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Sensitivity of transformer frequency response measurements to connection configuration

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Abstract

The paper presents results of deformational tests conducted on the real transformer. The aim of the research was to compare the influence of various winding deformations on the frequency response measured in standard end-to-end connection setup as well as in interwinding setup. The results showed that for all kinds of simulated deformations interwinding measurements show changes in wide frequency range. In many cases these changes are easier to be detected than for end-to-end measurements. It is recommended to perform interwinding measurements for transformers having changes in frequency response after standard end-to-end tests.

Keywords: Frequency Response Analysis, Transformer, Winding, Deformation.

Czułość pomiarów odpowiedzi częstotliwościowej uzwojeń transformatorów w zależności od układu pomiarowego

Streszczenie

W artykule przedstawiono wyniki badań mających na celu określenie wpływu lokalizacji i skali deformacji w uzwojeniu transformatora na jego odpowiedź częstotliwościową, której pomiar realizowany był w kilku różnych układach pomiarowych. Standardowym układem pomiarowym, zalecanym również przez wprowadzaną właśnie normę IEC 60076-18, jest pomiar pomiędzy końcami uzwojenia danej fazy. Przedstawione w artykule wyniki pomiarów przy różnych deformacjach, wskazują że większą czułość wykazuje układ międzyuzwojeniowy. Jest on realizowany przy podłączeniu aparatury pomiarowej na wejścia uzwojeń strony niskiej oraz wysokiej danej fazy, przy przeciwnych końcach otwartych (dla tzw. pomiaru pojemnościowego) lub uziemionych (dla tzw. pomiaru indukcyjnego). Dlatego zaleca się wykonywanie takich pomiarów w przypadkach, gdy podstawowy pomiar pomiędzy końcami uzwojenia (tzw. *end-to-end*) wskaże na różnice pomiędzy przebiegami referencyjnym oraz aktualnym dla danej fazy. W przypadkach braku różnic dla standardowego układu wykonywanie pomiarów międzyuzwojeniowych nie jest konieczne.

Słowa kluczowe: Analiza odpowiedzi częstotliwościowej (FRA), transformator, uzwojenie, deformacja.

1. Introduction

The well known problem in power industry asset management is reaching constructional lifetime by over half of transformers operated in Europe or the USA. The lack of investments in the assets in the last years has led to an increase in failure risk in power systems [1]. Therefore, it is very important to acquire detailed information on technical condition of transformers population in order to plan maintenance actions, repairs or replacements with the aim of avoiding failures.

Asset Managers are willing to prioritize investments on assets according to their technical condition and importance on the system. The technical condition can be determined by means of a condition assessment (CA) of the asset, where CA consists in the performance of a set of diagnostic tests for diagnosing the healthiness state of an asset and estimating its present position in its life cycle [2].

There are different diagnostic methods that can be applied to CA of the active part: dissolved gases analysis (DGA), winding resistance, transformer ratio, exciting current, short-circuit impedance, etc. Among these methods, the Frequency Response Analysis (FRA) have got popularity in the last years, mainly due to its capabilities to detect mechanical failure modes in the active part, although electrical and some thermal failure modes can also be detected by FRA. Typical examples of mechanical failure modes are: winding displacement (both radial and axial) or lead deformations.

Applicability of FRA method and various techniques of test systems and connection setups have also been widely discussed in [3-4]. At the current stage of the FRA method it is possible to perform repetitive results thanks to the use of suitable connection techniques, which is summarized in CIGRÉ document [5] in which recommendations are provided and at the present the IEEE (PC57.149/D8) and the IEC PT 60076-18 are working on the elaboration of standards under which test procedures and FRA instrument requirements are established.

The still pending problem of the FRA method is the interpretation of test results. In the majority of the cases the interpretation relies on human experts who analyze the results based on their experience and by access to large database of FRA measurements of transformers having well known failure modes. The results are assessed by comparing an actual FRA measurement to a reference, where the reference can be a fingerprint previously measured in the transformer under analysis or a FRA test performed in sister/twin transformers. Alternatively, when such reference tests are not available, a comparison among phases can be done for the assessment. However, this last option can lead to misleading assessment because the FRA response of the phases is not always similar.

In order to contribute to the interpretation of FRA measurements, different research works have been conducted by other authors. The research efforts can be grouped in four directions: investigation on the sensitivity of the FRA method by means of computer simulations and experimental deformations of coils [6-7], investigation of factors affecting the reproducibility [5-9], mathematical and physical modeling techniques [10-11] and use of statistical algorithms for automatic assessment [12-13].

From the literature review a lack of experimental works showing the effects of mechanical deformations on the FRA response have been identified. This motivated research works under which mechanical deformations are simulated in real transformer windings under controlled conditions as an attempt to characterization of the effects of such deformations of the FRA response. The idea was to perform deformations on a real transformer to provide useful information on influence of failure modes, which can be helpful for results analysis. By simulating deformations at different locations of the winding of different size transformers it was possible to identify specific patterns of deviations.

Another problem is selection of a measurement configuration. The most popular setups are end-to-end and inter-winding measurements. The end-to-end measurement is performed on a single phase winding with a signal applied to one end and the response measured on the other side, with the secondary (or tertiary) winding left open or shorted. The inter-winding measurement is based on applying a signal to one end of the primary winding and a measurement taken on the end of the secondary winding of the same phase, with other ends of both windings left open (capacitive inter-winding measurement) or shorted and grounded (inductive inter-winding measurement). In the industrial practice measurements are usually limited to the end-to-end measurement. Also the new standard on the FRA (IEC 60076-18) will recommend performing only the end-to-end, as standard, measurement with possibility of adding other measurement configurations. However, there should be a question asked whether some important information would be lost by applying only the end-to-end measurement? The experiment results described in this paper are trying to find the answer to this question.

2. Test object and methodology of measurements

The transformer used for experiment was a dry type unit with the following parameters: type of T3Ch/D800/6, power of 800 kVA, voltages of 6300/400V, group of Dy5.

In this transformer the failure modes listed in Table 1 were simulated and the four types of FRA tests were performed (end-to-end open, end-to-end shorted, inter-winding capacitive, inter-winding inductive). A detailed description of the FRA setups is omitted in this paper. For details see reference [5]. The transformer is air cooled type, so it was measured in its normal operating state, in the original casing.

Tab. 1. Failure modes simulated in the test transformer
Tab. 1. Deformacje symulowane w badanym transformatorze

ID	Simulated failure	Description
A	Axial deformation	Top discs of the high voltage winding were compressed by removing spacers between discs, starting from discs 1-2, up to 1-10
B	Axial deformation	The first disc was lifted up 4, 8 or 12 mm by inserting spacers between discs
C	Axial deformation	Ten top discs were lifted up, increasing gap under the tenth by 4, 8 or 12 mm
D	Radial deformation	Complete discs were shifted 2 cm to the side, without changes in their radial geometry

Fig. 1. The example of axial deformation (B)
Rys. 1. Przykładowa deformacja poosiowa uzwojenia (typ B)

All measurements were taken with a commercial FRA test device with a standard set of cables and clamps connected to the original transformer bushings. All deformations were taken on the outer winding (HV winding). For the end-to-end measurement the signal was applied to the winding beginning and measured on the other side, however as this is a delta connected winding, part of the signal flowed through the other phases as well. For interwindig measurements the signal was applied to the beginning of the HV winding and measured on the beginning of the LV winding. The other ends of both windings were left open for a capacitive measurement and were grounded for an inductive test.

3. Results of deformation tests

In the case of the transformer used for the experiment, all types of deformations resulted in changes in frequencies above approx. 200 kHz, therefore all graphs used for the analysis show only ranges of frequencies in which the changes were visible. The full measurement range is shown in Figs. 2 and 3.

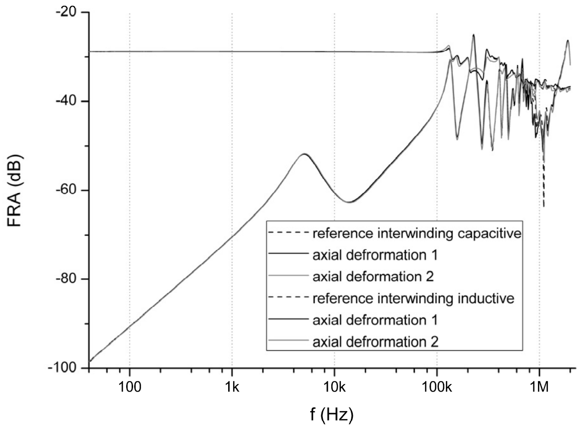

Fig. 2. The full frequency range of interwinding measurements. Differences between the curves for the reference measurement and after deformations are visible only above approx. 200 kHz
Rys. 2. Pełne spektrum częstotliwości dla pomiarów międzyuzwojeniowych. Różnice w przebiegach referencyjnym i z deformacjami widoczne są dla zakresu powyżej ok. 200 kHz

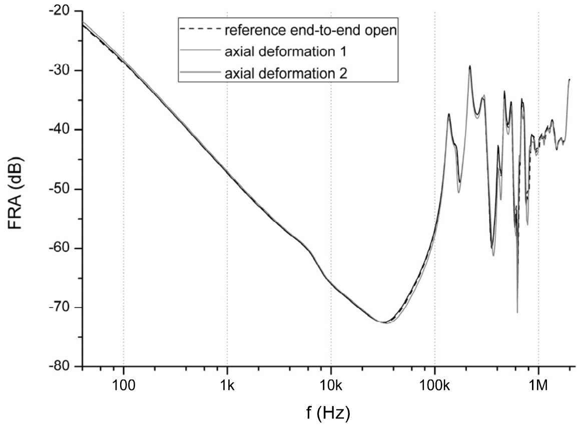

Fig. 3. The full frequency range of end-to-end measurements. Differences between the curves for the reference measurement and after deformations are visible only above approx. 200 kHz
Rys. 3. Pełne spektrum częstotliwości dla pomiarów między końcami uzwojenia. Różnice w przebiegach referencyjnym i z deformacjami widoczne są dla zakresu powyżej ok. 200 kHz

In the further analysis of the measured data the exact positions of resonances will not be taken under consideration, as each transformer has its own original response and such conclusions would not be helpful for wider application. The research is focused on the general influence of various deformations on different test setups.

A. Axial deformation (A)

The first deformation discussed in this paper is the axial deformation (A), based on compression of the winding. It is presented in Fig. 5. In the real case such a deformation may occur when solid insulation is aged and has lost its elasticity. Pressing of the winding may become insufficient and some spacers might be lost, after e.g. short-circuit. Finally, this can result in reducing the distance between the winding discs.

As it can be observed on the graph, such a deformation gives many changes in the frequency response in a wide spectrum of frequency for all three connection setups: standard end-to-end, interwinding capacitive and interwinding inductive. There are changes in damping and also shifts of resonance points along the frequency. These changes are caused by the fact that this situation influences the parameters referring to the damaged winding, especially the capacitance between turns and mutual inductances, but also the parameters connected with the other winding – interwinding capacitances and magnetic couplings. Therefore it should be easy to identify the deformation similar to the simulated one, by finding many changes in damping and resonant frequencies in end-to-end and interwinding measurements.

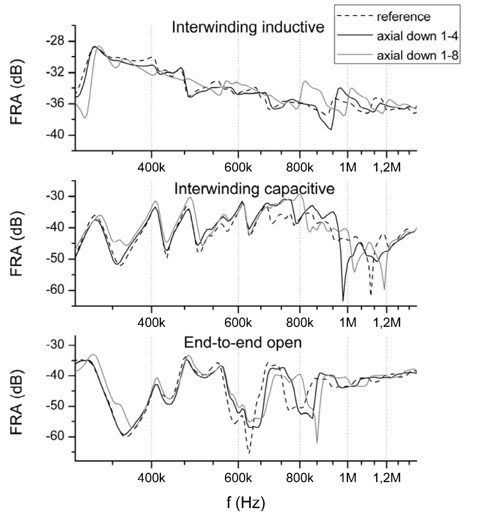

Fig. 4. The influence of axial deformation (A) on the frequency response in three connection setups

Rys. 4. Wpływ deformacji poosiowej (A) na odpowiedź częstotliwościową w trzech układach połączeń

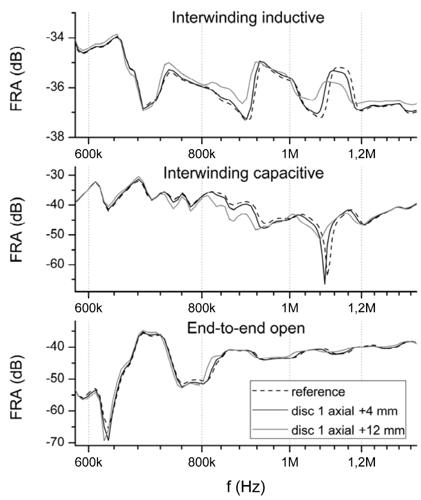

Fig. 5. The influence of axial deformation (B) on the frequency response in three connection setups

Rys. 5. Wpływ deformacji poosiowej (B) na odpowiedź częstotliwościową w trzech układach połączeń

B. Axial deformation (B)

Another case simulated in the experiment was lifting the top disc (deformation B). It is also related to loosening the winding compression and creating some space for the top turns of the coil to shift up during a high current event.

The influence of such a deformation is shown in Fig. 5. It can be seen that this time the end-to-end measurement gave smaller differences in FRA curves, especially if compared to the capacitive interwinding measurement. In the case of single disc axial displacement, the electric and magnetic parameters between two windings have stronger influence on the response measured in the parallel direction than the serial parameters of the HV winding. In all the three measurement setups 12 mm shift is better visible than 4 mm, confirming that the displacement is the cause of changes visible on the graph. The affected frequencies are very wide for the interwinding measurement and the changes are mainly in damping, without a shift along the frequency.

C. Axial deformation (C)

The third case was similar to the previous one, however ten top discs were shifted (deformation C). Such a change of the disc gap size can be caused either by lifting the winding part, as described in the case B, or by lowering the bottom part. The measurement results are given in Figs. 6 and 7. The first one presents the influence of the deformations of different scale occurred in the same disc, while the other shows three deformations of the same scale located at three heights of the winding – at the top, ¾ of the height and in the half.

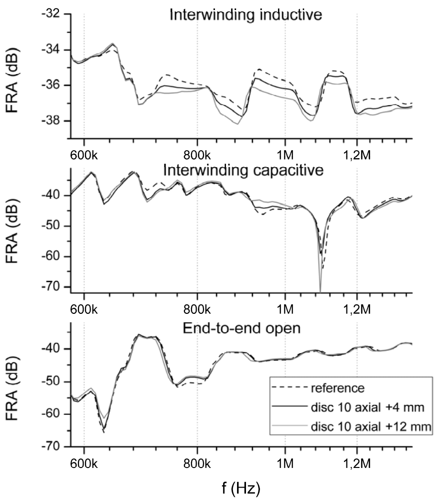

Fig. 6. The influence of axial deformation (C) on the frequency response in three connection setups; various scale of the deformation in the same place

Rys. 6. Wpływ deformacji poosiowej (C) na odpowiedź częstotliwościową w trzech układach połączeń; dla różnych rozmiarów deformacji w tym samym miejscu

Similarly to the previous case, based on the same type of deformation, both interwinding measurements show bigger changes in the wide frequency spectrum than the end-to-end measurement. It is also connected with the influence of particular parallel and serial electric and magnetic parameters on the measured frequency response, as explained in the previous case. The shape change of the recorded FRA curve is only in damping, especially seen for the inductive measurement. This is related to the strong change of magnetic couplings between two windings. This effect is probably most visible when the axial shift height is different from the distance between two discs (e.g. their top points).

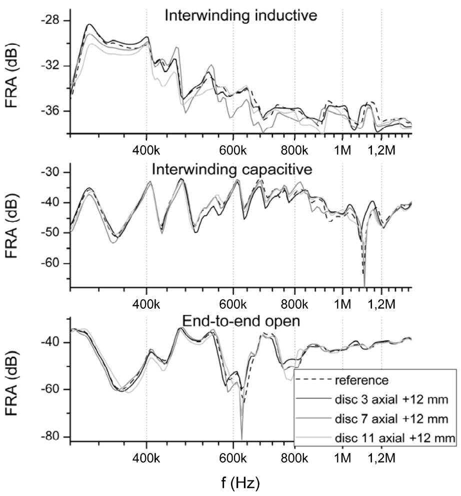

Fig. 7. The influence of axial deformation (C) on the frequency response in three connection setups; the same deformation in three locations
Rys. 7. Wpływ deformacji poosiowej (C) na odpowiedź częstotliwościową w trzech układach połączeń; taka sama deformacja w różnych miejscach uzwojenia

D. Radial deformation (D)

The fourth type of winding deformation was radial displacement (D). To allow repeatability in the experiment, the whole disc was shifted to the side, without changing its circular shape. In real cases of such failures the disc geometry is usually changed by radial bulking in one or many directions. The results of these measurements are given in Fig. 8.

This time changes in the frequency response are visible in the same range in all the three connection setups. The influence of both serial and parallel parameters is at the same level.

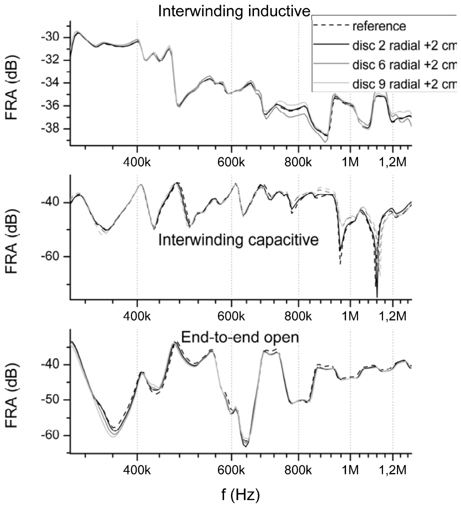

Fig. 8. The influence of radial deformation (D) on the frequency response in three connection setups
Rys. 8. Wpływ deformacji promieniowej (D) na odpowiedź częstotliwościową w trzech układach połączeń

4. Conclusions

On the basis of the performed experimental test it can be concluded that interwinding measurements are more sensitive to deformations in the winding than end-to-end measurements. Only in some cases it was observed that the interwinding measurements showed the same level of changes of the FRA curve as the standard end-to-end setup. For the interwinding tests the differences between the reference and deformation test curves are seen in the wide frequency range, making it easier to be detected. It can be also noted that for most deformations tested in the experiment there were only changes in the damping of the frequency response, while in the case of winding compression there were also frequency shifts of the resonant points. This allowed determining the general type of deformation in the winding. It can be suggested that the use of pattern recognition techniques might be applicable to development of automatic tools for assessment of FRA tests.

Another important conclusion is that in the cases of even very slight changes in the frequency response curve, measured in the standard end-to-end connection setup, it is worth taking measurements also in the interwinding connection setup. The information obtained from both kinds of measurement results would allow easier detection and identification of mechanical deformations in a transformer winding.

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