A New Method for Detection and Evaluation of Winding Mechanical Faults in Transformer through Transfer Function Measurements

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Abstract—Transfer function (TF) is an acknowledged method for power transformer mechanical faults detection. However the past published works mostly discovered how to specify the faults levels and paid less attention to detection of the type of faults using comparison of TFs, whereas, it seems important for most of the applications to specify the type of fault without opening the unit. This paper presents a new method based on vector fitting (VF) to compare the TFs and specify the type, level and location of the fault. For development of the method, and its verification the required measurements are carried out on four model transformers; under intact condition, and under different fault conditions (axial displacement, radial deformation, disc space variation and short circuit of winding) and the TFs are determined. Employing VF, the coefficients of TFs are determined with the required accuracy. Using those coefficients, a new index is introduced to specify the type, level and location of the fault in the winding. Convincingly good results were obtained. Therefore it is believed that this finding could be helpful in fault diagnosis in actual power transformer windings.

Index Terms—Transformer, Fault Diagnosis, Measurement, Transfer Function, Vector Fitting

I. INTRODUCTION

Power transformers are among the most important equipments in the electrical power transmission and distribution systems and occurrence of any fault in these transformers will reduces the power system reliability, in other words increases the possibility of power supply interruption. In addition, it will impose extra costs required for their maintenance and for their transportation to a repair factory. Due to the existence of a strong competition in the electrical power supply industry, the importance of application of the transformer monitoring systems has increased over the time [1].

Different fault modes in transformers are classified into two main groups; the mechanical types, and the electrical types. Different methods have been offered for detection of each of these faults, such as:

a – Oil analysis (Dissolved Gas Analysis, Furfural)
b – Partial discharge measurements
c – Dielectric response analysis
d – Transfer function analysis.

Among these methods, TF method is a well-known method for detection of the winding mechanical faults [2]-[4].

TF method is a comparative method; in this method a new measurement is put besides a referential measurement. If the deviations were remarkable, the direction and magnitude of deviations should be studied and analyzed.

Mechanical faults such as; axial displacement (AD), radial deformation (RD), disc space variation (DSV) and short circuit (SC) of the winding affect the TFs and cause dislocation of resonance frequencies and moreover will decrease or increase the magnitude of resonance frequencies in the TF. These changes will cause a relevant shift in the poles and zeros of TF. Therefore, by evaluation and comparison of the TFs, any variation in the structure of the winding due to a mechanical damage can be detected. TF evaluation and its comparison can be done in time domain or in frequency domain. The identification process is normally carried out in frequency domain through inspection of the rational functions.

Some studies [5]-[6] have shown that VF method is an effective and accurate method for estimating the transformer TFs. In [7]-[8] have proposed an index (based on TF estimation using VF) for determination of AD and RD extent. That index played its role only to specify the level of AD or RD and does not specify the type of fault. In addition, their proposed index only perceives the variations in the poles of the rational function where as, during incidence of winding mechanical faults both the poles and the zeros change. Therefore continuation of the researches on VF application for fault detection is necessary. In this paper employing VF, the TFs of the transformer are estimated both during faulty condition and during normal condition. Introducing a new algorithm the TF is identified and compared with the reference one. Not only this algorithm is able to recognize the type of fault, but also it can specify the level and location of fault. Comparing this new method with one of the past methods, it is shown that the proposed index is more efficient, even in determination of the fault level.

II. LITERATURE REVIEW AND PROBLEM DEFINITION

TF analysis is a reliable method for winding failures detection in power transformers. Different methods are introduced for evaluation of the TFs. Some of these methods are verified against the practical samples of mechanical
faults [9]. Also, some analytical investigations have been performed using the equivalent circuit models [10]. On the other hand, transformer modeling using its internal geometry and the material properties provided the possibility of evaluating the sensitivity of the TF parameters against the type of faults [11]-[12].

In this paper, the important winding faults, which are most likely to be detected using the TF analysis, have been studied. These faults can be classified as follows:

a- Axial Displacement [11]-[14],

b- Radial Deformation [8], [12]

c- Disc Space Variation [15] and

d- Short circuit [14], [16]

It should be noted that SC is not mechanical faults per se, but usually it do stem from them, because it can be detected using TF method.

The above faults have been studied analytically and experimentally in [7]-[17]. These researches have studied the sensitivity of TFs parameters against those faults separately and have not discussed that how a specific mechanical fault can be found and can be classified as to be in one of the AD, RD, DSV or SC categories.

In this analysis, the TF method is analyzed by a comparative method. However, in general the comparative algorithms introduced in the literature, can be classified into four major categories as follows.

A. Algorithms Based on Artificial Intelligence Methods

The methods such as neural networks, genetic algorithm, fuzzy logic, and so on can be included in this group [18]-[20]. Conclusions in these works emphasize the necessity for further investigations to classify the type and location of the fault. Moreover a limitation exists in these methods which made them applicable only for transformers like the one used as test transformer in the development of method.

B. Algorithms Based on Mathematical and Statistical Methods

Some of the methods of this category have been used for fault diagnosis in [21]-[24]. To establish the necessary measures for detection of the faults some parameters have been defined, namely: correlation coefficient (CC), standard deviation (SD). Disadvantages of these methods discussed in [21], [25]. Meanwhile all of the algorithms that employ specific equations with single-valued solutions for the evaluation of the measured TFs belong to this category.

The investigations carried out in [26]-[30] introduce some additional parameters to evaluate the fault level. However, those works do not determine the type and location of the fault. Since in this class of algorithms the phase response is not evaluated, therefore some of them contain unreliable comparison parameter [25].

C. Algorithms Based on Electric Circuit Models

Some investigations have been done to get information about the faults from the measured TFs by describing the TFs using an equivalent electric circuit model [31]. The parameters of the model representing the TFs can be calculated by the means of the details of the transformer design [12] or can be estimated using terminal measurements [32].

Determining the parameters of such models, which usually includes errors [12] and is more difficult for real windings and transformers, is ruled out by avoiding electric circuit models.

D. Algorithms Based on Estimation Methods

TFs of transformers can be approximated by rational functions consisting of two polynomials with real coefficients [5]. The estimation of such a rational function approximation to describe the measured terminal characteristic is employed for comparing TFs [7]-[8]. However, in this works only the AD and RD are considered; thus, specifying the type of fault by comparing different types of faults with each other is left as a subject to be studied.

VF is a widely applicable and general methodology for estimation of TF parameters from frequency response measurement results [5]-[6]. So, in this work VF is used for estimation of TFs.

The algorithms based on VF methods to analyze the process of fault detection are preferred in this work, because:

a- Applying these algorithms is very simple and the results have an excellent match,

b- The estimated functions are comparable in an easier way,

c- As it is discussed in [25], to have an efficient diagnostic tool, the magnitude and the phase responses must be taken into account for the analysis, and this is possible with VF method, and

d- Since the employed rational functions are not limited to have any specified order; it allows finding a function having a perfect fit with the measurements.

A comprehensive windings (mechanical) fault detection procedure, which entails the simultaneous identification of all the three faults characteristics (type, level and location), can be carried out by the algorithms based on application of VF.

The important windings (mechanical) faults, classified as: AD, RD, DSV and SC are simulated by application of those faults on four different model transformers of a similar size.

In the first step, introducing an algorithm based on VF, the type of fault among the four classified mechanical faults, (using a new presented index) is detected. Next, the level and location of the mechanical fault are determined.

III. TF IDENTIFICATION BY VECTOR FITTING

In principle, a TF approximation (of a given order) can be found by fitting it with a function which is made of the ratio of the two polynomials [5] as shown in equation (1):

\[ f(s) = \frac{a_m s^m + \cdots + a_1 s + a_0}{b_n s^n + \cdots + b_1 s + b_0} \]  

(1)

Where \( m \) and \( n \) are the number of numerator and denominator coefficients, \( a_i \) and \( b_j \) are the values of \( i^{th} \) coefficient for the numerator and denominator, respectively.

However, generally the TF of a passive system can be approximated by a rational function \( f(s) \) in the form [5] shown by equation (2):

\[ f(s) = \frac{a_0 + a_1 s + \cdots + a_m s^m}{b_0 + b_1 s + \cdots + b_n s^n} \]  

(2)
\[ f(s) = \sum_{i=1}^{n} \frac{r_i}{s - p_i} + ds + e \]  

(2)

The residues \( r_i \) and poles \( p_i \) are either real quantities or appear in complex conjugate pairs, whereas \( d \) and \( e \) appear in the denominator. The problem at hand is to estimate all of the coefficients \( r_i, p_i \), and unknowns \( p_i \) appear in the denominator.

Stage 1- Specifying the starting poles \( \tilde{p}_i \) in (2)

The starting poles should be complex conjugate with any ill conditioning problem, i.e., \( \alpha = 0.01 \beta \) can be a good choice.

\[
\left[ \begin{array}{c}
\sigma (s) \\
\sigma (s) \\
f(s)
\end{array} \right] = \left[ \begin{array}{c}
\sum_{i=1}^{n} \frac{r_i}{s - \tilde{p}_i} + ds + e \\
\sum_{i=1}^{n} \frac{R_i}{s - \tilde{p}_i} + 1 \\
f(s)
\end{array} \right]
\]  

(3)

Stage 2- Multiplying \( f(s) \) by an unknown function of \( \sigma(s) \) having poles similar with \( f(s) \), as shown in the following:

\[
\sum_{i=1}^{n} \frac{r_i}{s - \tilde{p}_i} + ds + e = \left( \sum_{i=1}^{n} \frac{R_i}{s - \tilde{p}_i} + 1 \right) f(s)
\]  

(4)

\[
(\sigma f)(s) = \sigma f(s) f(s)
\]  

(5)

Stage 3- Solving (6) by least square method and identifying the coefficients \( r_i, d \) and \( e \) of (2)

Stage 4- Calculation of new poles

If the functions in equation (5) are reformed as shown in equation (7):

\[
(\sigma f)(s) = d \frac{n+1}{k=1} \left( s - z_k \right) \\
(\sigma f)(s) = d \frac{n+1}{k=1} \left( s - \tilde{p}_k \right)
\]  

(7)

Then using equations (5), & (7) the equation (8), is derived as follows:

\[
f(s) = \frac{n+1}{k=1} \left( s - z_k \right)
\]  

(8)

IV. TEST OBJECTS (THE FAULTS MODEL TRANSFORMERS) AND MEASUREMENTS

In the present investigation, all measurements were executed in the time domain then using FFT acquired the frequency response of TF which is illustrated in [12]. Four model transformers were considered in this study and some tests were performed on them to development of the proposed method for finding type, level and location of the faults, as follow:

A. Study of AD

As a model transformer for the study of AD a high voltage winding with 31 double inverted discs, where 6 turns are present in each disc, and a four layer concentric low voltage winding, where 99 turns are present in each layer, were used. These particular windings were manufactured for the special experimental purposes, and they correspond to windings of a transformer with a rated voltage of about 10 kV and a rated output of 1.3 MVA. Its specific construction permits a gradual axial movement of the internal layer winding with respect to the outer winding. The test object has 82.7 cm height and therefore a 1 cm axial displacement is equivalent of 1.2% displacement.

B. Study of RD

As a model transformer for the study of RD a high voltage winding with 30 double inverted discs, where 11 turns exists in each disc, and one layer low voltage winding, having 23 turns are used. The double disc winding has a rated voltage of 10 kV and a rated output of 1.2 MVA. The deformation has occurred on the double disc winding in four degrees, as follow:

- Degree 1: The sixth up to the 54-th discs were all radially deformed on one side. Deformation was around 7% of the disc radius
- Degree 2: The sixth up to the 54-th discs were all radially deformed on two opposite sides. Deformation was around 7% of the disc radius
• Degree 3: The sixth up to the 54-th discs were all radially deformed on three sides with 90° with respect to each another. Deformation was around 7% of the disc radius
• Degree 4: The sixth up to the 54-th discs were all radially deformed on four sides with 90° with respect to each another. Deformation was around 7% of the disc radius

C. Study of DSV

For studying DSV the same model winding that is used in section 4-2 experimented. For this purpose another intact winding that space between its discs is 5mm, is selected. For research about the effect of DSV on TFs, the space of discs is changing to 7.5, 10, 15, 20 and 25mm, then TF of them is measured. To better studying the following states are experimented:

State 1 of DSV: space variation between disc 2 and disc 3
State 2 of DSV: space variation between disc 4 and disc 5
State 3 of DSV: space variation between disc 8 and disc 9
State 4 of DSV: space variation between disc 12 and disc 13
State 5 of DSV: space variation between disc 16 and disc 17

Although some of the DSV faults given above seem to be exaggerated and impossible to occur on real transformers, they have been executed in this work in order to accumulate more data about DSV and find out precise information concerning TF variations. Another important point is that the higher distances between discs implemented here are compensable with less circumference of winding covered with the DSV, so that the DSVs carried out in this work could be more similar to real faults in transformers.

D. Study of SC

For the study of SC a high voltage winding with 30 double inverted discs, where 9 turns exists in each disc is used. The double disc winding has a rated voltage of 10 kV and a rated output of 1.2 MVA. All discs of the model winding are provided with a tap, whereby the recording of the impulse voltage distribution is enabled along the winding. The input terminal of the winding is subjected with the impulse voltage, as response signals is the earth current at a selected tap along the winding recorded. A short circuit between two discs is applied to different places along the winding for the experimental determination of the effect of short circuits and their spatial arrangement on the TF. For each individual position of the SC the TF is measured.

To investigate the sensitivity of transfer TF measurements, for AD, RD, DSV and SC, different terminal conditions have been studied, as shown in Figure 1.

Figure 1. Different terminals connections, for sensitivity analysis of transfer functions measurements when examining: a) AD, b) AD, c) RD and DSV, d) RD, and e) SC

The measured results show that the mechanical faults (AD, RD, DSV and SC) affect the TFs and modify them. For example, the measured TFs (TF1, TF3 and TF4) are showed in Figures 2 to 4.
Figure 4. The measured TF of transformer winding when SC occurred (setup TF5)

V. PROPOSED METHOD FOR FAULT DIAGNOSIS

In this paper, fault diagnosis in transformer will be done with underneath assumptions:

Measurements is carried out on a frequency range of 10-1000 kHz

Measurements is limited to layer-disc type winding of transformer

Impact of other two phases on the TF of inspected phase is considered negligible

Using the three assumptions introduced in this section, there can be some misleading results only if those assumptions were not applicable in special cases. However to evaluate and identity those cases we plan to extend our verification work to cover some special type transformers in future.

Reminding that VF method is one of the best methods for estimating TF, in this paper using the measured data, the TFs are estimated by VF method. A 40-th order approximation has been fitted to these functions. This is employed to develop TFs for possible form of faults and to compare them with the TFs of the related normal conditions. Besides detecting the poles and residues of TFs, the coefficients of TFs’ polynomials in numerator and denominator are determined. A maximum error of less than 10^{-6} in all cases is the proof of a good fit.

References [7-8], introduce one index for comparison of TF using VF, as follows:

\[ SDP = \sum_{i=1}^{n} \frac{P_{di} - P_{wi}}{P_{di}} \]  \hspace{1cm} (9)

Where n is the number of poles, \( P_{di} \) and \( P_{wi} \) are the values of \( i^{th} \) pole for displaced (deformed) and intact cases, respectively. SDP is the sum of absolute differences of poles and doesn’t perceive the effect of zeros. However, Figure 5 shows that the mechanical faults cause dislocation of both poles and zeros. Therefore to compare the TFs, the effect of both of them (pole and zero) is considered in this method. For this purpose, a new index (FI: Faulted-Intact relation) is introduced as follows:

\[ FI = \left( \frac{\sum_{i=1}^{m} |a_{di}|}{\sum_{i=1}^{m} |a_{ni}|} \right) \left( \frac{\sum_{i=1}^{n} |b_{di}|}{\sum_{i=1}^{n} |b_{ni}|} \right) \]  \hspace{1cm} (10)

Where m and n are the number of numerator and denominator coefficients (in equation (1)), \( a_{di} \) and \( b_{di} \) are the values of \( i^{th} \) coefficient for the faulted conditions, \( a_{ni} \) and \( b_{ni} \) are the values of \( i^{th} \) coefficient for the normal conditions, respectively. This new index is the ratio of sum of the numerator coefficients in faulted condition to sum of the denominator coefficients in normal condition multiply by the ratio of sum of the denominator coefficients in faulted condition to sum of the numerator coefficients in normal condition.

The proposed index is used for detection of mechanical faults as follow:

A. Development of Winding Model for a Layer-Disc Type Winding

The test objects that is introduced in section 4, is employed for development of this winding model. Here it will be shown that all of the four fault types (AD, RD, DSV and SC) can be detected by application of the new method.

Based on our experiments as it will be shown in next section, for each of the four fault types the FI will preserve a value that is distinguishable from the other type easily. Although this finding can be used in fault detection of similar windings in real transformers, however this method will be extending to cover all types of windings in future.

A.1. Determining the Type of Fault

The related results demonstrate that the value of FI if AD or RD occurs is less than 1 however, if DSV or SC occurs is more than 1.

A careful inspection of Figures 2, 3 implies that the changes in TFs do not spread equally over the entire frequency range, and those are often bounded to several frequency ranges. On the other hand it is clear that by subdividing the entire frequency range into smaller ranges, it can increase the sensitivity of the comparison index, such as FI. In other words, existence of any similarity between the faulted TF and the intact TF depends on the frequency range of interest and the type of fault. Hence, evaluation of the TFs in a set of smaller frequency ranges can be more helpful in determining the type of fault.

Examining the simulation results, it has been shown in [12] that the variation of TF characteristics due to RD in the
winding occurs in the entire frequency range; whereas the variations due to occurrence of AD are located in the frequency ranges (approximately) above 100 KHz. Consequently, to distinguish the occurrence of an AD fault from an RD fault, FI index should be determined within the low frequency range of (10-100 KHz), which is named FI\textsubscript{lf}.

In tables I and II, FI\textsubscript{lf} results are determined under different possible faults types of AD and RD, and under different terminal connections. Studying the tables shows that the maximum variation due to occurrence of AD is 3.2% which is less than the minimum variation under occurrence of RD which is 6.5%; moreover these tables show that if the measured TF be admittance function, then the expected minimum variation of RD is 9.2%. Therefore it would be simple to distinguish between AD and RD.

Meanwhile as it is shown in Table III and Figure 6, due to occurrence of some other faults, such as; DSV and SC, the value of FI index will be more than 1. Reminding that SC causes a substantial variation, while DSV makes a little variation in the measured TF, it is easy to distinguish between them. Also they can be distinguished by examination of FI index, since the minimum value of FI during SC is 1.5501, whereas the maximum of FI during DSV is 1.1553. It means that during a SC, the minimum variation in FI is 55%, whereas the variation in FI during a DSV is 15.5% at most.

Therefore, to specify the type of a fault, the FI index is determined, if this index is more than 1, that fault is SC or DSV and otherwise the fault is AD or RD. Additionally, if FI is less than 1, the FI index in low frequency range should be determined (named FI\textsubscript{lf}) to specify the type of fault. However, if it’s more than 1, by determining the value of FI the type of fault can be specified.

\begin{table}[h]
\centering
\begin{tabular}{|c|c|c|}
\hline
State of DSV & Disc Space (mm) & FI\textsubscript{lf} \tabularnewline
\hline
State 1 & 1 & 0.974 \tabularnewline
State 2 & 2 & 0.996 \tabularnewline
State 3 & 3 & 1.019 \tabularnewline
State 4 & 4 & 1.046 \tabularnewline
State 5 & 5 & 1.087 \tabularnewline
\hline
\end{tabular}
\end{table}

**A.2. Detection of Fault Level**

To specifying the fault level, the suggested coefficients are calculated in both faulted and intact conditions within the whole frequency range. Using the value of FI index, the amount of AD, RD, DSV or SC occurred in a winding can be determined. As it is shown in the tables IV, and V any decrease in FI index, corresponds to an increase in the degree of deformation, or axial displacement of the winding. Whereas, Table III shows an increase in FI index is related to an increase in DSV.

Meanwhile, Table IV also shows that the values of SDP, for larger displacements (such as 6, 7 and 8 cm), are very closer to each other, and it is very hard to distinguish between these displacements. While, the value of FI index in these conditions are more desirable to be employed. Not only the FI index can specify the type of fault, but also it is a better measure in determination of the fault level than the other index.

Similarly, the level of SC can be detected using FI index. As shown in Figure 6, occurrence of SC between 2 discs changes the proposed index. However if SC occurs between 2 discs where 2 turns are short circuited, the FI index changes less than when 18 turns are short circuited. Moreover for all states of SC, the FI index has a unique and specific value for any SC between discs. Therefore if the value of FI is between 1.5501 and 1.9543, the SC between 2 discs is occurred across two turns and if the value of FI is between 2.9688 and 5.3011, 18 turns are short circuited. Therefore, the level of the SC can be determined with the help of the FI as shown in Figure 6.
A.3. Fault Localization

To demonstrate the ability of FI index (to recognize location of fault) in Table III, its value is given for different locations and levels of DSV. Table III demonstrates FI has a unique and specific value for any level and location of the fault. If the value of FI is (for example) between 1.0743 and 1.0881, the distance between two successive discs of the winding is 15 mm. If the fault level is known, the location of the fault can be determined with the help of the FI index and one column of the Table III for the known fault levels.

It means the proposed index, in addition to detection of the type and the level of the fault, can be employed to detect the location of fault.

B. Verification of Winding Model

In order to evaluate and validate the proposed method, another test object of similar type (layer-disc winding) with a different rating is examined. Specifications of this test object are:
- high voltage winding with 40 double inverted discs, where 12 turns are present in each disc
- low voltage winding with four layer concentric, where 88 turns are present in each layer

A short circuit is applied between two discs of the winding, in two different locations along the winding separately, and the TFs of them (according to fig. 1 (e)) is estimated in intact and faulted conditions. Subsequently by introducing a new index based on the calculated coefficients named FI, the TFs are compared. The obtained results show that:

a) The value of FI is less than 1 during AD or RD faults, and more than 1 during DSV or SC faults.

b) The difference between the FI indexes, for different degrees of faults, during DSV or SC faults are large and can easily distinguish between them.

c) Variation in TF in the low frequency range (10-100 KHz) during AD is less than during RD. Thus, to distinguish AD from RD, the FI index is calculated in the low frequency range. The measured results showed that it is easy to distinguish easily between AD and RD faults.

d) FI index has shown its effectiveness, even in the determination of the fault level, and

e) Results of the application of the proposed index for DSV fault show that the FI index can be used for detection of fault location.

In order to evaluate and validate the proposed method, another test object of similar type (layer-disc winding) with a different rating is examined. The related result showed the proposed method is valid for windings which have the same design.

Applicability of the proposed method on fault detection of different type of transformers (including several windings of different types) will be studied in the future works, too.

ACKNOWLEDGMENT

Authors would like to thank Mr. Kharazi and Mr. Firoozi for provision of the second sample winding, permission and assistance in performing the required measurements on the windings.

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Advances in Electrical and Computer Engineering

Volume 11, Number 2, 2011


