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Frequency response patterns of transformer windings with mechanical faults

Abstract. *The paper presents summary of FRA deformational tests results conducted on several transformers in order to find universal influence of windings deformations on FR curve. Different transformer constructions have various frequency response curve shape, but some frequency ranges and curve change patterns can be generalized for future assessment of such results.*

Keywords: Frequency Response Analysis, transformer, winding, deformation

Introduction

Frequency Response Analysis (FRA) is a test method used for detection of deformations and displacements in transformer windings. It has been introduced into industrial practice in the last decade, its measuring technology has been normalized [1], however there are still problems with interpretation of test results. FRA is a comparative method, so it can be clearly judged whether the mechanical condition of the winding is correct, when there are no differences between compared frequency response (FR) curves recorded e.g. in time intervals, but differences between these curves are usually hard to interpret. One of the research directions aimed at improving the interpretation of FRA test results of transformer windings is conducting experiments with introduced controlled deformations into them. Their aim is to directly link deformation or short circuit in the winding with a change in the shape of the FRA curve. Although this approach seems fairly obvious, deformation measurements are carried out very rarely, because of the need of transformer "destruction". Another problem is the lack of data from the industry verifying the frequency response measurements. There are very few examples of such experiments, taking into account only a small range of deformation made on a small transformer with an output of 100 kVA and the results of deformation in units 100 kVA and 440 MVA presented in [2], but more as a curiosity than a contribution to a deeper analysis. Simple axial displacement for a single 6.6 kV winding is described together with the results of measurements in [3], even without further analysis.

The problem of deformation measurements is lack of knowledge about the universality of the results. Is it possible to use experiences learned from one unit of in another transformer case, especially one having other dimensions or design? To answer this question it is necessary to perform measurements under controlled deformation in many units. Author arranged such research on several transformers of different powers and designs, selected results and conclusions are presented below. The results are discussed in various frequency ranges, so it is necessary to define them. The low frequency range is from the beginning of measurement spectrum (typically 20 Hz) to the inflection point of the capacitive (raising) slope of the first resonance. This resonance is connected to magnetic properties of the active part, bulk capacitances and inductances. The medium frequency range starts with the beginning of the previous one and lasts approximately to the half of the remaining frequency points, where high frequency range starts and ends at 2 or 5 MHz. All of these are based on the logarithmic presentation of test results. The actual location of all ranges depends on transformer construction and its geometrical size [4-6].

Transformers used for controlled deformations

The results presented in this paper were obtained from experiments performed on four transformers. Parameters of these units are given in Table 1 and their photos on Fig. 1. In following chapters there will be presented various types of faults introduced into transformer windings and their influence on windings of abovementioned transformers.

Table 1. Transformers used for measurements with controlled deformations.

Transformer code	Type	Voltages (kV)	Power rating (MVA)	Additional information
A	unknown (no tank)	110/15	16	Russian unit from 1970's
B	T3Ch/D800/6	6,4/0,4	0,8	air cooled
C	TRDT20000/20	15,75/6,3/6,3	20	
D	RTdxP	220/110/15,75	160	autotransformer

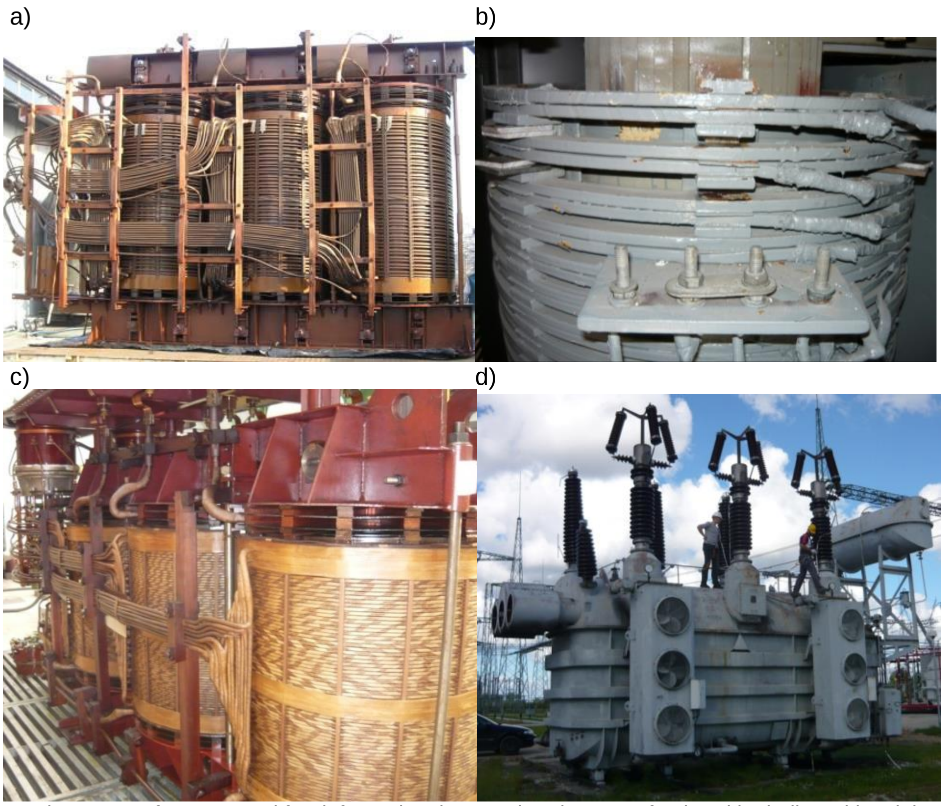


Fig. 1. Transformers used for deformational tests: a) active part of unit A, b) winding with axial deformation of unit B, c) active part of unit C, d) autotransformer D.

Rough deformations

Rough deformations are a result of a major change in the construction of the active part, e.g. one of windings has lost its continuity (e.g. regulation winding), or there was a shift of the whole winding against another one. Author has observed that such faults have always strong influence on the beginning of the medium frequency range. The exemplary results are given on Fig. 2, type of fault is described on the graph.

a) b)

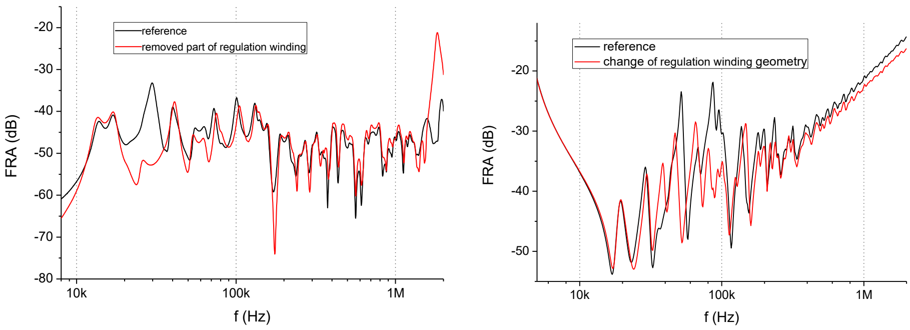


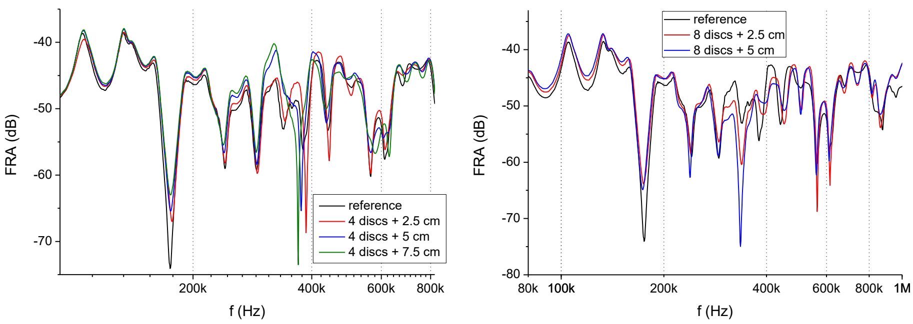
Fig. 2. FR results of rough deformations obtained from transformers A (a) and D (b).

In both cases there are very strong changes in FR visible below 100 kHz, having shifts in damping and frequency, but also changes in the shape of the curve, some resonances are gone, while others appeared.

Axial deformations

The second type of fault are axial shifts of windings fragments, usually one or couple of discs in disc-type winding. They have the strongest impact on the second half of the medium frequency range, which can be observed on Fig. 3. Description of the deformation is given on graphs.

a) b)



c) d)

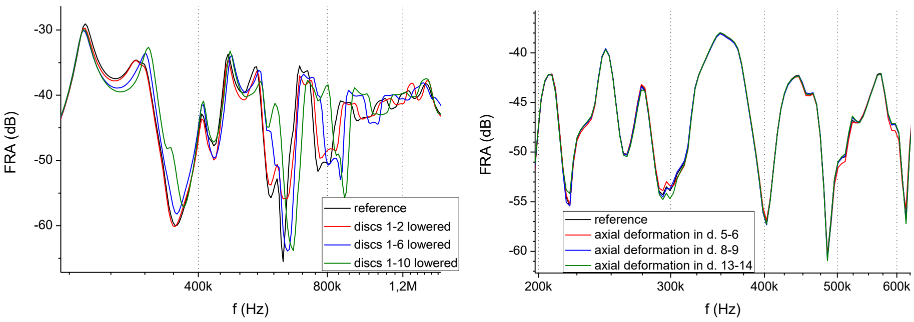


Fig. 3. FR results of axial deformations obtained from transformers A (a, b), B (c) and D (d).

The differences are mainly in changes of damping and resonant frequencies. In the case of smaller units (Fig. 3. a-c) they can be clearly seen. The impact of the deformation of the same extent as in these three cases introduced into the large winding of 160 MVA autotransformer is much smaller, due to smaller change in inter-disc capacitances if compared to the geometry of the whole winding, but it also can be easily distinguished. Results from Fig. 3c come from the smallest unit, so they appear in the highest frequency range in this group, from 300 kHz up to high frequency range. In the case of unit A changes are visible from approx. 200 kHz to 600 kHz, while for the unit D the biggest change is at 300 kHz. It can be concluded that exact location of FR changes for such deformation depends from the size, so it can be easily expected in which frequency range it will appear.

Radial deformations

Radial deformations are much harder to simulate in experiments, as it is not easy to perform them in repeatable way, which can be compared to another winding. Basically they can be described as a loss of circular shape of winding cross-section in given disc. Fig. 4 shows some examples of such faults. The range they are observed is similar to axial deformations, also depending on the size of the unit. It can be concluded that it is difficult to distinguish which type of deformation is present in the winding, both axial and radial deformations cause changes of the same type in the same frequency ranges.

a) b)

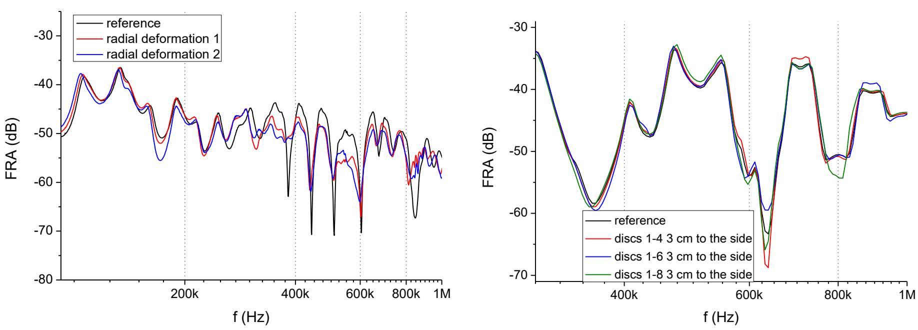


Fig. 4. FR results of radial deformations obtained from transformers A (a) and B (b).

Short-circuits

Quite different effect on FR have short-circuits in the Winding. They can be observed in the low frequency range, where magnetic circuit influences the response. Short-circuits cause curve to raise in the whole range, even in the case of just couple of turns shorted together. This can be observed on Figs. 5a and 6. There is also the influence in higher frequencies due to changes in local capacitances and inter-winding couplings (Fig. 5b), but low frequency changes are so obvious and clear to interpret that it is not necessary to perform analysis in higher frequencies.

a) b)

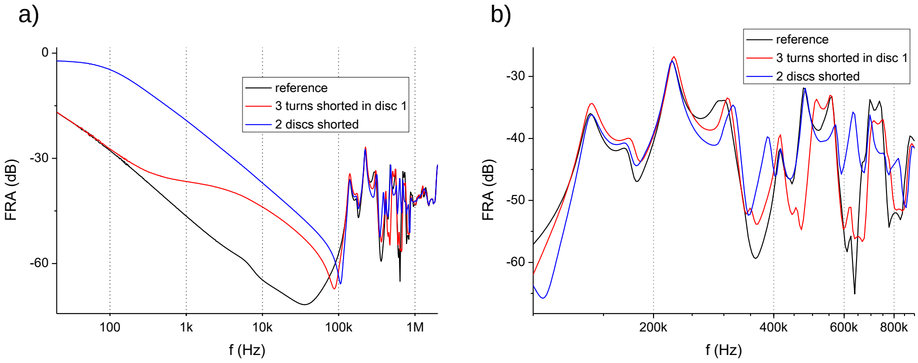


Fig. 5. FR results of short-circuit obtained from transformer B: a) the whole frequency range, b) zoomed range above 100 kHz.

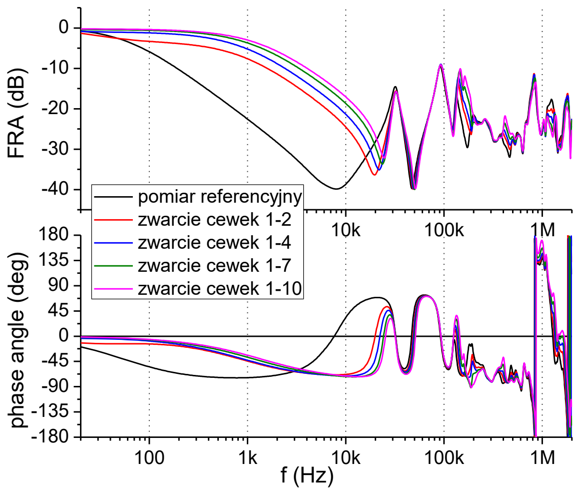


Fig. 6. FR results of short-circuit obtained from transformer C, damping and phase angle.

Other factors influencing FR

There are also other factors influencing Frequency Response in various way. Some of them may results from faults in the transformer (other than deformations of windings), while other come from measurement technology errors. The first example is change of permittivity of insulating medium (or usually lack of oil during one measurement). This results in shift of the whole FR curve along frequency due to change of all capacitances (see Fig. 7a). Another example is lost core grounding, also mostly influencing the capacitances (Fig. 7b). Changes visible in the whole frequency range as vertical shift of FR curve (damping change) are the result of additional resistance in the measuring circuit, e.g. when there is a bad contact of measuring clamp on the busing, or winding lead and the bottom of bushing. Also performing DC measurements before FRA test, resulting in the core magnetization, will give change in FR shape, in low frequency range. All these effects should be taken under consideration when analyzing results of FRA measurements.

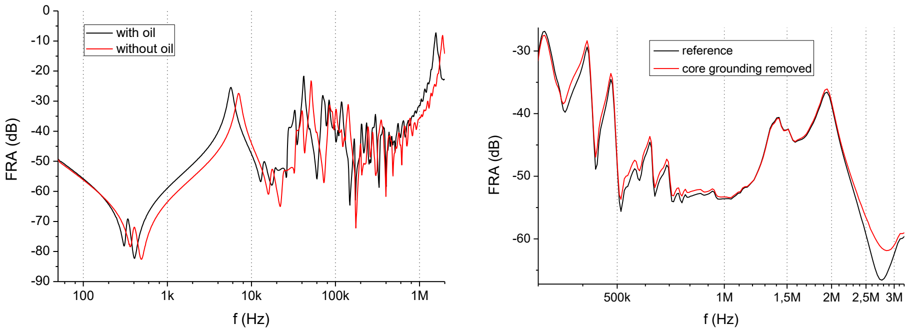


Fig. 7. FR results of transformer: a) with/without oil (autotransformer D), b) with core grounding lost (transformer B).

Summary

On the basis of the above experiments it can be concluded that the response of each winding has a different shape, a different number and location of individual resonances, thereby changes in the geometry in different ways influence the resonant frequency and changes in amplitude. However, some general conclusions on individual frequency ranges can be drawn. Some of them are presented below, all of them will be found in the full text, as well as more experimental results.

The medium frequency range can be divided into two sub-ranges. The first, beginning in the vicinity of the slope inflection point of capacitive FR characteristic shows differences in the case of the so-called rough changes, e.g. shift of larger fragments of windings, associated with the change of interwinding capacity or the magnetic coupling between the windings. In the second sub-range, starting usually with the presence of many smaller minimums and maximums on the curve, there can be observed the influence of local deformations (change in local capacity and magnetic coupling). Analyzing the results obtained from experimental measurements in the medium frequency range for tested transformers it can be assumed that the determinant of the deformation can change the damping, particularly in the higher sub-band of frequencies, as well as the position of resonances in the first sub-range of frequencies. Such changes were the most significant in the case of the introduction of deformation in the winding. This is particularly true in the case of parallel resonance with the greatest attenuation (in middle frequency range), position of which generally changes in the presence of deformations.

In addition, some changes can be observed in the whole range (outside the first inductive slope), which are associated with the permittivity of dielectric insulating medium (frequency shifts) and changes in damping over the entire range, by adding the series resistance (e.g. poor contact or the connection terminal by the resistance).

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