2010 IEEE International Conference on Power and Energy (PECon2010)., Nov 29 - Dec 1, 2010, Kuala Lumpur, Malaysia

Detection of Transformer Winding Axial Displacement Using Scattering Parameter and ANN

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Abstract—**The method of the on-line monitoring of transformer winding axial displacements using scattering parameters has been presented in this paper. In this method, the signature of the transformer is the scattering parameters, which are calculated using high frequency simulation software and saved for further analysis as a base case. The new simulations can be compared with this case, to detect the axial displacement of transformer winding. Based on simulations on the simplified model of the transformer winding, it is shown that the proposed method can discriminate between the displaced and intact windings. The displacement extent can be determined using Artificial Neural Network.**

***Index Terms*— Winding Axial Displacement, On-Line Monitoring, Transformer, Scattering Parameters, Artificial Neural Network.**

I. INTRODUCTION

Transformer winding failures account for 19 percent of the transformer failures [1]. Due to short circuits, mechanical forces mainly can cause axial displacement and/or radial deformation, which may not result in an immediate failure of the transformer, but the ability of transformer to resist against future dielectric and mechanical stresses may be highly decreased [2, 3].

Condition monitoring of transformers is desirable for increasing their availability, reducing consequential damage or catastrophic failure of power transformer. There are several transformer mechanical damages monitoring and diagnostic methods. Each method has its advantages and disadvantages [4, 5]. In recent years, several off-line methods such as Short Circuit test (SC) [2], Low Voltage Impulse (LVI) [5] and Frequency Response Analysis (FRA) [4] have been proposed for the detection of the winding displacement.

In the short circuit test method, the short circuit reactance is measured while the transformer is disconnected. 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 [4].

In the FRA method, experimental approaches of comparison are: time-based, type based and construction-based. The FRA method can be used off-line and on-line [7, 8].

In the off-line method, which means that the transformer is out of operation, 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) [7]. The well-known FRA method has been carried out off-line. The off-line methods will not meet all the needs of the transformer monitoring system.

In the on-line method, the frequency response should be measured during the operation of the transformer. The stochastic transient over-voltages caused by the switching and lightning can be used to determine the transfer function. This method does not require switching of the transformer and have the benefit of continuous monitoring of transformer winding. Many factors affect this method such as response of arresters and different power system topologies. The measurement timing depends on the time of occurrence of the over voltage transients [9]. This method is in the research phase and has not been used for any transformer.

Compared to off-line methods, an on-line method has the advantage of the stationary installation and hence an improved reproducibility of the test. The merit of an on-line monitoring method over off-line methods is the prediction of the important fault before its occurrence.

In this paper, a new on-line monitoring method has been proposed based on the simulation of scattering parameter of the winding. This method, the same as FRA method, is based on the comparison of results. The simulation results have shown that the scattering parameter of the winding can be used as a fingerprint for the detection of the winding axial displacement [10].

II. MONITORING BASED ON SCATTERING PARAMETER

This method is based on the measurement of the magnitude and phase of scattering parameters measured by several antennas. A scheme of a model transformer which is considered as an *N*-port microwave network is shown in Fig.1. It is assumed that *N* incoming waves are transmitted through the dielectric window on the tank of the transformer and *N* outgoing waves are received.

The *N* incoming wave complex amplitudes are usually

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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.

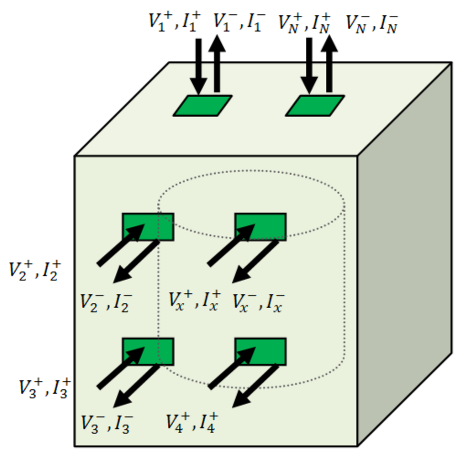

Fig.1: A model transformer as an N-port network

The relationship between these two vectors can be expressed by the equation (1):

$$\begin{bmatrix} V^-_1 \\ V^-_2 \\ \cdot \\ \\ \cdot \\ V^-_N \end{bmatrix} = \begin{bmatrix} S_{11} & S_{12} & . & . & . & S_{1N} \\ S_{21} & S_{22} & . & . & . & S_{2N} \\ . & . & . & . & . & . \\ . & . & & . & . & . \\ . & . & . & . & . & . \\ S_{N1} & S_{N2} & . & . & . & S_{NN} \end{bmatrix} \begin{bmatrix} V^+_1 \\ V^+_2 \\ . \\ . \\ . \\ V^+_N \end{bmatrix} \quad (1)$$

In equation (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 “Scattering parameters” or “*S*-parameters”, are frequency-dependent [11].

III. TEST SET-UP AND SIMULATION PROCEDURE

A simplified single-phase model of transformer, used in this paper, is shown in Fig.2. The model is based on ideal metallic cylinder in a metallic 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 percent of a real one and presented in Fig.2.

The antenna of the model is a rectangular aperture with the dimensions of a standard X-band waveguide (WR90). The excitation frequency should be between the first and second cut-off frequencies (*i.e.*, 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 31mm which is greater than one tenth of the distance between the high voltage winding disks in the reduced scales (i.e., 6mm×0.05=0.3mm). 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.

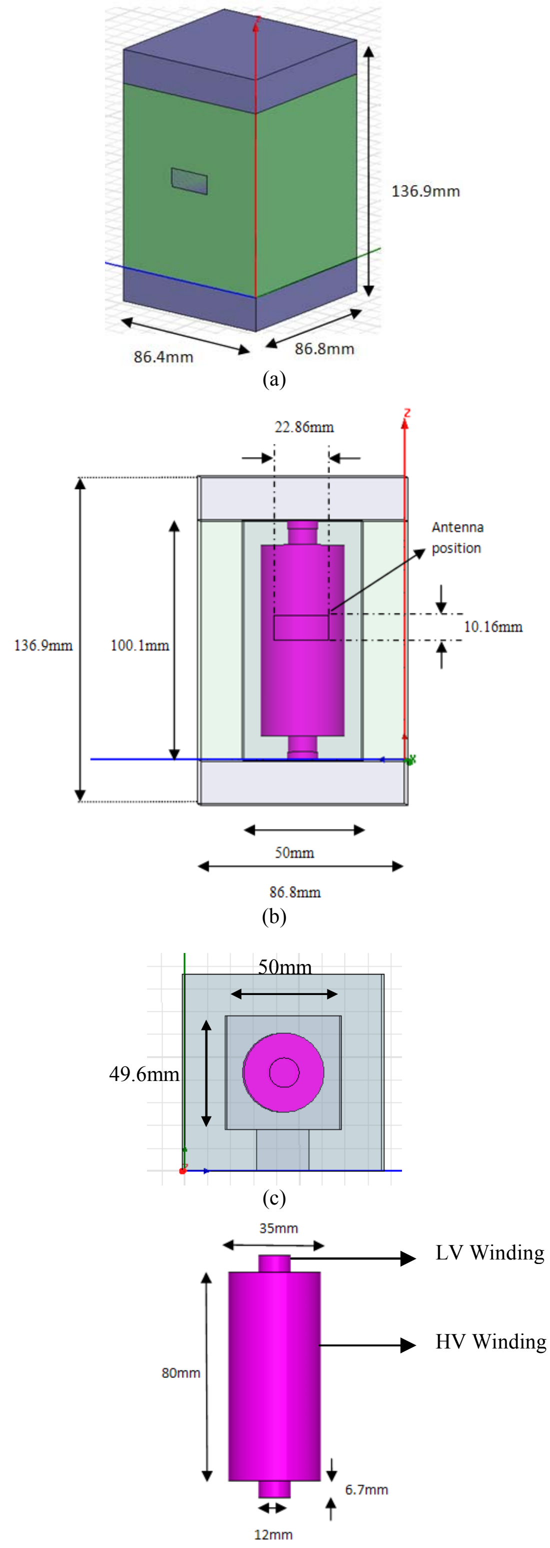

Fig. 2: Simplified model of transformer a) Three dimensional view, b) Side view of transformer model, c) Top view of transformer model and d) Side view of winding model

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

$$S_{11}=\frac{V_1^-}{V_1^+} \qquad (2)$$

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

$$|S_{11}|=\sqrt{\frac{P_{ref}}{P_{in}}} \qquad (3)$$

Where, P_{in} is the transmitting power and P_{ref} is the receiving power of the antenna [11].

The scattering parameters are simulated for different axial positions of the winding model.

Fig.3 and Fig.4 show the magnitude and the phase of scattering parameters over the frequency band for the reference position (normal condition) and for four other positions which the cylinder has been shifted in steps of % 0.125 of the transformer height.

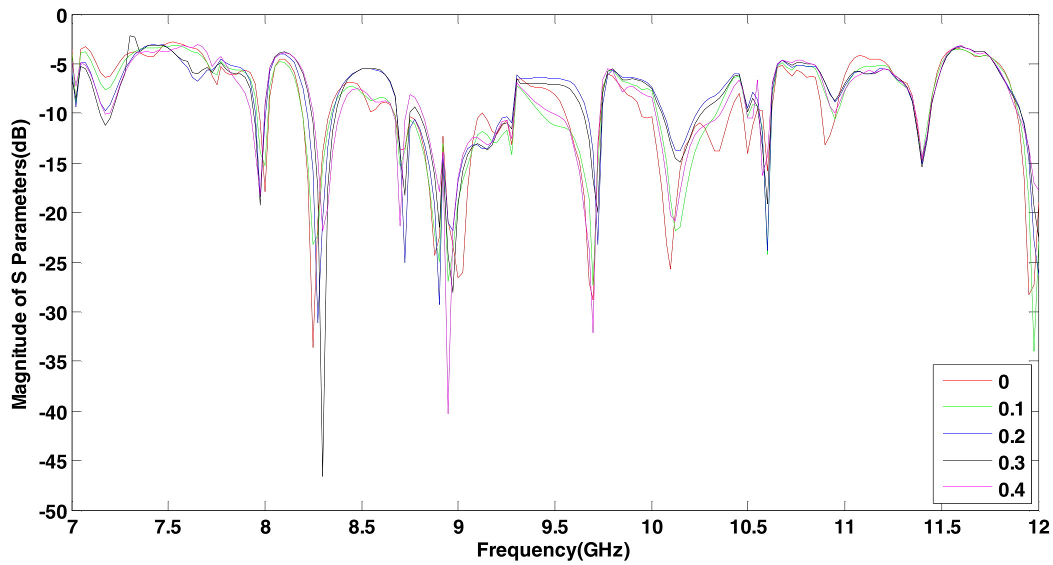

Fig.3: Magnitude of *S*-parameters over frequency band for reference position and for four other positions (mm).

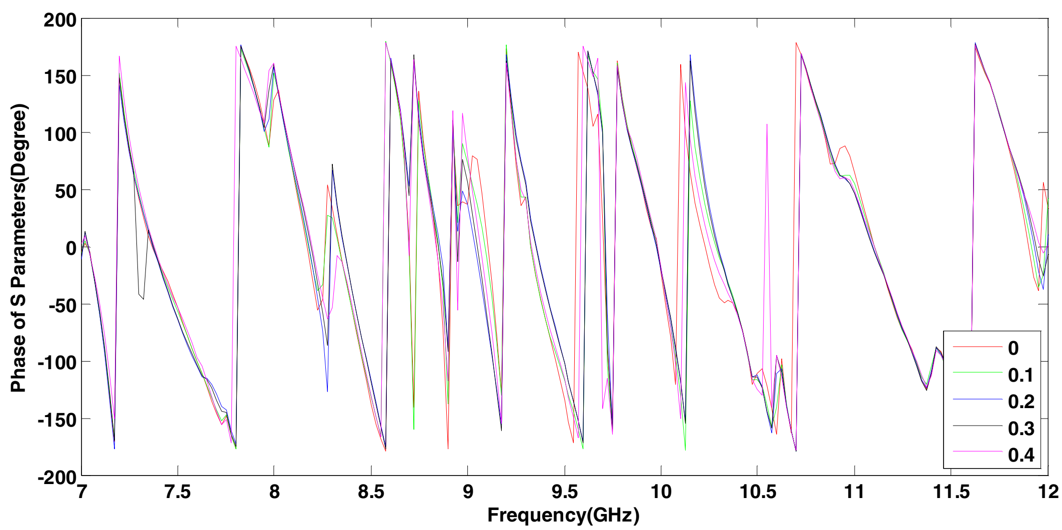

Fig.4: Phase of *S*-parameters over frequency band for reference position and for four other positions (mm)

IV. Determination of Axial Displacement Extent Using ANN

Artificial Neural Networks (ANNs) have been widely used in the system identification and modeling complex nonlinear systems, where obtaining a mathematical model is difficult and tiring [12]. Therefore, ANN can be used to model the nonlinear behavior of *S*-parameters. In this paper, the ANN is a four-layered multilayer perceptron (MLP) of MATLAB

Neural Network Toolbox. Levenberg–Marquardt (LM) feed forward back propagation algorithm has been used for the training of ANN. MLP networks with back-propagation have been used successfully for many fault detection and diagnosis applications [13, 14 and 15].

Different ANN topologies (different number of layers and number of neurons in each hidden layer) have been tested, to achieve good performance. The ANN with the best performance has 201 inputs, two hidden layers (with 15 and 8 neurons) and one output. Fig.5 shows the structure of the neural network.

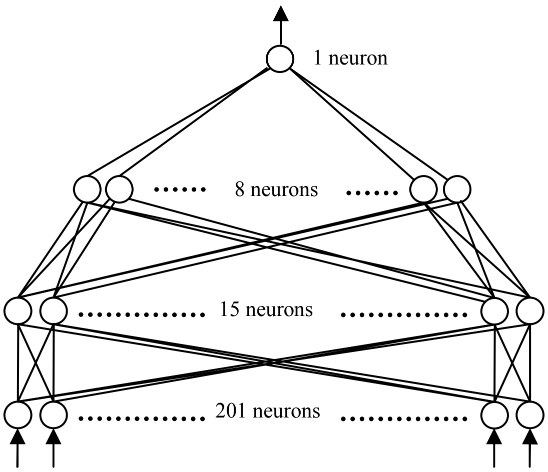

Fig.5: Proposed structure of ANN

Different displacements have been applied to the transformer model (Fig.2) and the magnitude and phase of *S*-parameters have been measured by the software for each position. The results have been divided to the training and test data.

The ANN has been trained by 71 different training data and then the proposed ANN has been used to estimate the amount of upward or downward displacement. The results are listed in Table I.

Considering the real and estimated displacement, the percent of error ($Error(\%)$) is calculated, by the following equation:

$$Error(\%) = \frac{Error(mm)}{Winding\ Height} \times 100 \quad (4)$$

As it can be seen in Table II, the axial displacement of the winding can be estimated with a maximum error of 0.65 %.

TABLE I:
REAL AND ESTIMATED DISPLACEMENT

Real Displacement (mm)	Estimated Displacement (mm)	Error (mm)	Error (%)
-4.6	-4.68	0.08	0.1
-4.3	-4.26	0.04	0.05
-4.1	-4.62	0.52	0.65
-3.8	-3.56	0.24	0.3
-3.5	-3.39	0.11	0.1375
-3.1	-2.91	0.19	0.2375
-2.8	-2.84	0.04	0.05
-2.3	-2.3	0	0
-2	-2.01	0.01	0.0125
-1.7	-1.48	0.22	0.275
-1.3	-1.43	0.13	0.1625
-1.1	-1.13	0.03	0.0375
0.1	0.163	0.06	0.075
0.4	0.331	0.07	0.0875
0.7	1.02	0.32	0.4
1	1.414	0.41	0.5125
1.4	1.594	0.19	0.2375
2	1.701	0.3	0.375
2.3	2.398	0.1	0.125
2.7	2.823	0.12	0.15
3.1	3.042	0.06	0.075
3.4	3.386	0.01	0.0125
3.7	3.762	0.06	0.075
4.1	3.858	0.24	0.3
4.2	4.443	0.24	0.3
4.4	4.707	0.31	0.3875
4.5	4.878	0.38	0.475
4.7	4.261	0.44	0.55

The results show that the displacement can be accurately determined by an expert system. The displacement determination method can be summarized, as follows:

Step 1: Measurement of scattering parameter of a transformer,

Step 2: Developing a data bank for scattering parameters in specified axial displacements of the transformer winding,

Step 3: Training of ANN and

Step 4: Using the trained ANN for the estimation of an unknown axial displacement extent in a sister unit transformer.

V. CONCLUSION

In this paper, the on-line monitoring of the transformer winding has been investigated using scattering parameters. To show the capability of the method, the scattering parameters of a simplified model of transformer have been simulated by using high frequency software in different axial positions. ANN has been used to estimate the exact extent of the displacement. It can discriminate between upward and downward displacements, too.
The merits of the proposed method can be summarized, as follows:

- In this method, there is not any 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.
- Transformers can be monitored in the specific intervals or continuously.
- The extent of the axial displacement can be determined by the suggested method.
- The sensitivity to displacements is higher than FRA method, because scattering parameters are measured at higher frequencies.
- The detection accuracy of the axial winding displacement depends on the transmitter frequency, i.e., decreasing the wavelength enhances the sensitivity of the proposed method.
- This method cannot be affected by the power factor of the load and loading conditions.
- The antenna movement is not necessary.

VI. ACKNOWLEDGMENT

The financial support of Tehran Regional Electric Co. (TREC) towards this research is hereby acknowledged.

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