Feasibility Studies on On-line Monitoring of Transformer Winding Mechanical Damage Using UWB Sensors

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Abstract— **On-line monitoring of transformer winding axial displacement and radial deformation using Ultra-wideband (UWB) sensors has been presented in this paper. Measurements of the received signals from a simplified model of the transformer winding demonstrate the high sensitivity of the proposed technique to the winding deformation and displacement.**

Index Terms— **Axial Displacement, On-Line Monitoring, Radial Deformation, Transformers, UWB Sensor.**

I. INTRODUCTION

THE radial deformations and axial displacements of transformer windings are usually the result of electromagnetic forces due to high short circuit currents. 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 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 the winding deformation have been proposed.

In the short circuit test method, the short circuit reactance is measured while the transformer is off-line. 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 [3].

The FRA method can be used off-line and on-line [6, 7]. 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]. 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 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 power system structures. 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.

The off-line methods will not meet all the needs of the transformer monitoring systems. 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 and axial deformations [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 detection method of the transformer winding damages has been developed using the electromagnetic waves analysis in the time domain. The ultra-wideband (UWB) signals used for this method have very high accuracy of fault detection and have more information about the type and location of the fault because of special characteristics of the UWB signals.

II. UWB SIGNALS

According to the U.S. Federal Communications Commission (FCC), 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 penetration capability of a UWB signal is due to its large frequency spectrum that includes low frequency components as well as high frequency ones. This large spectrum also results in high time resolution, which improves ranging (i.e., distance estimation) accuracy.

From a radar perspective, short-pulse UWB techniques exhibit distinct advantages over more conventional radar approaches. 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].

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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 damage, which can be considered as a slowly moving or stationary target.

III. Test Object

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 lists the model dimensions.

Fig.1: Transformer winding model

TABLE I:
DISK MODEL DIMENSIONS

	Disk	Spacer
Diameter	60 cm	60 cm
Thickness	2 cm	0.5 cm
Number	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 deformation is characterized by deformation length. The thickness of each sector is equal to the thickness of each disk. But their widths are different, as listed in Table II, 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

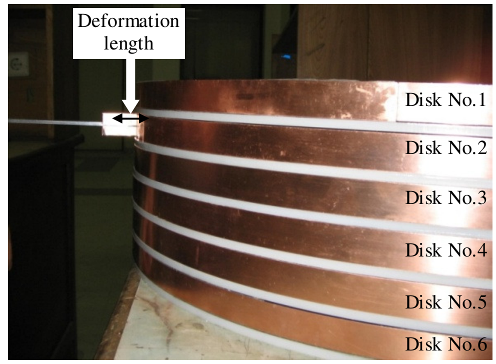

Fig. 2: Modelling of radial deformation (in disk No.2) and disk numbering

IV. Measurement Method

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. And 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.

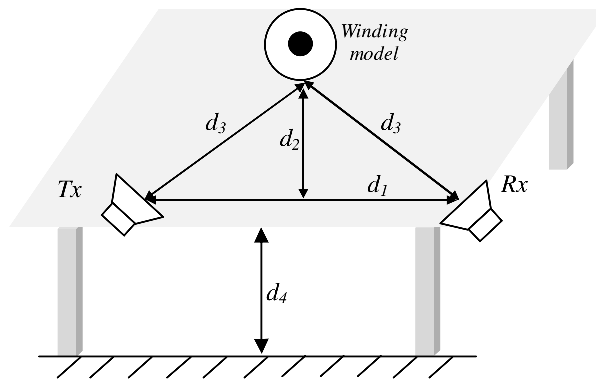

Fig. 3: Measurement set-up

In this figure, d1 is the distance between the transmitting and receiving antenna, d2 is the distance between the model and the center of the line connecting the antennas, d3 is the distance between the transmitting/receiving antennas from the model and d4 is the height of the set-up table from the ground.

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

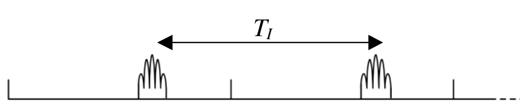

Fig .4: Transmitted UWB pulses (every T_I seconds)

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

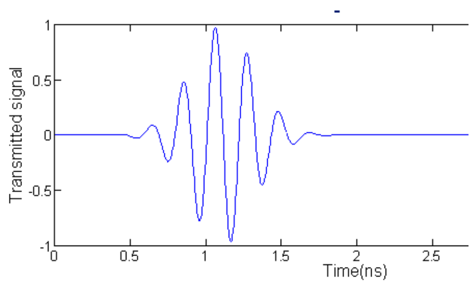

Fig. 5: Typical transmitted pulse

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 Td seconds, then Nr pulses can be sent, as follows:

$$N_r = \frac{T_d}{T_I} \quad (1)$$

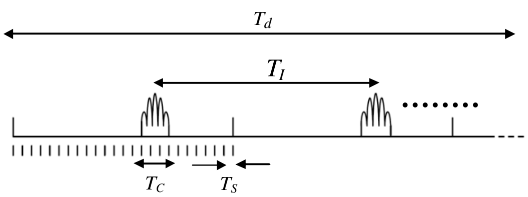

Fig.6: Timing of the pulses received in the receiver.

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

$$N_C = \frac{T_C}{T_S} \quad (2)$$

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 measurement*

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

•*Deformation measurement*

Different radial deformation and axial displacement have been applied to the winding but the test set-up configuration is the same for these cases.

V. Analysis Method

The analysis of the measured data, to detect the axial displacement and 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.

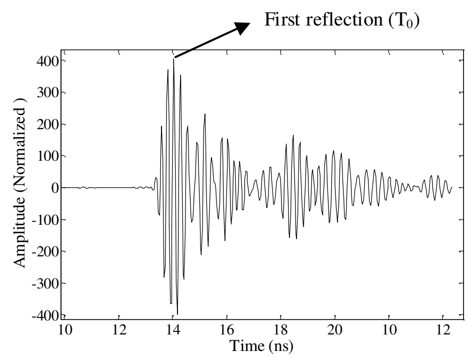

Fig.7: Selection of time origin

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), is 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 the 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 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 modeled 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:

$$T_1 = \frac{2d_3 - d_1}{3\times10^8} \quad (3)$$

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 (W1', W2', W3', …,Wn').

Fig. 8 shows a sample of received pulses for the reference and a displaced winding measurement. The window related to the winding reflections has been shown in this figure, too.

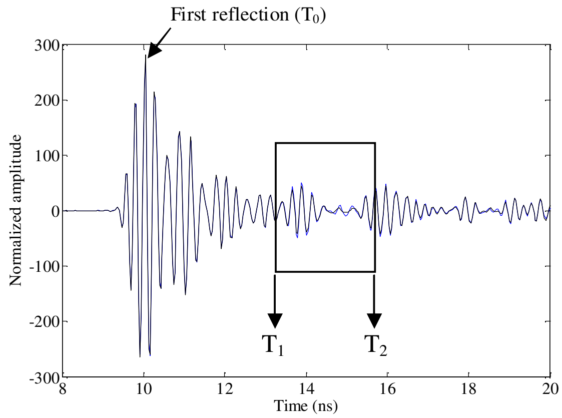

Fig.8: Received pulse can be windowed for detection of winding reflections

B. Comparison of Waveform of Each Test With Reference Case

After windowing, each pulse is compared with the reference case. The 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', …,W_n') can be compared with the signal of the reference case (W_1'), as follows:

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

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:

$$N = \frac{T_2 - T_1}{T_S} \quad (5)$$

Where, T_S is the sampling time.

VI. Measurement Results

The measurements of the axial displacement and radial deformation have been studied by using the proposed *MAD* index.

A. Axial Displacement

Table IV lists the parameters of the axial displacement measurement set-up.

TABLE IV:
PARAMETERS OF AXIAL DISPLACEMENT MEASUREMENT SET-UP

Parameter	Value
d_1	130 cm
d_2	80 cm
d_3	103 cm
d_4	100 cm
T_d	10s
T_s	31.79 ps
T_C	20ns
T_I	100ms

Fig.9 shows the reflected pulse in the case of the axial displacement of the winding model from 0 to 3 cm, in steps of 0.5 cm.

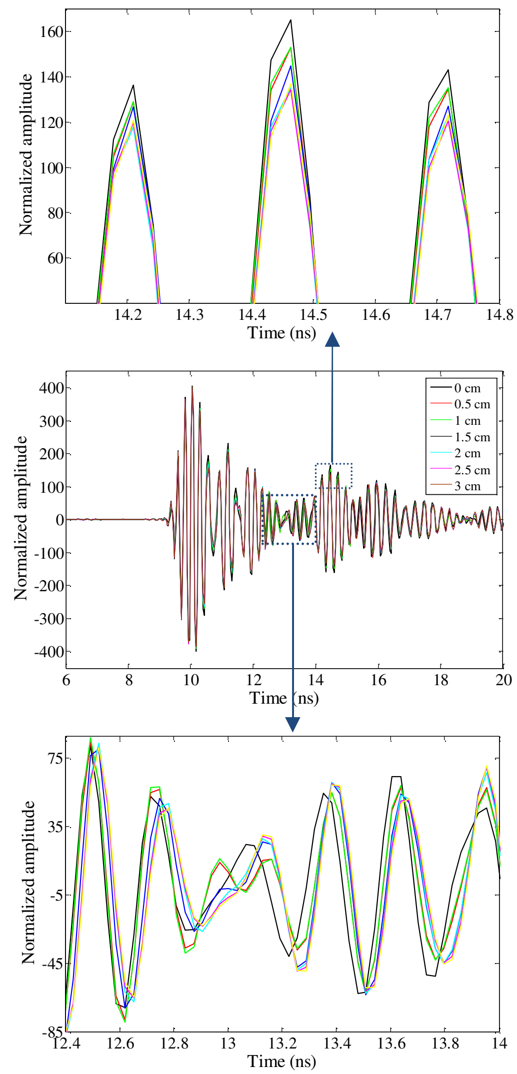

Fig.9: Reflected pulse for different axial displacement measurements

Table V lists the calculated *MAD* index for axial displacement measurements.

TABLEV:
MAD INDEX OF AXIAL DISPLACEMENT MEASUREMENTS

Axial Displacement (cm)	*MAD*
0.5	1.41
1	1.33
1.5	1.82
2	1.54
2.5	1.69
3	1.89

B.Radial Deformation

Table VI lists the parameters of the radial deformation measurement set-up.

TABLE VI:
PARAMETERS OF RADIAL DEFORMATION MEASUREMENT SET-UP

Parameter	Value
d_1	150 cm
d_2	100 cm
d_3	125 cm
d_4	100 cm
Disk Deformed No.	2
Deformation area	2 cm^2
T_d	10s
T_s	31.79 ps
T_l	100ms

Fig.10 shows the reflected pulses in the case of the radial deformation of the winding model.

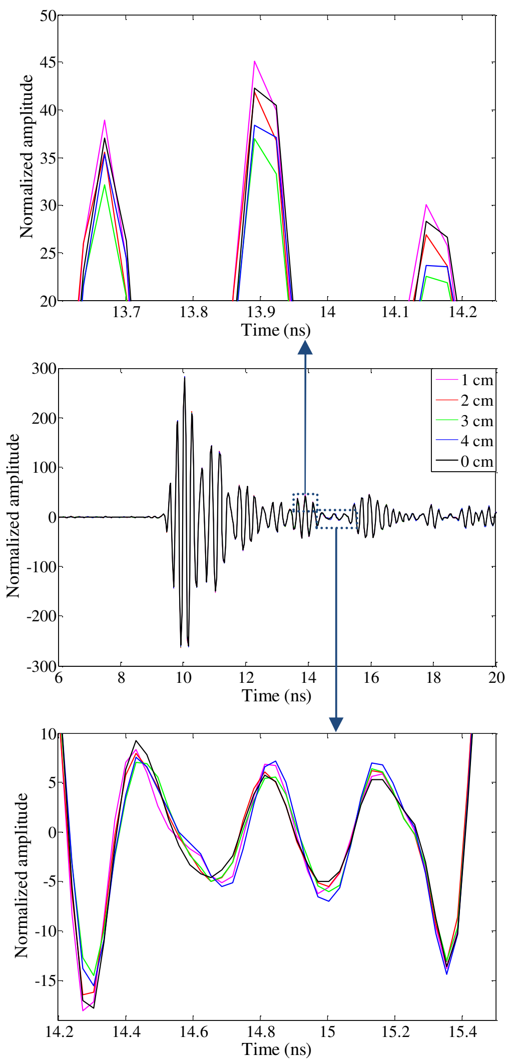

Fig.10: Reflected pulse for different length of radial deformation for 4cm^2 sector.

Table VII lists the calculated *MAD* index for the radial deformation measurements. The results of Table V show that the index is in the range 1.3< *MAD* <1.9. But, in the case of radial deformation, as listed in Table VII, the index is in the range 0.2 < *MAD* < 0.8. As a result, this index can be used as an index to discriminate between axial and radial deformations.

TABLE VII:
MAD INDEX OF RADIAL DEFORMATION

Deformation Area (cm^2)	Deformation length (cm)	*MAD*
4	1	0.3371
4	2	0.4396
4	3	0.4002
4	4	0.4605
2	1	0.3060
2	2	0.6137
2	3	0.4497
2	4	0.1940
1	1	0.4069
1	2	0.8008
1	3	0.2030
1	4	0.2901

VII. CONCLUSION

On-line monitoring of transformer winding axial displacement and radial deformation using UWB sensors has been proposed in this paper. Measurement on a simplified model of the transformer winding shows the sensitivity of the proposed method to the winding deformation and displacement. A new index has been proposed to discriminate between the axial displacement and the radial deformations.

VIII. ACKNOWLEDGMENT

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