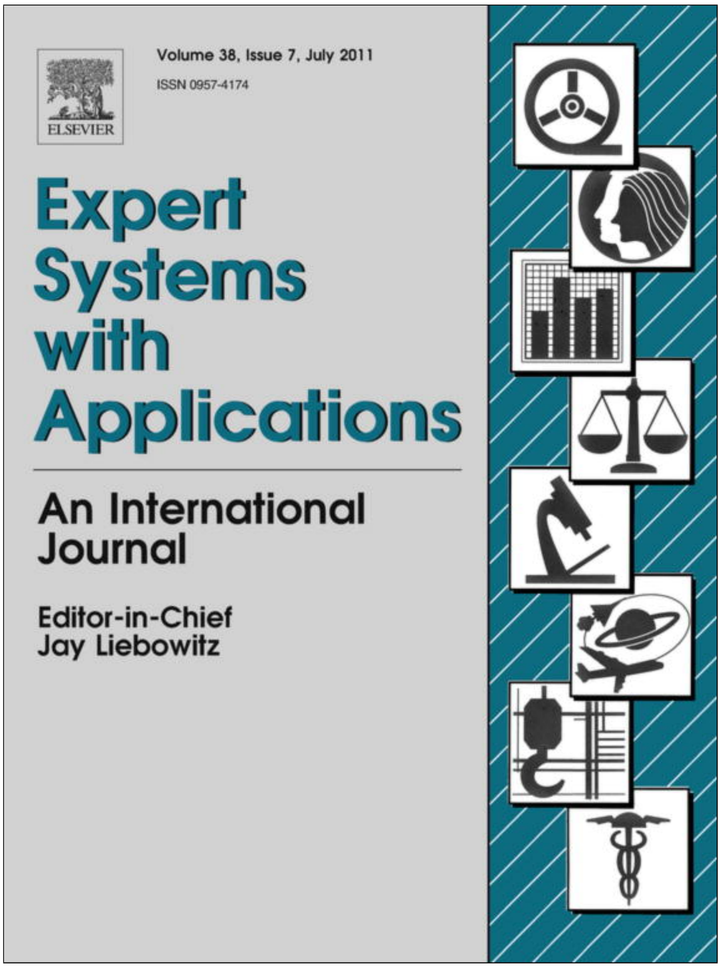
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A new on-line monitoring method of transformer winding axial displacement based on measurement of scattering parameters and decision tree

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A R T I C L E   I N F O

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A B S T R A C T

In this paper the scattering parameter of a simplified model of transformer has been measured in different axial displacement of the winding using a Network Analyzer. Two indices have been suggested to detect the axial displacement. The measurement results show the effectiveness of these indices. A new method of the detection of the axial displacement extent based on decision tree (DT) has been proposed, too. It has been shown that this method has a good accuracy to determine the displacement of the winding and its extent.

1. Introduction

The mechanical forces, due to the high short circuit currents, are a well-known cause of radial deformations and axial displacements of transformer windings. These mechanical damages do not necessarily lead to an immediate failure of the transformer, but the ability of the transformer to withstand future mechanical and dielectric stresses may be highly reduced (Morched, Marti, Brierly, & Lackey, 1996; Xu & Huang, 2001).

There are many transformer monitoring and diagnostic methods. Each method can be applied to a specific type of problem and has its own advantages and disadvantages (Christian & Feser, 2004; Rahimpour, Christian, Feser, & Mohseni, 2003). In recent years, several off-line methods such as short circuit test method (SC) (Xu & Huang, 2001), Low Voltage Impulse method (LVI) (Chen, Sun, Yun, & Xie, 2002) and Frequency Response Analysis method (FRA) (Christian & Feser, 2004) have been proposed, to detect mechanical damages.

In the short circuit test method, the short circuit reactance is measured while the transformer is off-line. In this method, the sensitivity of the reactance to the winding displacement is very low, and the type and the location of the mechanical damage in the winding cannot be determined (Christian & Feser, 2004).

In the FRA method, three experimental ways of comparison are known as: time-based, type-based and construction-based methods. Also, the model-based comparison has been presented recently for the FRA method, too (Leibfried & Feser, 1996, 1999). The FRA method can be used off-line and on-line (Leibfried & Feser, 1996, 1999).

- In off-line method, the transformer is switched on and off on the high voltage side (HV-side). Thereby the transformer is usually disconnected from the power network on the low voltage side (LV-side) (Leibfried & Feser, 1999).
- In the on-line method, it is suggested that the transient overvoltages caused by the switching and the lightning should be used to determine the transfer function. Many factors affect this method such as lightning arresters and different power system structures. The measurement timing is dependent to the time of occurrence of the over voltage transients (Wimmer & Feser, 2004). This method is in the research phase and has not been used for any transformer.

The off-line methods will not meet all needs of the transformer monitoring system. Outage of a transformer for an offline measurement imposes high expenses and risks to the power systems. On-line methods do not require switching of the transformer and have the benefit of continuous monitoring of the transformer winding.

Another advantage of an on-line monitoring method is the prediction of the important and destructive fault before its occurrence. The simulations have shown that the scattering parameter of the winding can be used as an index for on-line monitoring of winding axial displacement (Hejazi, Gharehpetian, & Mohammadi, 2007). The same as FRA method, this method was based on the comparison of results.

In this paper, the scattering parameter of a simplified model of a transformer has been measured using a Network Analyzer. The

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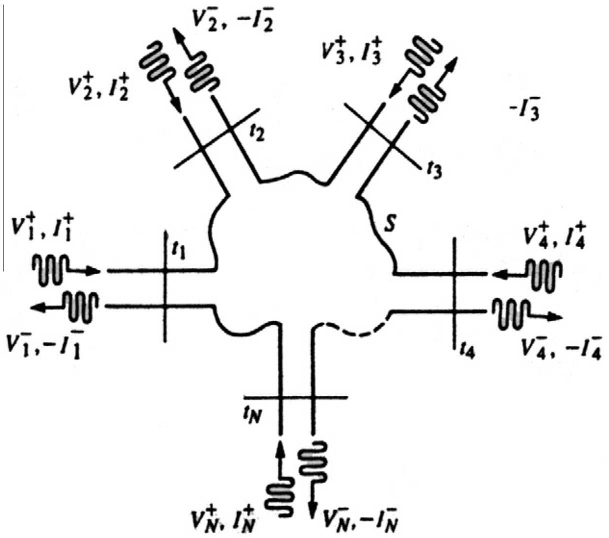

Fig. 1. *N*-port network.

measurement results have a good agreement with the simulation results. In the paper, two indices have been proposed to detect the axial displacement of the winding, too. The winding displacement extent has been determined by using the decision tree (DT) automatic learning method (Breiman, Friedman, Olshen, & Stone, 1984).

2. Scattering parameters

An *N*-port microwave network is shown in Fig. 1. This network has *N* terminals. The power can be injected or absorbed in all terminals. As a result, there are *N* incoming waves and *N* outgoing waves (Pozar, 2005).

The *N* incoming wave complex amplitudes are usually designated by the *N* complex quantities V_N^+ and the *N* outgoing wave complex quantities are designated by the *N* complex quantities V_N^-. The incoming and outgoing waves are sorted in vectors V^+ and V^-, respectively. The relationship between these two vectors can be expressed by the Eq. (1).

$$\begin{bmatrix} V_1^- \\ V_2^- \\ \vdots \\ V_N^- \end{bmatrix} = \begin{bmatrix} S_{11} & S_{12} & \cdots & S_{1N} \\ S_{21} & S_{22} & \cdots & S_{2N} \\ \vdots & \vdots & \cdots & \vdots \\ S_{N1} & S_{N2} & \cdots & S_{NN} \end{bmatrix} \begin{bmatrix} V_1^+ \\ V_2^+ \\ \vdots \\ V_N^+ \end{bmatrix} \tag{1}$$

$$V^- = \quad S \quad V^+$$

In Eq. (1), S is a $N \times N$ matrix with complex elements called the "scattering matrix". It completely determines the behavior of the network. In general, the elements of this matrix, which are termed "*S*-parameters", are frequency-dependent.

In this research, we have only one rectangular aperture. As a result, the *S*-matrix dimension is 1×1. The single element of the *S*-matrix is easily determined by the following equation:

$$S_{11} = \frac{V_1^-}{V_1^+} \tag{2}$$

The above equation can be written in the following simple form versus power values:

$$S_{11} = \sqrt{\frac{P_{ref}}{P_{in}}} \tag{3}$$

Fig. 2. Externally mounted UHF sensor on the tank of a 1000-MVA, 400/275 kV transformer.

where, P_{in} is the transmitting power and P_{ref} is the receiving power of the antenna.

3. New monitoring method based on scattering parameters

The principle of this method is based on the measurement of the magnitude and phase of scattering parameters measured by several antennas. These antennas can be placed inside or outside of the tank. If the antenna is placed outside of the tank, then it has a dielectric window which forms a robust electrical aperture for sending and receiving very high frequency electromagnetic waves. As an example, Fig. 2 shows an externally mounted UHF sensor on the tank of a 1000-MVA, 400–275 kV transformer (Judd, Yang, & Hunter, 2005).

This UHF sensor has been used for partial discharge detection inside the transformer and the antenna works in the receiving mode. In this paper, the idea is the application of the antenna in both transmitting and receiving modes. The reflected wave from the inside of the transformer can be received by the antenna. The data of the normal conditions can be stored in a database as a base case. The data can be measured in specified intervals and compared with the base case. Then, an expert system can be used to determine the occurrence, the type and the extent of mechanical deformations.

The proposed method is a new method to determine the axial displacements, which is based on comparisons. The FRA is a comparison based method that compares the measured transfer function with a reference one (Christian & Feser, 2004). It should be noted that the proposed method can be used on-line without disconnecting the transformer. In the proposed method, the scattering parameter is defined as the fingerprint of the transformer. In this paper, the comparison method of the scattering parameters is a *time-based* method. The *time-based* comparison is an accurate method because this method can be used on-line and the timing intervals between measurements can be decreased to have more information from the same transformer. This method is also the most accurate one in the FRA results comparisons (Judd et al., 2005). In this method, the measured parameters are compared with the latest measurements.

4. Test object and measurement procedure

A simplified model of transformer, used in this paper, is shown in Fig. 3. The model is based on ideal metallic cylinder in a metallic

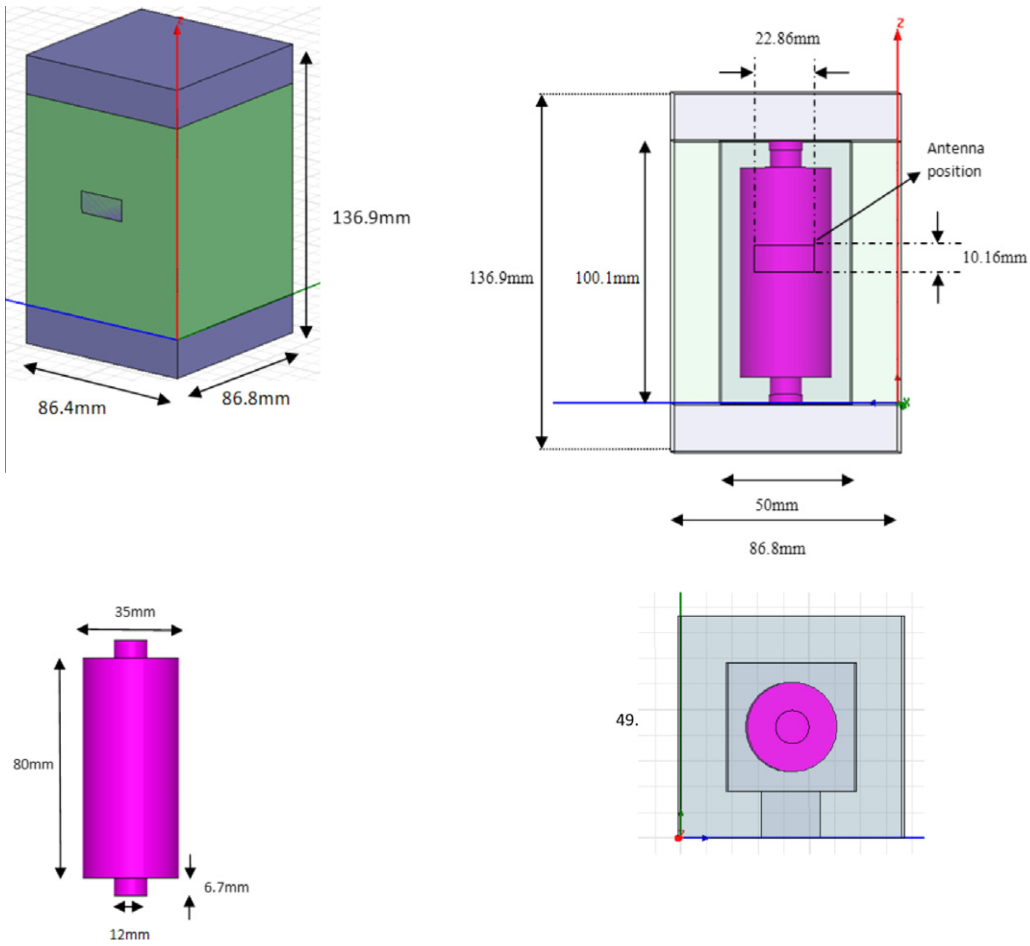

Fig. 3. A simplified model of transformer.

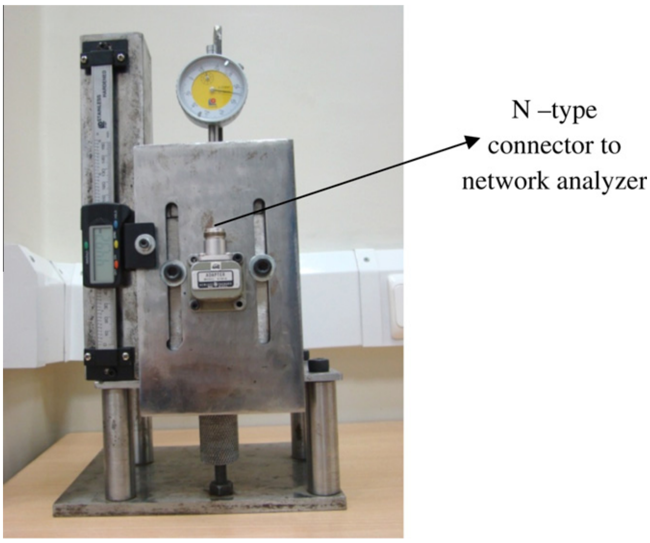

Fig. 4. Measurement set-up and connector to the Network Analyzer.

tank. The inner metallic cylinder represents the LV winding while the outer metallic cylinder represents the HV winding. The dimensions of the model are approximately 5% of a real one and presented in Fig. 3.

The antenna, used in the model, is a rectangular aperture with the dimensions of a standard *x*-band waveguide (22.86 mm × 10.16 mm). The excitation frequency should be between the first and second cut-off frequencies (6.6 and 14.7 GHz for the model) to have a single mode of propagation. From the electromagnetic waves point of view, if the diameter of a hole is less than 0.1 of the wavelength, then the wave cannot enter the hole. The wavelength at the middle of the band is 31 mm which is greater than one tenth of the distance between the high voltage winding disks in the reduced scales (i.e., 6 mm × 0.05 = 0.3 mm). As a result, considering the dimensions of the HV winding of a power transformer and the frequency of the electromagnetic wave, the inner parts (core and LV winding) can be neglected and only the outer surface of HV winding should be modeled, as shown in Fig. 3. Fig. 4 shows the test setup of the used model.

The scattering parameter of the model has been measured using an hp Network Analyzer. The excitation frequency has been changed from 7 to12 GHz in 250 MHz steps.

The cylinder has been shifted axial in 0.1 mm steps. The cylinder can be in 94 different positions (classes). In each position, the magnitude and the phase of scattering parameters have been measured and stored. The feature vector, used for the classification, contains both the magnitude and the phase at $n = 201$ frequencies (points). Figs. 5 and 6 show the magnitude and the phase of scattering parameters over the frequency band for the reference position (normal condition) and two other positions (a displacement of 2 mm in upward and downward directions).

Figs. 7 and 8 show the scattering parameters for a fine 0.2 mm upward and downward displacements.

It is obvious that the proposed method has a good sensitivity to the displacements higher than 0.2% of the test object height. In the

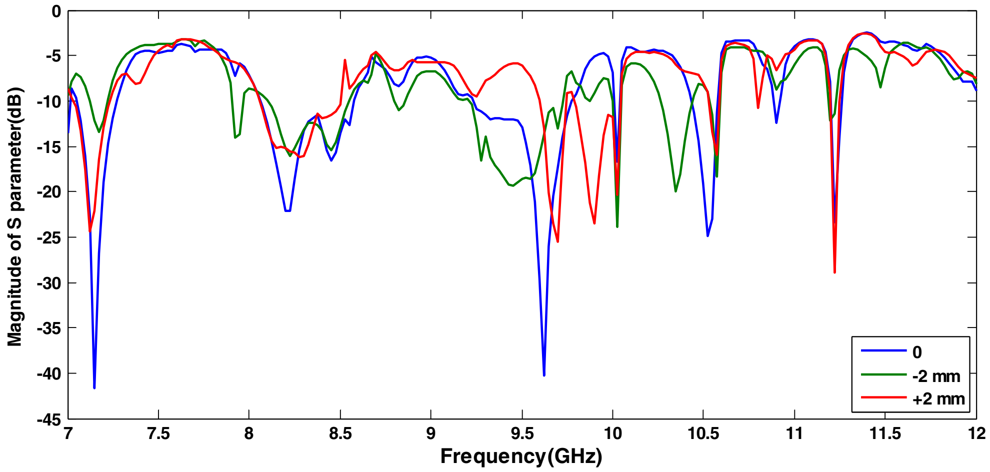

Fig. 5. Magnitude of the scattering parameters for the upward and downward and without displacement.

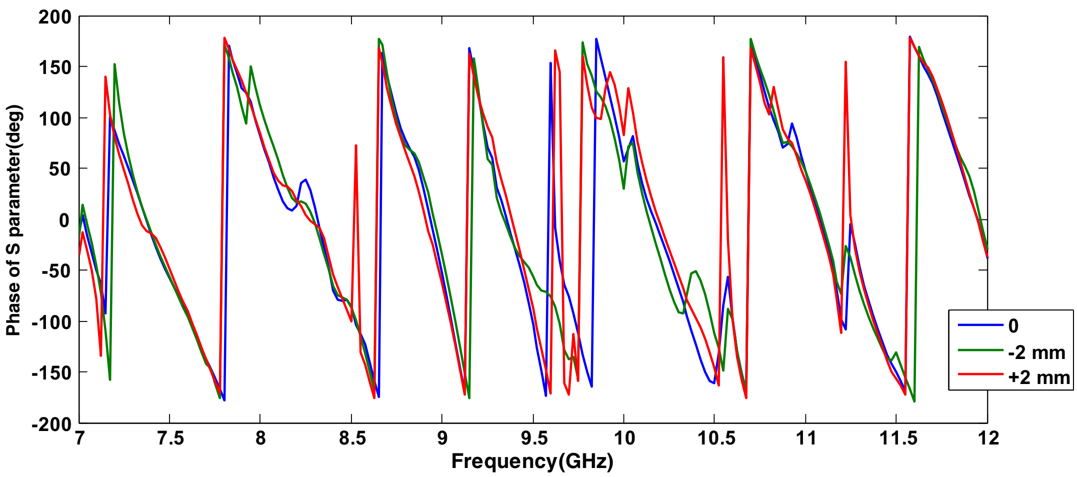

Fig. 6. Phase of the scattering parameters for the upward and downward and without displacement.

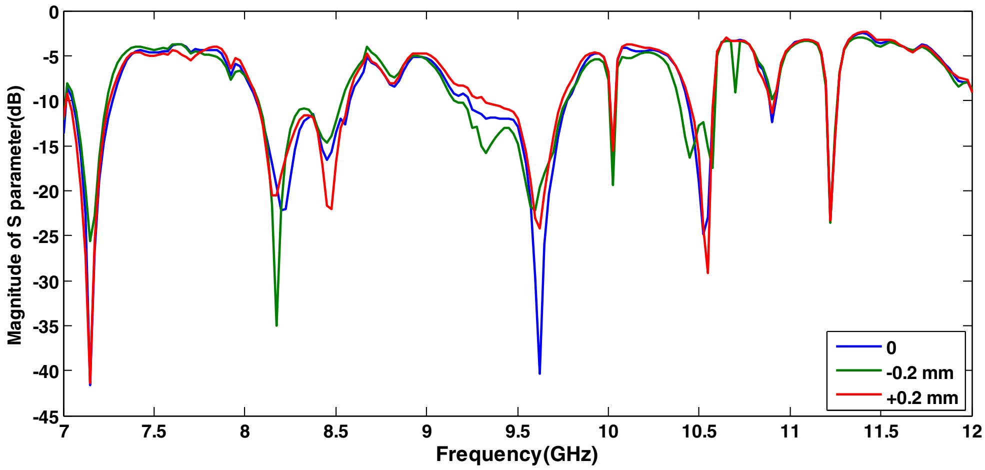

Fig. 7. Magnitude of the scattering parameters for the fine displacement.

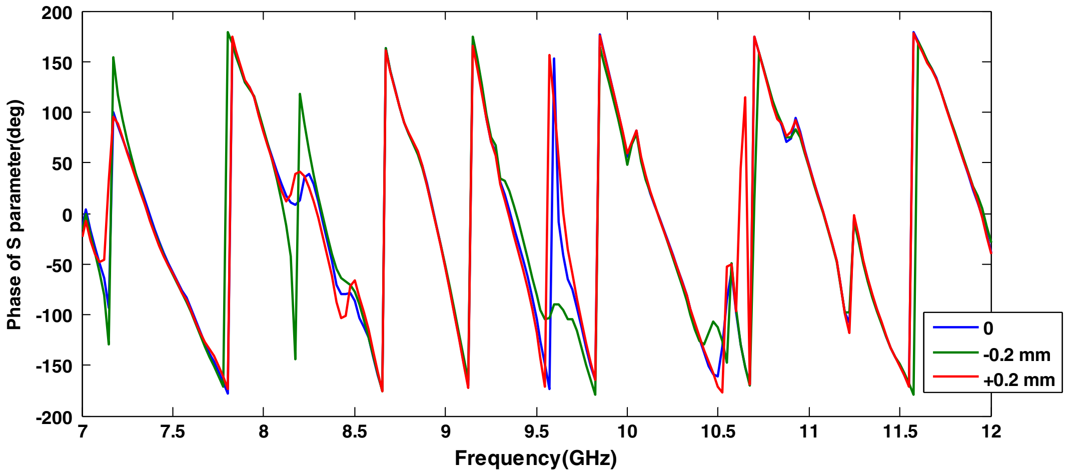

Fig. 8. Phase of the scattering parameters for the fine displacement.

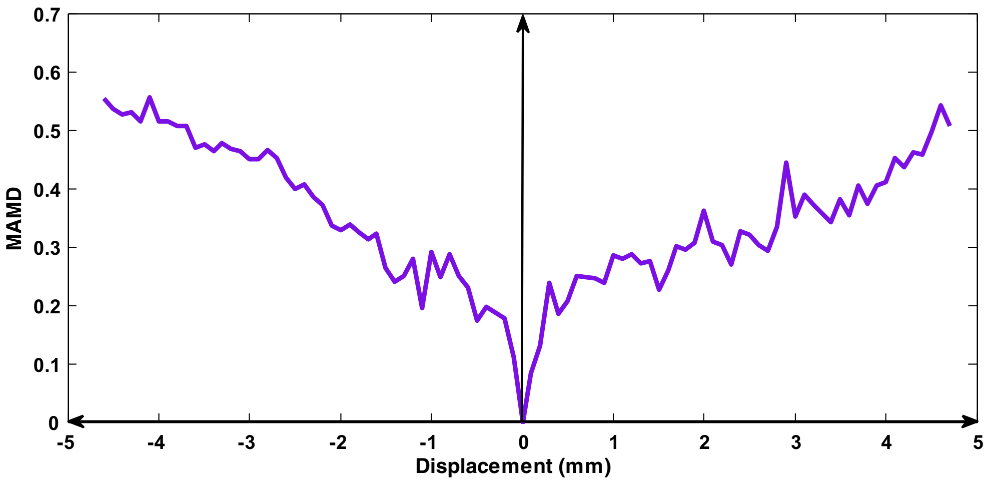

Fig. 9. MAMD (Mean Absolute Magnitude Distance) versus axial displacement (mm).

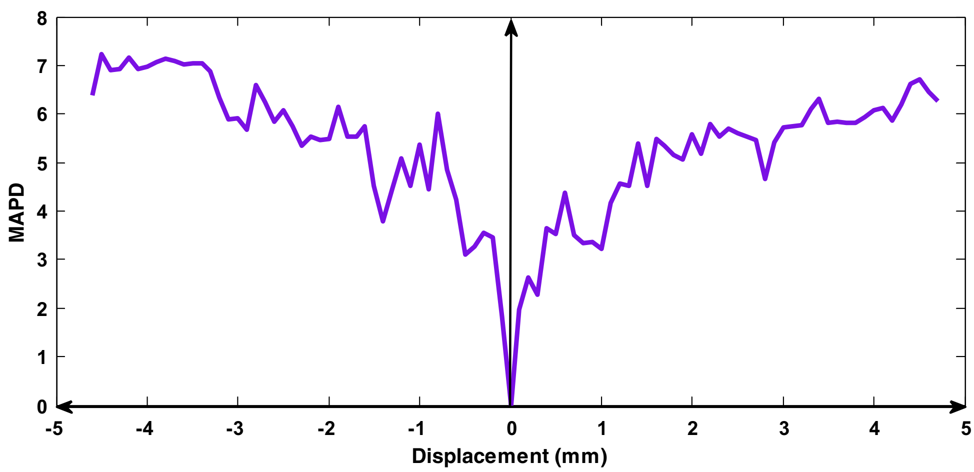

Fig. 10. MAPD (Mean Absolute Phase Distance) versus axial displacement (mm).

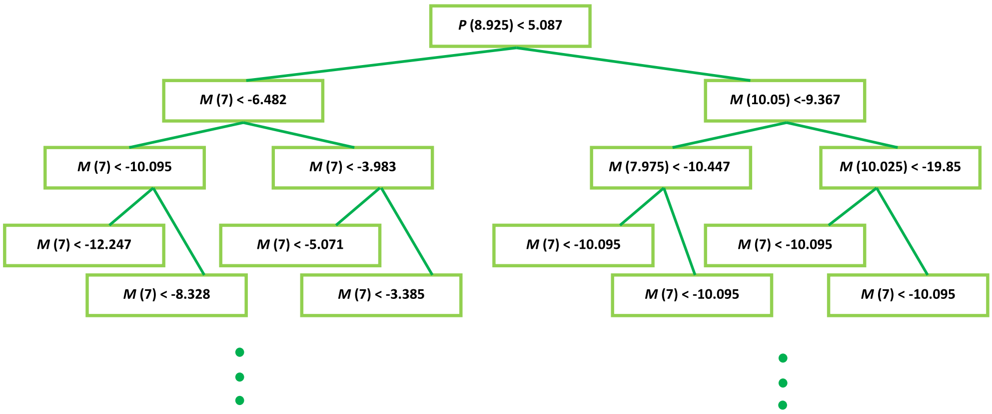

Fig. 11. Part of decision tree (*M*(*f*) shows the magnitude of scattering parameter at *f* frequency and *P*(*f*) is the phase of the scattering parameter at *f* frequency).

Table 1
DT test results.

Displacement (mm)	Estimated displacement (mm)	Absolute error (mm)	Error (%)
−4.3	−3.8	0.5	0.613497
−3.9	−3.5	0.4	0.490798
−3.3	−2.5	0.8	0.981595
−2.9	−3	0.1	0.122699
−2.3	−2.8	0.5	0.613497
−1.9	−1.5	0.4	0.490798
−1.3	−1.2	0.1	0.122699
−0.9	−1	0.1	0.122699
−0.3	0	0.3	0.368098
0.1	0	0.1	0.122699
0.7	0.2	0.5	0.613497
1.1	1.2	0.1	0.122699
1.7	1.5	0.2	0.245399
2.1	2.2	0.1	0.122699
2.7	2.5	0.2	0.245399
3.1	3	0.1	0.122699
3.7	3.8	0.1	0.122699
4.1	3.9	0.2	0.245399
4.7	4.6	0.1	0.122699

FRA method, the axial displacement sensitivity is limited to 1.2% of the winding height (Rahimpour et al., 2003).

5. Detection of winding axial displacement using suggested indices

The detection accuracy of the axial winding displacement is dependent to the transmitter frequency, i.e., decreasing the wavelength enhances the sensitivity to the displacement. In this paper, two indices of the fault detection have been used, as follows:

$$\mathrm{MAMD} = \frac{\sum_{i=1}^{n} ||S_i| - |S_{ref}||}{n} \quad (4)$$

$$\mathrm{MAPD} = \frac{\sum_{i=1}^{n} |\angle S_i - \angle S_{ref}|}{n} \quad (5)$$

In the above equations, MAMD is the mean absolute magnitude displacement, and MAPD is the mean absolute phase displacement of n measured S parameters at n frequencies. Figs. 9 and 10 show *MAMD* and MAPD versus displacement calculated for 201 frequency points (from 7 to 12 GHz). It is assumed that the central position of the cylinder is the reference and the cylinder has a positive or negative (upward or downward, respectively) axial displacement.

There are two important points in these figures:

(a) The increase of these indices is proportional to the increase of the axial displacement. As a result, they can be used as an index to detect the axial displacement and estimate the displacement extent, approximately.
(b) These indices cannot discriminate between the upward and downward displacement, i.e., MAMD and MAPD are even functions of the displacement.

6. Axial displacement and its extent determination using DT

In the previous section, it is shown that MAMD and MAPD can estimate the extent of the axial displacement approximately. In this section, the exact amount of displacement should be determined. The suggested technique is based on comparison of the new measured S parameters with the information in the database using the decision tree (DT).

6.1. Decision tree classifier

The DT is a nonparametric learning technique, which is able to produce classifiers about a given problem in order to deduce information for new unobserved cases. The DT has the hierarchical form of a tree structured upside down (Karapidakis & Hatziargyriou, 2002).

A decision tree model employs a recursive divide-and-conquer strategy to divide the data set into partitions so that all of the records in a partition have the same class label. Finding the best split point and performing the split are the main tasks in the decision tree (Tsai & Yang, 2004).

The type of DT developed in this research, is the Classification and Regression Trees (CART) introduced by Breiman et al. (1984). DT has several advantages to other methods of classification. Compared with neural networks, decision trees are less computationally intensive, relevant attributes are selected automatically and classifier output is a set of if-then conditional tests of the features (Breiman et al., 1984).

Usually, a common set of features is used jointly in a single decision step. An alternative approach is to use a multistage or sequential hierarchical decision scheme. Classification trees offer an effective implementation of such hierarchical classifiers. A decision tree classifier has a simple form which can be compactly stored and that efficiently classifies new data. Decision tree classifiers can perform automatic feature selection and complexity reduction (Breiman et al., 1984).

6.2. Splitting index

A splitting index is used to evaluate the *goodness* of the alternative splits for an attribute. Several splitting indices have been used. The criterion for division usually relies on the entropy as seen in C4.5 algorithm (Quinlan, 1993) or Gini's index as seen in CART (Breiman et al., 1984).

C4.5 builds decision trees from a set of training data using the concept of information entropy. The decision trees generated by C4.5 can be used for classification, and for this reason, C4.5 is often referred to as a statistical classifier. C4.5 has the following advantages:

- Handling training data with missing feature values – C4.5 allows feature values to be marked as missing values. Missing feature values are simply not used in gain and entropy calculations.
- Handling features with differing costs.
- Pruning trees after creation – C4.5 goes back through the tree once it is been created and attempts to remove branches that do not help by replacing them with leaf nodes.
- Handling both continuous and discrete features.

The Gini index is defined as follows:

Suppose S is a set of s samples. These samples have m different classes (C_i, $i = 1\ldots m$). According to the differences of classes, we can divide S into m subset (S_i, $i = 1\ldots m$). Suppose S_i is the sample set, which belongs to class C_i, s_i is the sample number of set S_i, then the Gini index of set S is:

$$\text{Gini}(S) = 1 - \sum_{i=1}^{m} P_i^2 \tag{6}$$

where P_i is the probability that any sample belongs to C_i and estimating with s_i/s (Shang et al., 2006).

6.3. Feature selection

Feature selection, i.e., selecting a subset of the features available for describing the data before applying learning algorithm, is a common technique for simplifying or speeding up computations (Guyon & Elisseeff, 2003). The layer relation of tree helps to make explanation for data, and help to eliminate redundant data and noise, and helps to select classification features. In 1999 Borak used decision tree to subtract classification feature from large amount of data (Borak & Strahler, 1999).

6.4. Proposed algorithm

The proposed algorithm is summarized, as follows:

- *Step 1:* The S parameters, measured in different axial positions of the model, are stored in a database. This data is used as a reference feature vector.
- *Step 2:* In new unknown axial positions the S parameters are measured.
- *Step 3:* The axial position of the winding is estimated using DT classification method.

To classify the S parameters as phasor quantities, it is possible to use the magnitude, the phase or both of them in the feature vector. The best results have been obtained in the case of the magnitude and the phase selection in the feature vector.

7. Measurement results

The scattering parameters magnitude and phase have been selected as feature vectors. A part of the decision tree obtained from 75 training samples is shown in Fig. 11.

The most important feature is the phase at $f = 8.925$ GHz ($P(8.925)$, the first node of Fig. 11). In the second level, the magnitudes at 10.05 and 7 GHz are important ($M(7)$ and $M(10.05)$ in Fig. 11). This decision tree has been tested by 19 test samples. Table 1 lists the decision tree test results. The average absolute error of the displacement detection is 0.258 mm. The percent of error is calculated, as follows:

$$\text{Error}(\%) = \frac{\text{Absolute error}}{\text{Winding height}} \times 100 \tag{7}$$

It is obvious that DT can discriminate between the symmetrical upward and downward displacements. In Borak and Strahler (1999), to determine the axial displacement extent using FRA, the winding has been moved in three steps. Each step was equal to 4% of the total winding height. In this paper, the winding has been moved in 94 steps. Each step is equal to 0.1% of the total winding height.

As it can be seen in Table 1, the proposed method has a maximum error of 0.98% (of the winding height). In Karimifard, Gharehpetian, and Tenbohlen (2008), this error was 4%. The ratio of the excitation frequency to the winding dimensions in the proposed method is much higher than the same ratio in the FRA method. The higher ratio results in higher accuracy, which can be seen in the proposed method results.

It should be mentioned that in a power transformer, the dimensions are 20 times larger. As a result, the frequency of the excitation should be 20 times smaller, i.e., in the UHF frequency band.

8. Conclusion

In this paper, the on-line monitoring of the transformer winding using scattering parameters has been suggested and investigated. In this research, the scattering parameter of a simplified model of the transformer has been measured using a Network Analyzer in different axial positions. Two indices have been defined from the magnitude and phase of scattering parameters, to detect the axial displacement. The results show that these indices can be used to detect the winding displacement and present information about the approximate amount of the displacement. A new method of the detection of the axial displacement extent based on DT has been proposed, too. It has been also shown that the proposed method has a good accuracy to determine the position of the winding (displacement) and can discriminate between upward and downward displacements.

The proposed method has the following advantages:

- In this method, there is no electrical connection to the windings. Therefore, neither the high voltage nor the low voltage windings of the transformer should be disconnected from the network.
- This method can be used for off-line and on-line applications.
- The test object can be monitored in the specific intervals or continuously.
- The displacement extent of the mechanical damage can be determined.
- The sensitivity to the displacements is higher than the FRA method, because these parameters are measured at higher frequencies.
- This method cannot be affected by the power factor of the load and loading conditions.

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