ARCHIVES OF ELECTRICAL ENGINEERING VOL. 67(1), pp. 51–64 (2018)

DOI 10.24425/118991

Analysis of Frequency Response measurement results with end-to-end/interwinding test setup correlation

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(Received: 29.05.2017, revised: 25.07.2017)

Abstract: The paper presents the idea of a Cross Test Comparison (CTC) method for the analysis of Frequency Response measurement results. FRA is used to detect deformations or electric faults in transformer windings. At the current stage of FRA method development, it is possible to perform repetitive measurements, however there are still problems with interpretation of test results. Authors of this paper found that analysis of results coming from two test setups (end-to-end and interwinding capacitive), which is done simultaneously is a more sensitive tool to detect some faults, and in addition it binds the influence of both voltage sides of a transformer in a single test result. The paper contains results obtained from laboratory tests, where controlled deformations were introduced into windings and also measurements from industry. The CTC method combines both the end-to-end and capacitive interwinding measurements into a single dataset, by subtracting the amplitudes at the corresponding frequencies. The resulting combined dataset is more sensitive in identifying deviations from baseline measurements.

Key words: Frequency Response Analysis, transformer, winding, deformation, test setup

1. Introduction

Frequency Response Analysis (FRA) is an important diagnostic method, which is used with other modern methods to assess transformer's technical condition. FRA is capable of detecting mechanical faults in the windings, as well as some problems in the core. Such problems may arise in a transformer due to forces related to short-circuit currents, especially in the unit with aged solid insulation, which had lost its elasticity, or can be caused during transportation of the unit. A transformer with deformed winding can still be operated under nominal conditions, however weakened insulation will lead to the failure during the first network event, causing inner short-circuit, with a risk of transformer fire and all costs related to power outage and unit's repairs or replacement. Therefore, early and reliable diagnostics is a key factor in modern management of power systems assets.

At the current stage of FRA method development it is possible to perform repetitive measurements, however there are still problems with interpretation of test results. There are used various approaches and automated tools, but – as FRA is a comparative method – it is hard to assess cases which show changes between compared curves; what kind and scale of difference (amplitude damping or frequency shift) can be classified as obvious deformation.

Typically, in industrial measurements, results are recorded in only one test configuration: end-to-end open in which only winding of the measured voltage side is taken under consideration. There are also other test setups, e.g. interwinding capacitive, which can give valuable information, but usually are not used in practice and even if tests are taken in two setup configurations their results are analyzed separately.

Authors of this paper found that the analysis of results coming from both test setups, which is done simultaneously is a more sensitive tool to detect some faults, and in addition it binds the influence of both voltage sides of a transformer in a single test result. It is difficult to consider the transformer as three separate columns, because one side is usually delta connected, so there is direct influence of other columns on the tested one, even under low voltage signal conditions used in the FRA method. By capacitive and inductive couplings there is also relation between high and low voltage sides. Therefore, the common analysis of results obtained both from end-to-end measurement and interwinding capacitive measurement gives results coming directly from two windings (HV and LV) geometry.

In following chapters of this paper the authors present basics of the FRA method, assumptions of the proposed analysis method and some examples of data obtained from tests conducted on the transformer with introduced controlled deformations. Some examples of industrial analysis are also given. The results of both experimental and industrial measurements were assessed with three different algorithms to obtain numerical indices, which allow standard test setups to be quantitatively compared and the Cross Test Correlation method to be proposed.

2. FRA method and deformations in the transformer's active part

The FRA test method is currently introduced into industrial practice, its measuring techniques are currently well known and standardized [1], so it is possible to perform repeatable measurement allowing reliable comparisons of test results. These results are usually assessed by a human expert, however some automatic tools are being developed. The interpretation of the measured data is still a pending problem. The FRA is a strictly comparative method, but in many cases reference data is not accessible, so measurements must be compared to sister or twin units, sometimes to other units of the same type. Another approach, very popular in industry, is comparison between the phases of the tested unit, however also in this case there are many possibilities of committing a misinterpretation. A Frequency Response (FR) range is usually divided into three main subranges, sometimes including additional sub-bands. These ranges are: low, medium and high frequencies. Their borders depend on the construction of the transformer, mainly on its geometrical size, usually connected with its power rating. Therefore, it is not possible to perform analysis in predefined frequency ranges. The bigger transformer is, the higher values of inner capacitances are and thus the frequency response is shifted into lower frequencies. If there is found a difference in FRA results compared to other phases or other transformers, it is not clear if it comes from deformation in the active part, or it is a result of natural differences between the compared objects. In the best case, when the compared curves showing differences come from the same phase of a transformer and were recorded in some time interval, it is clear that there are some changes in the active part or the winding connection setup, but usually it is not possible to assess the scale and location of the deformation [2, 3]. For these reasons there is a need to develop new approaches of the measured data assessment and new tools makeing it easier.

FR can be measured in various test configurations, however according to the standard [1] the main configuration is an end-to-end open test setup, where the signal is given on the beginning of the winding and measured on its end, with remaining windings left open. Another test setup configuration is based on capacitive couplings between windings of the same phase, without galvanic connection between them – it is an interwinding capacitive test setup. The signal is given on the beginning of one winding (HV side) and measured on the beginning of the other winding (LV). Other ends of both windings are left open. Responses of both mentioned test setups are different, especially at a low frequency range, where the influence of transformer's bulk capacitances on FR is large. However if results are compared to other phases or units measured in the same test setups, they give good conformity of curves.

FRA test results are typically presented in the form of Bode plots, with damping in (dB) and a phase angle shift presented separately on a logarithmic frequency scale. Fig. 1 presents schematic connection of both mentioned test setups and exemplary responses.

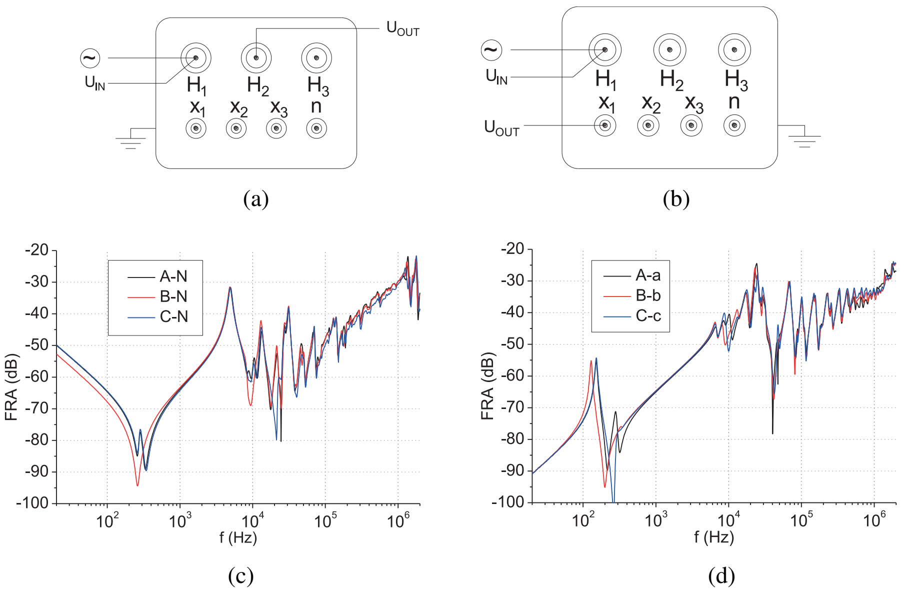


Fig. 1. Schematic measurement setups and corresponding examples of test results: (a), (c) end-to-end open measurement; (b), (d) interwinding capacitive measurement

One of the research directions aimed at improving the interpretation of FRA test results of transformer windings is conducting experiments with introduced controlled deformations. Their aim is to directly link deformation or a 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's 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 [4], but more as a curiosity than a contribution to a deeper analysis. Simple axial displacement for a single winding of 6.6 kV is described together with the results of measurements in [5], even without further analysis

Authors of this paper have performed measurements made under conditions of controlled deformations on several transformers, including two small 15/0.4 kV, 800 kVA units, two 110/15 kV, 16 MVA units and one large autotransformer 220/110/15.75, 160 MVA. The results coming from these experiments allowed the influence of deformations on changes in the frequency response to be assessed. Author's experiences show that it is possible to introduce a new method of assessment of results, based on cross-test comparison [6, 7].

To assess quantitatively test results authors used three algorithms, which are widely described in the literature, therefore only basic information of their application will be presented. The first of them is *ASLE* – Absolute Sum of Logarithmic Error, which is described with Formula (1) [8, 9].

$$ASLE_{(X,Y)} = \frac{\sum\limits_{i=1}^{N} \left|20\log_{10} Y_i - 20\log_{10} X_i\right|}{N}, \tag{1}$$

where: X, Y are the two data sets, N is the total number of points.

This algorithm allows data in desired frequency ranges to be assessed. It has just a single assessment criterion: when values of $ASLE > 0.4$, there is a deformation in the tested frequency range. The second algorithm used in this paper is *CCF* – Cross Correlation Factor, described with Formula (2) [8, 10].

$$CCF = \frac{\sum\limits_{i=1}^{N} \left(X_i - \overline{X}\right)\left(Y_i - \overline{Y}\right)}{\sqrt{\sum\limits_{i=1}^{N} \left(X_i - \overline{X}\right)^2} \cdot \sqrt{\sum\limits_{i=1}^{N} \left(Y_i - \overline{Y}\right)^2}}, \tag{2}$$

where: X, Y are the two series of compared data, $\overline{X}$, $\overline{Y}$ are the arithmetic mean values of all summed values of a data set.

This algorithm is also used in desired frequency ranges, usually four, and its assessment criteria depend on the criteria given in Table 1.

The third method chosen for assessment is *MSE* – Mean Square Error, presented in Formula (3) [8, 10].

$$MSE = \frac{\sum\limits_{i=1}^{N} (X_i - Y_i)^2}{N}, \tag{3}$$

where: X, Y are the two data sets, N is the total number of points.

Table 1. Assessment criteria for *CCF* algorithm

results conformity	***CCF* value**
good	0.95–1.0
acceptable	0.90–0.94
poor	< 0.89
none or very poor	≤ 0

The assessment criterion has two possible results: good conformity when $MSE < 1$, and poor for values equal or higher than one. Authors used assessment criteria proposed in the above-mentioned literature, however there is always a question on correctness of such detection levels. There are also other algorithms described in the literature, some of them implemented into software of commercial devices, e.g. a Chinese method described in standard [12], which cannot be used in the presented research as they are developed to assess end-to-end test setup results only.

3. Cross-test comparison method

Observations and analysis of test results obtained from industrial measurements, experiments with introduced deformations and other faults in transformer's active parts and also from computer modeling of frequency response [13, 14], led authors to assumptions of a new approach to assessment of measurements results. If measurements recorded in a given test setup are compared between phases, there are always visible similar differences, both for end-to-end and interwinding capacitive test setups. These changes are the results of various magnetic flux distribution, which for the middle column is symmetrical (via two side columns) and for the side column asymmetrical (via middle one and opposite side column). Therefore, comparison and assessment of curves measured for the same column may significantly reduce the influence of column geometry (middle or side). In addition there might be also reduced the influence of transformer's specific construction details, e.g. differences between two side columns in the middle frequency range, often observed in industrial results. The Cross-Test Comparison (CTC) method combines both the end-to-end and capacitive interwinding measurements into a single dataset, by subtracting the amplitudes at the corresponding frequencies. The resulting combined dataset is more sensitive in identifying deviations from baseline measurements. The CTC performed for each column will give three data sets (one for each phase), which subsequently might be compared together, giving additional information on the mechanical condition of transformer's active part, if compared to the standard approach. Authors have chosen to use subtraction for CTC data, which allows the proper unit of resulting data to be kept and has no risk of signal intensification or suppression in given frequency points if multiplication or division functions would be used. Such a risk would appear if there is, for example, a large difference between two phases in the case of both test setups, which may result in no changes visible in the CTC signal compared to these two phases, after dividing end-to-end and interwinding capacitive signals.

For the CTC method, test results are to be subtracted on the basis of a typical form of result presentation, which is amplitude damping in the function of logarithmic frequency:

$$\text{FRA (dB)} = 20\log\frac{U_{\text{out}}}{U_{\text{in}}}\,. \tag{4}$$

Such a form is the most popular for presentation of FRA results and most of test devices use it as a standard method of data acquisition. The CTC can be thus defined as:

$$\text{CTC}(f) = \text{FRA}_{\text{E2E}}(f) - \text{FRA}_{\text{CAP}}(f), \tag{5}$$

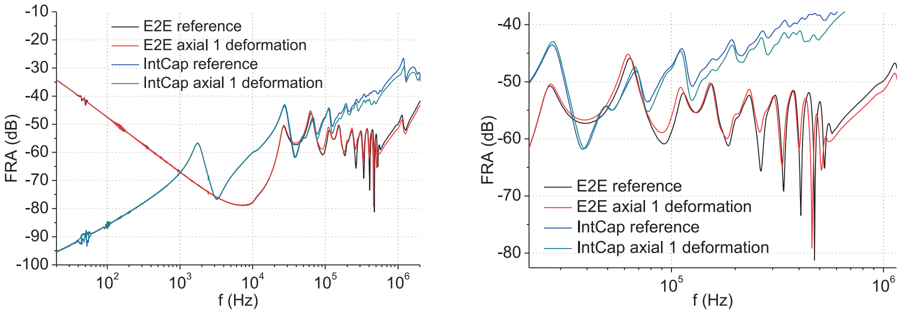
where FRA_{E2E} and FRA_{CAP} are the amplitudes of FR recorded respectively in end-to-end open (E2E) and interwinding capacitive (IntCap) test setups. This approach allows for binding together the influence of both voltage sides of a transformers and typical ranges of frequencies of both test setups in one graph. Observations done by authors show that these ranges are additive, as each test setup behaves differently under influence of given deformation, e.g. IntCap shows changes in much wider frequency range than E2E.

The described method was tested on data obtained from laboratory tests and industrial measurements, which is descried in following points.

4. Deformational laboratory tests

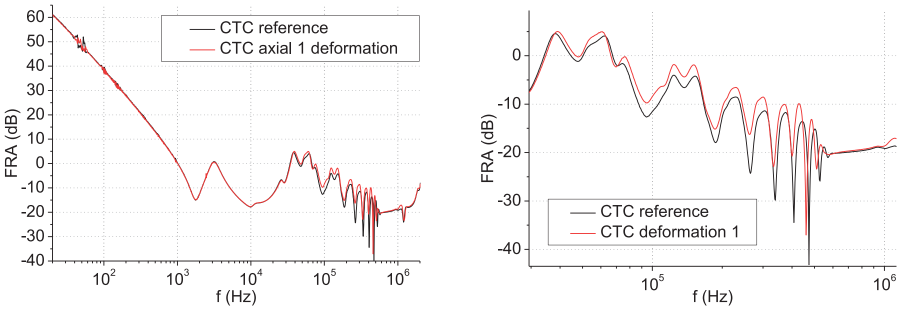
The first stage of experimental verification was testing a CTC algorithm with data coming from deformational tests. The results presented below were obtained from an 800 kVA, 15/0.4 kV transformer, which was thoroughly tested in laboratory. There were introduced several dozens of various deformations into windings, both HV and LV. Measurements were taken in four test setups: end-to-end open and interwinding capacitive, which are used in the CTC method, but also in end-to-end shorted and interwinding inductive. The latter two are not giving as good results as end-to-end open and interwinding capacitive, so they will be omitted. There were recorded several hundreds of FR curves. The unit is a rather small transformer, so its FR borders are shifted into high frequency direction, a medium frequency range starts approx. at $2 \cdot 10^4$ Hz and ends at $5 \cdot 10^5$ Hz. The results presented below show only examples of various deformations. The first deformation (axial 1) was based on axial shift of the winding. Subsequent top coils were shifted up, after removing the clamping system. In next extents of this deformation additional coils were shifted, keeping previous ones also with increased gap. Fig. 2 presents frequency response of such winding measured in two standard test setups: E2E and IntCap. There is showed a full frequency range and also a zoomed range in which deformation caused differences between curves. Local deformations in windings typically give FR changes in upper middle frequencies, so the obtained results are expected. For E2E test setup changes are in damping of resonances, but also in frequency shift of some of them. For IntCap there is visible damping shift for the wide frequency range.

The presented data was subtracted in pairs: reference curves and deformation curves, so two CTC curves were obtained. Again the full spectrum of frequency and zoomed range with visible differences is presented in Fig. 3.



(a) (b)

Fig. 2. FR measured for axial 1 deformation in two test setups (E2E, IntCap): (a) full frequency range; (b) zoomed range with visible deformations



(a) (b)

Fig. 3. CTC reference and axial 1 deformation curves presented in: (a) full frequency range; (b) zoomed to show differences

The comparison of reference and axial 1 deformation CTC curves shows that characteristic features of both test setups used to obtain the CTC are still visible. The data presented in Figs. 2 and 3 were assessed with algorithms *ALSE*, *CCF* and *MSE*. All three algorithms were used in the same frequency ranges, which have been defined for all experimental results with values presented in Table 2.

The results obtained from algorithms are presented in Table 3, divided into five frequency ranges. The most important for analysis are LF2, MF and HF1. There is added a color code to make interpretation easier, based on three levels: green (OK), yellow (light deformation) and red (obvious deformation). For *ASLE* and *MSE* there are two values (green and red), while for *CCF*, an additional yellow result is possible.

It can be seen that in the case of the *ASLE* algorithm, the CTC method is more sensitive, resulting in red fields in three frequency ranges, including important LF2 and MF ranges. The *CCF* result for the CTC method is the sum of conclusions drawn from separate *CCF* results obtained for traditional methods. The *MSE* showed one field less in red for the CTC, however the value in an important MF range is much higher than in the case of E2E and IntCap.

Table 2. Frequency ranges used for assessment of laboratory transformer 800 kVA

Code	Frequency range description	Frequency range values
LF1	low frequency 1	10 Hz – 1 kHz
LF2	low frequency 2	1 kHz – 100 kHz
MF	medium frequency	100 kHz – 600 kHz
HF1	high frequency 1	600 kHz – 1 MHz
HF2	high frequency 2	1 MHz – 20 MHz

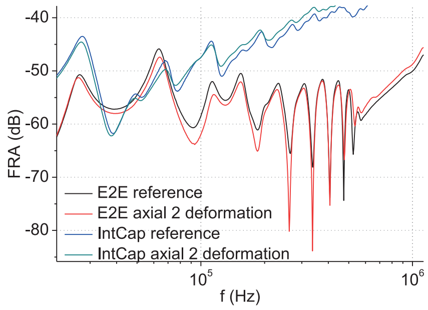
Table 3. Assessment results with algorithms for axial 1 deformation

Method	Assessment result in frequency range:					Test setup
	LF1	LF2	MF	HF1	HF2	
ASLE	0.026	0.048	0.332	0.244	0.430	E2E
CCF	0.9996	0.9990	0.5591	0.9998	0.9836	
MSE	0.071	0.329	15.46	2.33	4.183	
ASLE	0.026	0.049	0.395	0.438	1.060	IntCap
CCF	0.9981	0.9983	0.9604	0.9989	0.9318	
MSE	0.26	0.244	4.84	3.077	12.979	
ASLE	0.218	2.451	2.508	0.101	2.460	CTC
CCF	0.9995	0.9931	0.8290	0.9872	0.8563	
MSE	0.344	0.642	19.421	0.056	11.292	

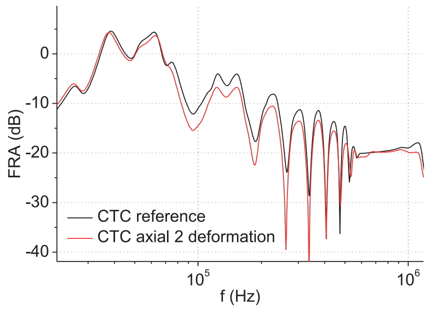
The next example shows the deformation based on reducing axial distance between coils (axial 2). In subsequent steps coils were lowered by removing spacers between them, so the whole winding was getting lower. The differences between curves are expected in the same frequency range as in the previous case, so only zoomed ranges of frequencies will be presented on following figures. Fig. 4 shows E2E and IntCap curves recorded for this deformation, and also their CTC counterpart. Changes in both original test setups are similar to the previous example, and also the CTC curve keeps features of both of them. All curves were tested with algorithms, results are presented in Table 4.

The analysis of the data shows clearly, that the CTC method is more efficient in detection of introduced deformation. In the case of *ASLE* and *CCF* algorithms the results obtained for E2E and IntCap test setups show good conformity or a single red field, while for the CTC there is obvious deformation in wide frequency range. *MSE* shows the same number of frequency ranges assessed as obvious deformation, but with higher numbers.

The last presented example of a winding fault is a short-circuit between turns in a single coil. Such a fault gives very clear changes in the FR curve, as it strongly influences a low frequency



(a)



(b)

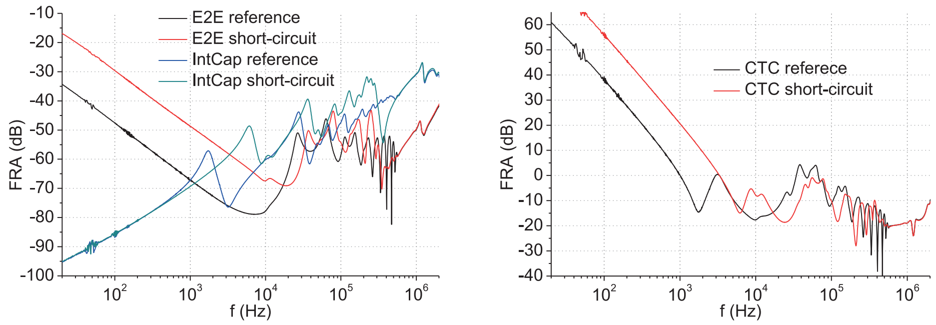
Fig. 4. (a) E2E and IntCap curves for axial 2 deformation; (b) their CTC curves

Table 4. Assessment results with algorithms for axial 2 deformation

Method	Assessment result in frequency range:					Test setup
	LF1	**LF2**	**MF**	**HF1**	**HF2**	
ASLE	0.018	0.076	0.272	0.196	0.409	E2E
CCF	0.9998	0.9981	0.8725	0.99574	0.9794	
MSE	0.035	0.714	7.831	1.498	3.766	
ASLE	0.015	0.085	0.294	0.397	0.751	IntCap
CCF	0.9994	0.9980	0.9755	0.97156	0.9558	
MSE	0.081	0.480	2.600	2.549	7.833	
ASLE	0.137	2.278	1.919	0.154	3.038	CTC
CCF	0.9998	0.9886	0.9479	0.76588	0.8819	
MSE	0.124	1.019	11.706	0.18	9.241	

(LF1 and LF2) range. In the case of E2E test setup changes are visible thorough the whole LF range, while for IntCap characteristic resonances are influenced in LF. There are also changes in other frequency ranges. Fig. 5 presents the influence of such a fault on the E2E, IntCap and CTC curves. Again the CTC keeps characteristic changes of both test setups, i.a. in low frequencies, so it can also be used for detection of short-circuits. In this case an analysis with algorithms was not presented, because differences between curves in all test setups are so big, that all algorithms give the same response – obvious deformation in all frequency ranges. This kind of fault is easy to detect, not only by means of the FRA method, but even with basic measurements (winding resistance, transformer ratio).

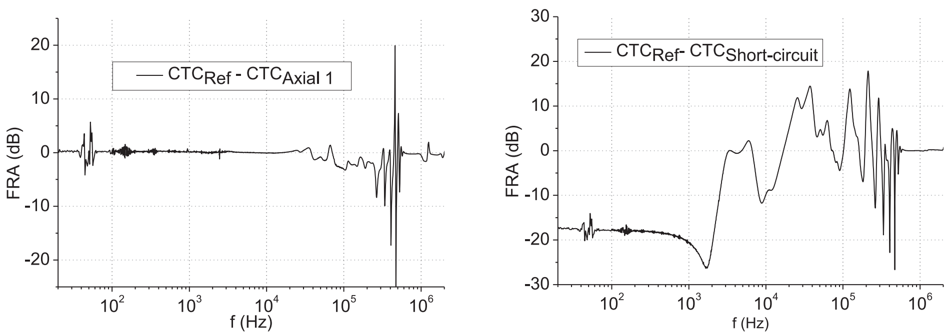
The examples presented above show that it is possible to use the CTC method for the analysis of the FRA test results. Such analysis may be based on the typical industrial approach, where human expert compares and assesses obtained data or where other approaches might be used, e.g. application of algorithms for automated assessment. Many various methods are used for



(a) (b)

Fig. 5. (a) E2E and IntCap curves for short-circuit; (b) their CTC curves

such assessment [11, 15], some of them were used in this paper. In future research the authors plan to test, which algorithms would be the most suitable for CTC results and develop their own original tools. The simples graphical approach is additionally presented in Fig. 6, it is typically used in industry for data comparison, which is subtraction of two curves. In other words, two CTC curves (reference and with deformation) are subtracted to obtain only one curve, that emphasizes differences between original CTC curves. It can be seen that the most visible variances from zero are in the upper medium frequency range (10^4–10^6 Hz) in the case of axial deformation and for the short-circuit in a low frequency range.



(a) (b)

Fig. 6. CTC reference and CTC deformation curves subtracted for: (a) axial 1 deformation; (b) short-circuit

5. Example of industrial application

The described method was also used with data recorded on larger units under industrial conditions. Fig. 7 presents standard measurements and CTC curves obtained for a 110/15 kV, 16 MVA transformer.

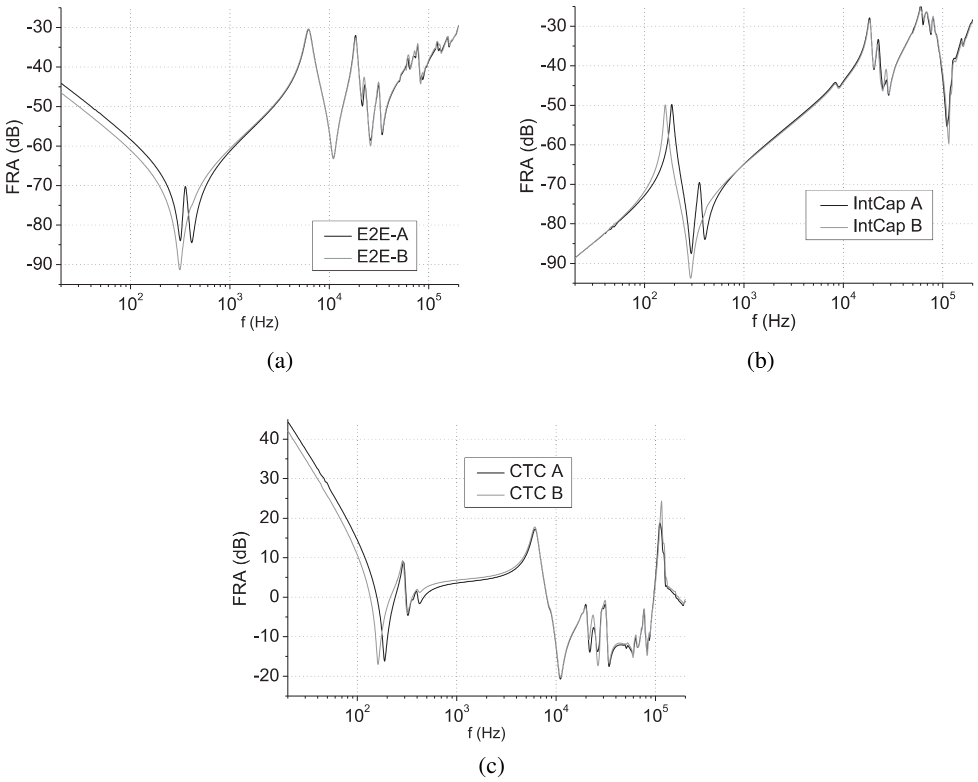


Fig. 7. Industrial example for 110/6.3 kVA, 25 MVA transformer, side and middle phases (A and B): (a) end-to-end measurement; (b) interwinding capacitive measurement; (c) CTC calculated for (a) and (b)

The results presented in Figs. 7a and 7b show typical frequency response of a transformer in end-to-end and interwinding capacitive test setups. The only visible significant differences between phases are in a low frequency range (10^2–10^3 Hz), which is expected due to a different magnetic flux flow in the core. Such a transformer should be considered as healthy. This influence appears in both test setups, making it impossible to compare, as there is additional resonance in the side phase. A similar effect can be seen on the other side phase (phase C), which wasn't presented on Fig. 7 to make it clearer. Therefore, in practical interpretation, only side phases (A and C) are compared in this frequency range, which may lead to errors in the analysis. By application of the CTC method this effect is removed, which can be seen in Fig. 7c. There is still very good conformity of curves in higher frequencies, but additionally, the LF range has now the same shape in both curves (the same number of resonances). The only difference is a slight shift of the first resonance along frequency, which is always visible in E2E comparison of side and middle phases. This issue is also typical and well known. The comparison of the first resonance damping in CTC curves, as well as the whole range from 10^2–10^3 Hz, leads to conclusions that this transformer is in a good mechanical condition.

This conclusion was also confirmed with algorithms used in this paper to assess the obtained data. The analyzed unit is bigger than the transformer tested in the laboratory, so new frequency ranges must be defined. They are given in Table 5. The HF2 range was omitted, because transformer was measured only to a frequency of 2 MHz, which is the value recommended by the standard [1]. Results of analysis with algorithms are given in Table 6.

Table 5. Frequency ranges used for assessment of 25 MVA transformer

Code	**Frequency range description**	**Frequency range values**
LF1	low frequency 1	10 Hz – 100 Hz
LF2	low frequency 2	100 Hz – 1 kHz
MF	medium frequency	1 kHz – 100 kHz
HF1	high frequency 1	100 kHz – 2 MHz

Table 6. Assessment results with algorithms for industrial example

Method	**Assessment result in frequency range:**				**Test setup**
	LF1	**LF2**	**MF**	**HF1**	
ASLE	0.421	0.454	0.08	0.396	E2E
CCF	0.9999	0.8347	0.9972	0.9795	E2E
MSE	6.358	20.244	0.394	2.347	E2E
ASLE	0.032	0.565	0.099	0.408	IntCap
CCF	0.9996	0.7607	0.9982	0.9803	IntCap
MSE	0.157	36.031	0.49	3.714	IntCap
ASLE	0.991	11.264	1.072	7.503	CTC
CCF	0.9998	0.6388	0.996	0.9175	CTC
MSE	7.925	22.672	0.922	6.243	CTC

In general, data from Table 6 show that the CTC results are summing features of two standard test setups. This can be seen in LF1 and HF1 ranges. All test setups show differences in LF2. In the MF range the CTC with the *ALSE* algorithm goes into red, due to summed little differences from two previous measurements. This proved that the CTC method is more sensitive to differences between the compared data. It should be remembered, that assessment criteria for algorithms are taken from the literature. In the case of the CTC results, new criteria should be elaborated and possibly also new algorithms, which will be dedicated to this method. Authors plan to continue research in this field.

6. Conclusions

Cross-Test Comparison of FRA results recorded in end-to-end and interwinding capacitive test setups is able to give information provided by two latter on one graph, with ability to strengthen measured differences without losing any of them. There is also additional reduction of natural differences observed for standard measurements between side and middle phases. It was confirmed in the paper by presented examples and three algorithms used for assessment of FRA data. The first group of analyzed results was obtained in a laboratory where controlled deformations were introduced into a winding. Typical features of frequency ranges for both standard test setups were kept in the resulting CTC curve (e.g. short circuit in the winding resulting in LF range changes). The second group of results coming from industrial measurement showed that also in practical application the CTC method allows for the thorough analysis of results. The new method needs, in the future, the elaboration of assessment criteria and new algorithms.

The presented method is ready to be introduced into industrial measurements, however tests must be recorded in both end-to-end and interwinding capacitive test setups, which is not a common practice currently.

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