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Fault diagnosis of actual large-power high-voltage windings using transfer function method

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Abstract: The transfer function (TF) method is presently a well-known method used to detect various types of winding damage in power transformers. Although abundant research has been done on this subject using laboratory windings as test objects, it is hard to find one, whose test objects are actual large-power transformer windings. Hence, a 400 kV disc winding consisting of 86 discs is used in this paper to study turn-to-turn short circuit with the help of the TF method. To evaluate the effects of this type of fault on TF curves, some mathematical comparison algorithms are used in this research.

Key words: turn-to-turn short circuit, transfer function (TF), comparison algorithms, actual winding

1. Introduction

Among the different methods of fault detection in power transformers, the transfer function (TF) method has been used to investigate specific types of faults inside transformers [1, 2]. Comparison between TF measurements can reveal information about the mechanical and electrical condition of transformer windings [1-3]. A change in the geometrical arrangement of windings has an effect on the electrical properties such as series and/or ground capacitances, self and/or mutual inductances, conductance and resistance of a transformer [3], and consequently on the TF curve. Thus, it is possible to draw conclusions about the condition of the winding on the basis of the changes in the curve progression [4].

The most important faults, which can be detected by using a TF method, can be categorized as the followings:

1) axial displacement [3, 5],
2) radial deformation [3],

3) disc space variation [6] and
4) turn-to-turn short circuit [7].

The faults mentioned above have been studied up to now mostly on small laboratory windings by the researchers. The ability of the TF method to detect these faults in actual large-power transformer windings is still unidentified or insufficiently identified. The objective of this paper is to contribute to the study of this ability of the TF method.

Since the location of a turn-to-turn short circuit can not be determined using standard test methods such as turn ratio method, this type of fault is evaluated in this paper by the TF method. The turn-to-turn short circuit is studied in this work with help of a large power 400 kV disc winding as a test object. The winding includes 86 discs, 9 turns in each disc. All TF curves related to different possible turn-to-turn faults along the winding are measured and compared to investigate the effect of this type of fault on a TF curve.

The comparison algorithms, which are introduced in the literatures to evaluate variations of TF curves, can be divided into two major following groups:

1) Artificial intelligence methods such as genetic algorithms, fuzzy logic, neural networks and so on [8-12] and
2) Mathematical methods like index of frequency deviation, index of amplitude deviation, correlation factor et cetera [3, 5, 13].

This paper focuses on the latter method.

2. Test object and measurements

A 400 kV disc winding consisting of 86 discs, 9 turns in each disc with an outer diameter and height equal to approximately 1.73 and 1.75 m is used as a test object. The winding contains four axial oil ducts within the discs. Two aluminum cylinders are used inside and outside of the test object to model the earth potential of core and tank (Fig. 1a). In order to make a short circuit between turns, a small part of outer cylinder equal to around 0.5 m (approximately 9 percent of outer cylinder periphery) was cut (Fig. 1b).

All of the external turns of the discs were accessible to make the required short circuits (Fig. 1c). It is necessary to mention that connecting two successive discs makes either one-turn short circuit or two-disc (equal to 18-turn) short circuit depending on the number of discs connected to each other (Fig. 1d).

It is possible to determine a TF either by using time or frequency domain measurements. The possible accuracy of both procedures is equal [14].

In the time domain, test objects are excited by low or high voltage impulses. Then, the input and output transients are measured and analyzed (Fig. 2). The shape of the impulse voltage depends on the test device and the test set-up. The bandwidth of the exciting signal should be as high as possible. Typical parameters of the impulse shapes are front times of 100 ns to 500 ns and time to half values of 40 to 200 μs. The spectral distribution of the time domain signals are calculated using Fast Fourier Transformation (FFT). The quotient of output to input signal represents the TF in the frequency domain [2].

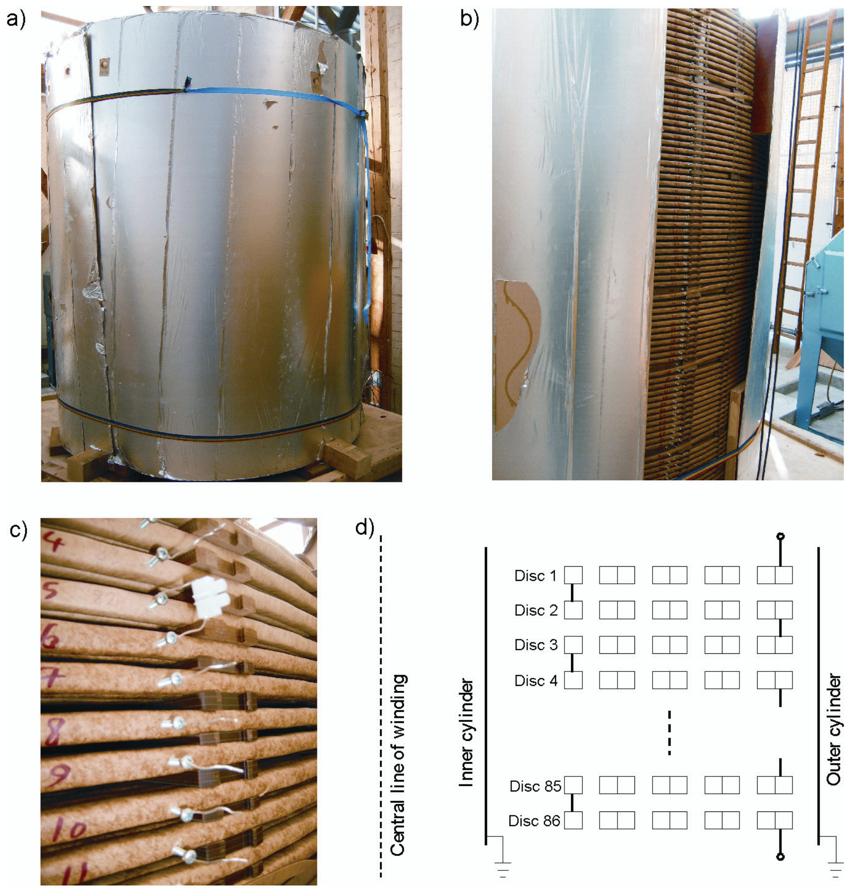

Fig. 1. Investigated test object: a) Outer cylinder of test object, b) The accessible part and taps of winding, c) Short circuit done between two successive discs, and d) Schematic diagram of the winding

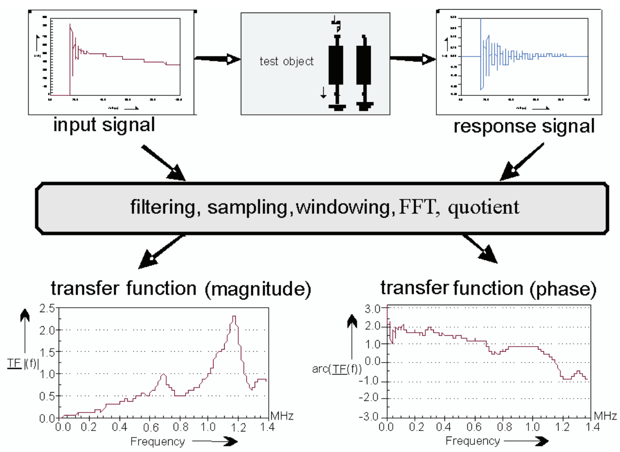

Fig. 2. Measuring the TF in the time domain

On the other hand, in the frequency domain measurements (Fig. 3), the input signal is a sinusoidal wave with variable frequency. In the frequencies higher than approximately 10 kHz, the output signal is a sinusoidal wave, as well [3]. Comparing the output and input signals in a specified frequency results the TF in that frequency. Varying the frequency of input signal enables the measuring of the TF in different frequencies. For each frequency, the magnitude of the TF is equal to the amplitude of the output signal divided by the amplitude of the input signal. Furthermore, the phase of the TF is determined as phase shift between the sinusoidal waves of the input and the output.

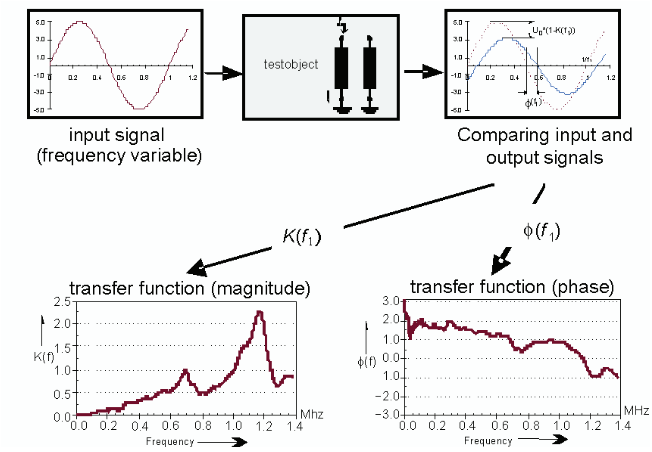

Fig. 3. Measuring the TF in the frequency domain

In the presented investigation all measurements were executed in the frequency domain with help of Frequency Response Analyzer, i.e. *Bode 100*, with the frequency range of 10 Hz to 40 MHz. *Bode 100* includes a direct digital synthesis signal source with an adjustable level and frequency for excitation of the device under test and two receivers processing the input and output signal. The amplitude of input sinusoidal voltage is automatically adjusted between 100 and 240 V to minimize the noise of output signal. Since a TF is a division of the output signal by the input signal and because of the linear behavior of the transformer in higher frequencies, the TF is independent of the amplitude of the applied input voltage [3]. Therefore, for the sake of simplicity, a low voltage is applied for the input voltage in the frequency domain measurements.

For each turn-to-turn short circuit or intact case of winding two different types of the TF, the current TF (TF_C) and the voltage TF (TF_V), are measured. TF_C and TF_V are defined by the following equations.

$$TF_C = \frac{|I_{Earth}(j\omega)|}{|V_H(j\omega)|}, \tag{1}$$

$$TF_V = \frac{|V_O(j\omega)|}{|V_H(j\omega)|}, \tag{2}$$

where V_H indicates the input voltage to the winding top terminal and I_{Earth} and V_O indicate respectively the output current and output voltage at the winding bottom terminal dependent whether the bottom terminal is grounded or isolated. Any voltage signal is measured directly by *Bode 100*, as shown in Figure 4a. Figure 4b demonstrates two cables connected to the top terminal of the winding, one cable is for applying input voltage and the other is for measuring the applied voltage. To measure the current signal, a suitable small resistance equal to 0.1 Ω is utilized between the bottom terminal and the ground, subsequently, its voltage drop is measured and divided by the value of resistance (Fig. 4c).

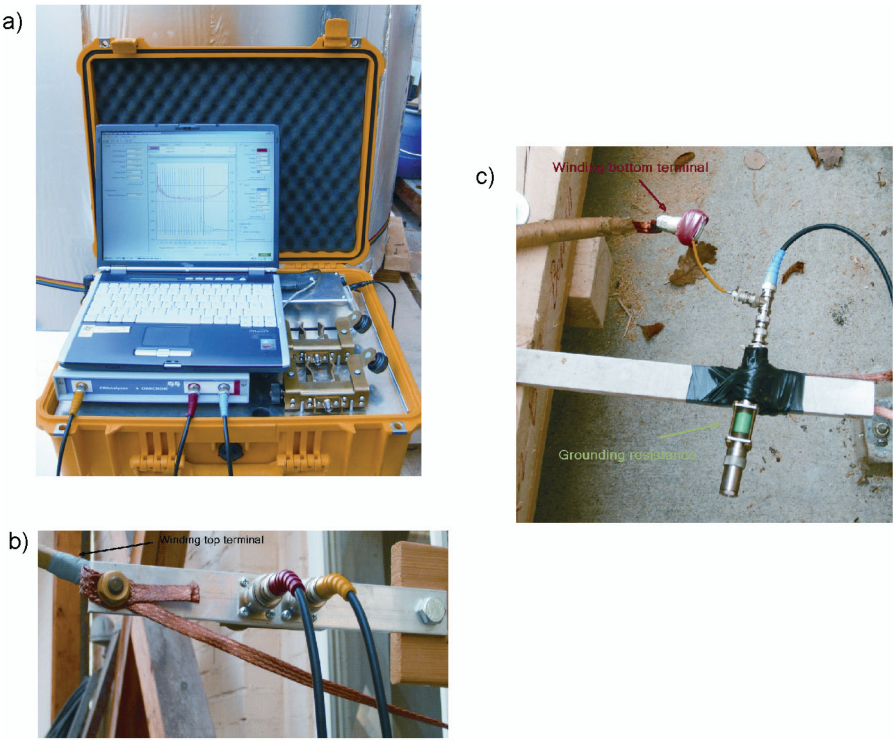

Fig. 4. The test setup: a) Bode 100, PC, and cable connection, b) Cable connections at the winding top terminal, and c) Grounding resistance and cable connection at the winding bottom terminal

Figure 5 shows for instance the measured current and voltage TFs at three different conditions, without short circuit, with short circuit between discs 9 and 10 (discs are numbered from top of winding, Figures 1d) and with short circuit between discs 10 and 11. With connecting disc 9 to disc 10, two discs, i.e. 18 turns, will shorten, while in the case of connection between discs 10 and 11 only one turn will shorten.

It is obvious from Figure 5 and other measured results that the current TF displays more clear changes than the voltage TF. Hence, the current TFs are used to evaluate the effect of turn-to-turn short circuit in the following sections.

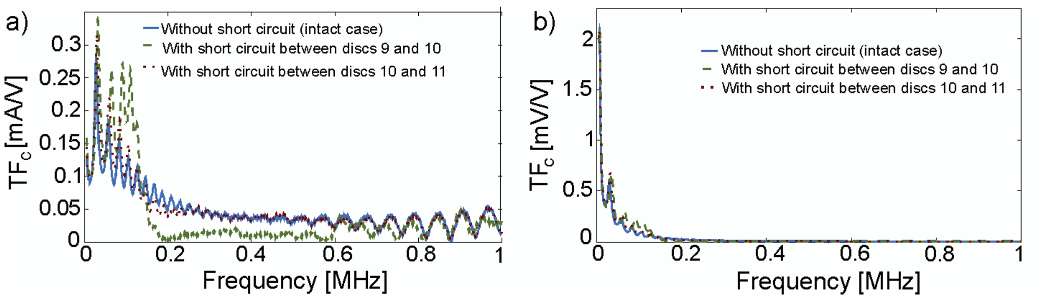

Fig. 5. Measured results: a) Current TFs and b) Voltage TFs

3. Comparison algorithms

The most important mathematical methods to compare TF curves are discussed in the following subsections.

3.1. Standardized difference area

The area under a TF curve within a determined frequency domain (for example from zero till one MHz) can be considered as a comparable parameter. Hence, **S**tandardized **D**ifference **A**rea (**SDA**) given in the following equation is one method to compare TF curves [15].

$$SDA = \frac{\int_{f_{\min}}^{f_{\max}} \left| TF_{Test}(f) - TF_{Ref}(f) \right| df}{\int_{f_{\min}}^{f_{\max}} TF_{Ref}(f)\, df}, \tag{3}$$

where at f_{min} and f_{max} represent minimum and maximum values of frequency domain and TF_{Test} is compared with TF_{Ref}.

3.2. Average value of standardized difference function

The difference function is perhaps the easiest way to expose the difference between the reference TF and the test TF.

$$\Delta_0(f) = \left| TF_{Test}(f) \right| - \left| TF_{Ref}(f) \right|. \tag{4}$$

It is necessary to do a standardization of the difference function [13], which directs to the following definable parameter:

$$\Delta_1(f) = \frac{\left| TF_{Test}(f) \right| - \left| TF_{Ref}(f) \right|}{\frac{1}{N} \sum_{i=1}^{N} \left| TF_{Ref}(f_i) \right|}, \tag{5}$$

where N denotes the number of measured samples. The average value of this standardized difference function is calculated by the following equation.

$$E = \frac{1}{N}\sum_{i=1}^{N} \Delta_1 (f_i). \tag{6}$$

3.3. Correlation factor

The correlation factor is a measure for the similarity of two curve progression. For two TF curves, TFA and TFB, this factor can be determined as follow [13]:

$$\rho = \frac{\sum_{i=1}^{N}\left(TFA^*(f_i)\cdot TFB^*(f_i)\right)}{\sqrt{\sum_{i=1}^{N}\left(TFA^*(f_i)\right)^2 \cdot \sum_{i=1}^{N}\left(TFB^*(f_i)\right)^2}}, \tag{7}$$

at which

$$\begin{aligned} TFA^*(f) &= |TFA(f)| - \frac{1}{N}\sum_{i=1}^{N} |TFA(f_i)|, \\ TFB^*(f) &= |TFB(f)| - \frac{1}{N}\sum_{i=1}^{N} |TFB(f_i)|. \end{aligned} \tag{8}$$

3.4. Index of frequency deviation

As characteristics for TF curves serve the resonant frequencies and their magnitudes (absolute values). Therefore, to measure the modification due to a defect, the relative shift of the *i*-th resonance frequency value, also referred to as *i*-th **I**ndex of **F**requency **D**eviation (**IFD$_i$**), were defined as follows in [3]:

$$IFD_i = \frac{\Delta f_i}{f_{o,i}} \times 100\% = \left(\frac{f_{k,i} - f_{o,i}}{f_{o,i}}\right) \times 100\%,$$

where at $f_{k,i}$ and $f_{o,i}$ represent the *i*-th resonance frequency with fault (turn-to-turn short circuit) and without fault, respectively.

One important problem with using the IFD_i is determining the *fundamental* maxima and minima (resonances). Figure 5 demonstrates that a number of resonance frequencies can appear or disappear in a TF due to a fault, which makes the comparison process with IFD method complicated. Some criteria is given in [13] to overcome this problem, whose application concludes the fundamental resonance frequencies given in Table 1.

The Table 1 shows only the resonance frequencies appearing in all TFs with different location of short circuit and even without fault. It is noticeable that the values given in this table are related to the TF in intact condition of winding. Between approximately 200 kHz and 700 kHz the TFs don't contain any fundamental resonances.

Table 1. Fundamental resonance frequencies of studied test object

Number of resonance frequency (***i***)	Value of resonance ($\boldsymbol{f}_{o,i}$) [kHz]
1	27.4
2	43.3
3	56.4
4	70.4
5	82.6
6	93.8
7	105
8	115
9	126
10	137
11	146
12	155
13	762
14	791
15	819
16	850
17	879
18	907
19	937
20	967

3.5. Index of amplitude deviation

Similar to the IFD_i, the relative deviation of amplitude in the i-th resonance frequency, so called i-th **I**ndex of **A**mplitude **D**eviation (**IAD$_i$**), can be evaluated to compare TF curves [3].

$$IAD_i = \frac{\Delta A_i}{A_{o,i}} \times 100\% = \left(\frac{A_{k,i} - A_{o,i}}{A_{o,i}} \right) \times 100\%, \tag{10}$$

where at $A_{k,i}$ and $A_{o,i}$ represent the amplitude of a TF at the i-th resonance frequency with and without fault, respectively.

4. Sensitivity analysis of turn-to-turn short circuit

In the previous section, five mathematical parameters, SDA, E, ρ, IFD_i and IAD_i are explained as vital factors to assess TF curves. The results of evaluation of SDA, E and ρ for turn-to-turn short circuit are given in Figure 6.

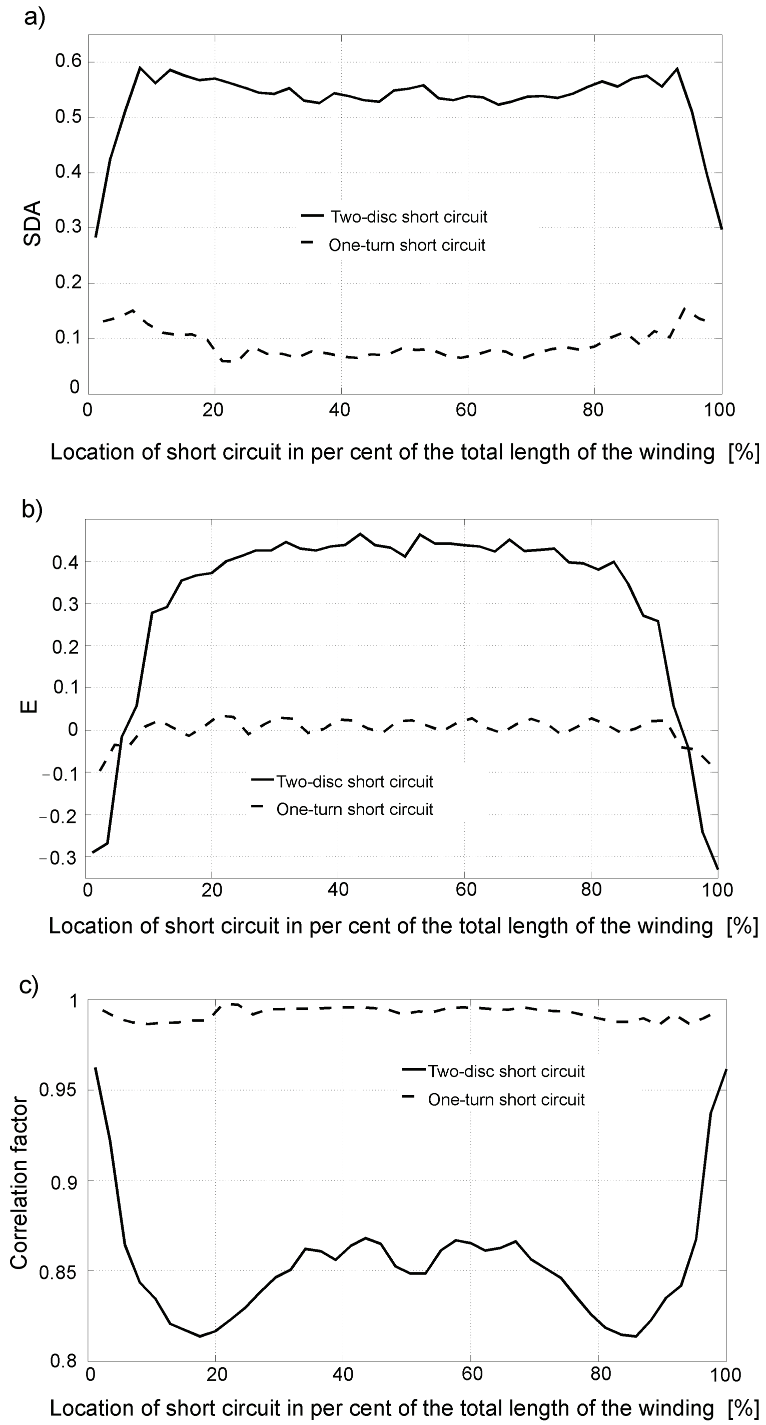

Fig. 6. Evaluation results of turn-to-turn short circuit: a) *SDA*, b) *E*, and c) ρ

The horizontal axis of these curves presents the location of the fault along the winding in per cent. It seems to be difficult to determine the location of fault merely using these curves. However, the amount of the fault (one-turn or two-disc short circuit) can be concluded with help of these parameters (especially *SDA* and ρ), which is also important from the view point of transformer operator.

The analysis of the measured TFs with IFD_i and IAD_i shows the high ability of these factors in determining the location of fault. A principally important point related to IFD_i and IAD_i is that the lower resonance frequencies, under approximately 110 kHz, give better results, at least with test object used in this work. Figure7 demonstrates the fault-localization ability of these parameters. Because of simplicity, only the results related to three resonance frequencies, 27.4, 43.3 and 56.4 kHz (see Tab. 1), are shown in Figure 7. In addition, only two-disc (18-turn) short circuit is analyzed in this figure.

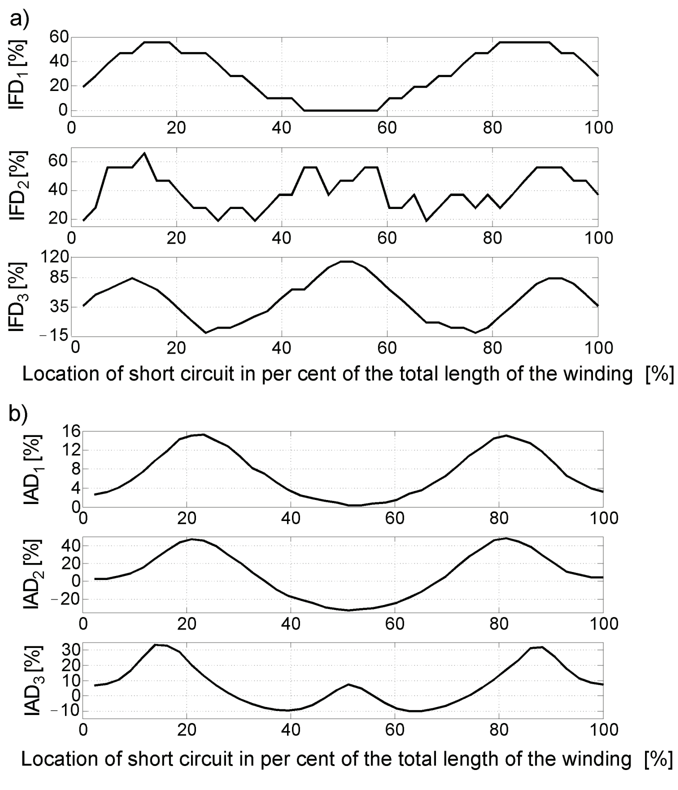

Fig. 7. Localization of two-disc short circuit along the winding: a) IFD_i and b) IAD_i

Knowing the IFD_i and IAD_i caused by a winding fault, Figure 7 allows the location of fault. Furthermore, this analysis indicates that IAD_i factors are more effective.

The similar results for one-turn short circuit are given in Figure 8. Although it doesn't seem straightforward to find out the position of one-turn short circuit from Figure 8, it must be considered that one-turn fault for the test object having 774 turns is a very small failure.

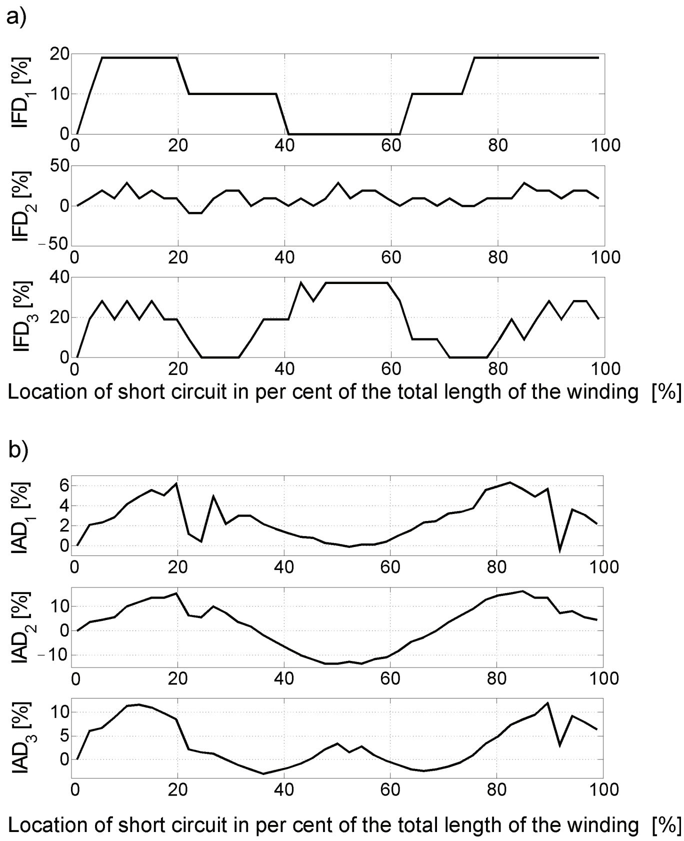

Fig. 8. Localization of one-turn short circuit along the winding: a) IFD_i and b) IAD_i

It should be pointed out that the second resonance frequency is a minimum point, whose IFD in Figure 7 and Figure 8 contains less regular changes. This fact is valid for almost all minimum points. That means the maximum points for such studies are more useful.

Moreover, the relative deviations of the resonance frequencies and the magnitudes show a symmetry in relation to the winding center, i.e. during such a symmetrical arrangement it cannot be determined that one short circuit due to detected pole shifts is situated in the upper or lower winding half. It must still be more investigated, how much such symmetry characters exist with real transformers. Since the arrangement of transformer windings in active parts does not indicate a symmetry plan on half winding height, it is to be assumed that visible symmetries under Figure 7 and Figure 8 do not occur in practical and whereby a unique fault location is possible.

The above given discussion proves the ability of the TF method to detect and localize the turn-to-turn short circuit. If the TFs in the fault and intact conditions are known, the mathematical comparable parameters can be calculated. With help of some of these parameters (*SDA* and ρ) the amount of the fault and with some of them (IFD_i and IAD_i) the location of the fault can be determined. It is useful for a power system engineer to possess more information about a faulty transformer such as its level and location in order to make appropriate decisions and thus take the right actions.

5. Conclusions

The ability of the transfer function (TF) method to analyze turn-to-turn short circuits in a real large-power 400 kV disc winding is investigated in this paper using the following mathematical algorithms:

1) Standardized difference area,
2) Average value of standardized difference function,
3) Correlation factor,
4) Index of frequency deviation, and
5) Index of amplitude deviation.

The most important results of the paper are summarized as follows:

1) The TF method is definitely useful to detect the amount and location of a turn-to-turn short circuit in a real large-power winding,
2) Applying all of the mentioned mathematical parameters in this paper together gives more precise results than using only some of them,
3) Difference area, average value of difference function and correlation factor give more accurate information about the amount of fault, while index of frequency and amplitude deviation implies the location of fault, and
4) For the test object employed in this work and turn-to-turn short circuit faults, lower resonance frequencies provide more obvious and meaningful results by means of index of frequency and amplitude deviation. Additionally, maximum resonance frequencies present clearer results than minimums.

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