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Detection of Winding Axial Displacement of a Real Transformer by Frequency Response Analysis without Fingerprint Data

Satoru Miyazaki

Central Research Institute of Electric Power Industry, 2-6-1, Nagasaka, Yokosuka 240-0196, Kanagawa, Japan; m-satoru@criepi.denken.or.jp

Abstract: Detection of the axial displacement of power-transformer winding is important to ensure its highly reliable operation. Frequency response analysis is a promising candidate in detecting the axial displacement. However, a method of detecting the axial displacement at an incipient stage without the need for fingerprint data has not been investigated yet. This paper focuses on resonances showing a bipolar signature in the transfer function of inductive interwinding measurement, which is sensitive to the axial displacement of the winding. Transfer functions in the inductive interwinding measurements of eight power transformers are measured before shipping to elucidate the features of resonances showing a bipolar signature. The measured resonances showing the bipolar signature can be divided into the "stair type" and the "crossing-curve type". It is found that the grounding points in an inductive interwinding measurement determine the type of resonance showing the bipolar signature, irrespective of the type of winding, such as interleaved or multilayer winding, the winding arrangement, and the existence of stabilizing and tertiary windings. On the basis of this finding, a method of detecting the axial displacement of a transformer winding is proposed. In the proposed method, the amplitudes of the resonances among three phases are compared, or the three-phase pattern of the resonances is compared with normal patterns. Therefore, the proposed method is applicable to three-phase transformers without fingerprint data. The proposed method is applied to a real transformer that experienced a ground fault due to a lightning strike at a nearby transmission tower, and the effectiveness of the proposed method is confirmed.

Keywords: power transformer; frequency response analysis; winding axial displacement; fingerprint data

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1. Introduction

Power transformers (hereafter referred to as transformers) are one of the key apparatuses in electric power networks. To ensure the high reliability of transformers, diagnoses of mechanical faults, such as winding deformation and winding displacement, are important [1]. Even if the mechanical faults of a winding do not necessarily lead to the immediate failure of the transformers, their ability to withstand future mechanical and dielectric stresses may be considerably reduced [2,3].

The ability to withstand mechanical stress, such as the electromagnetic force generated during short-circuit events, is one of the key points determining a transformer's life [4,5]. In short-circuit tests of aged transformers, the breakage of a pressboard triggers ground faults because of the axial compressive force [6,7]. Figure 1 summarizes short-circuit-test [8] results of aged transformers focusing on the average degree of polymerization of the pressboard [7], which is an indicator of their mechanical strength, and the compressive mechanical force applied to the pressboard. In Figure 1, open symbols mean that the tested transformers passed the test, and gray and black symbols mean that the tested transformers experienced some faults. The faults occur when the compressive force is high and the degree of polymerization of the pressboards is low, i.e., its mechanical strength is low.

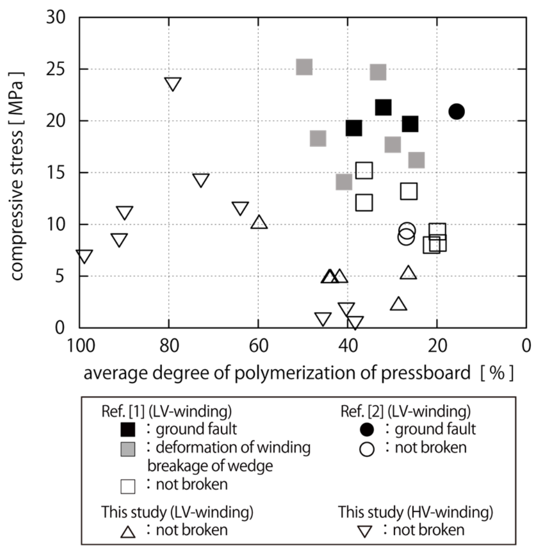


Figure 1. Summary of the short-circuit test results focusing on applied mechanical stress and average degree of polymerization of pressboards [7]. (Reference numbers in the legend are those in the original paper.).

The compressive stress, namely axial force, generated during short-circuit events may increase owing to the axial displacement of the winding (AD) [9,10]. A high mechanical force may break pressboards, and short circuits and ground faults occur inside transformers. Such a situation is catastrophic as it may cause an extended outage. Therefore, it is important to detect AD.

Because AD can change the spatial distribution of the leakage flux and the coupling between the electromagnetic force and transformer vibration [11], a potential detection method for AD is monitoring the vibration. A diagnostic method focusing on the change in the vibration characteristics of the windings and the core has been investigated [12]. However, the applicability of this method to real transformers is unclear. A diagnostic method using electromagnetic waves has also been investigated [13,14]. In this method, a set of antennas is employed. A transmitting antenna transmits an electromagnetic pulse, and the propagated signal is reflected from the transformer winding. A receiving antenna detects the reflected signal. By changing the location of antennas along the transformer winding, an image of the transformer winding is generated. To apply this method to real transformers, an evaluation of the effect of the inserted antennas on the insulation performance of the transformer and the development of a position control technique of the antennas in the transformer are necessary. Another diagnostic method focusing on the differential current between the primary and secondary sides of the transformer was proposed [15,16]. This method was demonstrated by a numerical simulation; however, the investigated AD is larger than 3.8% of the winding height [15–17] and is impractical.

Frequency response analysis (FRA) [18,19] is a promising AD detection method. In FRA, frequency responses, namely transfer functions (TFs), are measured. A TF is defined as the amplitude ratio between the voltages measured at two terminals of a tested transformer over a range of frequencies when one of the terminals is excited by a voltage source [20,21]. TFs are determined by the electrical parameters of transformers, such as the inductances of windings and capacitances between windings. These electrical parameters change owing to mechanical faults; hence, the TFs are changed. In FRA, the faults are basically detected by observing changes in TFs compared with fingerprint data [2]. Note that fingerprints are data measurements from former times [2].

Numerous studies on the diagnosis of AD by FRA have been conducted. Abbasi et al. proposed a diagnostic method for AD by FRA employing time-series analysis [22]. Jiang et al. investigated a diagnostic method for AD in an autotransformer with split windings by FRA [23]. Aljohani and Abu-Siada proposed a method of interpreting FRA results using a digital image processing technique [24]. Liu et al. demonstrated FRA interpretation with the help of a theoretical calculation by the finite element method to detect AD of a real transformer [25]. Tarimoradi and Gharehpetian proposed a new calculation method of the numerical indices that employed a moving window to interpret the FRA results [26]. Ghanizadeh and Gharehpetian proposed a detection and location method by FRA that employed an artificial neural network [17]. Al-Ameri et al. investigated the impact of AD on the TF using a circuit model [27]. Several papers [17,22–26] investigated OC measurement among the four connection schemes in FRA; however, OC measurement has low sensitivity for detecting the incipient AD as investigated in [28,29]. The target amounts of AD in these studies were from 1% to 5% [22–24], from 1% to 9% [25], and from 1.25% to 10% [17,26] of the winding height. The amount of AD investigated in [27] is not presented; however, it would be around 10% because the simulated variation in the capacitance between the high-voltage (HV) and the low-voltage (LV) winding is 10%. Such a large AD would result from breakage of the clamping structure into fragments, which will probably be followed by catastrophic electric faults such as a turn-to-torn short, a ground fault, and an arcing discharge. It is important to detect AD at an incipient stage rather than at a catastrophic stage. AD at an incipient stage cannot be detected by the method proposed by previous studies [17,22–26]. A diagnostic method for AD at an incipient stage is also useful as a soundness confirmation method of transformers that experiences, for example, external short circuits and earthquakes.

In this paper, the target amount of AD is set to be less than 1% of the winding height concerning the ratio of pressboard inserted in the winding of usual disc-type transformers. A quantitative diagnostic method for AD by FRA has already been proposed [28]. This method had been demonstrated for AD of less than 1% of the winding height. However, the application of this method is limited as it requires fingerprint data [2] to be measured when the transformers are normal, as explained in Section 2. The quantitative diagnostic method for AD will help in the detailed evaluation of the reliability of transformers [30]. Even when there are no fingerprint data and the quantitative AD diagnosis method cannot be applied, diagnostic information, such as whether the winding is axially displaced, will be useful in the maintenance and replacement planning of transformers [30]. Therefore, the development of a simple AD detection method without the need for fingerprint data is desired.

This paper proposes a detection method for AD at the incipient stage, i.e., less than 1% of the winding height, without the need for fingerprint data. When fingerprint data do not exist, construction-based and type-based comparisons are alternative choices [2]. In the type-based comparison, the TFs of identically constructed transformers are employed as reference data. In the construction-based comparison, the TFs of other phases are employed as reference data. The construction-based comparison is applicable to all three-phase transformers, whereas the type-based comparison may need additional measurements. Therefore, this paper proposes the AD detection method employing the construction-based comparison. Furthermore, the proposed method is applied to a real transformer that experienced a ground fault due to a lightning strike at a nearby transmission tower. The result of diagnosis by the proposed method is compared with that of an investigation by dismantlement. The comparison reveals the effectiveness of the proposed detection method of AD at the incipient stage by FRA without the need for fingerprint data.

2. Review of AD Diagnosis by FRA

In FRA, four connection schemes are standardized [20,21]: end-to-end open-circuit (OC), end-to-end short-circuit (SC), capacitive interwinding (CIW), and inductive interwinding (IIW) measurements.

Studies on the diagnostic method of AD at the incipient stage by FRA are rare. Samimi et al. investigated the sensitivity of the connection schemes on AD [29]. In their paper, a large variation in the TF of a specific connection scheme in FRA due to AD was expressed as "the connection scheme has a high sensitivity to AD". The investigated amount of AD was from 0.6% to 1.8% of the winding height. They found that both the IIW and CIW measurements have high sensitivity to AD. On the other hand, Miyazaki et al. measured TFs of a cast-resin transformer with a rated capacity of 160 kVA by axially displacing the high-voltage (HV) winding [28]. The investigated amount of AD was from 0.4% to 0.9% of the winding height. They found that the TF variation due to AD was most significant in IIW measurement.

The reason for the different results of these studies can be explained as follows [28]. The winding-radius ratio, which is the ratio of the outer radius of the low-voltage (LV) winding to the inner radius of the HV winding, of the transformer model in [29] was 98%. On the other hand, that of the tested transformer in [28] was 83%. The narrower spacing results in a larger capacitance between the HV and LV windings, which becomes more dominant in determining the TF in CIW measurement. Therefore, the TF in CIW measurement of the transformer model in [29] was sensitive to AD. A winding-radius ratio of 98% is impractical for cooling and insulation design. For example, the winding-radius ratio is 87% in an actual three-phase transformer with a rated voltage of 63 kV/6.6 kV and a rated capacity of 5 MVA [31].

Given the above discussion, this study focuses on IIW measurement. In IIW measurement, TFs are measured between the HV and LV windings, with the other ends of both windings grounded [20,21]. IIW measurement is explained in Figure 2. The external neutral point is grounded for a star-connected winding with an external neutral point (see Figure 2a). For a delta-connected winding, the grounding point is the terminal connected to the other end of the measured winding (see Figure 2b). The grounding point is not determined in the IEC [20] and IEEE [21] standards for a star-connected winding without an external neutral point. However, in this study, the terminals of the other two-phase windings are grounded as they are the possible grounding points (see Figure 2c).

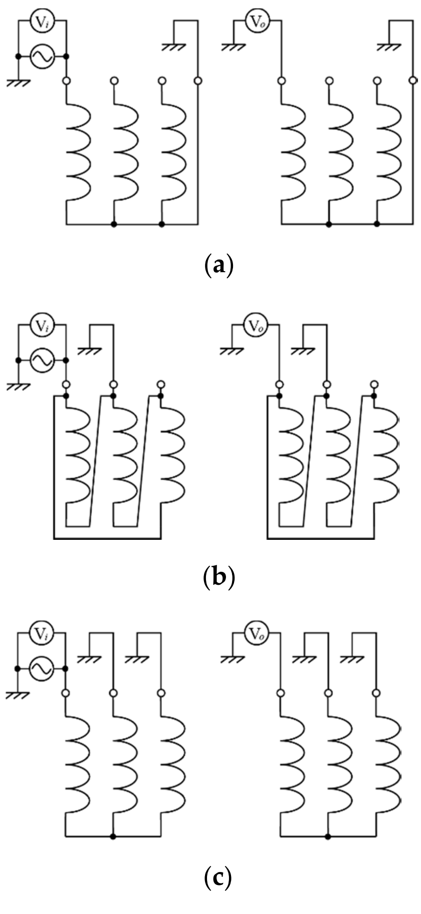


Figure 2. IIW measurement in FRA: (**a**) YNyn0, (**b**) Dd0, and (**c**) Yy0.

An example of the measured TF in IIW measurement of a transformer is shown in Figure 3. The rated voltage, rated capacity, and vector group of this transformer are 110 kV/10.6 kV, 12 MVA, and YNd11, respectively. Typically, TFs in IIW measurement are flat in the frequency range below several hundreds of Hz, as a TF in this frequency range is determined by the transformation ratio. In the case of Figure 3, this frequency range is below 600 Hz. The TF also typically shows a deep trough at around several tens of kHz. In the case of Figure 3, a deep trough can be found at around 16 kHz. Between these two frequencies, the TF is generally a smooth curve; however, there are resonances showing a bipolar signature (RBSs) at around several kHz. In the case of Figure 3, the RBS can be found at around 6 kHz.

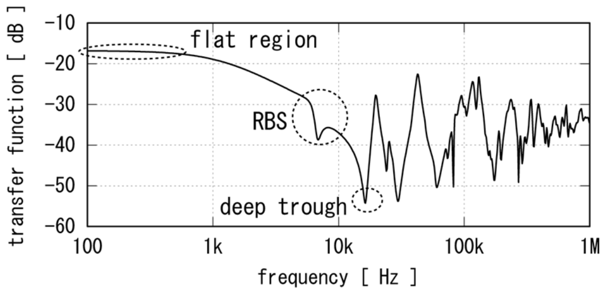
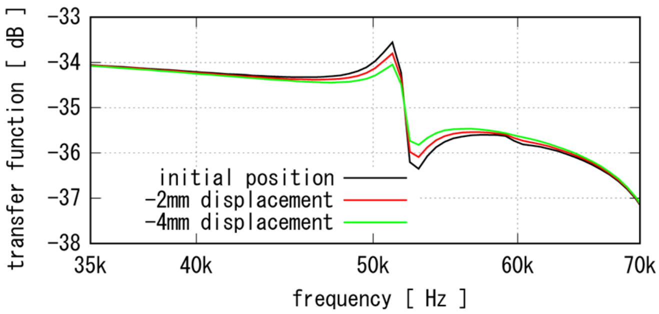


Figure 3. Example of TF in IIW measurement.

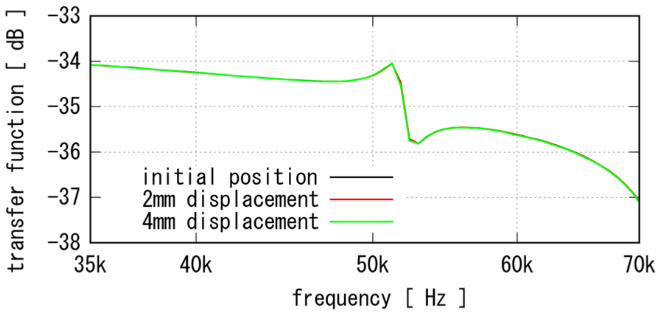
In [28], the RBS amplitude increased as the HV winding of the cast-resin transformer, whose height is 450 mm, was axially displaced downward, as shown in Figure 4a. Note that it is theoretically demonstrated that a circuit model can reproduce the RBS, and the amplitude of the RBS increases due to AD [28]. An advantage of the detection method for AD focusing on the RBS is robustness. Although the RBS has a high sensitivity to AD, it hardly changes with the horizontal displacement of the winding, as shown in Figure 4b. Figure 4b shows the measured TFs for the same cast-resin transformer in [28] before and after horizontal displacement of its HV winding. In Figure 4b, the winding was horizontally displaced along the yoke's line of symmetry. Horizontal displacement hardly changes the TF. When the winding is horizontally displaced perpendicular or oblique to the yoke's line of symmetry, the change in RBS would be smaller than that in the case in Figure 4b because of the change in capacitance between phases is smaller.

Concerning the setup of the IIW measurement, the TFs in the IIW measurement are mainly influenced by the magnetic coupling between the HV and LV windings. It can be considered that the influences of horizontal displacement and radial deformation on magnetic coupling are similar. Therefore, Figure 4b suggests that the RBS is hardly changed by horizontal displacement and radial deformation.

A quantitative diagnostic method for AD by FRA employing the TFs in IIW measurement was previously proposed [28]. In this method, a circuit model for the reproduction of the RBS was proposed. The proposed model reproduces the RBS of both the fingerprint and diagnosed data. The amount of AD is estimated from the difference between the circuit-model parameters in the reproductions. The quantitative diagnostic method for AD will help in the detailed evaluation of the reliability of transformers [30]. However, in practice, most real transformers do not have fingerprint data. Furthermore, in IEC 60076-18:2012 [20], only OC measurement is standard and the other connection schemes, including IIW measurement, are optional. Therefore, even if a transformer diagnosed by FRA has fingerprint data, it would be TF in OC measurement. Because fingerprint data of IIW measurement are rare, this method is applicable only to a small fraction of real transformers.



(**a**)



(**b**)

Figure 4. Example of amplitude variation of RBS due to (**a**) axial [28] and (**b**) horizontal displacement of HV winding. (The signs '-' in the legend in (**a**) indicate downward AD.).

3. AD Detection Method without Fingerprint Data

3.1. Accumulation of Data of Normal Transformers without AD

Comparisons of RBSs among three phases are helpful for the detection of AD without fingerprint data. To establish this method, the accumulation of data of normal transformers is essential [28]. In this paper, the TFs of eight transformers were measured. Table 1 shows the specifications of the tested transformers. Note that the letter in the transformer name, 'A' or 'B', identifies the manufacturer. Although the original vector group of Tr-A4 is YNyn0+d, additional IIW measurements were conducted in three cases. In the first case, the external grounding point of the stabilizing winding was disconnected, and its vector group was considered to be YNyn0d1 (referred to as Tr-A4a). In the second case, the external neutral points were disregarded, and its vector group was considered to be Yy0+d (referred to as Tr-A4b). In the third case, the external grounding point of the stabilizing winding was disconnected, the external neutral points were disregarded, and its vector group was considered to be Yy0d1 (referred to as Tr-A4c). The tested transformers have interleaved or multilayer windings. The arrangements of windings can be grouped into three, as shown in Figure 5 and Table 1. The TFs of these transformers were measured in factories before shipping. Therefore, the tested transformers are normal, and their windings are not axially displaced. The TF measurements in this paper follow IEC 60076-18:2012 [20]. A sweep frequency response analyzer, M5400, manufactured by Doble Engineering Company, was employed in the TF measurements. The connection method of the measuring lead is method 2 specified in IEC 60076-18:2012 [20]. Note that the grounding braid of this measuring lead is fixed along the co-axial cable and that the free part of the grounding braid, which reduces the repeatability of the measurement, is very short. Therefore, the influence of the measuring lead on the repeatability of measurement is negligible [32].

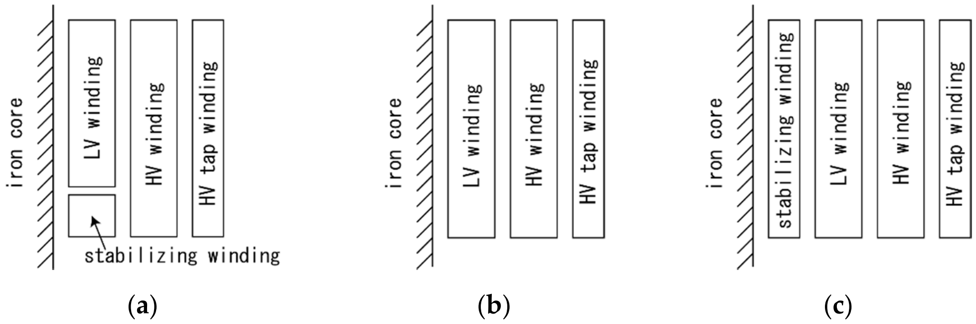


Figure 5. Winding arrangements of tested transformers.

Table 1. Specifications of measured new transformers before shipping in the factory and types of RBS in TFs in IIW measurement.

Name	Rated Capacity	Rated Voltage	Vector Group	Stabilizing Winding	Winding Arrangement	Winding Type	Grounding Point in IIW Measurement *2 HV	LV	RBS Type
Tr-A4	20	77.25/22	YNyn0+d	Available	Figure 5a	Interleaved	Neutral	neutral	Stair type
Tr-A4a *2	20	77.25/22	YNyn0d1	N/A	Figure 5a	Interleaved	Neutral	neutral	
Tr-A1 *3	30	66/6.6	Yy0+d	Available	Figure 5a	Interleaved	OPW *1	OPW	Crossing-curve type
Tr-A4b *4	20	77.25/22	Yy0+d	Available	Figure 5a	Interleaved	OPW *1	OPW	
Tr-A4c *5	20	77.25/22	Yy0d1	N/A	Figure 5a	Interleaved	OPW *1	OPW	
Tr-B1	20	66/6.9	Yy0+d	Available	Figure 5b	Multilayer	OPW *1	OPW	
Tr-B2	30	66/6.9	Yy0+d	Available	Figure 5b	Multilayer	OPW *1	OPW	
Tr-B3	15	66/6.9	Yy0+d	Available	Figure 5b	Multilayer	OPW *1	OPW	
Tr-B4	20	66/6.9	Yy0+d	Available	Figure 5b	Multilayer	OPW *1	OPW	
Tr-A2	20	66/6.6	YNy0	N/A	Figure 5c	Interleaved	Neutral	OPW	No RBS
Tr-A3	10	66/6.6	YNy0+d	Available	Figure 5a	Interleaved	Neutral	OPW	

*1 OPW: other-phase windings. *2 The same transformer as Tr-A4. Tr-A4 is treated as YNyn0d1 by disconnecting the external grounding point of the stabilizing winding. *3 The original vector group is YNy0+d; however, this transformer has an internal arrestor at the neutral point of the primary winding and is treated as Yy0+d. *4 The same transformer as Tr-A4. Tr-A4 is treated as Yy0+d, and it is considered that there are no neutral points in the primary and secondary windings. *5 The same transformer as Tr-A4. Tr-A4 is treated as Yy0d1 by disconnecting the external grounding point of the stabilizing winding and assuming that there are no neutral points in the primary and secondary windings.

Figure 6 shows examples of measured TFs in IIW measurement. The measured RBSs can be divided into two groups. The first one is the "stair type", as shown in Figure 6a. The measured TFs in IIW measurement show a characteristic stair-like RBS, and their amplitudes are almost the same among the three phases. Another type of RBS is the "crossing-curve type". In Figure 6b, the TF of the V phase is convex downward at around 7.9 kHz and convex upward at around 8.3 kHz. In contrast, the TF of the W phase is convex upward at around 7.9 kHz and convex downward at around 8.3 kHz. The TF of the U phase is almost their mean. Note that there are no RBSs in the TFs of Tr-A2 and Tr-A3, as shown in Figure 6c.

The effect of the stabilizing winding on the RBS shape in the IIW measurement is investigated using Tr-A4. Tr-A4a is the same transformer as Tr-A4; however, the stabilizing winding is floating. The measured TFs of the U phase are shown in Figure 7. The measured RBSs in the TFs in IIW measurement almost completely overlap, and the stabilizing winding does not affect the RBS shape. This result also suggests that the tertiary winding does not affect the RBS. Therefore, it can be concluded that the stabilizing winding and tertiary winding do not affect the existence of the RBS and its shape.

The effect of the grounding points in the IIW measurement on the RBS shape is also investigated using Tr-A4. Tr-A4b is the same transformer as Tr-A4, except that the external neutral points are disregarded, and the IIW measurement is conducted by grounding the other-phase windings, as shown in Figure 2c. The measured TFs of Tr-A4b are shown in Figure 8. The TFs of Tr-A4 are shown in Figure 6a. Although the measured RBSs of Tr-A4 are of the stair type, those of Tr-A4b are of the crossing-curve type.

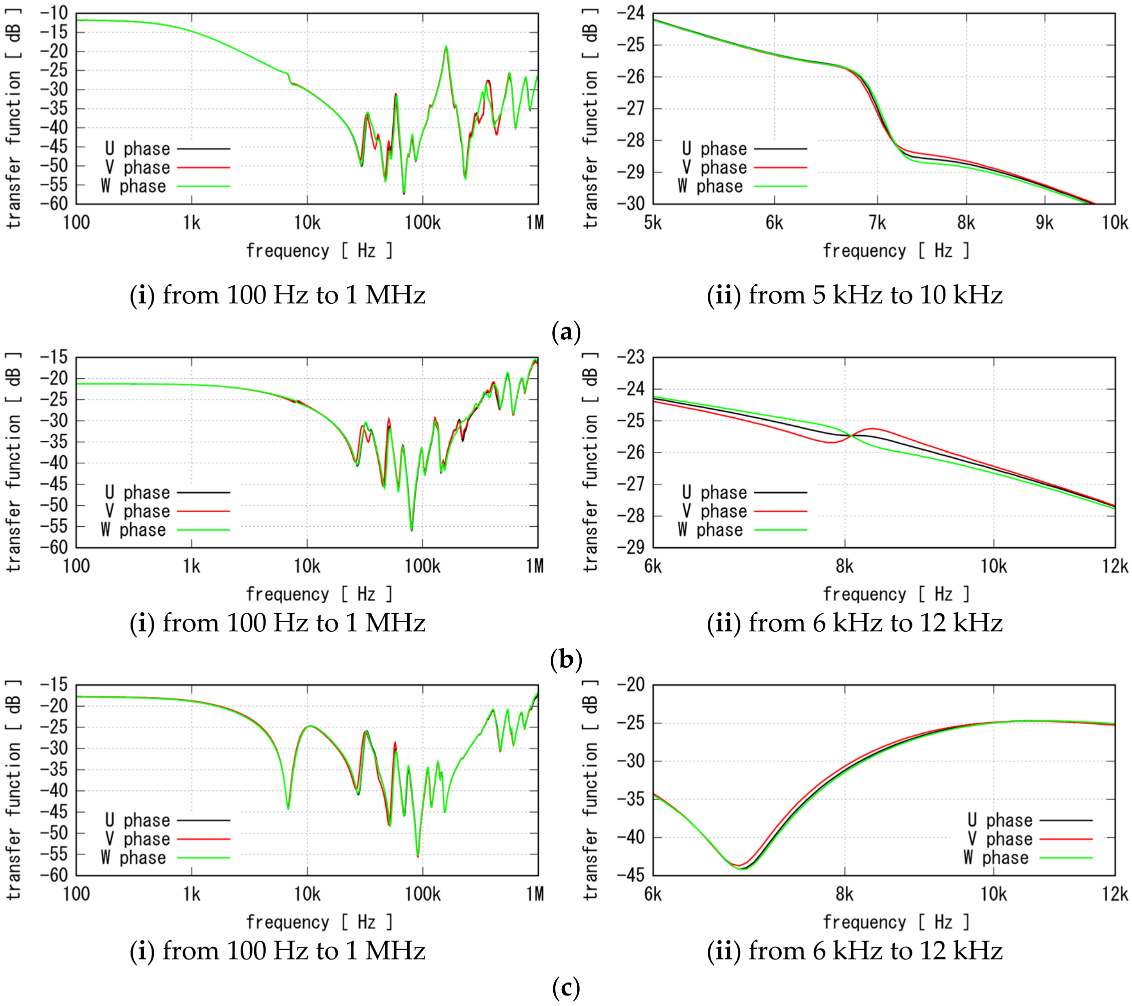


Figure 6. Examples of measured TFs in IIW measurement: (**a**) Stair-type RBS (Tr-A4), (**b**) crossing-curve type RBS (Tr-A1), and (**c**) TFs without RBS (Tr-A2).

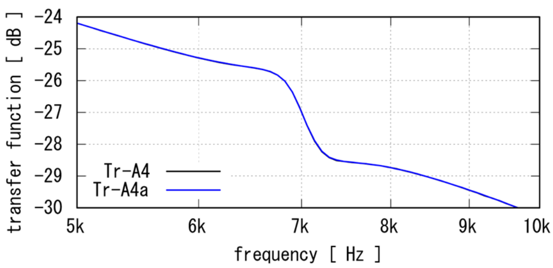


Figure 7. Effect of stabilizing winding on RBS (comparison between Tr-A4 and Tr-A4a).

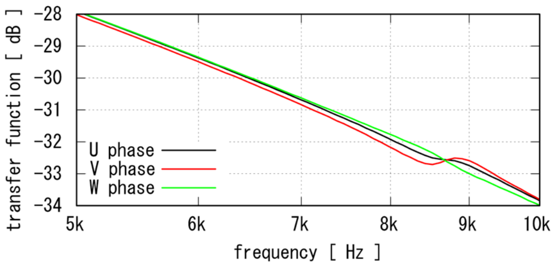


Figure 8. Effect of stabilizing winding on RBS (TFs of Tr-A4b).

Table 1 also shows the shapes of the RBSs in the TFs in IIW measurements. The tested transformers are grouped by the RBS shape in Table 1. The grounding points in IIW measurements, which are basically determined by the vector group, determine the RBS shape. The stabilizing winding and tertiary windings, winding arrangement, and winding type do not affect the RBS shape.

3.2. Proposal of AD Detection Method witouut Fingerprint Data

On the basis of the discussion in the previous section, a method of AD detection by FRA without the need for fingerprint data is proposed, as shown in Figure 9. The proposed method focuses on the RBSs in the TFs in IIW measurements. For transformers with a vector group of YNyn0, the neutral points are grounded in the IIW measurements. In this case, the RBS shapes in the TFs in IIW measurements are of the stair type, and their amplitudes are similar among the three phases when the winding is not axially displaced. Because the RBS amplitude is sensitive to AD [28], as shown in Figure 4a, it will be markedly different from those of the other phases when the winding is axially displaced. For transformers with a vector group of, for example, Yy0, YNy0, or Yyn0, terminals of other-phase windings are grounded. Following the standards [20], the neutral point should be grounded for the transformer whose vector group is YNy0 or Yyn0. However, there are no RBSs in TFs measured in such a manner, and it is difficult to detect AD. Therefore, other-phase windings are grounded even for the transformer whose vector group is YNy0 or Yyn0. In this case, the shapes of the RBSs in the TFs of the three phases are of the crossing-curve type. Because the amplitude of the RBS is sensitive to AD [28], the three-phase pattern of the RBS will be different from this three-phase pattern when the winding is axially displaced.

The proposed method is only for detecting AD, and it is difficult to determine the direction of displacement and whether it is oblique. Note that the quantitative diagnostic method proposed in [28] would determine the direction of AD.

The proposed method would also detect simultaneous AD of two or all three phases because the AD of the same extent in three-phase windings would be rare. In this case, the amplitudes of the stair-type RBSs do not agree with each other, and the three-phase pattern of the crossing-curve type RBS differs from that of the normal pattern shown in Figure 6b. It is difficult to identify the phase in which the winding is displaced. However, diagnostic information, such as whether the winding is axially displaced, will be helpful in the maintenance and replacement planning of transformers.

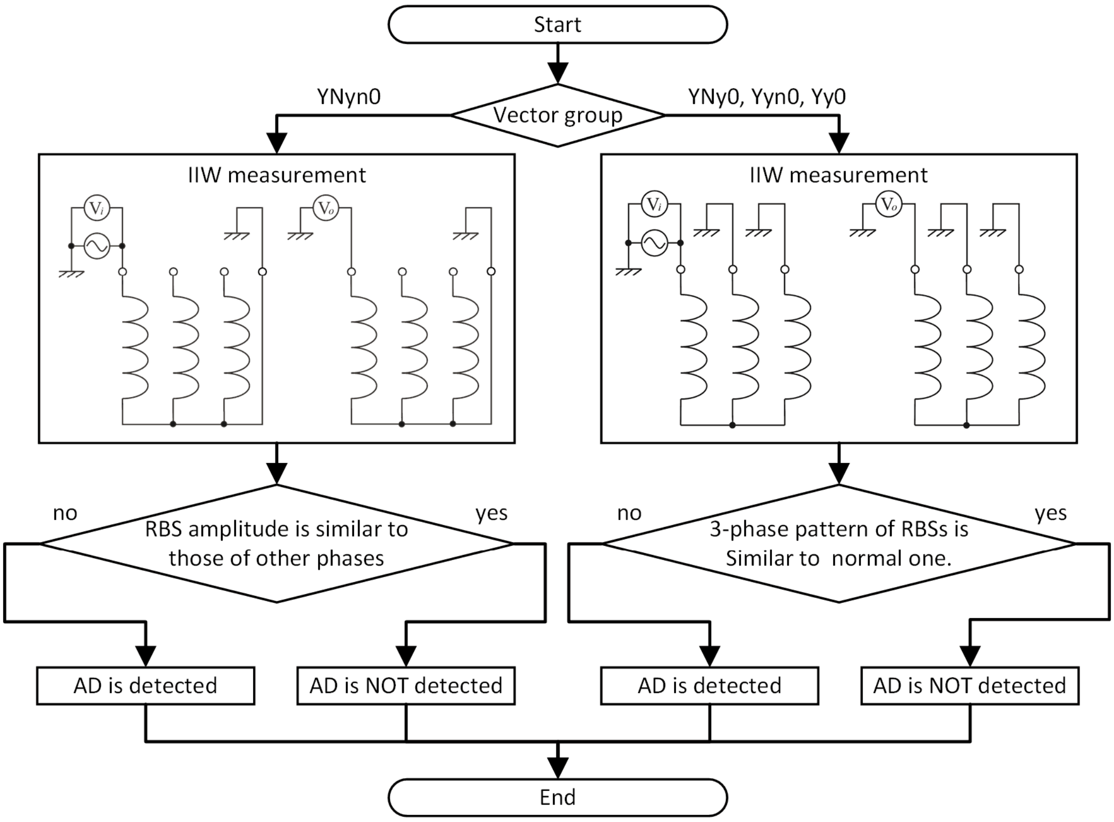


Figure 9. Proposed method of AD detection by FRA without fingerprint data.

In FRA diagnosis employing the OC measurement standardized in the standard [20], the winding fault is identified by detecting the change in TFs, and then, for example, the fault type is identified by the frequency range in which the TF has changed [33,34]. On the other hand, the proposed detection method of AD focuses on the specific connection scheme and the specific resonant frequency; therefore, the winding fault type can be easily identified as AD. It is worth noting that the RBS is not sensitive to horizontal deformation and radial deformation. Since in the proposed AD detection method, the amplitudes of RBSs are compared among the three phases or the three-phase pattern of the RBSs is focused on, it is applicable to three-phase transformers without the need for fingerprint data. The proposed method is also applicable when there are stabilizing or tertiary windings, as they do not affect the shape and amplitude of the RBS, as discussed in Section 3.1. It is worth noting that the proposed method is only for the detection of AD. The winding faults other than AD, such as horizontal displacement, radial deformation, and turn-to-turn short, would be detected separately by focusing on the different resonances in another frequency range or TFs of the other connection schemes.

Contaminations in oil such as dissolved gases and moisture may change its permittivity; however, the change is insignificant. Therefore, the influence on capacitances, and hence, the influence on FRA results, is negligible.

4. Detection of AD in Real Transformer without Fingerprint Data

The proposed detection method for AD was applied to a real transformer (referred to as Tr-A5 hereafter). Tr-A5 had been operated in a distribution substation, and it experienced a ground fault due to a lightning strike at a nearby transmission tower [35]. A high short-circuit current flowed into the winding, and an electromagnetic force was generated, resulting in some mechanical faults, including AD. The rated voltage, rated capacity, and vector group of this transformer are 75.25/22 kV, 20 MVA, and YNyn0+d, respectively. Its winding type is interleaved winding, and its winding arrangement is that shown in

Figure 5a. The tested transformer does not have fingerprint data; however, the proposed AD detection method is applicable.

Figure 10a shows the measured three-phase TFs in IIW measurement [35]. Because the RBS is sensitive to AD [28], the RBS is focused on in this paper. Figure 10b shows an enlargement of the RBS. Although the RBS amplitudes of the TFs of the U and V phases almost agree, that of the TF of the W phase is remarkably larger than them. Based on the proposed AD detection method in Figure 9, this result indicates the AD of the W-phase winding.

Tr-A5 was dismantled for further investigation [35]. Mechanical faults, such as deformation and displacement, were not found for the U- and V-phase windings. However, a slight tilting of the LV winding was found in the W-phase winding, as shown in Figure 11 [35]. Figure 11b shows the measured distance from the iron-core frame to the bottom of the LV winding. Although the initial states of the windings are not known, the LV winding of the W phase is tilted more than that of the U phase. Note that the tilting of the winding is a type of AD of the winding. It can thus be understood that the tilting of the LV winding of the W phase changes the RBS amplitude of the TF of the W phase.

The height of the HV winding is 980 mm. Therefore, the AD of 3 mm (5 mm−2 mm) indicated in Figure 11b is 0.3% of the winding height. It is difficult to evaluate the detection limit of the AD by the proposed method using a real transformer; however, it is less than 0.3%. Conventional diagnostic methods such as short-circuit impedance measurement were also applied to the same transformer. However, they failed to detect such a small amount of AD.

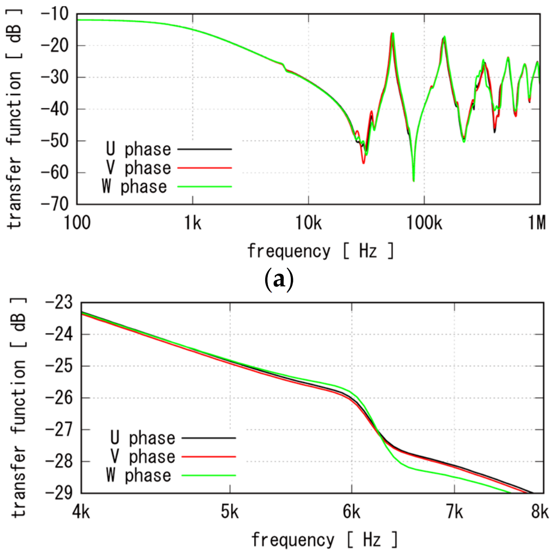
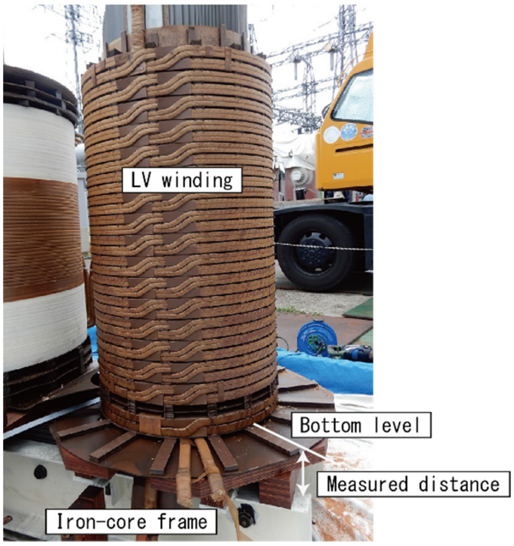
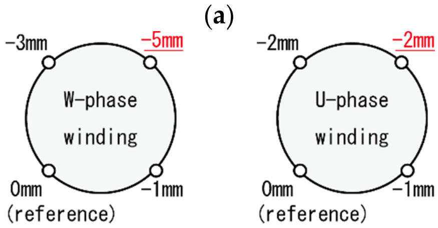


Figure 10. Measured TFs in IIW measurement of Tr-A5 from (**a**) 100 Hz to 1 MHz and (**b**) enlargement of RBS [35].



(a)



(b)

Figure 11. Result of the investigation by dismantlement: (**a**) Photo of LV winding and (**b**) measured distance from the iron-core frame to the bottom of LV winding (bottom view) [35].

5. Conclusions

TFs in IIW measurement of transformers were measured before they were shipped to elucidate the features of RBSs, which vary due to AD. The measured RBSs can be divided into two groups: the stair type and the crossing-curve type. It was found that the grounding points in IIW measurement determined the type of RBS. An AD detection method was proposed based on this finding. Because in the proposed AD detection method, the amplitudes of RBSs were compared among three phases or the three-phase pattern of the RBSs was focused on, it was applicable to three-phase transformers without the need for fingerprint data. The proposed AD detection method was applied to a real transformer that experienced a ground fault due to a lightning strike at a nearby transmission tower. The proposed method detected the AD of the W-phase winding, and the result is consistent with that of the investigation by dismantlement. This result reveals the effectiveness of the proposed AD detection method.

The proposed method successfully detects AD of 0.3% of the winding height. AD may reduce the ability of the transformer to withstand future mechanical and dielectric stresses and hence may reduce its reliability. The proposed method can detect AD at the incipient stage without the need for fingerprint data. Diagnostic information, such as whether the winding is axially displaced, will be helpful in the maintenance and replacement planning of transformers. The proposed method is also helpful in confirming the soundness of transformers that experience, for example, external short circuits and earthquakes.

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