Detection of Transformer Winding Radial Deformations by Using UWB pulses and DWT

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 on-line monitoring of transformer winding radial deformations using Ultra-Wideband (UWB) sensors and Discrete Wavelet Transform (DWT) has been presented in this paper. The measurements on a simplified model of the transformer winding demonstrate the high sensitivity of the proposed method to detect the winding radial deformation.**

***Index Terms*— Winding Radial Deformation, On-Line Monitoring, Transformer, UWB Sensor, Discrete Wavelet Transform.**

I. INTRODUCTION

Power transformers are most expensive and highly essential elements of electric power systems whose failures and abnormal operations may lead to the outage of a power system. The requirement of safe and reliable operation of power transformers leads to study and development of several fault detection and conditions monitoring methods. The short circuit due to electrodynamics forces 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 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 fault detection method has been developed, which uses Ultra-Wideband (UWB) sensors for the on-line detection of transformer winding radial deformations. The Discrete Wavelet Transform (DWT) is used for feature extraction and discriminating the different type of winding radial deformations.

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].

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. [13].

III. WAVELET TRANSFORM

Time–frequency transforms such as the Short Time Fourier Transform (STFT) and the wavelet transform are widely used for fault detection applications in the electrical systems.

The drawback of STFT is the fixed size of the time window for all frequencies. The wavelet transform is the breaking up of a signal into scaled and shifted versions of the mother wavelet [16]. Any discrete signal *x[n]* can be decomposed by using the wavelet function and the wavelet coefficients, as follows:

$$x[n]=\sum_{k} a_{j0,k}.2^{j0/2}.\phi[2^{j0}n-k]+\sum_{j=j0}^{J-1}\sum_{k} d_{j,k}.2^{j/2}.\varphi[2^{j}n-k] \quad (1)$$

where $\phi[n]$ is the scaling function, and $\varphi[n]$ is the mother wavelet, j is the scale of decomposition, k is the shifting factor, $a_{j0,k}$ are the approximation coefficients at a scale of $s=2^{j0}$, $d_{j,k}$ are the detail coefficients at a scale of $s=2^{j}$ and $N=2^{J}$, where N is the number of x samples.

The DWT divides the given function into different frequency components based on a power of two divisions. More concretely, if f_s (in samples per second) is the sampling rate used for capturing *x*, at the *j*th decomposition level, the detail d_j and the approximation a_j coefficient contains the information concerning the original signal components with the frequency bandwidth $\left[f_s/2^{j+1}, f_s/2^{j}\right]$ and $\left[0, f_s/2^{j+1}\right]$, respectively [16], [17].

Therefore, DWT carries out the filtering process. Note that the filtering is not ideal, a fact leading to a certain overlap between adjacent frequency bands [16], [18]. The shape of the frequency response for these filters depends on the type and the order of the mother wavelet used in the analysis.

IV. TEST OBJECT AND MEASUREMENT METHOD

As shown in Fig. 1, a simplified model of transformer High Voltage (HV) winding with the ability of modeling the axial displacement and radial deformation has been used as a test object. This model should represent HV winding disks of transformers. The 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 thicknesses. Table I lists the model dimensions.

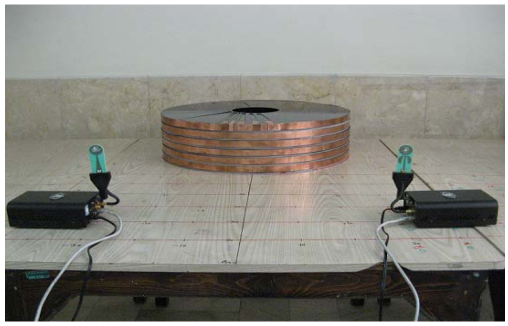

Fig.1: Transformer winding model and experimental setup

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, in order to model different radial deformations.

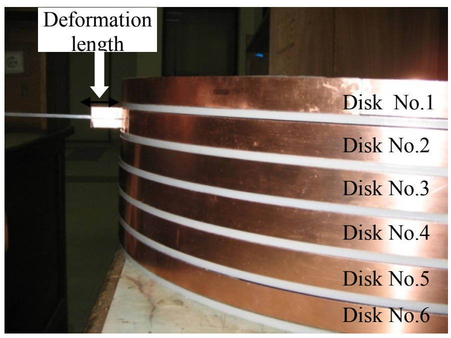

Fig. 2: Modelling of radial deformation (in disk No.2) and disk numbering

A bi-static transmitter and receiver have been used for the measurements.

•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 deformations have been applied to the winding but the test set-up configuration is the same for these cases. A typical waveform of received signal in the case of the radial deformation of the winding model is shown in Fig. 3.

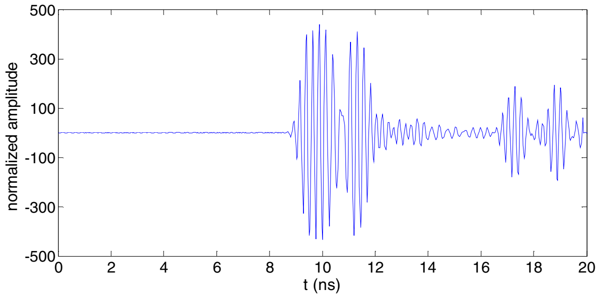

Fig. 3: typical waveform of receiving signal

V. ANALYSIS METHOD

In a classical Fourier analysis, the power of a signal can be obtained by integrating the Power Spectral Density (PSD), which is the square of the absolute value of the Fourier transform coefficients. A similar derivation can be obtained with the wavelet transform. Power Detail Density (PDD) can be described as the squares of the coefficients of one concerned detail. The power energy carried by this detail can be obtained by integrating the PDD of this detail [18]. The power-distribution function resulting from a wavelet transformation appears to be the optimal method to be applied to nonstationary signals to show changes in the amplitude and distribution of the harmonics [20].
The energies related to the approximation coefficient at jth decomposition level, E_j^a, and detail coefficient at jth decomposition level, E_j^d, can be computed as follows [21]:

$$E_j^a = \sqrt{\frac{1}{N_j}\sum_{i=1}^{N_j}(a_j)^2} \tag{2}$$

$$E_j^d = \sqrt{\frac{1}{N_j}\sum_{i=1}^{N_j}(d_j)^2} \tag{3}$$

where N_j is the data length of the jth decomposition level without the boundary effects and given by the following equation:

$$N_j = \frac{N}{2^{j+1}} \tag{4}$$

In this paper, the PDD difference between deformed winding and sound winding has been selected as an index for fault detection.

The type of wavelet function is important for the fault detection. Several wavelet functions such as daubechies 4, 8, 16, 28, 32, symlet 2, 4 8, coiflet 3 have been tested for a typical radial deformation. Table III gives the sum of PDD difference of different radial deformation for decomposition levels 2, 3, 4 and 5. It is obvious that daubechies 16 maximizes the fault index. Therefore, daubechies 16 has been chosen as the wavelet function for this application. The approximate a_5 and details d_1, …, d_5 for daubechies 16 mother wavelet are shown in Fig. 4.

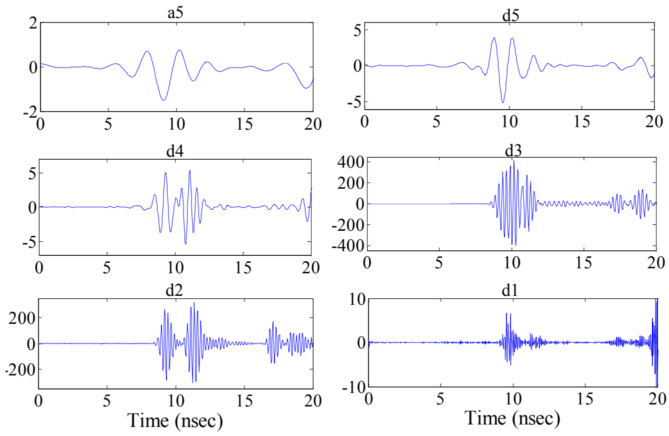

Fig. 4: Typical waveform of detail and approximate components of receiving signal for daubechies 16

TABLE II
SUM OF PDD DIFFERENCE OF DIFFERENT WAVELETS FOR DIFFERENT DECOMPOSITION LEVELS

Wavelet Type	Sum of PDD difference			
	d_2	d_3	d_4	d_5
db 4	0.64	1.01	3.88	1.89
db 16	1.06	0.60	**6.45**	2.43
db 28	1.06	0.60	6.17	2.67
db 32	0.58	0.68	5.99	2.77
sym 2	0.33	0.86	2.7	3.44
sym 4	0.84	0.50	4.18	4.06
sym 8	0.76	0.56	5.44	3.56
coif 3	0.66	0.85	3.77	4.73

Fig. 5 shows detail *d4* of receiving signal for daubechies 16 mother wavelet for the case, which has not any deformation and the case with 1, …, 4 cm deformation length. The deformation area is equal to 4 cm^2 in Fig. 5.

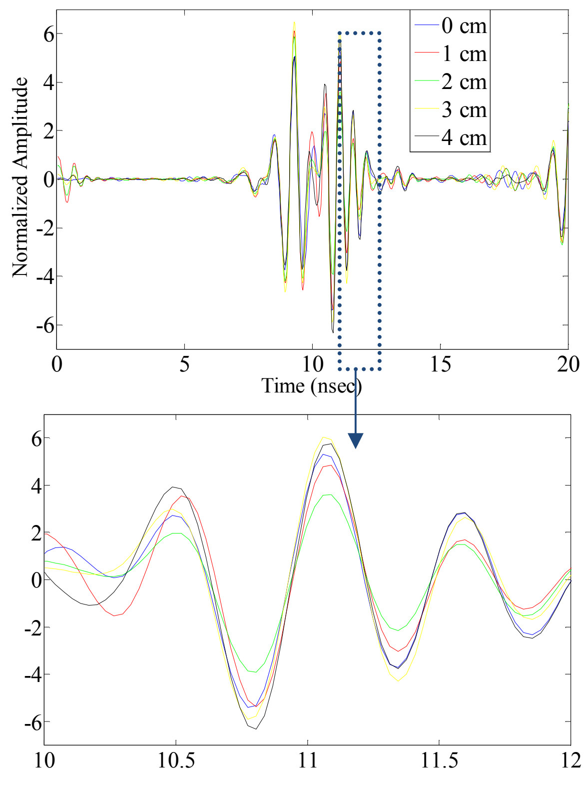

Fig. 5: d_4 component of receiving signal for daubechies 16 mother wavelet.

The results of applying PDD difference index for the case of $2\times 2\ cm^2$ radial deformation are listed in Table III.

TABLE III
PDD DIFFERENCE OF RADIAL DEFORMATION

Deformation Area (cm^2)	Deformation length (cm)	*PDD* difference
2	1	-0.1472
2	2	-0.1110
2	3	-0.2604
2	4	-0.2962
4	1	0.5487
4	2	0.4369
4	3	0.2439
4	4	0.3029
6	1	0.0166
6	2	-0.2188
6	3	-0.3483
6	4	0.0100
8	1	0.8065
8	2	0.7506
8	3	0.8443
8	4	0.8876

The results of Table III show that the PDD difference for different radial deformation has different values. As a result, this index can be used as an index to discriminate between different radial deformations.

VI. CONCLUSION

On-line monitoring of transformer winding axial displacement using UWB sensors has been proposed in this paper. A new index has been proposed to detect the radial deformation. This index is defined as the estimation of the energy content of any decomposed detail in the DWT. The measurement on a simplified model of the transformer winding shows that the proposed method can be used discriminate between different winding radial deformations.

VII. ACKNOWLEDGMENT

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