Improved Detection Sensitivity with Combined WPT and HHT for Power Transformer Winding Deformation Analysis

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ABSTRACT

The success of health monitoring and condition assessment of power transformers based on winding current signature analysis lies on proper extraction of features. The extraction of features in turn depends on appropriate signal processing methods. Fourier based signal analysis provides only frequency information and also suitable only for stationary signals. In this paper we present a combined Wavelet Packet Transform (WPT) and Hilbert Huang Transform (HHT) based time scale and time frequency analysis for the extraction of power transformer winding current features through an experimental study. The experimental work is based on short circuit test conducted on a 33 kV/11 kV, 10 MVA power transformer and axial winding deformation fault is introduced by loosening the bolts of winding structure. It is observed that Combined WPT and HHT offers better feature extraction strategy than analysis using HHT alone.

Keywords- transformer, WPT, HHT, axial deformation, feature extraction, detection sensitivity

1. 1. INTRODUCTION

2. Power transformers are most expensive equipment in power industry 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 the study and development of several fault detection and condition monitoring methods. The electrodynamics forces created due to short circuits cause radial deformations and axial displacements of transformer windings [1]. 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 highly be decreased.

Transformer failures are various types and can occur due to various causes. The winding deformation is one such severe fault that occurs due to a short circuit or vibration during transportation. Hence it is essential that power transformers need to be demonstrated for their short circuit withstand capability through a special test namely the short circuit test [2]. After the test procedure, transformer tank is subjected for visual check to identify whether the windings have experienced any mechanical deformation. Transfer function (TF) method [3] and frequency response analysis (FRA) method [4] exists for detecting the mechanical deformation of the transformer windings but do not provide time information.

Applications of short time Fourier transform and wavelet transform (WT) have been dealt but these methods offer only time scale analyses that do not provide frequency information directly [5]. It has been shown that Hilbert Huang transform (HHT) an empirical mode decomposition and subsequent Hilbert spectral analysis is suitable for non stationary signal analysis and offers instantaneous variation of frequency [6] and hence this method has been attempted and validated for winding deformation analysis [7]. However due to shortcomings in EMD process mode mixing occurs and meaningless intrinsic mode functions are generated. Thus the results from HHT will lead to misinterpretation of frequency contents present in the signal. Since WPT has a multi resolution analyzing capability, this beneficiary feature is exploited and combined with HHT to seek for solving the mode mixing problem encountered in HHT [8-9]. This paper presents an experimental method of validation of the proposed scheme for demonstrating winding deformation analysis on a 33 kV/11 kV, 10 MVA power transformer that serves as the device under test (DUT).

2. WINDING DEFORMATION IN DUT

The DUT to demonstrate the winding deformation analysis using the proposed method is shown in Fig. 1. Low voltage impulse excitation method is adopted for winding deformation detection. The high voltage (HV) winding is excited with a signal similar to standard lightning impulse of 10 V, 1.2/50 μs from an Agilent arbitrary function generator. The low voltage (LV) winding is shorted. The axial winding deformation is simulated by loosening the bolts of the winding structure and the winding current is measured before tightening and after tightening the bolts using Agilent digital storage oscilloscope. The winding currents measured after tightening is referred as no fault current (without axial deformation) and before tightening is referred as fault current (with axial deformation) respectively.
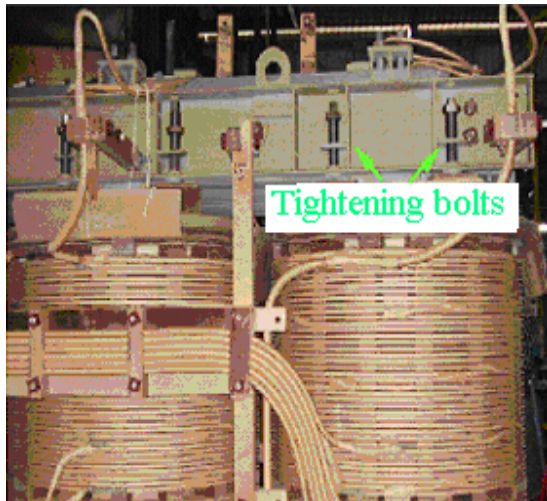
Figure 1: Device under test
(Power transformer 33 kV / 11 kV, 10 MVA)

The measured winding currents without axial deformation and with axial deformation are shown in Fig. 2 and Fig. 3 respectively. The frequency domain representations of the winding currents computed through FFT are shown in Fig. 4.
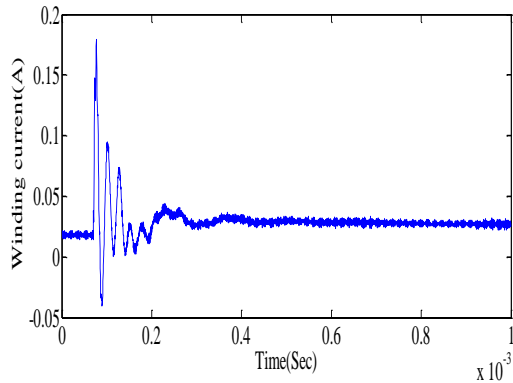

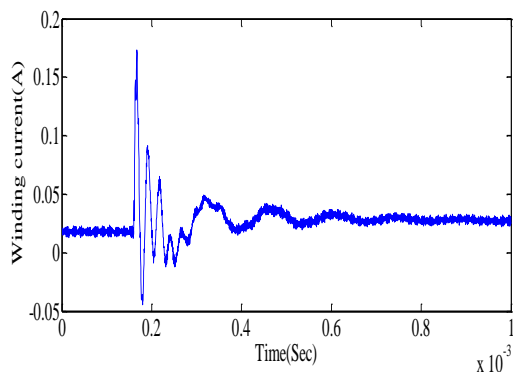**Figure 2: Measured winding current under no fault condition**

Figure 3: Measured winding current under fault condition
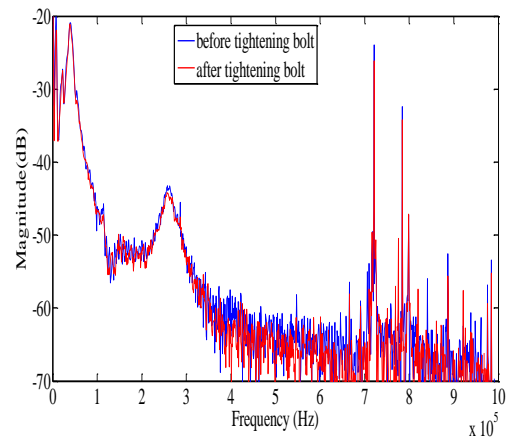

Figure 4: Measured no fault and with fault winding current in frequency domain

The frequency domain representation reveals that the measured winding current has 40 kHz, 260 kHz and 721 kHz as dominant resonant frequencies. Further it is observed that the resonant frequency 721 kHz responds to winding deformation effectively by indicating the shift and change in magnitude. However the other resonant frequencies such as 861 kHz, 921 kHz, 976 kHz and 984 kHz are observed with low energy levels or in other words low magnitude levels.

3. HILBERT HUANG TRANSFORM

Most of the real time signals are basically non-linear and non-stationary. The existing time frequency analysis methods do not have good efficiency to analyze such type of real signals. To overcome the deficiencies of the existing methods a new method namely Hilbert Huang Transform (HHT) was introduced by Norden E.Huang [10].

The HHT is derived from the principals of empirical mode decomposition (EMD) and the Hilbert Transform. In the EMD process the acquired signal is decomposed into collection of intrinsic mode functions (IMF's). It is carried out by sifting process. These IMF's should satisfy the following two conditions.

(1) In the whole data segment, the number of extreme points and the number of zero-crossing must be equal or have a difference of one at most.

(2) At any time considered, the average of the envelope formed by and the local maximum point and the envelope formed by the local minimum point is zero.

In the second stage the instantaneous frequency and amplitude are extracted from each IMF. The sifting process is described through a flow chart as shown in Fig. 5.
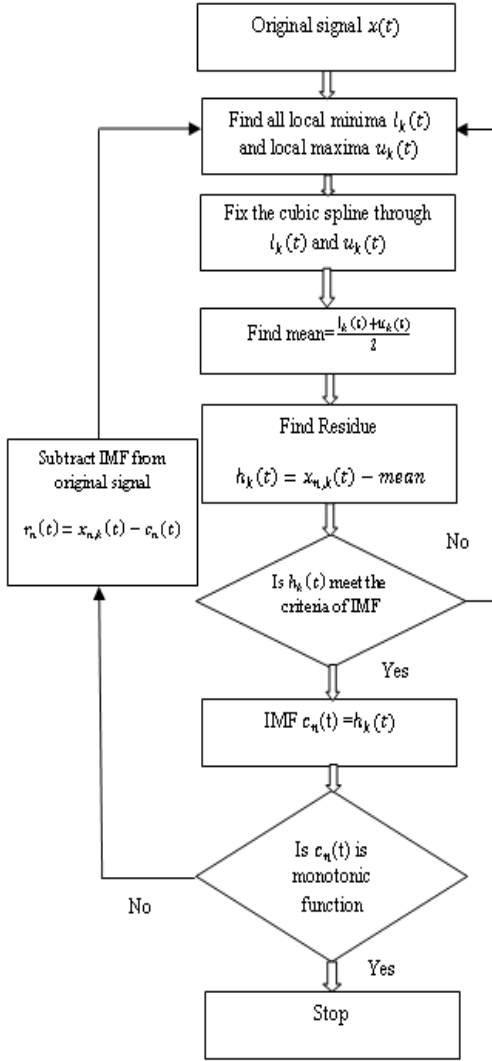
Figure 5: Flowchart of sifting process

The original signal is equal to sum of all the IMF's and its final residue.

$$Z_j = x_j + iy_j \qquad (1)$$

In the complex form x is the original signal and y is the Hilbert transform of the original signal. Instantaneous frequency and amplitude are calculated through the formulae as mentioned below.

$$\phi_j = tan^{-1}\left(\frac{y_j}{x_j}\right) \qquad (2)$$

$$a_j = \sqrt{(x_j^2 + y_j^2)} \qquad (3)$$

$$f_j = \frac{1}{2\pi}\frac{d\phi_j}{dt} \qquad (4)$$

4. WAVELET PACKET TRANSFORM

The wavelet packet transform is an efficient and powerful technique that provides time scale representation of a non-stationary signal with good time resolution than a Fourier transform. WPT is an extension of Short Time Fourier Transform (STFT) that has a constant window length and allows high frequency components to be analyzed with short

time interval and low frequency components with long time intervals. WPT decomposition of a signal produces narrow band signals consisting of high and low frequency sub bands. The two levels WPT decomposition is shown in Fig. 6 where "LF" and "HF" are the low-pass and high-pass filters, respectively. 'A' and 'D' denote approximation and detail coefficients at different levels. Recently WPT has been used along with HHT to analyze vibration signals acquired accelerometer sensor from a power transformer [11]. The frequency selective feature of this approach permits its effective usage in fault classification problems also.
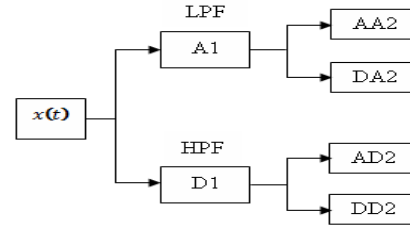

Figure 6: Two level Wavelet packet decomposition

In the WPT algorithm, both the detail and approximation coefficients (high and low frequency constituents) are decomposed into lower levels by convolving them with an expanded version of the mother wavelet (low-pass filters) or a compressed version of the mother wavelet (high-pass filters) as the case may be and then down sampling by a factor of two [12]. The cutoff frequencies for the low-pass and high-pass filters have been selected on the basis of length of the signal sampling period and based on the frequency content of the signal.

5. HHT BASED DEFORMATION ANALYSIS

HHT algorithm is implemented through Matlab coding. The winding current signals acquired from a 33 kV / 11 kV, 10 MVA power transformer under no fault and with fault condition are subjected to HHT based analysis. The time frequency representations of the first three IMF's of no fault and with fault winding currents are shown in Fig. 7. It is evident that the resonant frequencies in the high frequency region respond to axial deformation in an effective manner. Further the time frequency representations of the IMF's of no fault and with fault show clear distinction and hence offer better visual interpretation of changes in resonant frequencies along with time information. Thus it is possible to identify the time at which the fault would have occurred. Table 1 and Table 2 presents the details of features extracted using HHT. The shift in resonant frequency and change in amplitude are the evidences of axial deformation fault. Further it is observed that the low energy resonant frequency 260 kHz as observed from Fig. 4 show increased amplitude change in comparison to other resonant frequencies.
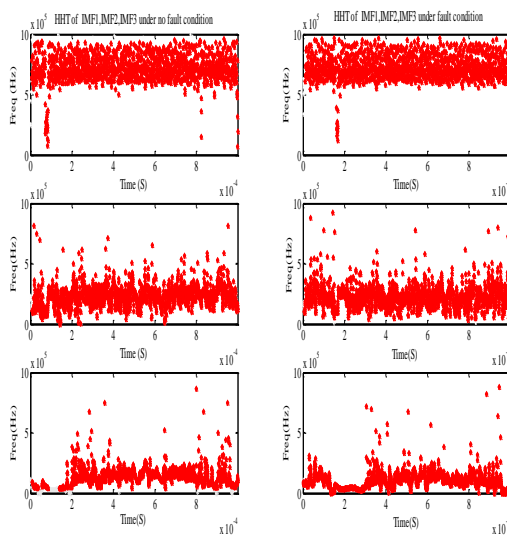
Figure 7: Time frequency representation of IMF's of no fault and with fault winding current based on HHT

6. WPT AND HHT BASED DEFORMATION ANALYSIS

The statistical features extracted from the results of HHT based analysis reveals that the distinction is not clear for winding deformation detection. The low energy resonant frequency 260 kHz is observed with less amplitude and detection based on this may not be sensitive. Hence we proceed to apply combined WPT and HHT analysis. For decomposition of the winding current with WPT 'dB5' mother wavelet is chosen and two level decomposition of the winding current under no fault and with fault condition is obtained. Since the winding current of transformer is highly noisy the selection of mother wavelet is very important for extracting the meaningful component. Each of the decomposed narrow-band signals have a relationship with the original signal that can be identified through the computation of correlation factor. Hence the narrow-band signal that does not contain the resonant frequencies of interest is filtered and only the narrow-band signal that has a correlation factor above average is considered for further analysis. Consequently other narrow-band signals will be made zero. After filtering, the signal is reconstructed and processed by HHT. Fig. 8 show the time frequency representations of IMF's of no fault and with fault winding current subjected to combined WPT and HHT analysis. It is evident from Fig. 8 that IMF's show changes in the instantaneous frequency variation between no fault and with axial deformation fault conditions. Tables 1 and 2 indicate the features extracted from HHT results and combined WPT and HHT results. Table 1 high lights that the resonant frequency 260 kHz is observed with better magnitude level when analyzed with combined WPT and HHT than the analysis with HHT alone. Further the standard deviation is higher for all the IMF's with combined WPT and HHT analysis than with HHT alone. To verify whether the level of decomposition will improve the detection sensitivity further, we subjected the measured winding current under no fault and with fault condition using 4 levels decomposition with WPT. Fig. 9 shows the tree diagram of 4 levels WPT decomposition. The results of feature extraction for the low energy resonant frequencies are shown in Table 3 and Table 4.
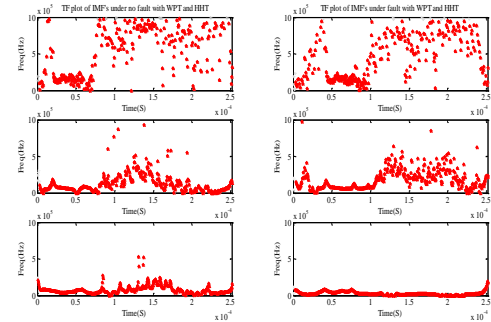

Figure 8: Time frequency representation of IMF's of no fault and with fault winding current based on combined WPT and HHT
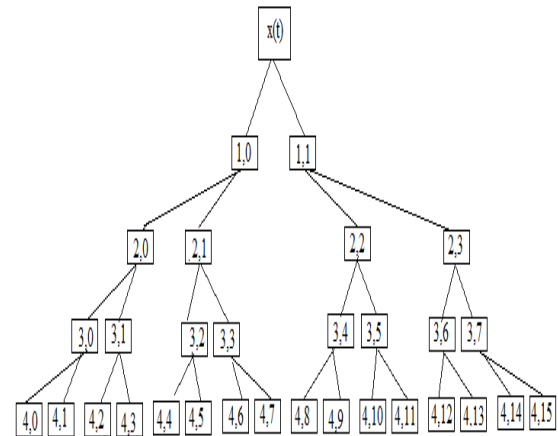

Figure 9: Tree diagram of 4 level WPT decomposition

Table 1: Features extracted from HHT, combined WPT and HHT analysis of winding current

	Before Tighten (Fault)		After Tighten (No fault)	
	Resonant Frequency (KHz)	Amplitude (dB)	Resonant Frequency (KHz)	Amplitude (dB)
HHT	721	-49.22	720	-50.94
	263	-72.89*	260	-79.95**
	39	-47.09	40	-48.23
HHT WITH WPT	724	-70.86	720	-72.13
	264	-68.06*	260	-68.27**
	44	-46.02	40	-48.89

Table 2: Statistical features extracted from HHT, combined WPT and HHT analysis of winding current

IMF's	Standard deviation for HHT		Standard deviation for HHT WITH WPT	
	Before Tightening (Fault)	After Tightening (No fault)	Before Tightening (Fault)	After Tightening (No fault)
IMF1	0.0033	0.0029	0.0270	0.0277
IMF2	0.0017	0.0015	0.0163	0.0152
IMF3	0.0119	0.0113	0.0152	0.0123

Table 3: Features extracted from FFT, HHT and combined WPT and HHT analysis of winding current under no fault

After Tighten(No Fault)					
FFT		HHT		HHT with WPT (4,0)	
Freq (KHz)	Amp (dB)	Freq (KHz)	Amp (dB)	Freq (KHz)	Amp (dB)
861	-61.74	860	-86.58	863	-45.78
921	-57.62	920	-82.59	939	-46.94
976	-59.39	975	-84.15	969	-47.67
984	-55.20	983	-80.12	984	-48.40

Table 4: Features extracted from FFT, HHT and combined WPT and HHT analysis of winding current with fault

Before Tighten(Fault)					
FFT		HHT		HHT with WPT (4,0)	
Freq (KHz)	Amp (dB)	Freq (KHz)	Amp (dB)	Freq (KHz)	Amp (dB)
863	-63.62	862	-89.43	863	-43.28
921	-62.42	920	-87.73	924	-46.94
976	-56.84	975	-82.08	967	-46.82
984	-53.38	983	--78.90	984	-46.61

7. CONCLUSION

This paper presented experimental validation of the proposed method of power transformer winding deformation detection based on combined WPT and HHT. The method was validated through short circuit test with low voltage impulse excitation on a 33 kV/ 11 kV, 10 MVA power transformer based on the results of measured winding currents. The method concentrated on effective feature extraction strategy to achieve improvement in detection sensitivity. Further the advancements in high speed computing facilities and high resolution sampling based instrumentation pave way for applying this type of signal analysis methods for winding deformation detection.

8. REFERENCES

[1] K.Karsai, D. Kerenyi and   L. Kiss. (1987). Large power transformers. Elsevier   Science Publishers.

[2] S.Santhi, S.Jayalalitha, V.Jayashankar, V.Jagadeesh Kumar. (2005). Detection of winding deformations during short time currents tests. Proceedings of IEEE IMTC Ottawa, Canada. May 17-23. 2005.

[3] E. Rahimpour, J. Christian, K Feser and H. Mohseni. (2003). Transfer function method to diagnose axial displacement and radial deformation of transformer winding. IEEE Trans. on Power Delivery. vol. 18, No.2. 493-505.

[4] S.A.Ryder. (2003). Diagnosing transformer faults using frequency response analysis. IEEE Electrical Insulation Magazine. Vol.19. No.2.16-22.

[5] S.Santhi,V.Jayashankar,V.Jagadeesh   Kumar.(2008). Time frequency analysis of method for the detection of winding deformation in transformers during short circuit test. Instrumentation and Measurement Technology Conference proceedings, I^2MTC 2008.Canada. 1-5.

[6] Weihua Xiong, Ruisong Ji. (2006). Nonlinear Time Series Analysis of Transformer's Core Vibration. IEEE Proceedings of the 6th World Congress on Intelligent Control and Automation. June 21 - 23, Dalian, China. 5493-5496.

[7] Arivamudhan M, Santhi S, Abirami S. (2013).Broad band excitation for transformer winding deformation detection and analysis using Hilbert Huang transform. Proceedings of the International conference on Trends in Industrial Measurements and Automation (TIMA-2013). December 2013, Chennai. 79-83.

[8] Shuyou Wu, Weiguo Huang, Fanrang Kong, Pugliang Zhe.(2009) Vibration feature extraction of power transformer using an time scale frequency analysis method based on WPT and HHT. Power Electronics and Motion Control Conference. IPEMC'09.2577-2581.

[9] Z.K. Peng, Peter W. Tseb, F.L. Chu. (2005). An improved Hilbert–Huang transform and its application in vibration signal analysis. Journal of Sound and Vibration. 286.187–205.

[10] N.E. Huang, Z.Shen, S.R.Long, et al.(1998).The empirical mode decomposition and the Hilbert spectrum for nonlinear and non-stationary time series analysis. Proceedings of Royal society of London, Series A. 903-994.

[11] Shuyou Wu, Weiguo Huang, Fanrang Kong, Qiang Wu, Fangming Zhou, Ruifan Zhang, Ziyu Wang.(2010). Extracting Power Transformer Vibration Features by a Time-Scale-Frequency Analysis Method. J. Electromagnetic Analysis and Applications. 2. 31-38.

[12] Gao Sheng-Wei, Zhang Mu, Yuan Chen-Hu, Sun Xing-Tao, Zhang Chuang.(2011). Wavelet Packet Analyzing of Power Transformer Partial Discharge Signals. IEEE International Conference on Control, Automation and Systems Engineering (CASE), 30-31 July 2011, Singapore.