Procedures for Detecting Winding Displacements in Power Transformers by the Transfer Function Method

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***Abstract*—The paper investigates three different ways of using the transfer function method for detecting mechanical winding displacements in power transformers. The most reliable approach is *time-based comparison*, which requires finger print data from a previous measurement. Such information is, however, usually not available. For multilegged transformers without zigzag-connected windings the results of separately tested legs can be used as mutual references (*construction-based comparison*). A third approach is to compare the transfer functions with those obtained from an identically constructed transformer (*type-based comparison*). However, for a transformer with given nominal specification data, the winding design may over time undergo changes which causes changes to the transfer function. It is proposed to solve this problem by calculating tolerance bands using transfer functions from a big group of the same-type transformers. A novel statistical algorithm for this purpose is presented. The approach is demonstrated for a set of 28 specified identically 200-MVA power transformers.**

***Index Terms*—Fault diagnosis, frequency domain analysis, power transformers, transfer functions, winding displacements.**

I. INTRODUCTION

HIGH short-circuit currents are a well-known cause of deformations and displacements of transformer windings due to mechanical forces. Such deformations do not necessarily lead to an immediate failure of the transformer, but its ability to withstand future mechanical and dielectric stresses may be strongly reduced (e.g., due to brittling of the paper [9], [3]). To ensure a sufficient ability to withstand short circuits modern diagnostic methods should identify such predamaged power transformers.

In the IEC standard 76-5 [12], the reactance measurement is described as a diagnostic method to demonstrate the integrity of windings. According to the standard, deviations of the reactance of more than 2% are inadmissible for power transformers having a rated power of 100 MVA and above. Deviations between 1–2% are subject to an agreement between the manufacturer and the user. Although the detailed specification suggests a sufficient reliability of the test procedure, the reactance measurement is usually not applicable for detecting winding displacements at power transformers already in service. The main reason is that displacements have only a very small effect on the reactance of the winding in concern.

In order to detect predamaged power transformers, it is necessary to develop new diagnostic methods having a better sensitivity toward changes in the winding geometry. One basic idea is the wideband examination of the impulse response of a power transformer, because changes in the winding geometry have a strong effect on the characteristic frequencies of the transfer behavior [1].

The transfer function (TF) is an approximation to the Fourier-transformed impulse response $\underline{H}(\omega)$. It is calculated as the quotient of an applied input signal $\underline{X}(\omega)$ and its response $\underline{Y}(\omega)$ in frequency domain according to

$$\underline{\mathrm{TF}}(\omega) = \frac{\underline{Y}(\omega)}{\underline{X}(\omega)}. \tag{1}$$

For this investigation, $X(\omega)$ and $Y(\omega)$ have been determined by a Fourier transformation of an applied low-voltage impulse $x(t)$ and its response signal $y(t)$ (low-voltage impulse frequency response analysis) [2], [11].

There is a redundancy between the magnitude and the phase of $\mathrm{TF}(\omega)$ for minimal phase systems [6]. Therefore, only the magnitude $|\mathrm{TF}(\omega)|$ is chosen for an experimental evaluation of transfer function results.

The transfer function method is an approach for diagnosing changes in core-and-coil assemblies of power transformers by comparing a measured transfer function with a reference. The main objective of this paper is to investigate the applicability of three procedures utilizing transfer function results. The investigation is based on measured transfer functions for different types of power transformers and for a set of 28 identically specified power transformers.

II. DIAGNOSIS BASED ON TRANSFER FUNCTIONS

There are three well-known experimental ways of obtaining transfer functions for comparative diagnostic usage—*time-based*, *construction-based*, and *type-based*. The principle of these methods is illustrated in Fig. 1. The most often used and the most accurate one is the time-based comparison which uses test results from former times as [2]. This type of comparison is applicable for any type of transformer. To reproduce results, which have been obtained several years ago, detailed information about set-up, test procedure, and signal processing is required.

This comparative method has been checked under nonideal onsite conditions in a 110/220-kV substation. Fig. 2 shows that

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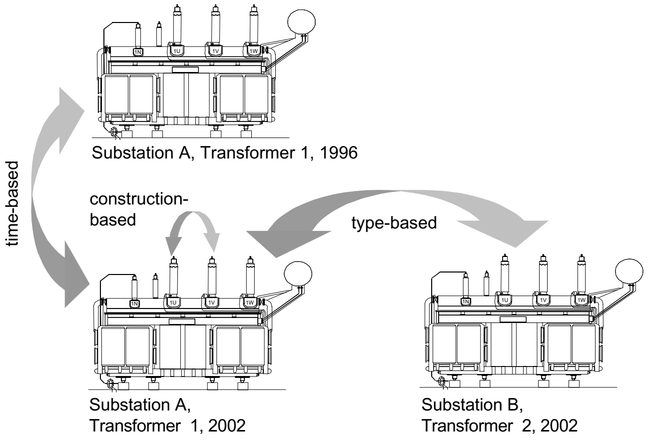

Fig. 1. Types of comparison for transfer function measurements of power transformers.

if the tests are carefully done, the comparability of the results becomes very high. Transfer function measurements have been performed twice for a 200-MVA power transformer in substation of Kelsterbach (21.12.99 and 16.06.00). As it can be seen in Fig. 2, the transfer function of the neutral current as well as the result of the transferred voltage have identical characteristic frequencies (frequencies of peaks and minima) and magnitudes. Slight deviations of the resonance peak at 400 kHz are an effect of the limited measuring accuracy.

Fingerprint measurements from former times are rarely available, so alternative methods must normally be applied. One approach is to compare the transfer functions of a given transformer with respect to symmetry, in relation to the symmetry properties of the transformer design [10]. In practice, this means to compare the transfer functions obtained for the different phases or different legs (construction-based comparison). A very similar transfer behavior of leg U and V is presented in Fig. 2.

The separately tested phases show nearly identical transfer characteristics. Above 50 kHz, each characteristic frequency of leg V is identical with those of leg U. Only slight deviations of the attenuation rate are detectable. The comparability of such results is affected by the type of construction and the type of vector group. This topic is investigated in Section III.

As a third method, the results of an identically constructed transformer can be applied as [8]. The result of an actual measurement is compared with the transfer function data determined for a second transformer. The specification of both transformers must be same. If both transformers have been manufactured in the same factory as a set (detectable due to continuous serial numbers), the similarity of the core-and-coil assemblies becomes maximum. The type-based comparison of two transformers (Kelsterbach and Dauersberg) is shown in Fig. 2. There are slight deviations in the comparison of the neutral current in the range of 500 to 600 kHz. Additionally, the transfer functions of the transferred medium voltage are not identical from 50 to 100 kHz. One explanation could be a modified HV winding. Such a modification has been annotated in the windings specification of the manufacturer (Table I). Unfortunately, there is no detailed documentation available. This type of comparison has been carried out for 28 same-typed power transformers of one manufacturer. Further investigations to evaluate the results of this type-based comparison are presented in Section IV.

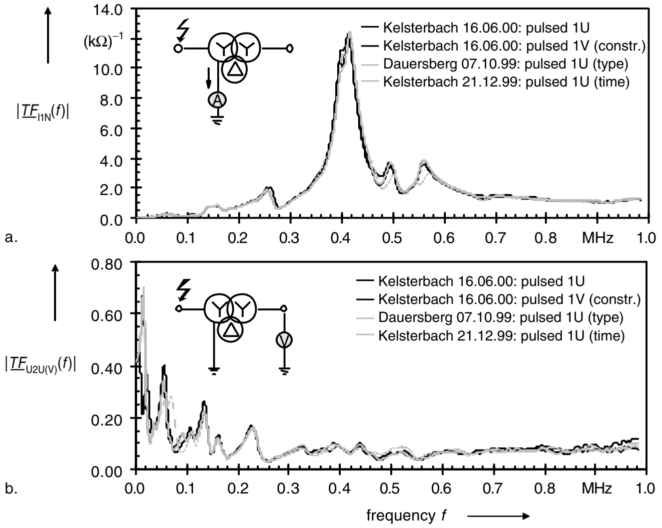

Fig. 2. Performing three types of comparison for transfer function results at a power transformer (220/110/10 kV, 200 MVA, Yyd5): time-, type- and construction-based method; (a) TF (magn.) of the primary neutral current to input voltage, and (b) TF (magn.) of the transferred voltage of 110-kV winding to input voltage. The excitation has been applied to the 220-kV terminals of phase U or V.

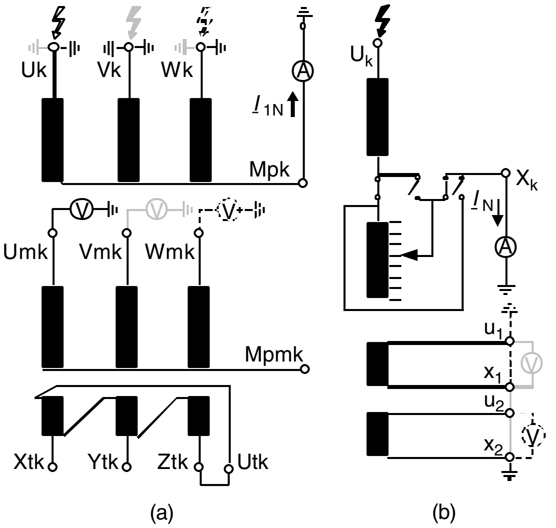

Fig. 3. Test setup for applying a construction-based comparison: cyclic exchange of the terminal set-up; (a) three-phase coupling transformer (Yyd5), and (b) single-phase, double-leg generator transformer (Ii0/i0).

III. Applicability of Construction-Based Comparison

Applying a construction-based comparison for power transformers means comparing transfer function results with respect to the symmetry of a multileg core-and-coil assembly. In practice, test setups are performed to determine the transfer function of each leg separately.

Fig. 3 presents one example of a setup for a three-phase power transformer (YYd) and a single-phase generator trans-

TABLE I
INVESTIGATION FOR THE APPLICABILITY OF A TYPE-BASED COMPARISON FOR A SET OF 28 SAME-TYPED POWER TRANSFORMERS FORM ONE MANUFACTURER (220/110/10 kV, 200 MVA, YNynd5)

No.	Substation:	Transf.-No.:	manuf. year:	Type of winding specification: A	B	C	D	Notes:
1	Limburg	21	1973			X		
2	Limburg	22	1970		X			modified assembly
3	Osterath	21	1972			X		
4	Norf	22	1968	X				
5	Osterath	22	1976				X	
6	Brauweiler	22	1970		X			
7	Walsum	21	1974				X	
8	Pfalzdorf	22	1976				X	
9	Utfort	21	1973			X		
10	Pfalzdorf	21	1974				X	
11	Opladen	23	1969	X				
12	Opladen	24	1975				X	
13	Dünnwald	23	1974				X	
14	Ibbenbüren	21	1975				X	
15	Lüstringen	23	1976				X	
16	Lüstringen	21	1973			X		
17	Ibbenbüren	22	1976				X	
18	Lübbecke	21	1973			X		
19	Schwelgern	21	1969	X				short-circuit event
20	Mündelheim	23	1975				X	
21	Dauersberg	21	1971		0			modification of HV
22	Fühlingen	22	1975				X	
23	St. Barbara	21	1974				X	
24	Kelsterbach	23	1970		X			
25	Siegburg	22	1973			X		
26	Tiengen	23	1975				X	
27	Pfungstadt	21	1972			X		
28	Kelsterbach	22	1969	X				modification of HV

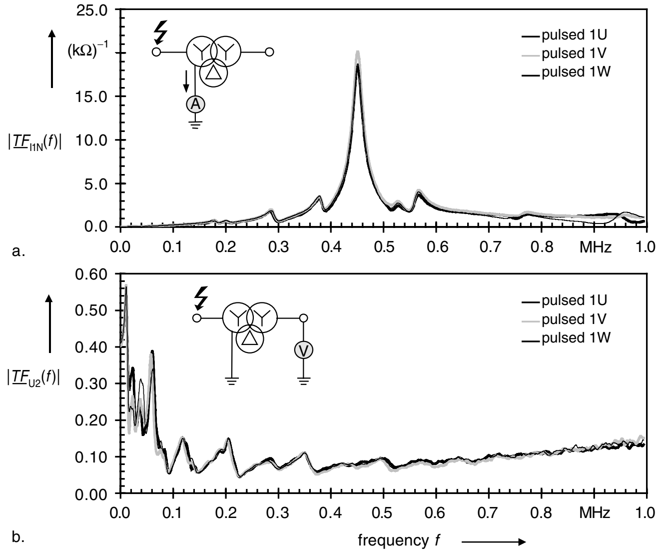

Fig. 4. Construction-based comparison applied for a three-phase coupling transformer (220/110/10 kV, 150 MVA, Yyd5, full voltage transfer rate); (a) TF (magn.) of the primary neutral current to input voltage, and (b) TF (magn.) of the transferred voltage of 110-kV winding to input voltage.

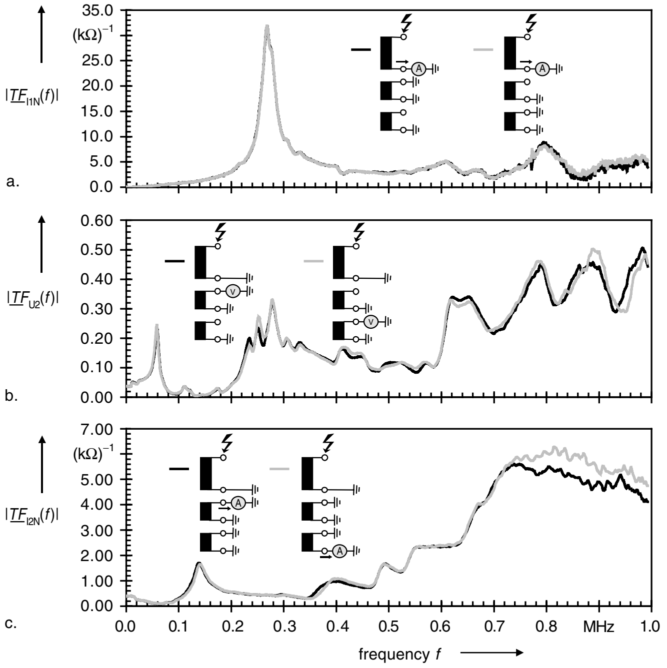

Fig. 5. Construction-based comparison applied to a single phase generator transformer (420/2 × 10 kV, 133 MVA, Ii0/i0, two parallel legs, full voltage transfer rate); (a) TF of the primary neutral current to input voltage, (b) TF of the transferred voltage of one leg to input voltage, and (c) TF of the transferred short-circuit current of one leg to input voltage.

former (Ii0/i0). To perform transfer function measurements for each leg, the setup of the terminals will be cyclically exchanged.

The geometrical properties of the core-and-coil assembly as well as the type of vector group affect substantially the comparability of the results of different legs. To get more information about the applicability of this kind of comparison, different types of transformers must be investigated.

Typically, in Central Europe, coupling transformers are used in Yyd-configuration to connect different electrical power networks. The results of a three-phase 220/110/10-kV coupling transformer are shown in Fig. 4.

Fig. 4 shows a very similar transfer behavior for the neutral current for each excited leg. The resonance frequencies as well as the peak values are nearly identical. The characteristics of the transferred voltage are also identical above 50 kHz. From 10 to 50 kHz, some small deviations between leg U, V, and W can be detected.

Multilegged assemblies are not exclusively used for three-phase power transformers. Even single-phase transformers can be constructed as a double-legged assembly. The results of such a transformer are shown in Fig. 5. A cyclic exchange of the test setup leads to similar results of the separately tested legs. The characteristics of the transferred voltages and currents as well as the input admittance [Fig. 5(a)] are identical. Deviations above 700 kHz are possible effects of a limited measuring accuracy [Fig. 5(a)] as well as a significant difference of the transfer functions [Fig. 5(c)].

The transfer function method is regarded as a method to detect mechanical defects caused by high current stress in windings. Therefore, transfer function measurements are of particular interest for industry transformers which are subjected to frequent switching operations and high peak currents. The test results of a 17-MVA rectifier transformer are shown in Fig. 6. In spite of

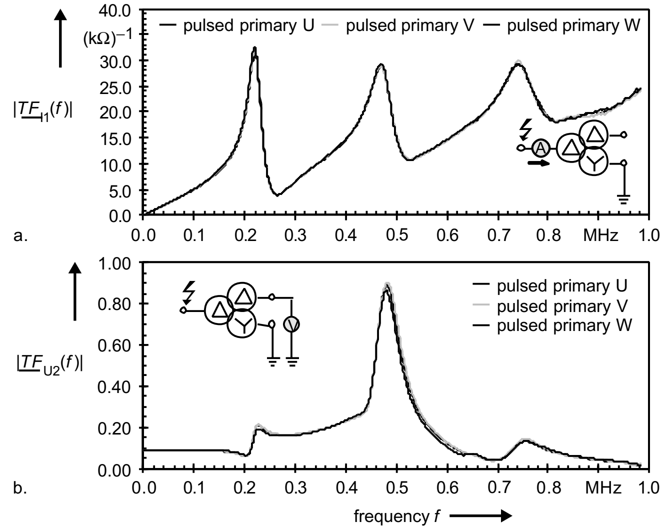

Fig. 6. Construction-based comparison applied to a three phase rectifier transformer (10 kV/892/894 V, 17 MVA, Dd0y1, nom. voltage transfer rate); (a) TF of the primary input current to input voltage, and (b) TF of the transferred voltage of secondary delta winding to input voltage.

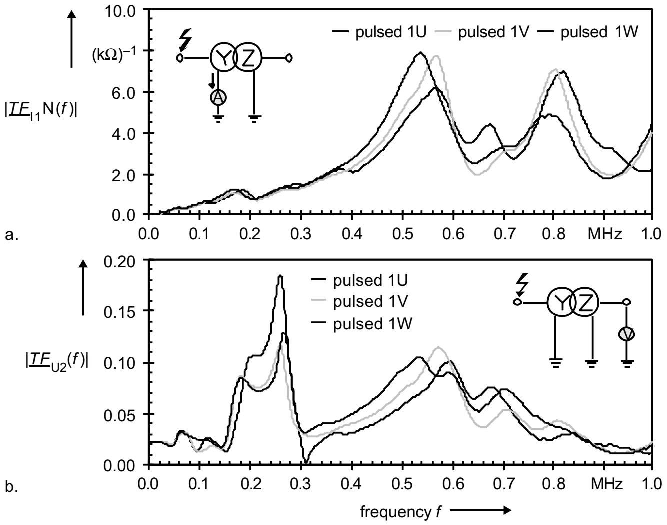

Fig. 7. Construction-based comparison applied for a three-phase distribution transformer (10/0.4 kV, 150 kVA, Yz5, nominal voltage transfer rate); (a) TF of the primary neutral current to input voltage, and (b) TF of the transferred voltage of secondary Z-winding to input voltage.

two LV windings, it is possible to perform a comparison between the different legs.

Fig. 6 shows that the input admittance for the three legs has the same frequency behavior. The voltage transfer from 10 kV to the LV delta winding is also identical. Further investigations have shown a similar comparability of leg U, V, and W for the transferred voltage of the second LV winding (Y winding).

In Central Europe, the majority of distribution transformers includes a zigzag-connected LV winding. Because of the large amount of distribution transformers in service, a construction-based comparison was carried out for a 150-kVA, Yz5 distribution transformer. As it can be seen in Fig. 7, this type of vector group is not suited for a construction-based comparison. The shape of the transfer function curves are similar but not identical. The number of resonances and antiresonances are identical, but the peak values and their frequencies deviate significantly for the input impedance as well as the transferred voltage. The straight Z-connection of two neighbored legs results in three different transfer functions of the phases U, V, and W.

It can thus be concluded that construction-based comparison is not suitable for detecting displacements or other mechanical damages for transformers with a Z-connection.

Fortunately, most three-phase power transformers are connected in Yy, Yd, and Dy. Z-connections are quite unusual for this kind of power transformer. Consequently, the ratio for the applicability of a construction-based comparison becomes larger than for distribution transformers.

IV. EVALUATION OF TYPE-BASED RESULTS

In order to achieve efficient maintenance and planning of replacement, some utilities use their own specification standard for power transformers. Transformers are sometimes ordered as a set of identical transformers which results in several identically constructed transformers placed in service. As an external, visual identification of two identical core-and-coil assemblies, the serial numbers can be used. The presence of two objects with continuing identification numbers suggests that both transformers have been manufactured in turns or simultaneously. Then, the probability of identical transfer behavior becomes high.

To investigate the applicability of a type-based comparison, transfer function measurements have been performed for 28 same-typed transformers of one manufacturer. A schedule of this experiment is shown in Table I.

In spite of the short span of time (eight years) for the manufacturing duration and in spite of identical nominal specification data, the design for the winding changed three times. The effect of different manufacturing and construction details are not well known yet. Therefore, a type-based comparison should only be applied on transformers of identical manufacturing specification. The amount of test objects in Table I has to be divided in four sets of different transfer function behavior. The majority is specified in winding type "D." To achieve the most representative results, the transfer function measurements of type "D" have been evaluated. The results of the transfer functions are shown in Fig. 8.

The measurements of 13 transformers lead to a set of nonidentical results. Certain deviations for the transfer function characteristics (maximum and minimum) can be detected. Possible reasons for these deviations are:

- different transfer behavior because of tolerances due to manufacturing processes;
- nonspecified changes in manufacturing details;
- ambient noise;
- limited measuring accuracy because of low signal-to-noise ratio.

The effect of a limited accuracy can be quantified from the spectra of the time domain signals [2]. Disturbances by ambient noise have to be checked onsite during or after performing the time domain records. Both effects can be taken under consideration for transfer function calculations. Therefore, it is possible to

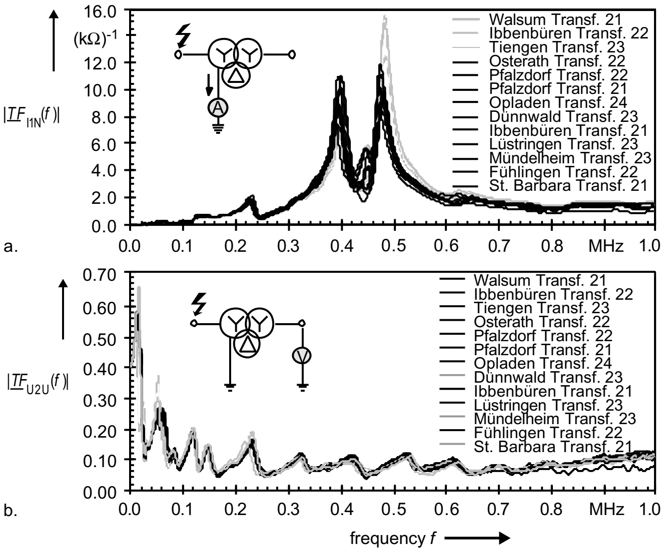

Fig. 8. Type-based comparison applied for a set of 13 identically specified power transformers (Lepper, 220/110/10 kV, 200 MVA, Yyd5, type D, full voltage transfer rate); (a) TF of the primary neutral current to input voltage, and (b) TF of the transferred voltage of the 110-kV winding to input voltage. The excitation has been applied to the 220-kV terminal of phase U.

separate the effects of measurement procedure from the underlying transfer function behavior. The distribution of the transfer function results presented in Fig. 8 cannot be explained by the effect of noise and a low signal-to-noise ratio. To separate the effect of manufacturing tolerances from significant deviations due to possible defects in windings, a normal (Gaussian) distribution for the effect of manufacturing tolerances has been proposed [7].

Manufacturing tolerances will change the transfer behavior in the frequency domain. Therefore, the characteristic data of the transfer functions will be affected by manufacturing processes. To evaluate the results of Fig. 8, a normal (Gaussian) distribution for the transfer function characteristics is supposed. This distribution is assumed for the magnitude as well as the frequency of each transfer function maximum and minimum.

According to the method of least-square optimization, the arithmetic mean x_Σ of n samples x_i is the most probable estimated value for the expected value of the normal distribution [5]

$$x_\Sigma = \frac{1}{n} \cdot \sum_{i=1}^{n} x_i. \tag{2}$$

As an estimation for the standard deviation σ of the normal distribution the empirical standard deviation s is used

$$s = \sqrt{\frac{1}{n-1} \cdot \sum_{i=1}^{n} (x_i - x_\Sigma)^2}. \tag{3}$$

The confidence range m_C for the estimation of the expected value by using the arithmetic mean is [5]

$$m_\mathrm{C} = \frac{t \cdot s}{\sqrt{n}} = t \cdot \sqrt{\frac{1}{n \cdot (n-1)} \cdot \sum_{i=1}^{n} (x_i - x_\Sigma)^2}. \tag{4}$$

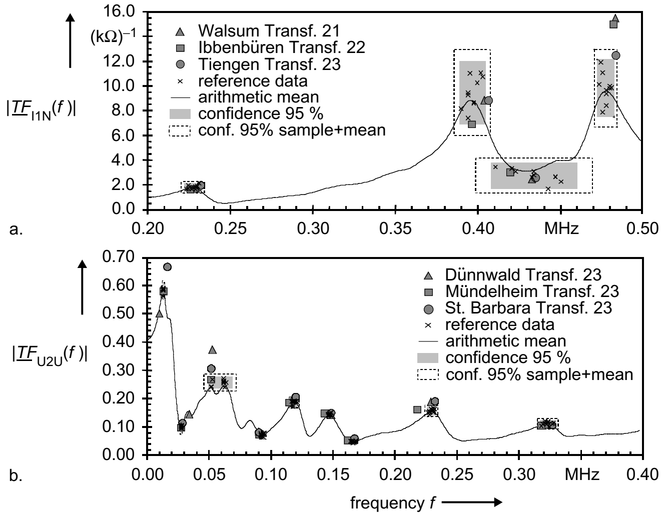

Fig. 9. Evaluation of type-based results of Fig. 8 assuming a Gaussian distribution for the transfer function characteristics to input voltage; (a) TF of the primary neutral current to input voltage, and (b) TF of the transferred voltage of the 110-kV winding.

Applying a confidence level of 95% for $n = 13$ transformers the student's parameter t is chosen to 2.23 [5]. The 95% confidence level range for a sample x_i of a supposed $\mathrm{N}(x_\Sigma; s)$ normal distribution is [5]

$$x_i \in [x_\Sigma - 2s; \quad x_\Sigma + 2s]. \tag{5}$$

To take into account the student's distribution of the arithmetic mean, a combined estimation for a confidence range can be given

$$x_i \in [x_\Sigma - 2s - m_\mathrm{C}; \quad x_\Sigma + 2s + m_\mathrm{C}]. \tag{6}$$

Both confidence ranges are evaluated for the transfer functions of Fig. 8. The results for the transfer function characteristics (resonance peaks and minima) are shown in Fig. 9.

Each maximum and minimum sample of all transfer function tests is marked as a cross ("reference data") in Fig. 9. According to (5) and (6), the confidence range of level 95% can be calculated for the characteristic frequencies as well as the magnitude. The grey-filled areas represent the 95% confidence range of the $N(x_\Sigma; s)$ normally distributed samples. The dashed area includes the uncertainty of the student distributed arithmetic mean as an estimation for the real expected value of the normal distribution ("conf. 95% sample + mean"). Those characteristics which are supposed to deviate significantly from the reference data are not included in the calculation of the estimated parameters of the supposed normal distribution.

As it is shown in Fig. 9, the resonance peaks of the neutral current at 480 kHz of the transformers in Walsum and Ibbenbüren are significantly out of the confidence range. The probability to explain these deviations as an effect of a normal distributed manufacturing quality is lower than 5%. The result of Tiengen at 480 kHz scarcely fits to the confidence range. Therefore, no certain evaluation can be given. For the transfer function of the transferred voltage, a significant deviation from the confidence ranges can be detected for the transformers in Dünnwald, Mündelheim, and St. Barbara [Fig. 9(b)]. Consequently, this deviation is unlikely to be an effect of a statistical quality distribution of the transformer production. This certainty is higher than 95%.

Up to now, there is no obvious indication for the different transfer behavior of the transformers in Walsum, Ibbenbüren, Dünnwald, Mündelheim, and St. Barbara. The results of Fig. 9 should be taken as an occasion to apply further investigations. It can be useful to have a look at former repair activity documentation, probable accumulation of short-circuit events, or other faults. Exchanges in core-and-coil assemblies, due to repair and maintenance, may probably cause different transfer behavior. Short-circuit events result in mechanical stress in transformer coils. Sometimes, mechanical deformations in windings may occur due to this stress. This kind of mechanical changes in coil assemblies affects the transfer behavior of transformers, especially at higher frequencies.

V. INDICATION OF MECHANICAL DAMAGES IN WINDINGS

A. Sensitivity Analysis

The time-based comparison is the most reproducible procedure for an evaluation of transfer function results. Therefore, experimental investigations of the absolute sensitivity to mechanical defects are performed by analyzing actual and fingerprint results. Radial buckling and axial displacement have been experimentally simulated in laboratory using two test limbs of a 1.2-MVA distribution transformer [4]. The extend of manipulation has been increased successively. For each degree of damage, the transfer function has been determined. The absolute sensitivitiy to radial buckling and axial displacement has been figured out to

axial displacement	axial shift: 1.2 % of total coil height;
radial buckling	depth: 3.5% of outer coil diameter; axial extension: 10% of total coil height; tangential ext.: 5% of coil circumference.

B. Indication of Mechanical Changes

The sensitivity limit correlates directly with the measurement accuracy [2]. A significant deviation of transfer functions can be declared if there is no overlapping of tolerance bands. Consequently, the sensitivity could be increased if the measurement becomes more accurate. From the experimental point of view, deviations of transfer function results appear by shifts of resonances and antiresonances as well as deviations in magnitude (damping rate).

Shifts in characteristic frequencies (frequencies of resonances and antiresonances) are indicators for changes in core-and-coil assemblies. Deviations of the magnitude may also be an effect of a different signal damping rate and, therefore, an effect of the test setup. A pure deviation in magnitude without any change in characteristic frequencies is uncertain to indicate a mechanical defect inside the transformer. For practical use, a mechanical change is only declared if there is a significant deviation in at least one characteristic frequency.

According to former experiments, the frequency shift of 1.7% of one resonance corresponds to a declared sensitivity limit. Thus, the proposal for an evaluation criteria could be a deviation of more than 1.5% for at least one characteristic frequency in a certain analyzed frequency range. This statement is only valid if there is no common range for tolerance bands of this frequency range [2].

The proposed criteria are only applicable for a high repeatability of transfer function results. The criteria are proved for time-based comparisons.

For a construction-based comparison, this criteria is only applicable if an identical transfer behavior of each limb is ensured. If there is no information about the comparability of the examined phases or limbs, the proposed criteria is not practical.

For a type-based comparison, the proposed criteria can only be applied if the design of the tested transformers is really identical. Usually, two identically manufactured large power transformers are rarely available, even if there are identical nominal specifications. If there are small design modifications, other criteria must be applied. One method could be the statistical evaluation as it is presented in paragraph IV. The 95% confidence-interval seems to be a rough criteria to detect mechanical defects. Other experiments must prove the practical use of this statistical criteria to perform onsite diagnosis for power transformers.

VI. CONCLUSION

This contribution discusses the practical applicability of three types of comparison based on measured transfer functions: *time-based, construction-based,* and *type-based* comparison. Generally, each type of comparison is suited for transfer function evaluation. The highest level of comparability is obtained by a former fingerprint measurement in a time-based comparison. There is no limitation for the application of a time-based comparison due to the transformer's type and vector group.

The results of separately tested legs can be applied as reference only for Y- and D-coupled windings (construction-based comparison). This method is applicable for three-phase assemblies as well as multileg single-phase transformers. The similarity of the transfer behavior of zigzag coupled windings is not sufficient for performing any diagnosis.

Usually, a type-based evaluation leads to distributed transfer function results. A statistical evaluation method is presented for separating the effects of manufacturing processes from the effects of defects and changes in core-and-coil assemblies due to service, suitable for sets including more than ten test objects.

Further investigations on distribution transformers as well as on standard transformers, which are produced in larger numbers, is recommended to gain more knowledge about the distribution of transfer function results for a construction-based comparison.

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