Exact Determination of a Winding Disk Radial Deformation Location Considering Tank Effect Using an Analytical Method

H. RahbariMagham[1], M.A. Hejazi[2], H. Karami Porzani[1], M.S. Naderi[1,3], G.B. Gharehpetian[1,3]
[1] Electrical Engineering Department, Amirkabir University of Technology, Tehran, Iran
[2] Electrical Engineering Department, University of Kashan, Kashan, Iran
[3]Iran Grid Secure Operation Research Center, Amirkabir University of Technology, Tehran, Iran
Phone/Fax number: +98-21-64543504,
E-mails: h.rahbarim@aut.ac.ir, akhavanhejazi@aut.ac.ir, h.karami@aut.ac.ir, salaynaderi@aut.ac.ir, grptian@aut.ac.ir

***Abstract**: Power transformers are one of the most expensive components of the power system. Timely detection of fault arose in the transformer can be used to prevent unwanted outage of transformer and repair costs. Using electromagnetic waves has recently been proposed for on-line monitoring of the transformer. The presence of the tank in the transformer structure causes problem for analyzing the electromagnetic waves. In this paper, a new analytical method based on locus of the objects in the space is proposed to detect the radial deformation location of a disk winding considering tank effect. The proposed experimental set-up for this method has been modeled using CST (Computer Simulation Technology) software. In this paper, Vivaldi antennas suitable for measurements in environments with multi-path routing are used and the analysis is performed in the time domain. The simulation results show that exact determination of radial deformation location can be detected with good accuracy using this method.*

Keywords: transformers, electromagnetic waves, determination of radial deformation.

1. Introduction

Power transformers are the main elements of the generation, transmission and distribution of electric power network [1]. In industrial plants, mechanical damages such as radial deformations are caused by forces due to high short circuit currents. There are many transformer monitoring methods each of which have advantages and disadvantages [2,3]. Short circuit test method is needed to measure the short-circuit reactance. And it can be performed simultaneously with the operation of the transformer, but does not provide any information about the type and location of the fault [4]. Frequency response analysis method, although this method has been mentioned in the literatures as the on line mode [5], but only the high voltage side of the transformer in the circuit remains. The low voltage side of the transformer is removed from the circuit. In this case transformer is switching from high voltage side by power switch. Low voltage impulse test method, the transformer during this procedure must be isolated from the network. Also, any changes in the waveform produced by a source of change in the response waveform and output could be wrong conclusion [6]. The off-line methods will not meet all the needs of the transformer monitoring system. And the operator should turn off the transformer in order to carry out the measurement. On-line methods have the benefit of continuous monitoring of the power transformer winding. So, on-line monitoring of the transformer winding is very important.

In the new transformer monitoring systems, mechanical damages are detected using Ultra Wide Band (UWB) waves [7,8]. In this method, the narrow pulses generated by the transmitting UWB radar system using the Ultra-wideband antennas are emitted to the transformer and its reflection is stored [9-11]. In the proposed method in this paper, received signal is analyzed in the time domain. The presence of the tank in the transformer structure causes problem for analyzing these signals.

This paper presents an analytical method based on locus of objects in space to detect the radial deformation location of a winding disk using Ultra Wide Band (UWB) waves considering tank effect. This method provides a new analysis of the signals, which ultimately helps suppress the problems of the transformer tank effect on the waves. The pulses signals used for this method have very high accuracy of deformation detection because of excellent spatial resolution of the Ultra Wide Band system. In this study CST software is used to simulate the structure for the modeling of the winding displacement considering the transformer tank.

The paper is organized as follows: the UWB systems application in the transformer monitoring in section II. The system which should be simulated in this study is presented in section III. Section IV describes the proposed analytical method. Simulation results are prepared in Section V and finally, Section VI concludes the paper.

2. UWB Systems Application in the Transformer Monitoring

According to established standards, UWB systems refers to systems that relative bandwidth used in them is more than a quarter or greater than 500 MHz (Fig. 1).
The relative bandwidth is defined by the following equation:

$$2\frac{(f_H - f_L)}{(f_H + f_L)} \qquad (1)$$

Where f_H is the 10dB upper cut-off frequency and f_L is the -10dB lower cut-off frequency.

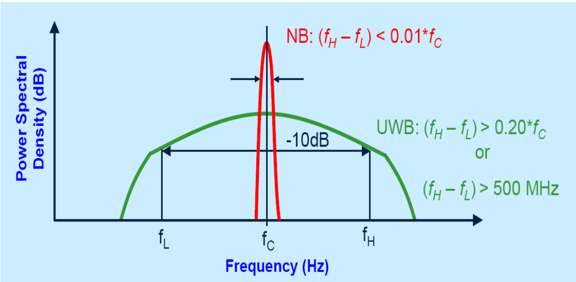


Fig. 1: Relative bandwidth of narrowband and broadband systems

A UWB pulse is sent toward the transformer winding in a direction which by a transmitting antenna signal encounters to the target (winding). Part of the energy that reflected from the transformer winding and tank walls is received and stored by the receiving antenna [12-15].

3. System Modeling

The system which should be modeled and simulated in CST software has the following parts:

- Transformer winding
- Antenna
- Tank

3.1. Transformer Model

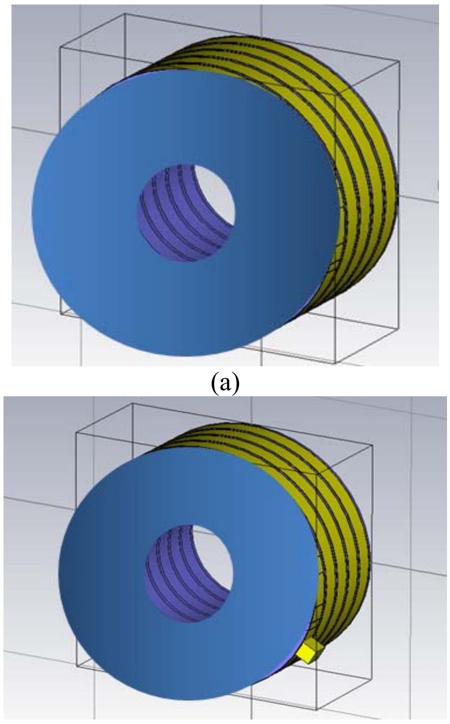
Due to the complexities of the transformer and its dimensions the model was simulated much simpler, smaller in size and for single-phase. To simulate the model the most important thing is having a material similar to the actual transformer windings. So the best choice is Plexiglas which is covered by a layer of copper.

As shown in Fig. 2, this model consists of five disks with a layer of copper. Dimensions of the model are listed in Table I.

TABLE I: Transformer model parameters

Phase number	1
Space between disks	5 mm
Number of disks	5
height	125 mm
outer diameter	300 mm

For modeling radial deformation a metal sector with a width of 2 cm on one of the disks has been created. As shown in Fig. 2 (b), to simulate the radial deformation sectors are pushed directly to the outside.



(a)

(b)

Fig. 2: Schema of simulated transformer winding. (a) The normal mode of transformer. (b) The defective mode of transformer.

3.2. Antenna model

Vivaldi antenna is a suitable antenna for UWB applications [16,17]. Frequency of antennas used is between 3.2 to 6.1 GHz frequencies. Fig. 3 shows a schematic of the Vivaldi antenna.

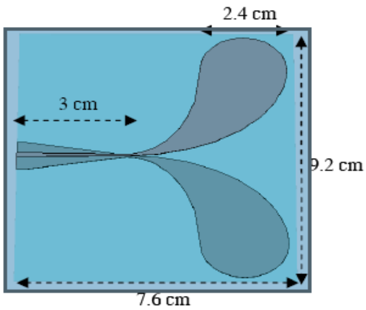


Fig. 3: Structure of the Vivaldi antenna

4. Exact determination of a winding disk radial deformation location considering tank effect

The paper focus is on analyzing the received signals for the exact determination of the radial deformation location in the transformer winding. The novelty of this paper, is considering the tank in the transformer model which has been omitted in the previous researches for the simplification of the model [9-14]. Considering the transformer tank effect due to reflection of transmitted signals from the tank walls the received signals will have large fluctuations.

Due to the large fluctuations in the received signals, deformation diagnose can be difficult.

In this paper, the location of the deformation in the model can be detected by comparing and subtracting the signal of the sound model with the deformed model.

The proposed method is based on locus of objects in space. In order to perform the test, a transmitting antenna and two receiving antennas are used (Fig. 4).

If a deformation occurs in the transformer windings, two receiving antennas see the fault in different time intervals (t_1 and t_2). The signal propagation speed which is the speed of light can be used for transforming the time interval to the difference of distance as follows:

$$x_1 = t_1 \times c$$
$$x_2 = t_2 \times c \qquad (2)$$

Where C is equal to 3×10^8 m/s.

In the above formula X_1 and X_2 are the first and second receiving antennas distance from the fault respectively.

Thus, for a certain deformation the distance difference from two fix points (receiving antennas) can be obtained. The locus of points with constant difference of distance from two fix points is a hyperbola which the receiving antennas are its foci. The equation of the hyperbola can be written as:

$$\frac{(x-\alpha)^2}{a^2} - \frac{(y-\beta)^2}{b^2} = 1 \qquad (3)$$

Where 2a is the difference of the distance of the points on the hyperbola from hyperbola foci (receiving antennas). The parameters α and β are the coordinate of the symmetry point of the hyperbola. And parameter b is calculated using the following equation:

$$b^2 = c^2 - a^2 \qquad (4)$$

Where c is the distance from the center (transmitting antenna) to either focus point (receiving antennas) of the hyperbola. Thus according to Equation 3, the locus of deformation is obtained. The transformer locus is considered as a circle in a surface. On the other hand, the typical deformation is assumed on one of the transformer disks model. Consequently, locus of the transformer model is a circular. According to the layout of the experiment and Fig. 4, the circular and hyperbolic equations are obtained as follows:

$$\frac{(x)^2}{a^2} - \frac{(y-l)^2}{b^2} = 1 \qquad (5)$$

$$x^2 + y^2 = d^2 \qquad (6)$$

Where l and d are the distance between transformer center and transmitting antenna location and transformer model radius respectively. All of parameters are shown in Fig. 4 and listed in Table II.

TABLE II: Simulated system parameters

c	150 mm
d	150 mm
l	550 mm

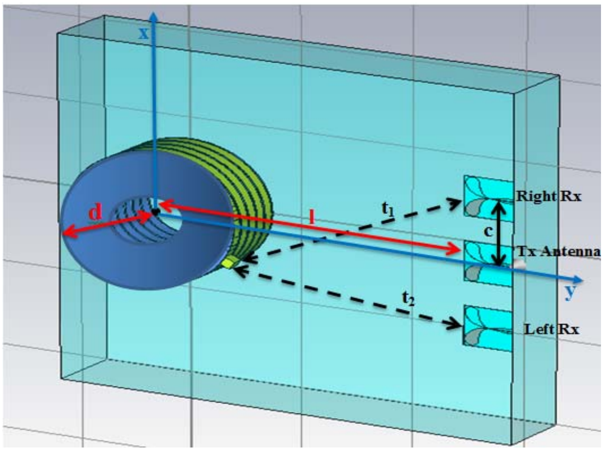


Fig. 4: schematic diagram of the adopted simulated system

By solving the above equations, the deformation location is obtained. In other words, an intersection of the hyperbola and circle detects exact location of deformation. The obtained hyperbola with locus of transformer winding has four intersection points. Two points that are located near the antennas are acceptable. From these two points the one which is near to the antenna that first detect the signal difference is the acceptable point.

5. Simulation Results in CST software

In this section, the proposed method has been tested for the detection of radial deformation in different locations. In order to test, the model of transformer windings in normal mode (i.e. the winding without buckling) has been simulated. In this mode, sending and receiving signals are performed by Vivaldi antennas; and the data are stored.

Signal profile is shown in Fig. 5.

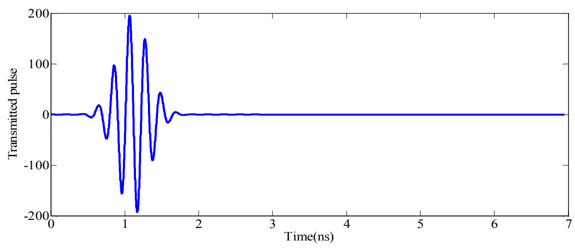


Fig. 5: A sample of transmitted signal

Then the buckling on the disk is created by the dimensions of 2 x 2 cm^2.

To solve the problem of large fluctuations affected by tank walls, the normal mode signal is subtracted from defective. Thus, effects of fluctuations are eliminated. Fig. 6 (a) and (b) shows the received signals by one of the receiving antennas in the normal and defective conditions of transformer model considering tank effect. Fig. 6 (c) shows the result of subtracting the signal of normal and defective transformer. In Fig. 6(c) t_1 is the point of starting the change in the resultant signal produced by the subtraction of sound and deformed signal which is related to the fault distance from the antennas.

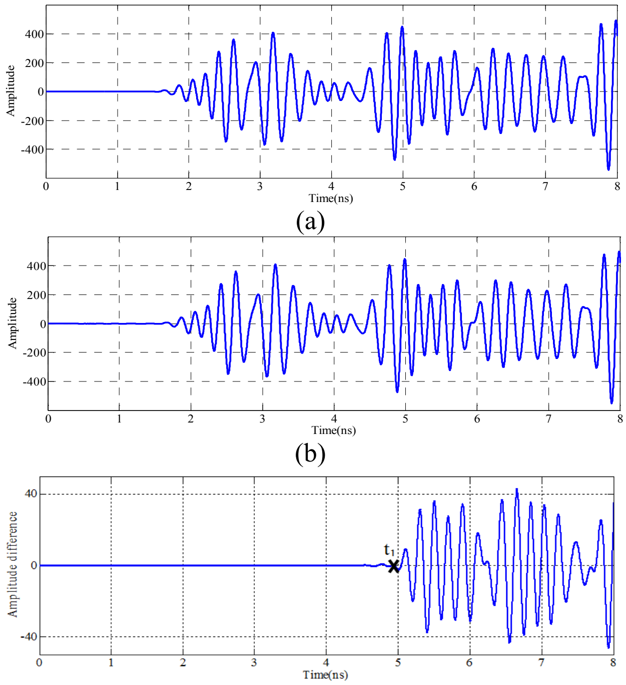


Fig. 6: Received signals by the receiving antennas. (a) In the normal mode of transformer. (b) In the defective mode of transformer. (c) Signals difference in normal and defective mode of transformer

5.1. Radial Deformation Location in the Middle of the Disk Winding

According to Fig. 7, deformation is located exactly on the y-axis on the surface of the disk. In other words in this arrangement, the radial deformation of transformer winding is simulated in the middle of the disk model at (x=0 , y=15).

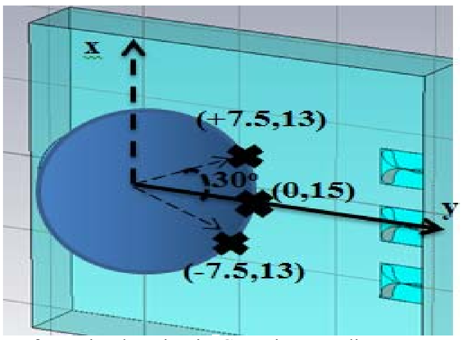


Fig. 7: Deformation location in Cartesian coordinate system in two dimensions

Fig.8 shows the result of subtracting the signal of normal and defective transformer. Fig. 8 depicts amplitude difference of the resultant signals for the left and right antennas. Fluctuations affected by tank walls are eliminated by subtracting sound and deformed winding signals. Fig. 8 shows that both antennas detect the change of signal simultaneously. Thus, from (2) it is obtained that:

x_1-x_2=0

Thus, difference between the distances of deformation from two receiving antennas would be 0 cm.

According to the above calculations, the point (x=0 , y=15) specifies the exact location of the radial deformation considering the center of the winding disk model as origin of coordinates.

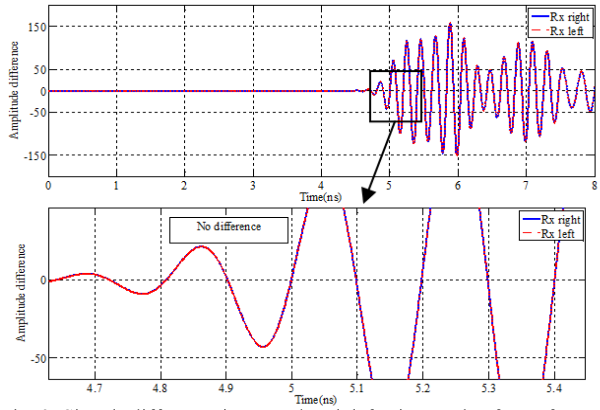


Fig. 8: Signals difference in normal and defective mode of transformer for radial deformation location in the disk middle

5.2. Radial Deformation Location in the Right Side of Disk Winding

In this section, buckling is simulated at an angle of 30 degrees from the y-axis at the point (x=7.5 , y=13). Fig. 9 illustrates the result of subtracting the signal of normal and defective transformer model. Fig. 9 shows amplitude difference of the resultant signals for the left and right antennas. Consequently, time difference of the beginning of the change in the received signals from the two antennas is equal to 0.16 ns. From (2) it is obtained that:

x_1-x_2=4.97 cm

This means that 2α =4.97 cm, thus parameter b can be obtained from (4). According to Fig. 4 and Table. II:

$$\frac{(x)^2}{2.49^2}-\frac{(y-55)^2}{14.8^2}=1 \quad (7)$$

$$x^2+y^2=15^2 \quad (8)$$

From solving the above equations, the points (x=±7.5 , y=13) are obtained. Due to Fig. 9, right antenna has observed start of signal amplitude changes (deformation) earlier than the left antenna; so the only point (x=+7.5 , y=13) is acceptable. It should be noted that the location of antennas has no change compared to before.

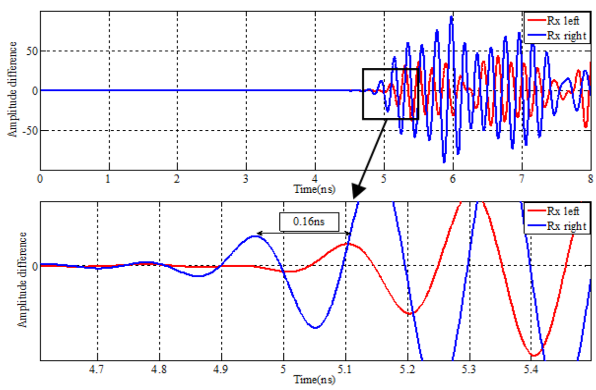


Fig. 9: Signals difference in normal and defective mode of transformer for radial deformation location in the disk right side

5.3. Radial Deformation Location in the Disk Left Side

In order to confirm the results of the previous section buckling is simulated at the left side of the y-axis at the point (x=-7.5 , y=13). Similar to the previous sections, the effect of fluctuations affected by tank is eliminated by subtraction of the sound and deformed winding signals. Fig. 10 shows amplitude difference of the resultant signals for the left and right antennas. As the figures suggest, time difference of the changing start of signals for two receiving antennas is equal to 0.16 ns. Difference between the distances of deformation to two receiving antennas would be 4.97 cm.

Adopting (7) and (8), the points (x=±7.5 , y=13) are obtained. Due to Fig. 10, left antenna has observed start of signal amplitude changes (deformation) earlier than the right antenna; so the only point (x=-7.5 , y=13) is acceptable. As in previous cases, antenna location is not changed.

Despite the destructive effects of tank walls on received signals, location of the deformation has been detected with high accuracy.

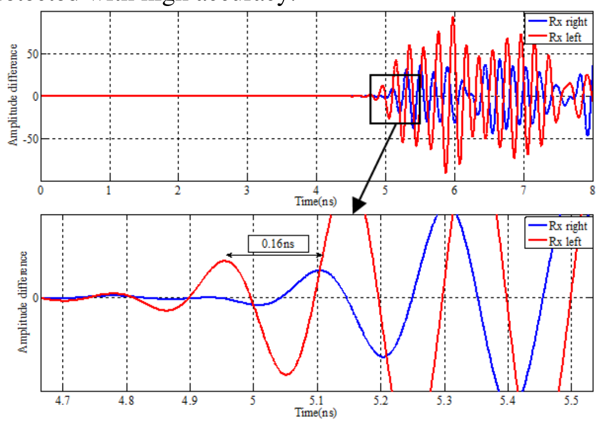


Fig. 10: Signals difference in normal and defective mode of transformer for radial deformation location in the disk left side

6. Conclusion

In this paper, a new method for the detection of transformer radial deformation location is presented considering the tank effects. In this method, Vivaldi antennas have been used. To detect the deformation location the analysis of signals is performed in the time domain. To solve the problem of large fluctuations affected by tank walls, the normal mode signals have been subtracted from the defective mode ones. The simulation results show that location of radial deformation can be exactly determined by this method.

Acknowledgment

The authors would like to express their sincere thanks to Tehran Regional Electric Co. (TREC) for financial support.

References

[1] C. Bengtsson , "Status and trends in transformer monitoring," Power Delivery, IEEE Transactions on , vol.11, no.3, pp.1379-1384,Jul 1996.

[2] J.Christian and K.Feser, “Procedures for Detecting Winding Displacements in Power Transformers by the Transfer Function Method,” IEEE Transaction on Power Delivery, Vol.19, No.1, pp.214-220, Jan. 2004.

[3] T. Leibfried and K. Feser, “Monitoring of power transformers using the transfer function method,” IEEE Trans. Power Delivery, Vol. 14, pp.1333-1341, August 2002.

[4] D. K. Xu, J. H. Hung, “On-line Monitoring of Winding Deformation of Power System,” IEEE Conference on Electrical Insulating Material, 2001, pp. 853- 856.

[5] T.Leibfried and K.Feser, „ Off-line and On-line Monitoring of Power Transformers using the Transfer Function Method ″,IEEE International Symposium on Electrical Insulation ,Montreal ,Quebec ,Canada , June 16-19 ,1996, pp.34-111.

[6] A. S. Morched, L. Marti, R. H. Brierly, J. G. Lackey, “Analysis of Internal Winding Stress in EHV Generator Step-up Transformer Failures,” IEEE Transaction on Power Delivery, Vol. 11. No. 2, April 1996.

[7] M. A. Hejazi, G. B. Gharehpetian, A. Mohamadi, “Characterization of On-line Monitoring of Transformer Winding Axial Displacement Using Electromagnetic Waves,”15th International Symposium on High Voltage Engineering, Slovenia, August 2007.

[8] A. G. Yarovoy; L.P. Ligthart; J. Matuzas; B. Levitas; "UWB radar for human being detection [same as "UWB radar for human being detection", ibid., vol. 21, n. 11, 06]," Aerospace and Electronic Systems Magazine, IEEE , vol.23, no.5, pp.36-40, May 2008.

[9] M. A. Hejazi, G. B. Gharehpetian, G. Moradi,H. Alehosseiny, M. Mohammadi; "On-line Monitoring of Transformer Winding Axial Displacement and its Extent Using Scattering Parameters and k-Nearest Neighbor Method" , IET Generation Transmission & Distribution , Vol.5 , NO.8 , PP.824 _ 832 , 01 October2011.

[10] M. A. Hejazi, G. B. Gharehpetian, R. Faraji-Dana, G. Moradi, M. Mohammadi, H. Alehosseiny; "A New On-line Monitoring Method of Transformer Winding Axial Displacement Based on Measurement of Scattering Parameters and Decision Tree" , Expert Systems with Applications , Vol.38 , NO.7 , PP.8886 _ 8893 , 01 July2011.

[11] M. A. Hejazi, J. Ebrahimi, G. B. Gharehpetian, M. Mohammadi, R. Faraji-Dana, G. Moradi; " Application of Ultra-Wideband Sensors for On-Line Monitoring of Transformer Winding Radial Deformations–A Feasibility Study" , IEEE SENSORS JOURNAL, VOL. 12, NO. 6, PP. 1649 - 1659, June 2012.

[12] G. Mokhtari, G. B. Gharehpetian, R. Faraji-dana, M. A. Hejazi, “On-line Monitoring of Transformer Winding Axial Displacement Using UWB Sensors and Neural Network”, International Review of Electrical Engineering (IREE), Vol. 5, No. 5, October 2010 (ISI-ranked).

[13] M. A. Hejazi, J. Ebrahimi, G. B. Gharehpetian, R. Faraji-Dana and M. Dabir, “Feasibility Studies on On-line Monitoring of Transformer Winding Mechanical Damage Using UWB Sensors”, XIX International Conference on Electrical Machines, ICEM 2010, September 6-8, 2010, Rome, Italy.

[14] G. Mokhtari, M. A. Hejazi and G. B. Gharehpetian, “Simulation of On-line Monitoring of Transformer Winding Axial Displacement Using UWB Waves”, XIX International Conference on Electrical Machines, ICEM 2010, September 6-8, 2010, Rome, Italy.

[15] J. Ebrahimi, G. B. Gharehpetian, H. Amindavar and M. A. Hejazi, “Antennas Positioning for On-line Monitoring of Transformer Winding Radial Deformation Using UWB Sensors”, 3rd International Power and Energy Conference (PECon), Nov. 29-Dec. 1, 2010, Kualalumpur, Malaysia.

[16] A.Mehdipour, K. Mohammadpour- Aghdam, R. Faraji- Dana, "Complete Dispersion Analysis of Vivaldi Antenna for Ultra Wide Band," Progress In Electromagnetic Reasearch, PIER 77, 85-96, 2007.

[17] K. Y. Yazdandoost and R. Kohno, “Slot antenna for ultra wideband system,” Proc. Of IEEE Wireless Communications and Applied Computational Electromagnetics Conference (ACES), pp. 212-216, 2005.