Antennas Positioning for On-line Monitoring of Transformer Winding Radial Deformation Using UWB Sensors

Javad Ebrahimi
Electrical Eng. Dept.
Amirkabir Univ. of Tech.
Tehran, Iran
j_ebrahimi@aut.ac.ir

Gevorg B. Gharehpetian
Electrical Eng. Dept.
Amirkabir Univ. of Tech.
Tehran, Iran
grptian@aut.ac.ir

Hamidreza Amindavar
Electrical Eng. Dept.
Amirkabir Univ. of Tech.
Tehran, Iran
hamidami@aut.ac.ir

Maryam A. Hejazi
Electrical Eng. Dept.
Amirkabir Univ. of Tech.
Tehran, Iran
akhavanhejazi@aut.ac.ir

Abstract— **The application of Ultra-Wideband (UWB) sensors is a new method for on-line monitoring of transformer winding radial deformations. The measurements of received signals from a simplified model of the transformer winding demonstrate the high sensitivity of the proposed method to detect winding deformations. The proper position of transmitter and receiver antennas on the transformer tank is an important problem for the monitoring system. This problem has been studied in this paper.**

***Index Terms*— Transformers, On-Line Monitoring, Radial Deformation, UWB Sensor, Antenna Positioning.**

I. INTRODUCTION

The requirement of safe and reliable operation of power transformers leads to study and development of different fault detection and conditions monitoring methods. The short circuit current can cause radial deformations and axial displacements of transformer windings. These mechanical damages may not lead to an immediate failure of the transformer, but the ability of the transformer to withstand future mechanical and dielectric stresses may be highly decreased[1,2].

There are many different transformer monitoring 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 (SC) [1], Low Voltage Impulse test (LVI) [5] and Frequency Response Analysis (FRA) [3] for the detection of the winding deformation have been proposed.

In the SC test method, the short circuit reactance is measured while the transformer is off-line. The sensitivity of this method to the winding displacement is very low, and the type and the location of the mechanical damage in the winding cannot be determined [3].

The FRA method can be used off-line and on-line [6, 7]. The well-known FRA method has been carried out off-line. In this method, three experimental approaches of comparison are: *time-based*, *type based* and *construction-based*. Also *model-based* comparison has been presented recently for the FRA method. In the off-line FRA method, the transformer is switched on and off, on the high voltage side (HV-side). Therefore the transformer is usually disconnected from the power network on the low voltage side (LV-side) [6].

In the on-line FRA method, it is suggested that the transient over-voltages caused by the switching and the lightening can be used to determine the transfer function. Many factors affect this method such as lightning arresters and different substation topologies. The measurement timing depends on the time of occurrence of the overvoltage transients [8]. This method is in the research phase and has not been used for any transformer.

It should be mention that the off-line methods will not meet all the needs of the transformer monitoring systems. But, the on-line methods do not require switching of the transformer and can continuously monitor the transformer winding. The other advantage of the on-line monitoring method is the prediction of important faults before their occurrence.

The simulations have shown that the scattering parameter of the winding can be used as an index for on-line monitoring of winding radial deformation and axial displacement [9, 10]. The same as FRA method, this method is based on the comparison of results. This method is also in the research phase and has not been used for any transformer.

In this paper, a new on-line detection method of the transformer winding radial deformation has been developed using the electromagnetic waves analysis in the time domain. The Ultra-Wideband (UWB) signals and sensors, used for this method, have very high accuracy and more information about the type and location of the fault.

II. UWB SIGNALS

A UWB signal is defined to have an absolute bandwidth of at least 500 MHz or a fractional (relative) bandwidth of larger than 20% [11].

Large bandwidths of UWB signals bring many advantages for positioning, communications and radar applications, as follows [12]:

- Penetration through obstacles,
- Accurate position estimation,
- High-speed data transmission and
- Low cost and low power transceiver designs.

The short-pulse UWB techniques exhibit distinct advantages over more conventional radar techniques. These advantages include:

- Higher range measurement accuracy and range resolution due to the shorter spatial extent of the transmitter waveforms,
- Enhanced target recognition due to detection of additional information from a target's separate elements,

- Increased radar operational security because of the extremely large spectral spreading and
- Ability to detect very slowly moving or stationary targets [13].

Numerous applications of short-pulse technology were developed for short-range radar sensing, metrology, communications, and more recently, precision positioning [14].

For communications applications, short-pulse UWB techniques offer increased immunity to multipath cancellation due to the ability to discriminate between direct and time-orthogonal reflected waves. Low-pulse-rate UWB systems have the additional advantage of having extremely low duty cycles, which translate into low average prime power requirements, ideal for battery-operated equipment.

For active Radio Frequency (RF) tracking and positioning applications, short-pulse UWB techniques offer distinct advantages in precision time-of-flight measurement, multipath immunity for leading edge detection (i.e., first Time of Arrival (TOA)) and low prime power requirements for extended-operation RF Identification (RFID) tags [15].

In this research, UWB pulses have been used for on-line monitoring of transformer winding mechanical damages, which can be considered as a slowly moving or stationary target.

III. SIMPLIFIED METHOD OF HV WINDING

The proposed method of this paper is in the development phase. As a result, it is based on some assumption and simplified model. The simplified model of transformer HV winding with the ability of modeling the axial displacement and radial deformation has been built, as shown in Fig.1. This model should represent HV winding disks of transformers. Dimensions of the model are approximately 1/3 of a real one. Disks have made from plexiglass sheets which are covered by a layer of copper. They are separated from each other by spacers, which have equal thickness. Table I gives the model dimensions.

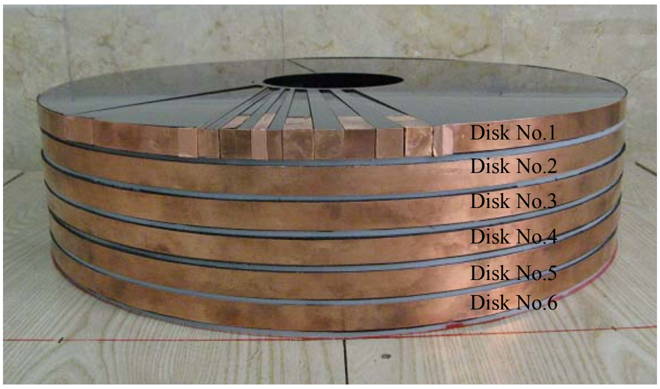

Fig.1: Simplified transformer winding and disk numbering

TABLE I:
DISK MODEL DIMENSIONS

	Disk	Spacer
Diameter	60 cm	60 cm
Thickness	2 cm	0.5 cm
Numbers	6	6

One of these disks has been cut in sectors with different dimensions. These sectors can be moved in radial direction as shown in Fig.2. The amount of the deformation is characterized by the deformation length. As listed in Table II, the thickness of each sector is equal to the thickness of each disk. But their widths are different, in order to model different radial deformations.

TABLE II:
SIZE OF SECTORS

Deformation width (cm)	0.5	1	2
Deformation thickness (cm)	2	2	2
Deformation area (cm^2)	1	2	4

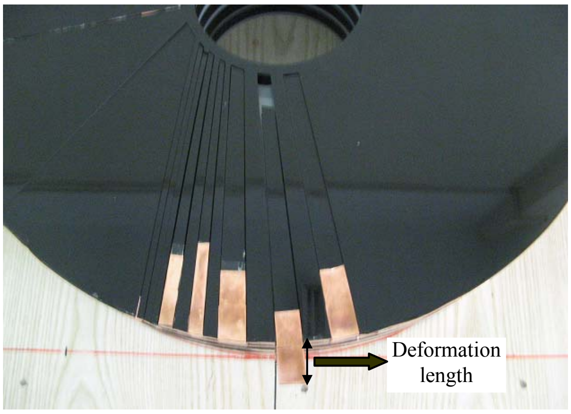

Fig. 2: Modelling of radial deformation

IV. MEASUREMENT SET-UP

In the oil-immerged power transformers, the oil is the propagation medium. In this paper, the propagation medium is considered to be air and the transformer tank is not modeled. Also, the radial deformation of only one phase of the transformer has been studied. It is assumed that there is not any high frequency source of electromagnetic waves in the transformer except the transmitter.

A bi-static transmitter and receiver have been used for the measurements. Fig. 3 shows the measurement set-up.

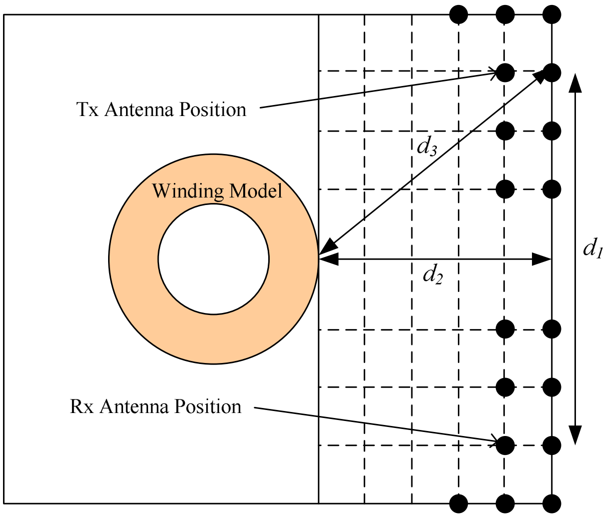

Fig. 3: Measurement set-up

In this figure, d_1 is the distance between the transmitting and receiving antenna, d_2 is the distance between the model and the center of the line connecting the antennas, d_3 is the distance between the transmitting/receiving antennas from the model.

As shown in Fig. 4, UWB pulses are radiated to the transformer model from the transmitter every T_1 seconds. As the deformation occurrence (fault) in the transformer has very low frequency, for example once in a year, the time interval (T_I) between transmitted pulses is not an important factor.

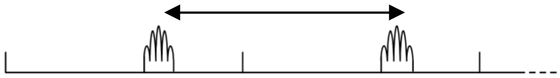

Fig .4: Transmitted UWB pulses (for every T_I seconds)

A typical transmitted pulse is shown in Fig. 5 and its parameters are listed in Table III.

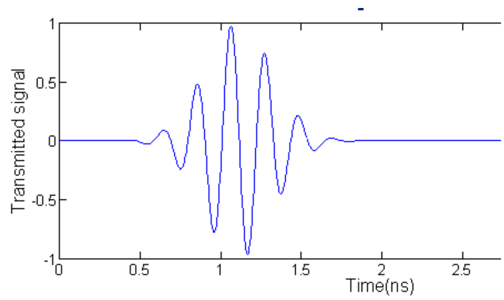

Fig. 5: Typical transmitted pulse

TABLE III:
PARAMETERS OF TRANSMITTED PULSE

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

Fig. 6 shows the timing of pulses received in the receiver. If the test duration is T_d seconds, then N_r pulses can be sent and we have:

$$N_r = \frac{T_d}{T_I} \tag{1}$$

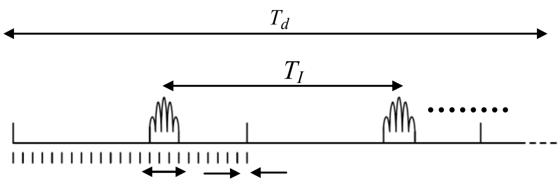

Fig.6: Timing of pulses received in receiver.

The total number of samples in each scan (N_C) is defined, as follows:

$$N_C = \frac{T_C}{T_S} \tag{2}$$

Where, T_S and T_C are the sampling time and receiving duration time in each scan, respectively.

Two kinds of measurement have been studied in this research:

•Reference measurements

There is no deformation or displacement on the transformer model. The results of this test have been stored as a normal and base case for the each position of antennas.

•Measurement of deformed cases

Different radial deformations have been applied to the winding but the test set-up configuration is the same for each antennas position.

V. ANALYSIS METHOD

The analysis of the measured data, to detect the radial deformation, has two essential stages. The first stage is the selection of a window in the time axes and the second stage is the comparison of the test results with the reference measurement using the mean absolute distance method.

A.Selection of Window Based on TOA Method.

Only a part of the received signal is related to the transformer model and the other parts are the signals, which are reflected from the surrounding objects of transformer model. In the first stage, the unwanted parts of the signal should be omitted based on TOA (time of arrival) method by using the following steps:

Step1: In this step, the time origin should be determined. Considering the Fig. 3, the shortest distance between the transmitter and the receiver is equal to d_1. The received signal has the waveform as shown in Fig. 7. In this figure, the first peak of the signal is related to the direct line of sight of the transmitter and receiver. The instant of this peak determines the time of origin (T_0). Based on this method, for each test the time of origin of each signal can be determined.

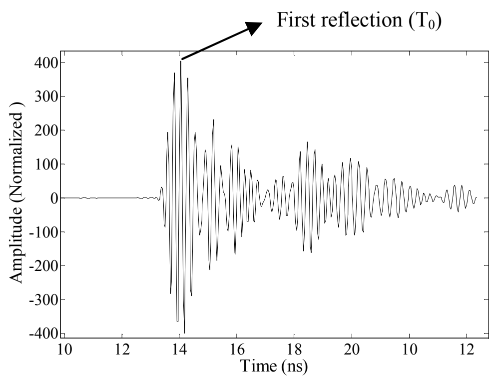

Fig.7: Selection of time origin

Step2: In this step, a matrix which has the data of received signals should be obtained.

The sampled data of each signal, received in the test duration time (T_d), are placed in a row of this matrix. The number of the matrix columns is equal to the number of samples in each scan (N_C). The matrix has N_r rows, where N_r is the number of pulses, which have been sent in T_d seconds (test duration time). It can be said that for each test set-up configuration, the test has been repeated for N_r times and the result of each test have been saved in a row. The results of the reference case (measurement) are stored in the matrix named w_1. The received pulses for the cases modeling the deformations, are stored in the matrix w_2, w_3 and w_n, where (n-1) is the number of the deformations.

Step 3: In this step, a representative vector is obtained for each deformed case. First, the time origin of all rows of the matrices w_1, w_2, w_3, …, w_n should be determined. Now, the columns of each matrix should be averaged to form a representative vector for each deformed case named, (W_1, W_2, W_3, …,W_n).

Step 4: In this step, in order to decrease the size of the matrix, the time interval related to the transformer winding is determined in the received waveform. The distance between the antenna and the winding is known (d_3). So, the moment of the first reflection from the transformer winding is known. This time can be calculated by the following equation:

$$T_1 = \frac{2d_3 - d_1}{3\times10^8} \tag{3}$$

Where, T_1 is the receiving time of the first reflection received from the model of the winding.

The timing interval of reflections (related to the winding) can be determined (using the winding dimensions) by the same equation.

The part of the pulse related to the winding can be extracted from the received pulse for the reduction of unwanted reflections ($W_1', W_2', W_3', \ldots, W_n'$).

As an example, Fig. 8 shows the received pulses for the reference and displaced winding measurements. The window, related to the winding reflections, has been shown in this figure, too.

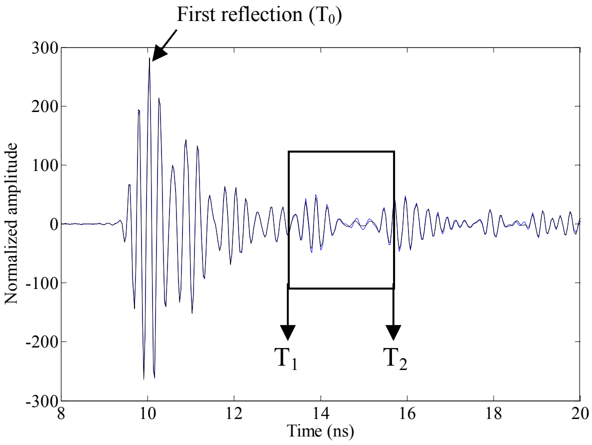

Fig.8: Received pulse can be windowed for detection of winding reflections

B. Comparison of Waveform of Each Test With Reference Case

After windowing, each pulse is compared with the reference case. The measurement set-up surrounding objects have not any movement and only the deformation has been applied to the transformer winding. By using the Mean Absolute Distance (*MAD*) method, the signals received in different deformation tests ($W_2', W_3', \ldots, W_n'$) can be compared with the signal of the reference case (W_1'), as follows:

$$MAD(k) = \frac{1}{N}\sum_{j=T_1}^{T_2}\left|\frac{W_k'(j) - W_1'(j)}{W_1'(j)}\right| \quad ,k = 2,\ldots,n \tag{4}$$

where, T_1 is the beginning time of the window or receiving time of the first reflection from the transformer, T_2 is the end instant of the window and N is defined, as follows:

$$N = \frac{T_2 - T_1}{T_S} \tag{5}$$

where, T_S is the sampling time.

VI. Measurement Results

The measurements of the radial deformation have been studied by using the proposed *MAD* index for each antenna position. Table IV lists the parameters of the radial deformation measurement set-up.

TABLE IV:
PARAMETERS OF RADIAL DEFORMAATION MEASUREMENT SET-UP

Antennas Position No.	Parameters						
	d_1 (cm)	d_2 (cm)	d_3 (cm)	T_d (s)	T_s (ps)	T_C (ns)	T_1 (ms)
1	140	50	86	10	31.79	20	50
2	120	50	78.1	10	31.79	20	50
3	100	50	70.7	10	31.79	20	50
4	80	50	64.3	10	31.79	20	50
5	60	50	58.3	10	31.79	20	50
6	140	40	80.6	10	31.79	20	50
7	120	40	72.1	10	31.79	20	50
8	100	40	64	10	31.79	20	50
9	80	40	56.6	10	31.79	20	50
10	60	40	50	10	31.79	20	50
11	140	30	76.2	10	31.79	20	50

As an example, Fig.9 shows the reflected pulse in the case of the radial deformation of the winding model.

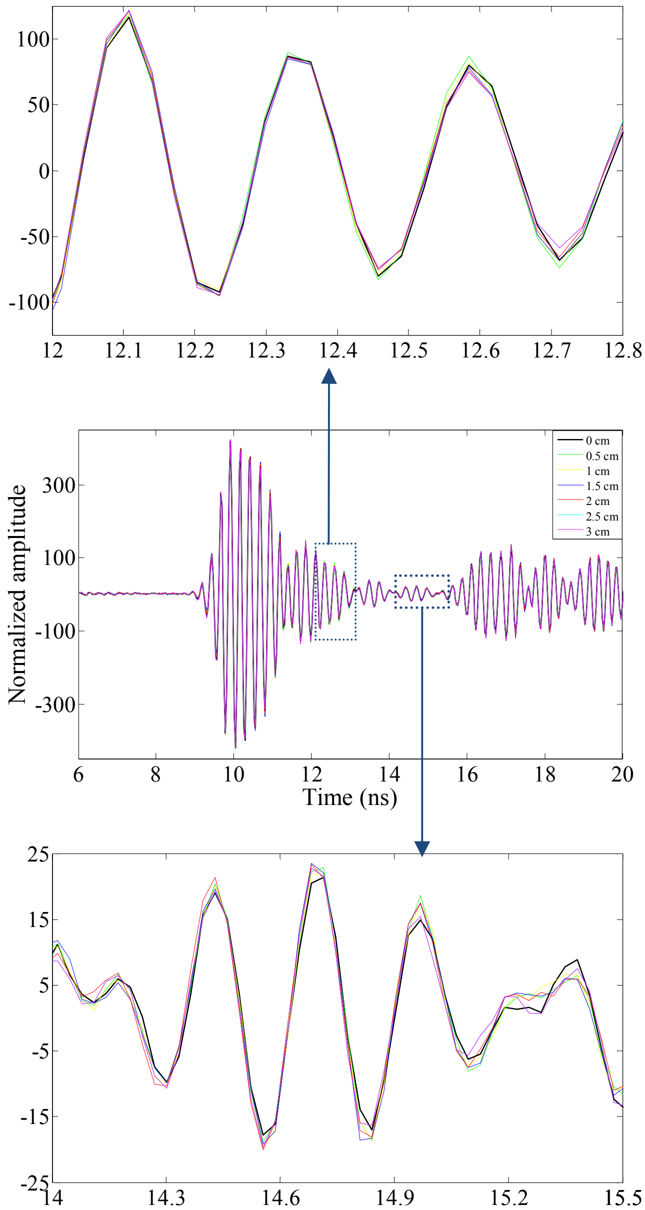

Fig.9: Reflected pulse for different radial deformation measurements

Table V gives the sum of *MAD* indices for radial deformations in each antenna position.

TABLE V:
SUM OF *MAD* INDICES IN DIFFERENT ANTENNAS POSITIONS FOR RADIAL DEFORMATIONS

Antennas Positions No.	Sum of *MAD*s
1	2.8570
2	**17.4044**
3	3.4197
4	4.9250
5	2.5133
6	9.9634
7	7.6238
8	7.0890
9	2.3671
10	2.2461
11	1.0330

Based on the results of Table V, it can be said gives that the position No. 2 has maximum MADs for different states of winding radial deformations. Therefore, this position has been selected for the installation and monitoring of different radial deformations. Table VI lists the calculated *MAD* index for the radial deformation measurements in position No. 2. The results of Table VI show that the *MAD* index for different radial deformations has different values. As a result, *MAD* can be used as an index to discriminate between different radial deformations. In the future work, proper algorithms should be used to assess radial deformation dimensions.

TABLE VI:
MAD INDEX OF RADIAL DEFORMATION

Deformation length (cm)	Deformation Area (cm^2)	*MAD*
0.5	1	4.03
1	2	2.96
1.5	3	4.82
2	4	3.17
2.5	5	1.26
3	6	1.17

VII. CONCLUSION

In this paper, on-line monitoring of transformer winding radial deformation using UWB sensors has been presented. The position of receiving and transmitting antennas is studied by a proposed index. The measurements on a simplified model of the transformer winding show the sensitivity of the proposed method to winding deformations. Based on measurement results and using the proposed index, it is shown that the best position can be selected, to install the monitoring antennas.

VIII. ACKNOWLEDGMENT

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