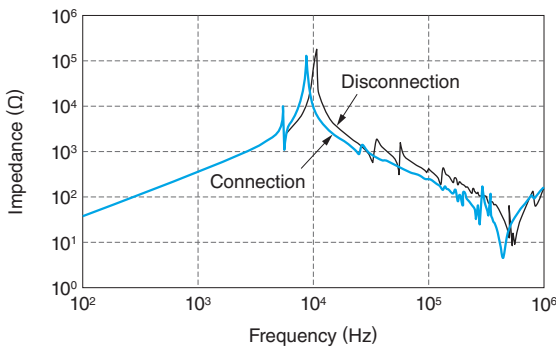
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There are similarities with the trends in actually measured characteristics.

Fig. 6 shows the result of simulations on a circuit in a similar situation shown in Fig. 3. In conjunction with the characteristics observed when lead wires were connected, the following features were identified in the characteristics observed when a lead wire was disconnected:

（1） The first fr value is high.

（2） Impedance Z with the first fr value increases.

（3） Compared with the first fr value, there is a difference in Impedance Z on high-frequency side.

（4） Impedance Z in the domain of frequencies at 4kHz or lower is identical with each other.

These features are almost identical with those of characteristics from actual measurements.

4.1.3 Examination

As a factor of changes in FRA waveforms due to presence of a lead wire connection or disconnection, matters, which will be described below, can be presumed. Fig. 7 shows static capacitance around HV windings.

Under the condition that the grounding lead wire was connected, capacitance to ground around the HV winding was approximately 4500pF as shown in (a), while capacitance to ground around the HV winding with the grounding lead wire disconnected (electrostatic shield at a floating potential) was approximately 2800pF as shown in (b). This is
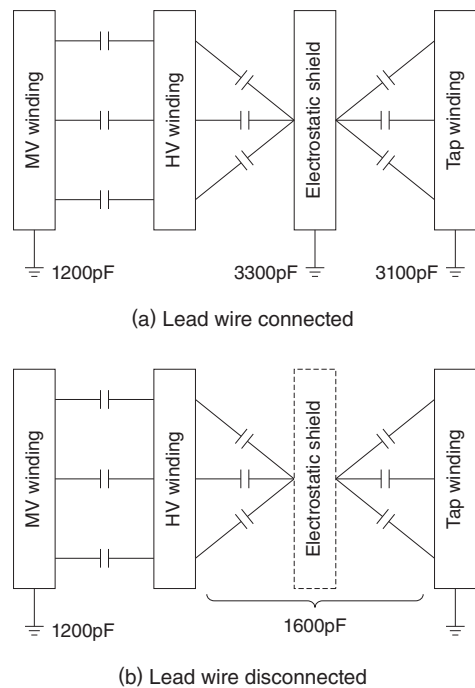

(a) Lead wire connected

(b) Lead wire disconnected

When the grounding lead wire is disconnected, electrostatic capacitance between the HV winding and tap winding is lowered.

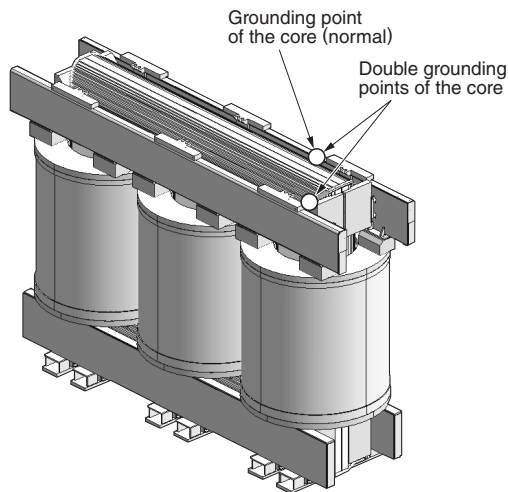equal to a decrease of about 38%. As such, according to Expression (1), static capacitance with a lead wire disconnected is theoretically increased by approximately 27%. In this case, the first fr value with the lead wire disconnected is about 26% higher than the value with the lead wire connected, both actually and analytically, as suggested in **Fig. 5** and **Fig. 6**. This fact coincides with the result of the theoretical approach.

In both cases of actual measurement and analytical approach, a new resonance point was found to appear at 30～70kHz and 100～300kHz when the lead wire was disconnected. The reason is considered to be due to a fact described below. When the lead wire is connected, mutual influence between an HV winding and tap winding is suppressed by the effect of the electrostatic shield. While with the lead wire disconnected, the HV winding is influenced by resonance with the tap winding through inter-winding capacitance.

4.2 Diagnosis on Double Grounding in the Core
4.2.1 Contents of Diagnosis

When the internal structure of a transformer including its core is multiply grounded, local overheating may be caused by the effect of a circulating current. We, therefore, investigated the behavior of a 3-phase power transformer (230kV, 150MVA) through the comparison of two cases when the core is normally grounded and when treated by double grounding. **Fig. 8** shows the grounded parts in the core.
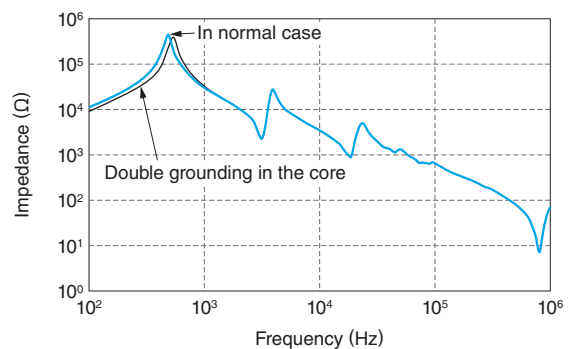
4.2.2 Result of Measurement and Examination

As a typical example of the result of FRA measurement, **Fig. 9** shows a comparing waveform (in Phase U) of FRA characteristics in an open-circuit state. Features of the FRA characteristics for the core in the state of normal grounding and double grounding are that they were perceived only in the domain of low frequencies (0.1kHz～1kHz) and no significance was perceived in other frequency domains (1kHz～1MHz).

Compared with normal grounding, double grounding results in a higher frequency of the first resonance. In addition, impedance at the resonance point is small. The reason for such a phenomenon is considered due to the fact that the effect of double grounding led to a partial short-circuiting in the core, thus reducing the excitation inductance. As a result, resonance frequency was increased in proportion to $1/\sqrt{L}$.

5　Postscript

When a grounding lead wire of the electrostatic shield is disconnected, it is possible to presume the location of the faulty part by making a 3-phase comparison and comparison with the simulation data of the FRA characteristics even though initial data are lost. This paper proved that FRA diagnosis is effective in finding a fault in the winding system. Our achievement was already reported[4][5] in regard to the detection of a lead wire disconnection fault in the electrostatic shield of an aged transformer by an externally executed FRA diagnosis.

In the case of double grounding in the transformer core, changes in FRA characteristics were perceived in the domain of low frequencies. Based

on this fact, we concluded that FRA measurements are applicable to externally executed diagnosis on the transformer core, provided that initial data are available.

・All product and company names mentioned in this paper are the trademarks and/or service marks of their respective owners.

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