EVALUATION OF MEASUREMENT PARAMETERS ON FRA CHARACTERISTICS FOR TRANSFORMERS

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Abstract: Appropriate monitoring and maintenance become important as the oil-immersed transformer ages. Generally Dissolved Gas Analysis is effective for the on-line diagnosis, and if abnormality is detected, Frequency Response Analysis is effective for the off-line diagnosis to localize the failed part. Frequency Response Analysis diagnosis detects the slight change of waveforms, however external factors may influence the results. Here, we discuss the influence of an insulating oil presence, tap position, and measurement lead wire length as possible parameters to influence Frequency Response Analysis characteristics. It was confirmed that the measurement parameters examined here greatly influence the Frequency Response Analysis characteristics. In the actual diagnosis, it is important to remove these external parameters as much as possible, and keep a detailed record of the measurement parameters.

1 INTRODUCTION

The need for electricity rapidly grew in the high-growth period of Japan. Along with it, many electric equipment such as oil-immersed transformers were manufactured. On the other hand, while the life expectancy of a transformer is generally 30 years, many transformers have passed more than 30 years after fabrication, as shown in Figure 1 [1], and are still at work. It is expected that we will have more aged transformers, which are in need of appropriate maintenance management.

An oil-immersed transformer is composed of an oil-impregnated composite insulation system, which uses both insulating oil and insulating paper to secure the insulation and cooling performance, and the inside is generally diagnosed by Dissolved Gas Analysis (DGA). A control criterion was established in the "Maintenance and management of oil-filled transformers" [2] by Electric Technology Research Association (ETRA) based on the gas pattern and the abnormality diagnostic figure, and accurate diagnosis became possible including the distinction between discharge and overheat. In addition, in the "The guideline for refurbishment of electric power transformers" [3] by ETRA, the diagnosis based on equivalent overheating area and trend analysis was introduced, and diagnostic accuracy was further increased.

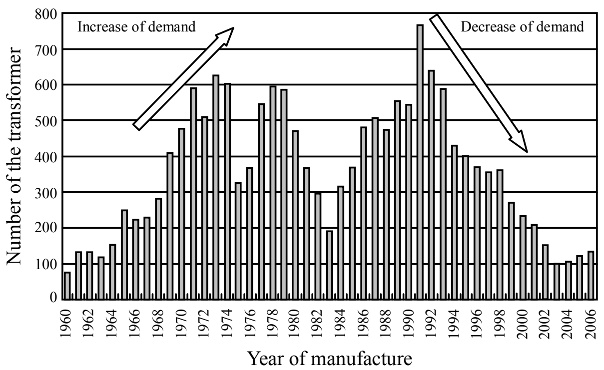

Figure 1: Age distribution of transformers (22kV or more) [1].

If abnormality is diagnosed by the DGA, secondary diagnoses, such as electrical tests including winding resistance, short-circuit impedance, partial discharge, flow electrification, and Frequency Response Analysis (FRA), are carried out. Among them, in late years, FRA attracts attention as a new diagnostic technique for diagnosing winding deformation, poor contact and so on from outside the transformer. There are many reports about FRA available on the accuracy and techniques of diagnosis [4][5], and a report was published in April, 2008 by CIGRE WG SC A2.26 on the diagnosis of transformers using FRA measurements [6]. Further, IEC standardization is being planned, and a guideline will be presented for measurement techniques and diagnostic techniques. However, CIGRE and IEC are the guidelines mainly for macroscopic diagnosis made by transformer users, and the analysis is thought difficult to accurately identify the abnormal region. We can do virtual experiments and malfunction simulation for finding the abnormal region, but there are still many uncertainties under the present conditions.

In performing such detailed diagnosis, it becomes important to detect the slightest change in the FRA waveforms. On the other hand, there is a possibility that we could not get an accurate diagnosis if the FRA characteristics are influenced by the arrangement of the measurement lead wire and the grounding, etc. In this paper, we report on the result on evaluating the major measurement parameters - insulating oil presence, tap positions, and measurement lead wire length - that can influence the FRA characteristics of an oil-immersed transformer.

2 PRINCIPLE OF FRA AND MEASUREMENT METHODS

2.1 Principle of FRA

The impedance Z of a transformer is mainly the combination of the inductance of winding and the ground capacitance. The impedance Z has a resonance at a certain frequency, and the resonant frequency fr is generally given by Equation (1):

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

where: L = Inductance
C = Capacitance

The parameters fr and Z change with L or C. We can detect local resonance points between sections or turns of the winding by widely changing the frequency. Therefore, we can possibly estimate the partial deformation or change, which we cannot detect by the conventional diagnostic technology.

2.2 Measurement methods

Figure 2 shows the FRA measurement system. For the measurement frequency of 100Hz-1MHz, a sine wave (10Vpeak) was automatically swept and applied to the HV terminal. All the other terminals were grounded. Here, the impedance Z of the transformer was calculated from the ratio of inter-terminal voltage V and the current I (Z=V / I) to find the frequency characteristics of the impedance.

3 EVALUATION OF MEASUREMENT PARAMETERS AFFECTING THE FRA CHARACTERISTICS

Table 1 shows the major measurement parameters and the ratings for the transformers. In each case, we compared the measurement with the simulated FRA waveforms. Figure 3 shows an example of simulation circuit. The winding was simulated by an RLC ladder circuit for surge analysis [4], and was simulated with a Frequency Scan function of EMTP.

3.1 Case1: Insulating oil presence

As for FRA of an oil-immersed transformer, the measurement and evaluation are usually made with the transformer filled with oil, but there is the case in which we have to compare the FRA measurement result with and without insulating oil depending on the schedule. We made our study also assuming such cases.

The comparative measurements and simulations of FRA were made in insulating oil ("normal"), where the inside of the transformer is filled with insulating oil, and in air after the oil is removed. Figure 4 shows the measurement result, and Figure 5 shows the simulation result. As reported in Reference [6]-[8], it was recognized that we have different characteristics in oil and in air, at and over the first resonant frequency fr_1, and that each resonant frequency is higher in air than in oil.

This is due to the difference of relative permittivity between insulating oil and air (oil > air); therefore,

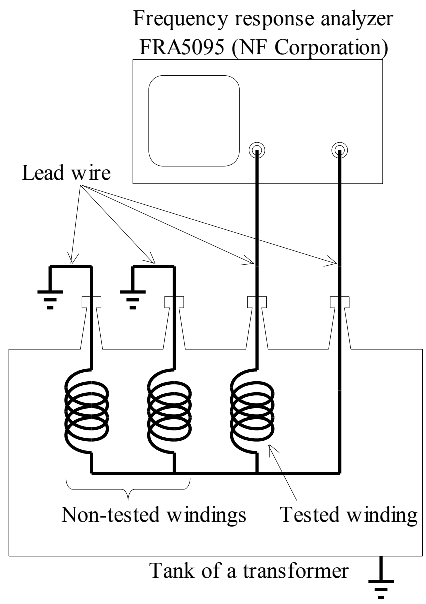

Figure 2: FRA measurement system

Table 1: Measurement parameters and ratings for the transformer

	Examination case	Case 1 (Insulating oil presence)	Case 2 (Tap position)	Case 3 (Lead wire length)
Ratings	Rated power	40 MVA		50 MVA
	Rated voltage	132 / 11.5 kV		132 / 12 kV
	Phase displacement symbol	YNyn0+d		YNd1
	Tap changing method	Coarse / Fine		Coarse / Fine
	Number of taps	25		19

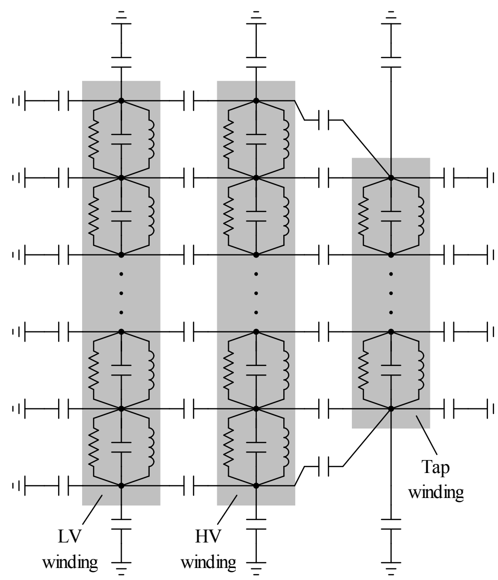

Figure 3: Example of EMTP simulation circuit for FRA

each resonant frequency is greater in air than in oil according to Equation (1). However, as Figure 6 shows, near the main HV winding to which voltage is to be applied, the insulator between windings is not of single insulation structure including only insulating oil / air, but of composite insulation structure with solid insulators and oil / air. Furthermore, the insulation structure between the sections of winding is also of composite, and the ratio of *fr* related to such a region cannot be expressed only by the relation between oil and air.

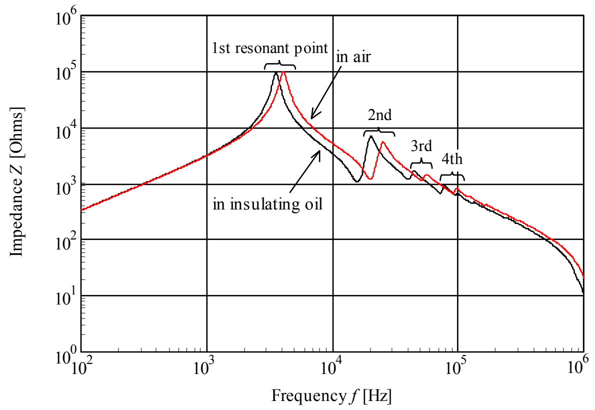

Figure 4: Measurements in insulating oil and in air

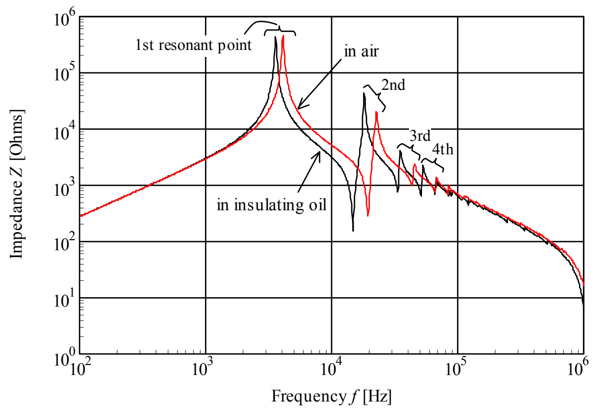

Figure 5: Simulations in insulating oil and in air

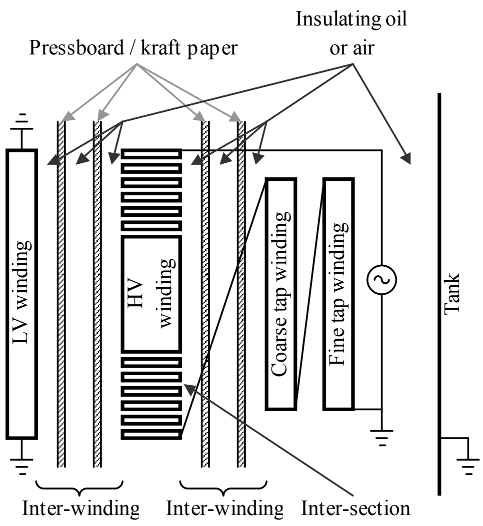

Figure 6: Insulation structure around HV winding

When the ratio of resonant frequency in the air to that in the oil is considered by dividing into the ratio of oil / air (fr_1), the ratio between windings (fr_2) and the ratio between sections (fr_3), each ratio is given as Equations (2)-(4) respectively:

$$fr_A = \sqrt{\frac{\varepsilon_O}{\varepsilon_A}} \cong 1.50 \qquad (2)$$

where: ε_O = Relative permittivity of insulating oil
ε_A = Relative permittivity of air

$$fr_B = \sqrt{\frac{\varepsilon_{WO}}{\varepsilon_{WA}}} \cong 1.15 \qquad (3)$$

where: ε_{WO} = Relative permittivity of insulating materials between windings (in oil)
ε_{WA} = Relative permittivity of insulating materials between windings (in air)

$$fr_C = \sqrt{\frac{\varepsilon_{SO}}{\varepsilon_{SA}}} \cong 1.23 \qquad (4)$$

where: ε_{SO} = Relative permittivity of insulating materials between sections (in oil)
ε_{SA} = Relative permittivity of insulating materials in between sections (in air).

On the other hand, Table 2 shows the ratios of the first to fourth resonant frequencies between in insulating oil and in air as measured and simulated by FRA. The ratio of the first resonant frequency fr_1 almost agreed with fr_B. In addition, the ratios of the second to fourth resonant frequencies (fr_2, fr_3, and fr_4) were found greater than that of fr_1 and closer to fr_C.

From the above, it is considered that fr_1 shows the characteristics between windings around the main HV winding while fr_2, fr_3, and fr_4 show the characteristics affected by such regions as between sections etc. except for between windings. As for the FRA characteristics in insulating oil and air, the number of resonance points is the same although there is a difference in resonant frequency, and differential diagnosis between in insulating oil and in air is considered possible by considering these characteristics.

Table 2: Ratio of resonant frequency between in insulating oil and in air

Resonant point	Ratio of resonant frequency (in air / in insulating oil)	
	Measurement	Simulation
1st	1.14	1.15
2nd	1.27	1.25
3rd	1.26	1.29
4th	1.26	1.29

3.2 Case2: Tap positions

If the tap position is different, it is expected that the FRA characteristics are affected through the different of inductance and capacitive coupling between tap windings. It was reported that there was hardly a difference of FRA characteristics between adjacent taps [6]. This time, we evaluated the FRA characteristics at all tap positions, and considered to find recommended tap positions for the actual diagnosis. Here, Figure 7 shows the diagram of tap connection for the transformer.

Figure 8 shows the FRA measurement result in all tap positions. The characteristic waveforms are classified into Band 1 (less than 10kHz), Band 2 (10kHz-25kHz), and Band 3 (35kHz-100kHz). The waveforms almost agreed in the frequency range over 100kHz at all tap positions.

Band 1 is in the frequency range near and lower than the fr_1, where the characteristics are greatly influenced by the winding inductance L. As the tap voltage decreased (from No.1 to No.25), fr_1 increased and the impedance at fr_1 decreased. Assuming the number of turns n across the entire HV winding, and the tap voltage V_{Tap}, we have the following relations, Equations (5) and (6):

$$L \propto n^2 \tag{5}$$

$$n \propto V_{Tap} \tag{6}$$

In addition, since Equation (7) is derived from Equation (1), Equation (8) holds, indicating that fr_1 is inversely proportional to V_{Tap}:

$$fr \propto \frac{1}{\sqrt{L}} \tag{7}$$

$$fr \propto \frac{1}{V_{Tap}} \tag{8}$$

On the other hand, since the main component of Z is L, Equation (9) holds. In addition, from Equations (5) and (6), Equation (10) holds, indicating that Z is proportional to the square of V_{Tap}:

$$Z \propto L \tag{9}$$

$$Z \propto V_{Tap}^{\;2} \tag{10}$$

Furthermore, Equations (8) and (10) lead to Equation (11), which indicates that Z is inversely proportional to the square of fr.

$$Z \propto \frac{1}{fr^2} \tag{11}$$

This indicates that in the low frequency range, fr, Z and V_{Tap} correspond to each other in 1 to 1, so that if the FRA characteristic at any tap position is obtained, the FRA characteristics at the other tap positions can be estimated. In addition, these relations are obtained also from the measured waveforms.

From the features of waveforms, Band 2 and Band 3 are classified into Group A (No.1-14A), Group B (No.14B), and Group C (No.15-25). In Group A, the coarse and fine tap windings are connected at [0 - +], and in Group C, at [0 - –]; the FRA waveform changes linearly with the tap position in the respective groups. In Group B, the connection is at [0 - –] just like in Group C, but the characteristics are somewhat different from those of Group C. Here, we paid attention to the three taps of No.14A (Group A), No.14B (Group B), and No.15 (Group C) where the connections between coarse and fine tap windings are changed. These waveforms are extracted from Figure 8 and shown in Figure 9. Further, Figure 10 shows the simulation result.

In Band 2 (10kHz-25kHz), the waveforms of No.14B and No.15 almost agree with each other and differ from that of No.14A, and so it is thought that the difference of waveforms is only due to the difference in the connection between coarse and fine tap windings, that is, due to the capacitive coupling between them.

Band 3 (35kHz-100kHz) is also basically greatly affected by the difference of connection between coarse and fine tap windings, and fr_3 is about 45kHz in the waveform of No.14A, but changes into about 55kHz in the waveforms of No.14B and No.15. However, since there is a difference between the waveforms No.14B and No.15, it is thought that the difference of the neutral position, that is, the ground capacitance of tap winding is

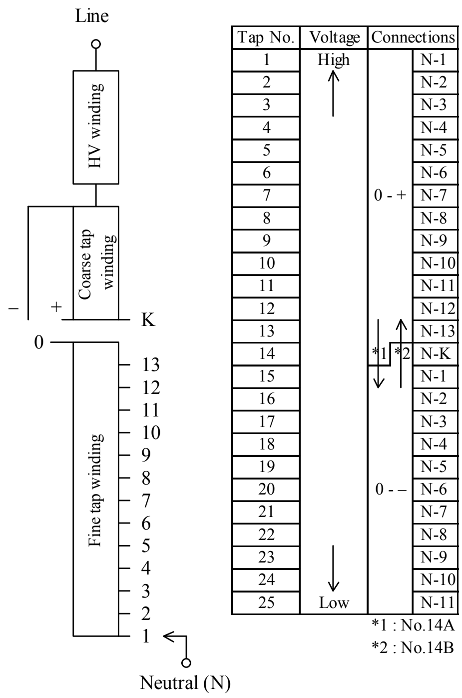

Figure 7: Tap connections (for one phase only)

also an influential factor.

It is thought from above that the characteristics of tap windings affect Band 2 and Band 3, and in the case of anomaly such as the deformation or the falling of wires in tap winding, it is thought that the examination of the difference of waveforms in these bands is important.

As a result, if an abnormality in the tap winding is assumed, it is thought that it is desirable to use one tap position each from Group A, Group B, and Group C in the FRA measurement (fingerprint) during the factory acceptance test of transformers. In particular, the maximum tap (No.1) for Group A and the minimum tap (No.25) for Group C are

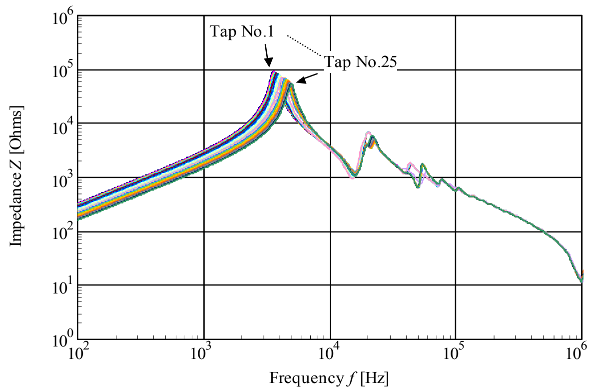

Figure 8: Measurements on all tap connections

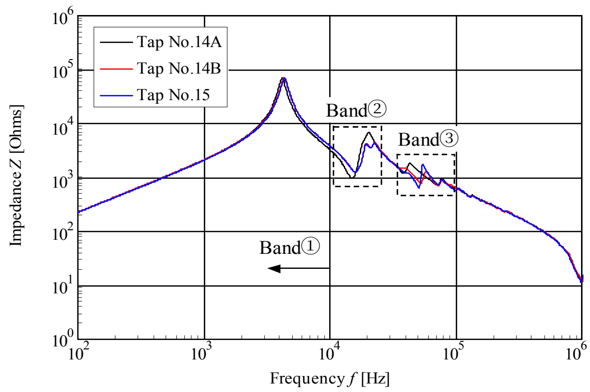

Figure 9: Measurements on tap No.14A, 14B and 15

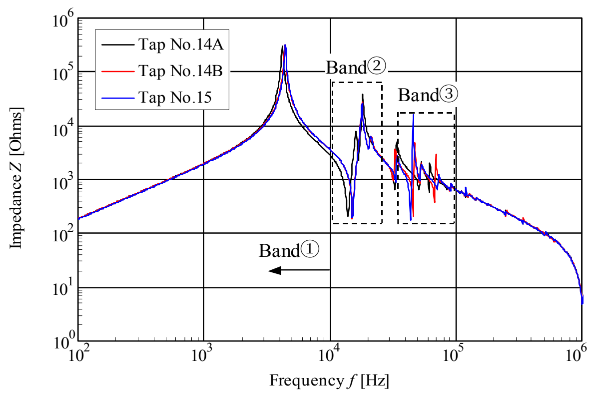

Figure 10: Simulations on tap No.14A, 14B and 15

recommended for measurement. Furthermore, diagnostic accuracy may be improved by adding another point from Group A and another point from Group C. It does not seem necessary to even further increase measurement points, and so the FRA measurement at the tap positions as shown in Table 3 is recommended.

3.3 Case3: Measurement lead wire length

In the FRA measurement, we use measurement lead wires to apply voltage to the transformer and to acquire the response signal. Generally we use a coaxial cable as a measurement lead to reduce noise from outside, but the measurement lead itself may possibly influence the FRA measurement. To investigate this, the length dependence of the measurement lead wires in the HV side for the five cases of l_H=12, 22, 32, 42, and 52m was examined. Here, the length l_L in the LV side was kept constant to be 12m. Table 4 shows the characteristics of the measurement lead wire used here.

Figure 11 shows the measurement result, and Figure 12 shows the simulation result. As the result, it was recognized that the characteristics of the frequency range near and higher than fr_1 changes by the measurement lead wire length. This change is very probably caused by the ground capacitance of the measurement lead by the following reasons.

a) In the frequency range equal to or less than 1kHz where the influence of *L* is dominant, there is no influence of the measurement lead wire length. This is because the inductance of the measurement lead wire is as small as 3μH (l_H=12m) to 13μH (l_H=52m) whereas the inductance of the winding is greater than 100mH.

b) In the frequency range in the near and higher than fr_1, the influence of *C* is great. Both the ground capacitances of the measurement lead wire and of the HV winding are of comparable magnitude, several thousand pF, and so it is thought that the FRA characteristics change with the measurement lead wire length.

Table 3: Recommended and optional tap positions for FRA diagnosis

Group	Recommended	Optional
A	No.1 [0 - +], [N - 1]	No.14A [0 - +], [N – K]
B	No.14B [0 - –], [N - K]	
C	No.25 [0 - –], [N - 11]	No.15 [0 - –], [N - 1]

Table 4: Characteristics of the measurement lead wire

Characteristic impedance	50 Ω
Inductance	0.25 μH/m
Capacitance	100 pF/m

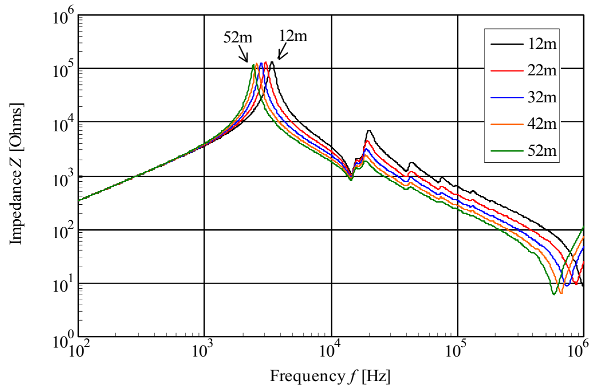

Figure 11: Measurements with various lead lengths.

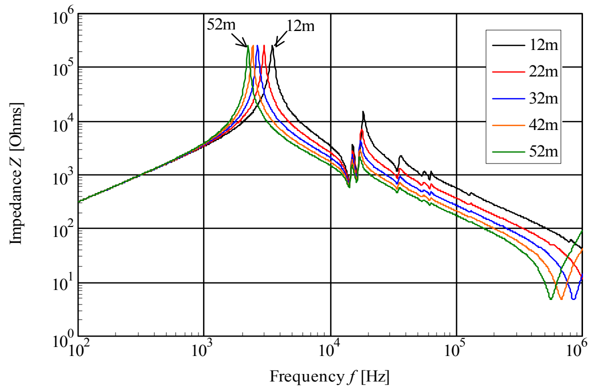

Figure 12: Simulations with various lead lengths

4 CONCLUSIONS

We examined the measurement parameters affecting the FRA characteristics - insulating oil presence, tap position, and measurement lead wire length - and obtained the results as follows.

Insulating oil presence: In the FRA waveforms, each resonant frequency is higher in air than in oil. However, since the number of resonance points is the same, it is thought that the diagnosis is possible through the comparison of FRA in oil and in air by considering the frequency shift.

Tap position: By arranging the FRA waveform for every tap position, the frequency range where the waveform depends linearly with the tap position and the range where the waveform depends non-linearly with the tap position were clearly separated. In the frequency range of 10kHz-100kHz, we found the influence by the difference of the connection of coarse and fine tap windings. In addition, advisable tap positions for diagnosis were determined

Measurement lead wire length: It was confirmed that if the measurement lead wire length is changed, the ground capacitance of the measurement lead wire changes and influences the FRA characteristics. The measurement lead wire length is an important parameter, and it is necessary to record data in the diagnosis.

Other factors including the place and the method of grounding, power-supply noise and inductive noise are expected to influence the FRA characteristics, and should be studied in future. Since the FRA diagnosis is made through comparing with the normal waveform, it is important to remove these outside factors as much as possible and to record the measurement parameters in detail in order to make the measurement condition closer to that of the reference condition as much as possible.

In addition, we made not only the measurements but also the simulations. Although the predicted impedances at the resonance points did not agree with the measurements, but we successfully determined the overall features of measured waveforms depending on the measurement parameters. In the actual diagnosis, the improvement of diagnostic accuracy is expected by performing the simulation by taking measurement parameters into consideration.

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