A Novel Method for Exact Determination to Localize Radial Deformation along the Transformer Winding Height

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Abstract: *In order to reduce time out of the transformer circuit, implementation of methods for online monitoring is important. Using electromagnetic waves has recently been proposed for on-line monitoring of the transformer. In this paper, a new analytical method based on locus of objects in space to detect the radial deformation of winding, is proposed. The proposed experimental set-up for this method has been modelled using CST (Computer Simulation Technology) software. The simulation results show that exact determination of radial deformation location along the transformer winding height can be detected with good accuracy using this method.*

Keywords: Transformer Monitoring, Radial Deformation, UWB Antenna, Hyperboloid Method, CST.

1. Introduction

Transformers are one of the most important parts of the electric utility. Mechanical deformations of them can lead to catastrophic failure of the transformer and possibly outage in part of the electric utility. So, continuous monitoring of the transformer winding can solve a lot of problems.

Online monitoring of transformer is very important. On-line monitoring not only avoid direct damages of transformers and provides personnel safety, but also prevent indirect damage caused by interrupted energy flow and increase the reliability of the power system [1]. Many transformer monitoring methods have been proposed and some of disadvantages of each are listed below [2, 3]. Short circuit test, which does not give any information about the location and type of winding deformation [4, 5]. Frequency response analysis method, in which transformer should be barren [6, 7]. Low voltage impact 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 [8].

In the new monitoring systems, electromagnetic waves are used for determination of transformer winding deformation location. 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.

The purpose of this paper is to use ultra-wideband antennas and an analytical method for detecting radial deformation location along the transformer winding height using CST (Computer Simulation Technology). In this case, 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. This analytical method based on locus of objects in space detects the exact location of the deformation; the simulation results have confirmed the validity of this method.

The paper is organized as follows: the concept of UWB systems is described in Section II. The simulated structure for the modelling of the winding displacement which has used in this study is presented in section III. Section IV describes hyperboloid method to detect the radial deformation of transformer winding. Simulation results, evaluating the priority of this method by comparing and analysing the results is prepared in Section V and finally, Section VI concludes the paper.

2. Concept of UWB systems

A surprising amount of bandwidth dedicated to this technology is 7.5 GHz, which is much more than the bandwidth of conventional systems. According to FCC standards an ultra wide band signal has a bandwidth of at least 500 MHz or a relative bandwidth of greater than 20 per cent. Relative bandwidth is defined by the following equation:

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

Where f_H and f_L are the 10db upper cut-off frequency and -10db lower cut-off frequency respectively.

Because of very low pulse width, UWB technology has a high spatial resolution and suitable for deformation detection.

In this method, by an antenna a signal (UWB pulse) is sent toward the transformer winding in a direction which signal encounters to the target (winding). Part of the energy that reflected from the transformer winding is received and stored by the receiving antenna [9-12]. The schematic of the procedure is depicted in Fig. 1.

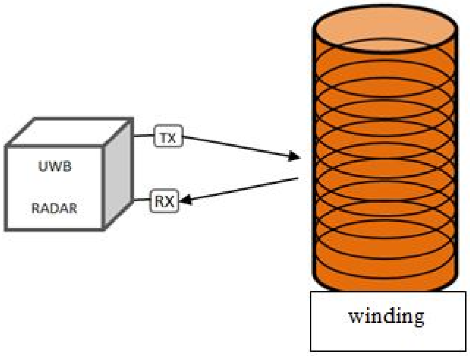


Fig. 1: Transformer monitoring using UWB sensor

In this research, a novel method has been proposed to detect radial deformation location along the transformer winding height using CST software.

3. The proposed algorithm to determine the exact location of the deformation

The proposed method is used to detect the exact location of the radial deformation based on locus of objects in space. In three-dimensional space, the locus where the distance between two fixed points is constant is called hyperboloid where the two fixed points are the foci of the hyperboloid.

In order to perform the test, a transmitting antenna (Tx) and two receiving antennas (Rx) are used as shown in Fig. 2.

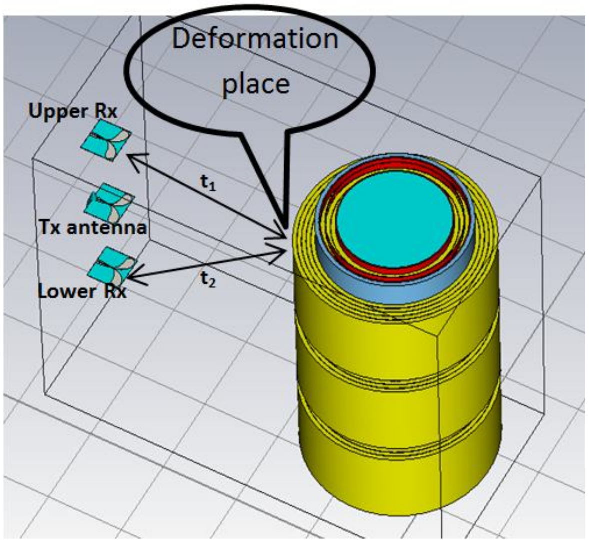


Fig. 2: The placement of the transceiver antennas and transformer model

If a deformation occurs in the transformer windings, two receiving antennas with different time intervals (t1 and t2) are finding it. This feature can be used to determine the exact location deformation. The speed of signal propagation which is the speed of light can be used to the time difference between signals which are turned away. Two first and second receiving antennas detect deformation in the distance X1 and X2 respectively. X1 and X2 are obtained as follows:

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

Where C is the speed of light (3×10^8 m/s).

The difference of distance between x1 and x2 with respect to the two receiving antennas is constant. When a deformation occurs in a certain place, it is possible to obtain the difference between the deformation distances from the two fixed points –receiving antennas. Through mathematic equations, it can be demonstrated the difference between the distances of the deformation location from the antennas is constant; hence, the locus of these points is called hyperboloid. The hyperboloid equation can be obtained as follows:

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

In this study, the transformer locus is considered as a cylindrical surface. On the other hand, the typical deformation is assumed along the transformer winding height. Since the aim of this method is to locate the deformation on the plan z=0, the antennas are placed in the line on this page. On the plan z = 0, locus of the transformer model is a rectangle. Consequently to locate the deformation, the locus of this rectangle must be crossed by the hyperboloid locus as shown in Fig. 3.

The y-axis is considered along the transformer winding in this study. The simulated transformer wining under study has a diameter of 23.9 cm and a height of 44.2 cm. Consequently, the rectangular equations are obtained as follows:

$$\begin{cases} z = 0 \\ d \le x \le d + 23.9 \\ -22.1 \le y \le +22.1 \end{cases} \qquad (4)$$

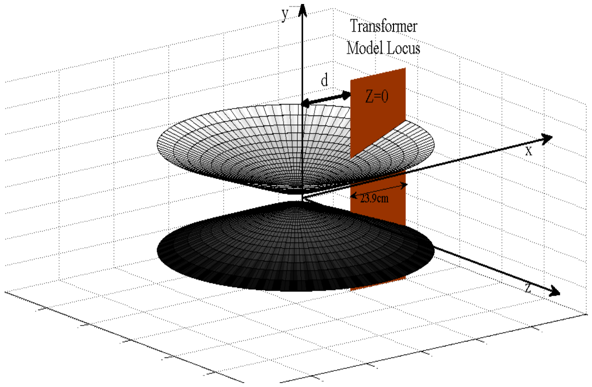


Fig. 3: Transformer model and hyperboloid locus

It should be noted that the location of the transmitting antenna is assumed as the coordinate origin.

Considering to be located on the deformation has occurred in the transformer surface; as a result the rectangular geometry of the transformer model is targeted only the line X = d.

Where d is the distance between the antennas and the simulated transformer model.

By solving the above equation, the value of y is obtained as follows:

$$y = \pm a\sqrt{1+\left(\frac{d^2}{b^2}\right)} \tag{5}$$

Where y is deformation location along the axis of the transformer and other parameters are determined based on X_1 and X_2 values.

To draw this hyperboloid, a and b parameters are need. The distance between points on the hyperboloid from hyperboloid focal (receiving antennas) is equal to 2a. So a can be obtained. On the other hand, c is the distance between the focal (receiving antennas) and centre (transmitting antenna) hyperboloid. Given a and b, the parameter c is calculated using the following equation:

$$b^2=c^2 - a^2 \tag{6}$$

Intersection between hyperboloid and transformer winding model are two points. By assuming that one antenna sees the start of signal difference of deformation, earlier; only one point can be acceptable.

4. Set up Modelling

The set-up which should be modelled has the following parts:

- Transformer Winding model.
- Model of Vivaldi antenna

4.1 Transformer Winding Model

To approve the proposed method, a transformer is simulated in CST software. The parameters of this model are listed in Table I.

Fig. 4 shows schematic of the simulated transformer winding in CST software.

TABLE I: Transformer model parameters

Phase number	1
Core material	Steel
Insulation width between H.V. and L.V.	1.5 mm
Duct width between H.V. and L.V.	5 mm
H.V. height	442 mm
H.V outer diameter	239 mm
H.V inner diameter	186.2 mm
Space between coils	5 mm
Insulation width between H.V. layers	0.3 mm
Number of H.V. coils	8
Number of H.V. layers	24
L.V. height	570 mm
L.V. outer diameter	156.2 mm
L.V. inner diameter	138 mm
Insulation material between L.V. layers	Pressboard
Insulation width between L.V. layers	0.5 mm
Insulation material between L.V. and core	Pressboard
Insulation width between L.V. and core	1.5 mm

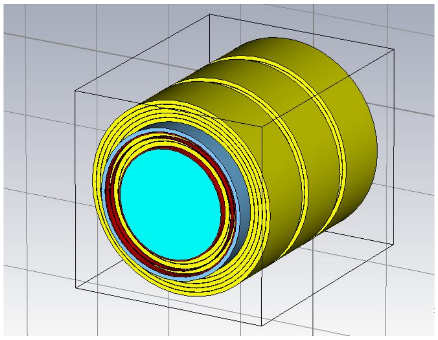


Fig. 4: schema of simulated transformer winding in CST software

4.2 Vivaldi antenna Model

In this paper, Vivaldi antennas were used for simulation [13, 14]. The antenna in the 3.2 to 6.1 GHz frequency band is simulated. The antenna structure which is used and its dimensions are shown in Fig. 5.

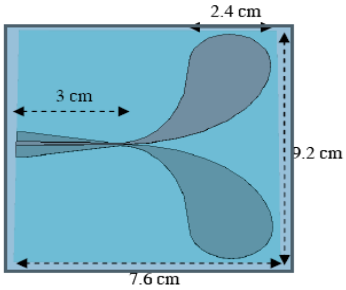


Fig. 5: Structure of the Vivaldi antenna [13]

5. Simulation Results

In this section, the proposed method has been tested in order to exact determination of radial deformation location along the transformer winding height.

Fig. 6 shows a schematic diagram of the adopted simulated system in CST software. The parameters of the proposed set-up are given in Table II.

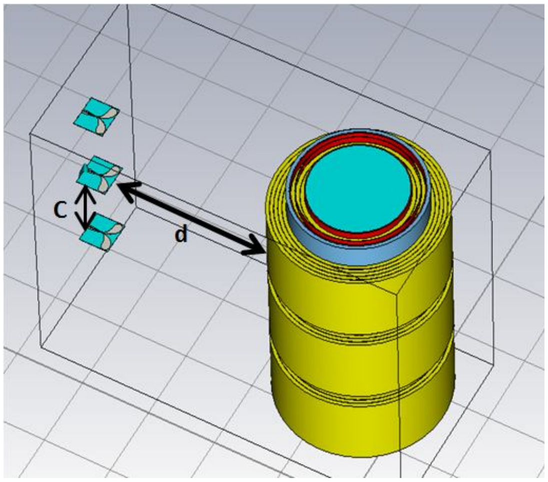


Fig. 6: schematic diagram of the adopted simulated system

c is the distance between the transmitting and receiving antenna, *d* is the distance between the transformer model and the receiving antenna.

TABLE II: Set-up parameters

C	17cm
d	50cm

First, the model of transformer winding in the normal mode (i.e. without deformation) has been simulated in this mode; sending and receiving signals are performed by Vivaldi antennas. In the next stage, a radial deformation defect composed of a 2*2 cm lumped area is simulated on the transformer model. This lumped area is considered consisting of the same material of the winding. Sending and receiving signals to be redone. Finally, the analysis of signals and comparison with normal and defective conditions, deformation location is obtained. To evaluate the proposed method, a typical deformation on the transformer model is investigated in the next section.

Fig. 7 shows a sample of transmitted pulse that is used in this study. The parameters of these transmitted pulses are listed in Table III:

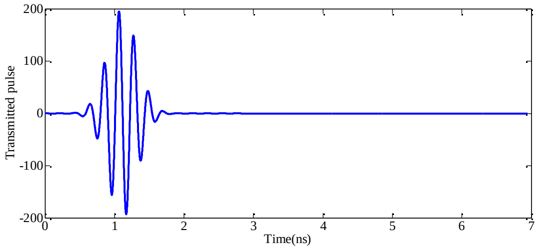


Fig. 7: A sample of transmitted pulses

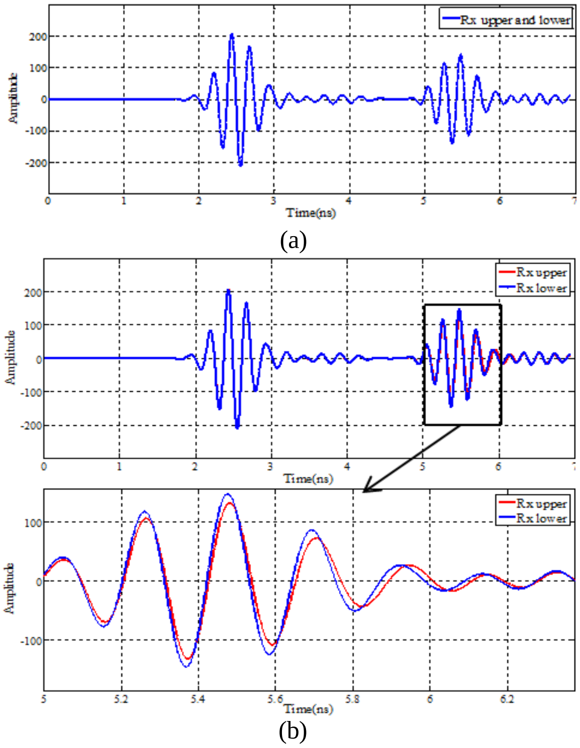
TABLE III: Transmitted pulse parameters

PRF (Pulse Repetition Frequency)	9.6 MHz
Center Frequency (radiated)	4.7GHz
Bandwidth (10 dB radiated)	3.2 GHz
EIRP	12.8 dBm
Power consumption	6.5 Watts

5.1 Localization of a Typical Radial Deformation at the Top of the Winding

In this arrangement, the radial deformation location is simulated at the height of 17cm of the transformer winding model and assuming that the transmitting antenna is on the coordinate origin.

Fig. 8 shows the received signals by the receiving antennas in the normal and defective conditions. As Fig. 8(a) shows in the normal transformer state, antennas receive the same waveform while in the defective condition (Fig. 8(b)), received signals affected by deformation in a certain time period are different. In the proposed method, amplitude difference of signals in normal from defective mode of transformer has been used as a criterion to locate the winding deformation, are also depicted in Fig. 9.



(a)

(b)

Fig. 8: received signals by the receiving antennas. (a) In the normal mode of transformer. (b)) In the defective mode of transformer

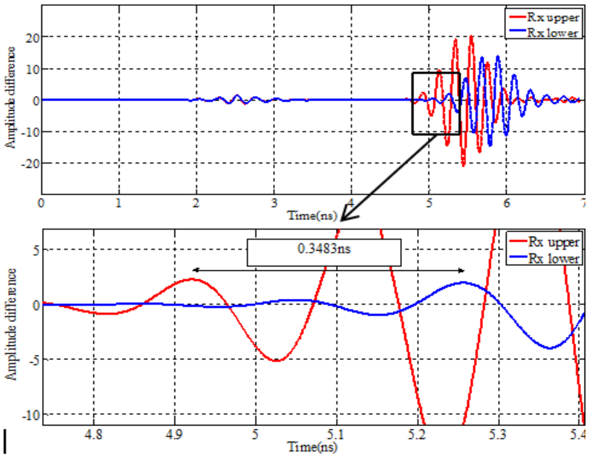


Fig. 9: Signals difference in normal and defective mode of transformer

According to the Fig. 9, top antenna has observed start of signal amplitude changes (deformation) earlier than the down antenna. Time difference of the received signals for two receiving antennas is equal to 0.3483 ns. Consequently, difference between the distances of deformation to two receiving antennas would be 10.44 cm and thus x_1-x_2=10.44 cm. This means that 2α =10.44 cm and due to having c = 17 cm; parameter b can be obtained from equation 6. According to Fig. 6 and Table.

II, *d* is equal to 50 cm. With the above parameters, from (5) the value of y is obtained as follows:

$$y = \pm 5.22\sqrt{1+\left(\frac{50^2}{16.178^2}\right)} \tag{7}$$

So y=16.956 cm.

This indicates that deformation is at the height of 16.956 cm from the center of the transformer. Since the radial deformation is simulated at the height of 17 cm of the model, y value which has been obtained from the proposed technique is acceptable and the error percent is:

$$\%\text{ Error} = \frac{17-16.956}{17}\times 100 = 0.26\% \tag{8}$$

Deformation location estimation error is small and verifies that the proposed method is quite effective.

6. Conclusion

In this paper, a new analytical method has been proposed for exact determination of radial deformation location along the transformer winding height. This method is based on the locus of objects in space, which makes use of Ultra-wideband antennas to locate deformation. In this method, one transmitting antenna and two receiving antennas were used. With the time difference between received pulses, the exact location of deformation is determined. The simulation results confirm the validity of the algorithm.

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