Characterization of On-line Monitoring of Transformer Winding Axial Displacement Using Electromagnetic Waves

M.A. Hejazi, G. B. Gharehpetian , A. Mohammadi

Electrical Engineering Department, Amirkabir University of Technology, Tehran 15914, Iran
Email: grptian@aut.ac.ir

Abstract: Mechanical or electromechanical forces can cause axial displacement of transformer winding. In this paper a new measuring method for detection of axial displacement of high and low voltage windings is proposed. This method can be used for off-line or on line applications. The high and low voltage windings have been modeled using HFSS software. It is shown that upward and downward axial displacement of the high voltage and/or the low voltage winding can be detected by the on-line monitoring of the scattering parameters.

1INTRODUCTION

The high short-circuit currents are the well-known cause of the deformations and displacements of transformer windings. These deformations 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[1,2]. As a result, the modern diagnostic methods should detect such predamaged power transformers. 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 [3, 4]. In recent years, several off-line methods such as Short Circuit test method (SC)[1], Low Voltage Impulse method (LVI)[5] and Frequency Response Analysis method (FRA)[3] for the detection of winding deformation have been proposed.

The advantage of an on-line monitoring method is the prediction of the fault before its occurrence. This paper presents a feasibility study on on-line monitoring of transformer winding axial displacement using electromagnetic waves. In this method there is no electrical connection to windings therefore neither the high voltage nor the low voltage windings of the transformer need to be disconnected from the network. This method can be used for off-line or on-line applications. It is shown that the scattering parameter of the winding can be used as an index for on line monitoring of winding axial displacement. This method can not be affected by the power factor of the load and loading conditions.

2 SCATTERING PARAMETTERS

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 thus N incoming and N outgoing waves [6].

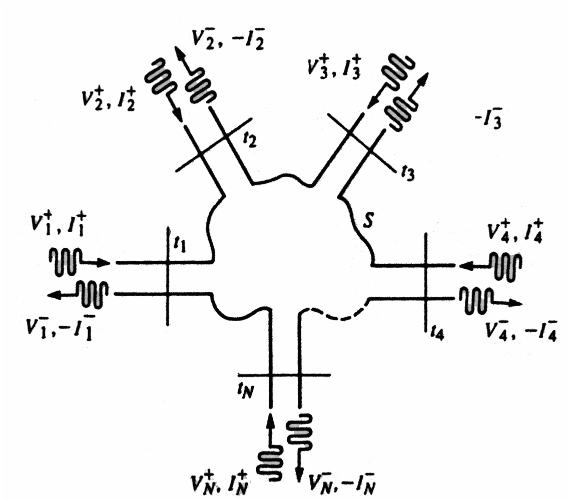

Fig. 1. N-port network

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 equation (1).

$$[V^-] = [S][V^+] \tag{1}$$

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

In this equation 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.

3 MODELING OF HV WINDING AXIAL DISPLACEMENT

From the electromagnetic waves point of view, if the length of a hole is less than 0.1of the wavelength, then the wave can not enter the hole. As a result, considering the dimensions of the HV winding of a power transformer and the frequency of the electromagnetic wave, e.g. 9GHz, the inner parts (core and LV winding) could be neglected and only the outer surface of HV winding should be modeled. The model used for simulation in HpHFSS software is shown in Fig. 2. The model is based on ideal metallic cylinder in a metallic box. The geometrical dimensions are presented in the figure.

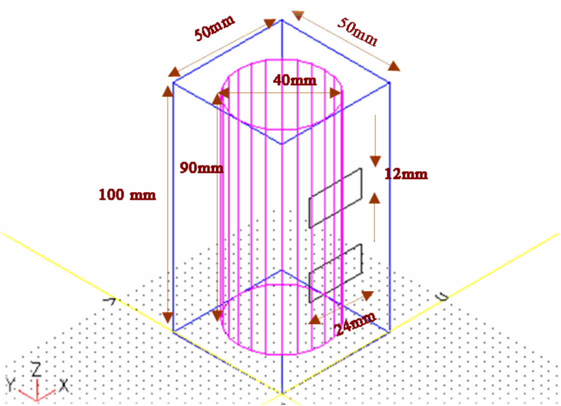

Fig. 2. Model of HV winding

Dimensions of the model are approximately 0.05 of the dimensions of a real one. Two X-band waveguide apertures for transmitting and receiving waves are modeled, too. The scattering matrix is 2x2 because we have two apertures.

$$S = \begin{bmatrix} S_{11} & S_{12} \\ S_{21} & S_{22} \end{bmatrix} \qquad (2)$$

The software can calculate the scattering parameters with different accuracy, because a curve is approximated by segments in this software. One of the simulation parameters is Segment Angle. For example, if the segment angle is 9° for an arc of 180 degrees, that means the model has nine degrees per segment and the arc is made up of 20 segments.

The nodes number is another parameter of the software which is defined as the number of nodes in the wavelength. For example, if the simulation frequency is 9.5GHz, then considering the fallowing equation, the wavelength is equal to 3.157 cm.

$$\lambda = \frac{c}{f} = \frac{3e8(m/s)}{9.5e9(Hz)} = 3.157cm$$

In this case, if the node number has been assumed to be equal to 4 then in a cube with the dimensions $3.157_{cm} \times 3.157_{cm} \times 3.157_{cm}$ we have $4 \times 4 \times 4$ nodes.

To simulate the HV winding axial displacement, the model is moved upward and downward and the magnitudes of the scattering parameters have been calculated for each position. Table I and II show the result of simulation of the HV winding axial displacement for different segment and node numbers.

The scattering parameters, S11 and S12, are given in Table I, for positive (upward) and negative (downward) displacement. In this table the segment and node numbers are 15 and 4, respectively.

The same parameters are given in Table II for the segment and node numbers 5 and 4, respectively. The graphical presentation of the parameters S11 and S22 are shown in Fig.3, for the above mentioned case. As it can be seen using the scattering parameters, it is possible to detect the axial displacement of the HV windings, without using any electrical connections. It must be emphasized that this method can be used on-line.

4 MODELING OF LV WINDING AXIAL DISPLACEMENT

The simulated model of the LV winding is shown in Fig.3. The LV winding is the inner winding. Dimensions of this model are the same as the model used for HV winding axial displacement except that HV winding height is 85mm. LV winding diameter is 20mm and its height is 90mm. As the length of the LV winding is slightly higher than the HV winding, its displacement can be studied and a change in the height difference between LV and HV winding means the displacement of the LV winding.

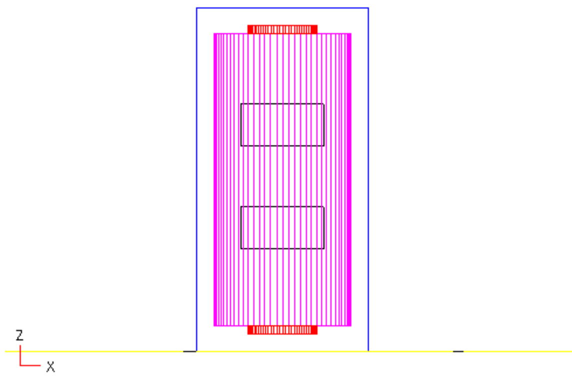

Fig. 3: Model used for simulation of the LV winding axial displacement

In the model, the position of the inner cylinder has been moved upwards and downwards and the magnitudes of the scattering parameters have been calculated for each position. Table III and IV show the simulation results of the LV winding axial displacement.

The scattering parameters are listed in Table III for an asymmetrical structure. In this structure the waveguide apertures don't have equal distance from the upper and lower surface of the cylinder. The same parameters are presented in the Table IV for a symmetrical structure. In the symmetrical structure the distance between the waveguide aperture and the upper and the lower surfaces of the cylinder are equal. Fig. 4 shows parameter S11 and S12 for the above mentioned cases. It is obvious that using these parameters, it is possible to detect the LV winding displacement, too.

TABLE I:
Simulation results of HV winding axial displacement (Segment No. =15 and Node No. =4)

Displacement (mm)	S11(dB)	%ΔS11	S12(dB)	%ΔS12
4	-5.67759493	-9.94494269	-1.37003	4.624355
3.5	-	-	-	-
3	-2.84490956	24.77925136	-3.1822	-15.0772
2.5	-0.19357816	69.32026732	-13.6928	-74.6781
2	-0.92258425	55.68925517	-7.18084	-46.4089
1.5	-2.74830946	26.17472904	-3.28911	-16.116
1	-5.20538943	-4.91360504	-1.5591	2.37159
0.1	-5.36500233	-6.64496693	-1.47109	3.41406
0(normal)	**-4.76775707**	**0**	**-1.76268**	**0**
-0.1	-4.72455405	0.498632224	-1.78442	-0.2499
-1	-3.78191439	12.01911424	-2.35532	-6.59537
-1.5	-4.7725707	-0.05540358	-1.76024	0.028175
-2	-0.29497432	67.35517158	-11.8267	-68.6095
-2.5	-0.88287902	56.40257627	-7.35268	-47.4587
-3	-7.91526287	-30.3975207	-0.7656	12.1642
-3.5	-10.4596018	-48.0712629	-0.4094	16.8596
-4	-8.75533264	-36.8139479	-0.62073	14.05069

TABLE II:
Simulation results of HV winding axial displacement (Segment No. =5 and Node No. =4)

Displacement (mm)	S11(dB)	%ΔS11	S12(dB)	%ΔS12
4	-5.0412	27.18555	-1.63195	-7.71295
3.5	-	-	-	-
3	-1.66808	87.54005	-4.96303	-37.1093
2.5	-0.44626	115.8664	-10.1027	-65.1982
2	-2.85914	63.50869	-3.16693	-22.6622
1.5	-5.69247	17.99795	-1.36454	-4.82756
1	-6.69251	5.165322	-1.04672	-1.28067
0.1	-6.96766	1.886149	-0.97461	-0.4577
0(normal)	**-7.12996**	**0**	**-0.93476**	**0**
-0.1	-6.64273	5.769799	-1.06035	-1.43546
-1	-5.51039	20.49767	-1.43372	-5.58259
-1.5	-6.60121	6.276559	-1.07194	-1.56687
-2	-2.90538	62.64061	-3.11792	-22.2246
-2.5	-0.05568	125.7948	-18.9669	-87.4573
-3	-5.91116	15.0642	-1.28653	-3.96895
-3.5	-10.3114	-30.6692	-0.42434	6.052541
-4	-7.89196	-8.39905	-0.77006	1.914318

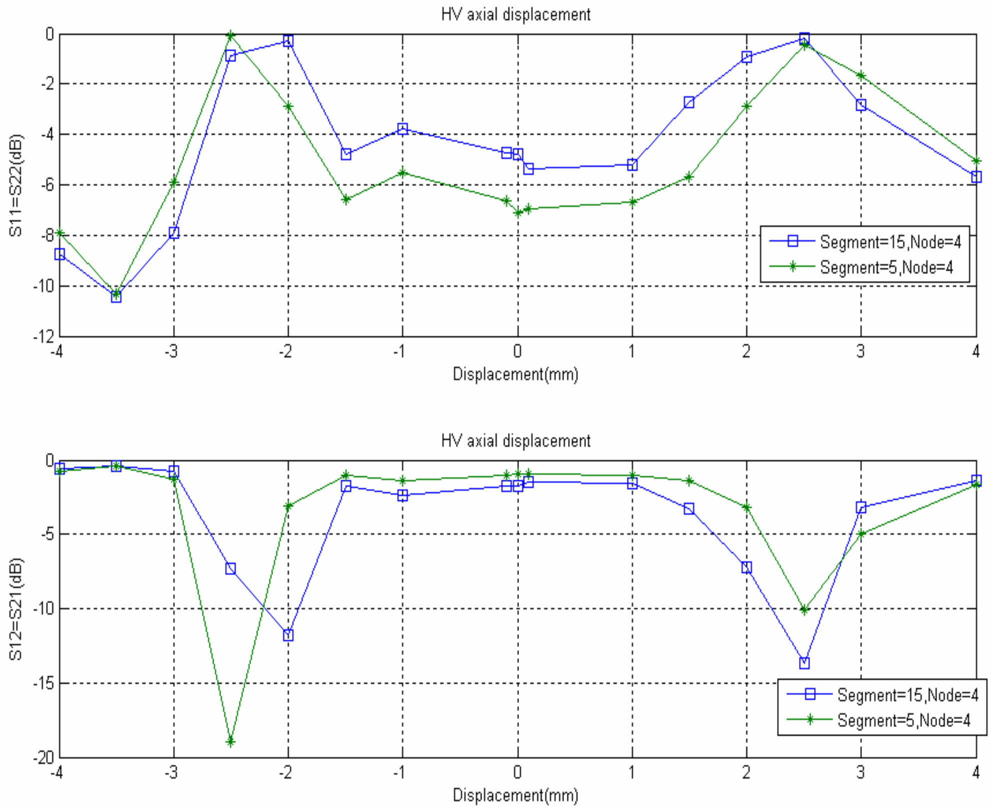

Fig.3: Simulation results of HV winding axial displacement

TABLE III:
Simulation results for LV winding axial displacement (segmentNo . =5, Node No. =4 asymmetrical structure)

Displacement (mm)	S11(dB)	%ΔS11	S12(dB)	%Δ S12
2.5	-6.0944	350.0045	-1.2251	-12.6229
2	-9.16991	215.821	-0.56039	-5.67355
1.5	-13.5263	91.25896	-0.19722	-1.64602
1	-19.8673	-7.83335	-0.04502	0.092564
0.5	-27.8353	-63.1724	-0.00713	0.530229
0 (normal)	**-19.1587**	0	**-0.05306**	0
-0.5	-13.8202	84.89607	-0.18408	-1.49712
-1	-10.3706	175.0477	-0.32784	-3.11396
-1.5	-7.61166	277.8796	-0.82662	-8.52089
-2	-5.21789	397.7852	-1.55369	-15.8666
-2.5	-3.17406	529.8448	-2.85251	-27.5518

TABLE IV
Simulation results for LV winding axial displacement (segmentNo . =5, Node No. =4 symmetrical structure)

Displacement (mm)	S11(dB)	%ΔS11	S12(dB)	%ΔS12
2.5	-4.76204	424.6074	-1.76566	-17.895
2	-7.01603	304.7018	-0.96257	-9.94154
1.5	-9.87667	191.141	-0.47153	-4.70365
1	-13.7159	87.12898	-0.19233	-1.59069
0.5	-19.2117	-0.60815	-0.05236	0.008049
0(normal)	**-19.1587**	**0**	**-0.05306**	**0**
-0.5	-19.0436	1.334302	-0.05446	-0.0161
-1	-13.6245	89.10774	-0.19269	-1.59471
-1.5	-9.9602	188.3544	-0.462	-4.59901
-2	-7.14161	298.8926	-0.95132	-9.82483
-2.5	-4.71468	427.4757	-1.78943	-18.1193

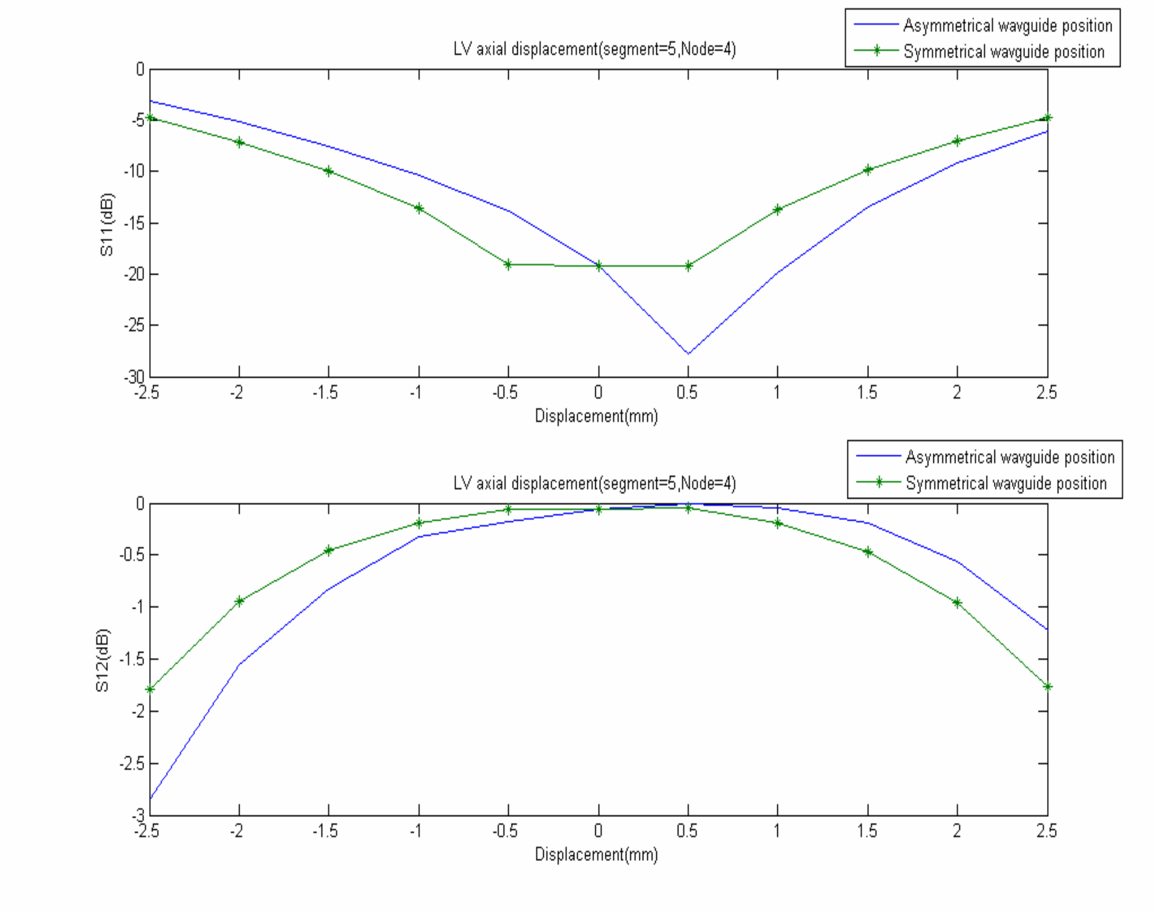

Fig.4: Parameters S11 and S12; Simulation results for LV winding axial displacement

5CONCLUSIONS

In this paper a new measuring method for detection of axial displacement of the high and low voltage winding has been proposed. This method can be used for off-line or on-line applications. It is shown that upward and downward axial displacement of the high voltage and/or the low voltage winding can be detected by the on line monitoring of scattering parameters.

6 ACKNOWLEDGMENT

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