ISSN : 2248-9622, Vol. 3, Issue 5, Sep-Oct 2013, pp.1444-1454

RESEARCH ARTICLE OPEN ACCESS

Fault Current Detection of Three Phase Power Transformer Using Wavelet Transform

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Abstract
The disturbances of power systems are nonperiodic, nonstationary, short duration and impulse super-imposed nature.The wavelet transform is one of the most suitable tool for the analysis of power system disturbances. In this paper, the application of wavelet transforms to determine the type of fault and accurate classification for the change in the wave shape due to fault occurrence is investigated. The maximum detail coefficient and energy level of each type of fault are characteristic in nature and are used for distinguishing the fault types.
Keywords-Transformer faults, differential protection, frequency analysis, wavelet transforms, Matlab simpower power system disturbance.

I. INTRODUCTION

Power transformer protection has always been a challenging problem for protection engineers. The main concern in protecting this particular element of power systems lies in the accurate and rapid discrimination between magnetizing inrush and different internal faults currents [1] and [2]. Since the magnetizing branch appears as the shunt element in the transformer equivalent circuit, the magnetizing current upsets the balance between the currents at the transformer terminal and is therefore experienced by differential relay as fault current. Magnetizing inrush currents sometimes have high magnitudes that cause traditional differential relays to initiate trip actions disconnecting the protected transformer from the system. Such mal-operation of differential relays can affect both the reliability and stability of the whole power system. In addition, magnetizing inrush current contains a high amount of the second and sometimes the fifth harmonics [1]-[2] Most of the conventional transformer protection relays employ the harmonic analysis approach to identify the type of the current that flows in the protected transformer. The main idea of the harmonic restraint differential relays is to extract the fundamental (1^{st}), the second (2^{nd}) and sometimes the fifth (5^{th}) harmonics and to compare the ratios of the 2^{nd} and 5^{th} harmonics with 1^{st} to a predefined threshold value. There have been different algorithms to carry out the harmonic analysis. Among these algorithms, sine cosine correlations, rectangular transform, discrete Fourier transform (DFT), Least-square method, Walsh functions, Haar functions and Kalman filtering technique, etc. are significant [1] and [3]. The main drawbacks of the 2^{nd} harmonic restraint approach that the 2nd harmonic may also exist in some internal faults of the transformer windings. In addition, the new low-loss amorphous core materials in modern power transformers are capable of producing magnetizing inrush currents with low 2^{nd} and 5^{th} harmonic contents [1]-[3]. These traditional signal processing tools used for frequency analysis are based on the conditions of stationarity and periodicity. However, disturbance power systems are of a nonperiodic, nonstationary, short duration and impulse super-imposed natures [4]. Efficient frequency analysis should be able to overcome the limitations of the traditional signal processing tools. The wavelet analysis is one of the newly applied frequency tools for processing signal with complex characteristics.Transients in power systems result from a variety of disturbances of power transformer, such faults currents, are extremely important. Faults currents are classified as external and internal faults currents. Wavelet theory is the mathematics, which deals with building a model for non- stationary signals, using a set of components that look like small waves, called wavelets. It has become a well- known useful tool since its introduction, especially in signal and image processing [5].

II. WAVELET TRANSFORM

The wavelet analysis and wavelet transforms have emerged recently as a powerful tool for signal processing in different applications, particular for power system applications. The transient characteristics of wavelets can be employed to carry out exact and effective analysis of signals with complex frequency-time plane. Moreover, the wavelet analysis can accommodate non uniform bandwidths as the bandwidth is higher at higher frequencies, which make it possible to implement the wavelet analysis through different levels of decimation in a filter bank [1]. The applications of wavelet analysis in power systems include analysis and detection of electromagnetic transients, power quality assessment, data compression, and fault detection [4]. The wavelet analysis has been recently used in current differential pilot relay, where current diagnosis is based on comparing the first level approximation with a predefined threshold value [4]. Frequency analysis is not suited for transient analysis, because Fourier based analysis is based on the sine and cosine functions, which are not transients. These results in very wide frequency spectrum in the analysis of transients Fourier techniques cannot simultaneously achieve good location in both time and frequency for a transient signal [5]. The main advantage of wavelet transform over Fourier is that the size of analysis technique varies in proportion to the frequency. Hence offer a better compromise in terms of localization [5].

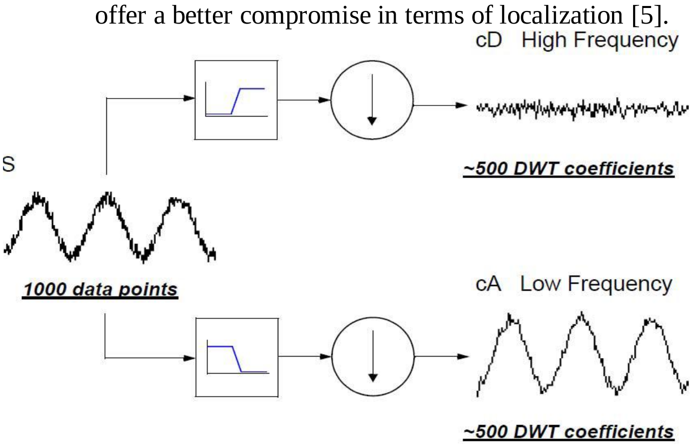

Fig. 1. Analyses of signal using wavelet transform

The wavelet transform decomposes transients into a series of wavelet components, each of which corresponds to a time domain signal that covers a specific octave frequency band containing more detailed information. Such wavelet components used to detect, localize, and classify the sources of transients. Hence, the wavelet transform is feasible and practical for analyzing power system transients [5-9]. The discrete wavelet transform (DWT) is normally implemented by Mallat's algorithm its formulation is related to filter bank theory.

Wavelet transform is largely due to this technique, which can be efficiently implemented by using only two filters, one high pass (HP) and one low pass (LP) at level (k). The results are down-sampled by a factor two and the same two filters are applied to the output of the low pass filter from the previous stage. The high pass filter is derived from the wavelet function (mother wavelet) and measures the details in a certain input. The low pass filter on the other hand delivers a smoothed version of the input signal and is derived from a scaling function, associated to the mother wavelet. The idea is illustrated in Figure 2 which mathematically is expressed as [5].

$$Y_{High}\ [k] = \sum_n x\ [n].\ H\ [2k - n]$$
$$y_{Low}\ [k] = \sum_n x\ [n].\ L\ [2k - n]$$

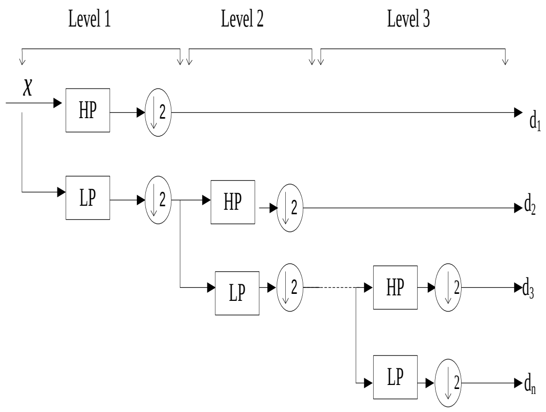

Fig.2. DWT multi-filter bank framework.

The wavelet analysis is one of the newly applied frequency analysis tools for processing signals with complex characteristics. There are different wavelet families, and they are classified according to the characteristics of the generated basis functions. Wavelet families are classified as orthogonal, bi-orthogonal and non-orthogonal [10]. Daubieches, Coiflet, Symlet and Meyer are examples of orthogonal wavelet families, while B-Spline is an example of bi-orthogonal wavelet families. Morlet, Gaussian and Mexican Hat are examples of the non-orthogonal wavelet families [2], [9]. Appropriate selection of the mother wavelet for signal representation can maximize the advantages of this technique. Moreover, the wavelet analysis will be simplified in terms of the required number of levels of analysis [10]-[12].One of the new methods for optimal wavelet analysis selection is the Minimum Description Length (MDL) data criteria. This method is based on the optimal number of wavelet coefficients to be retained for the signal reconstruction [7].In this work, results are carried out by using the db6 as mother wavelet for signal analysis .The wavelet energy is the sum of square of detailed wavelet transform coefficients. The energy of wavelet coefficient is varying over different scales depending on the input signals. The energy of signal is contained mostly in the approximation part and little in the detail part. The approximation coefficient at the first level contains much more energy than the other coefficients at the same level of the decomposition tree. The faulty signals have high frequency components; it is more distinctive to use energy of detail coefficients. These feature of the current waveform used to distinguish between fault and healthy condition.

II.A. THE DISCRETE WAVELET TRANSFORM

For a signal $x(t)$, the set of analysis and synthesis coefficients are:

$$Analysis \quad c_{j,k} = \int_{-\infty}^{\infty} x(t)\psi_{j,k}(t)dt \tag{1}$$

$$Synthesis : x(t) = \sum_j \sum_k c_{j,k}\psi_{j,k}(t) \tag{2}$$

Assuming the existence of a scaling function, $\phi(t)$ we can modify the above definition as follows.

Since the spaces V_j are getting larger and larger as j goes to ∞ we can approximate any signal $x(t)$, closely by choosing a large enough value of $j = J$ and projecting the signal into V_J using the basis $\phi_{J,m}(t)$, (all values of m).

$$cA_0(m) = \int_{-\infty}^{\infty} x(t)\phi_{J,m}(t)dt \tag{3}$$

From these we can approximately recover the signal as:

$$x(t) \approx \sum_m cA_0(m)\phi_{J,m}(t) \tag{4}$$

In effect, we replace the signal $x(t)$, by the approximate signal given by the projection coefficients, $cA_0(m)$. After this approximation the signal is now in the space V_J and we can be decomposed it using the subspaces V_{J-n} and W_{J-n} with their bases $\phi_{J-n,k}(t)$ and $\psi_{J-n,k}(t)$. It is to be noted that the scale is $V_J = W_{J-1} + V_{J-1}$ getting larger and larger as the index $J-n$ gets more negative [23].If we take $n = 1$ we get: Using the basis $\psi_{J-1,k}(t)$ in W_{J-1} and $\phi_{J-1,k}(t)$ in V_{J-1} we have:

$$\begin{aligned} x(t) &= \sum_m cA_0(m)\phi_{J,m}(t) \\ &= \sum_k cA_1(k)\phi_{j-1,k}(t) + \sum_k cD_1(k)\psi_{J-1,k}(t) \\ &= A_1(t) + D_1(t) \end{aligned} \tag{5}$$

As before, we call the signals $A_1(t)$ and $D_1(t)$ the approximation and detail at level 1.We call the coefficients $cA_1(k)$ and $cD_1(k)$ the approximation coefficients and the detail coefficients at level 1. We can further decompose $A_1(t)$ to get [12]:

$$\begin{aligned} x(t) &= A_1(t) + D_1(t) \\ &= \sum_k cA_2(k)\phi_{J-2,k}(t) + \sum_k cD_2(k)\psi_{J-2,k}(t) + \sum_k cD_1(k)\psi_{J-1,k}(k) \\ &= A_2(t) + D_2(t) + D_1(t) \end{aligned} \tag{6}$$

III. MODELING OF THREE PHASE POWER TRANSFORMER USING MATLAB SIMULINK:

The single line diagram of system under consideration is shown in Fig. 4. The specifications and connection of the system are as follow: - Rating of Generator is 132 kV, 30MVA and three-phase power transformer is 25MVA, 132/66 kV. Transformer is connected in delta on primary side and it is connected in star on secondary side with grounded. For load of 10MVA.

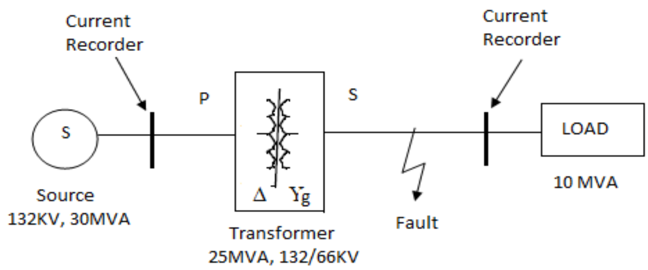

Fig.3: SLD of the System under consideration.

For the above system the protection scheme for three phase transformer is developed based on differential protection. The system is analyzed when the system is energized at different internal and external fault with the load connected in the circuit at all times.

Figure 4 is modeled figure 5 in MATLAB simulink with differential protection scheme applied on transformer as shown in fig.5

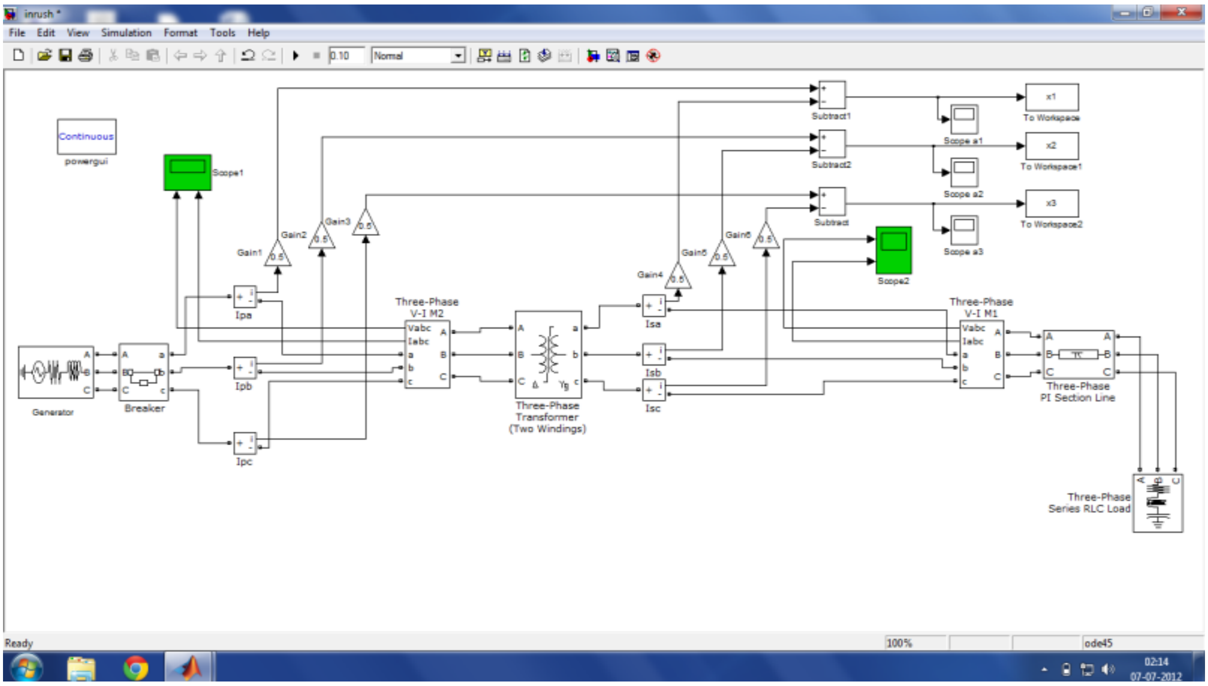

Fig.5 Implementation of Power system model under investigation in MATLAB

IV. FAULT IDENTIFICATION

In this proposed method, wavelet transform is first applied to decompose the differential current signals of power transformer system into a series of wavelet components each of which covers a specific frequency band. Thus the time and frequency domain features of the transients' signals are extracted for normal current, magnetizing inrush current, over excitation current, internal fault current. The sample of the differential current for 0.4 sec. is taken and is proceed in MATLAB Wavelet Tool box. One of the most popular mother wavelets suitable for a wide range of applications used is Daubichies's wavelet. In this work Db6 wavelet is used. The implementation procedure of Wavelet Transform, in which x[n] is the original signal obtain from workspace $X_{1,}$ X_2 and X_3 . At the first stage, an original signal $X_{1,}$ X_2 and X_3 is divided into two halves of the frequency bandwidth, and sent to both high-pass filter and low-pass filter. Then the output of low pass filter is further cut in half of the frequency bandwidth, and sent to the second stage; this procedure is repeated until the signal is decomposed to a pre-defined certain level 6. The set of signals thus represent the same original signal, but all corresponding to different frequency bands. It is pointing out that the frequency band of each detail of the wavelet transform is directly related to the sampling rate of the original signal. If the original signal is being sampled Fs Hz, the highest frequency that the signal could contain, from Nyquist's theorem, would be Fs/2 Hz. This frequency would be seen at the output of the high frequency filter, which is the first detail. Thus the band of frequencies between and would be captured in detail 1; similarly, the band of frequencies between and would be captured in detail 2, and so on. The WT is applied with four types of waveform. These are normal condition, magnetizing inrush condition, over excitation condition and internal fault condition. WT coefficients for each condition obtained, For instance the average value, maximum value and normalization value can be calculated for these wavelet transform coefficients. The total number of the wavelet transform coefficients stays the same due to the nature of the discrete transform process. The mean values of d1 (first level), a1 (first level), the average value of d1 (first level), a1 (first level), and the normalization of d1 (first level), a1 (first level) are calculated and stored. Each of the value of every single coefficient is also a feature of the data. The signal data generated by **SimPowerSystems** in **MATLAB.** Signals are sampled at the sampling rate of 40 samples per cycle (over a data window of half cycle).

V. RESULTS AND DISCUSSION.

Simulation of Power System using Matlab Simulink: Different types of faults have been considered for the purpose of analysis these faults are detected based on recognizing their wave shapes, more precisely, by differentiating their wave shapes from the fault current wave shapes using wavelet transform. These are as follows

Normal current Condition

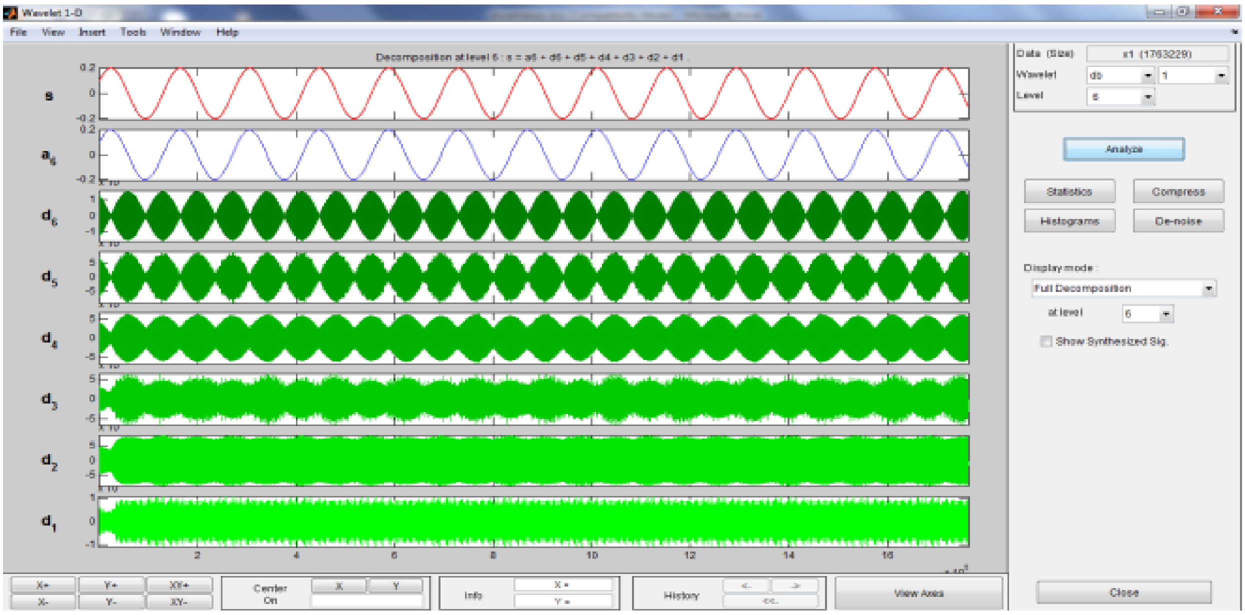

Fig.5 (a) WT of differential current for at phase A.

The differential current for this case is obtain when star connected balance RLC load is connected to the transformer at line voltage. After it has been energized, the above figure shows the differential current Ia, Ib, and Ic signals represent and its wavelet response. Which indicate that when there are no faults, the detail coefficient of these signals has very small threshold (approx.zero) and energy of each signals are also small, which are present in table 1.

TABLE 1

Maximum, Minimum detail coefficient and energy level of three phases at Normal current condition

Phases	**Max. Current Dev. (A)**	**Min. current Dev. (A)**	**Energy Level**
A	0.0004186	-0.0003597	6.19 KJ
B	0.0004207	-0.0003599	6.17 KJ
C	0.0004199	-0.0003606	6.14 KJ

Magnetizing Inrush condition.

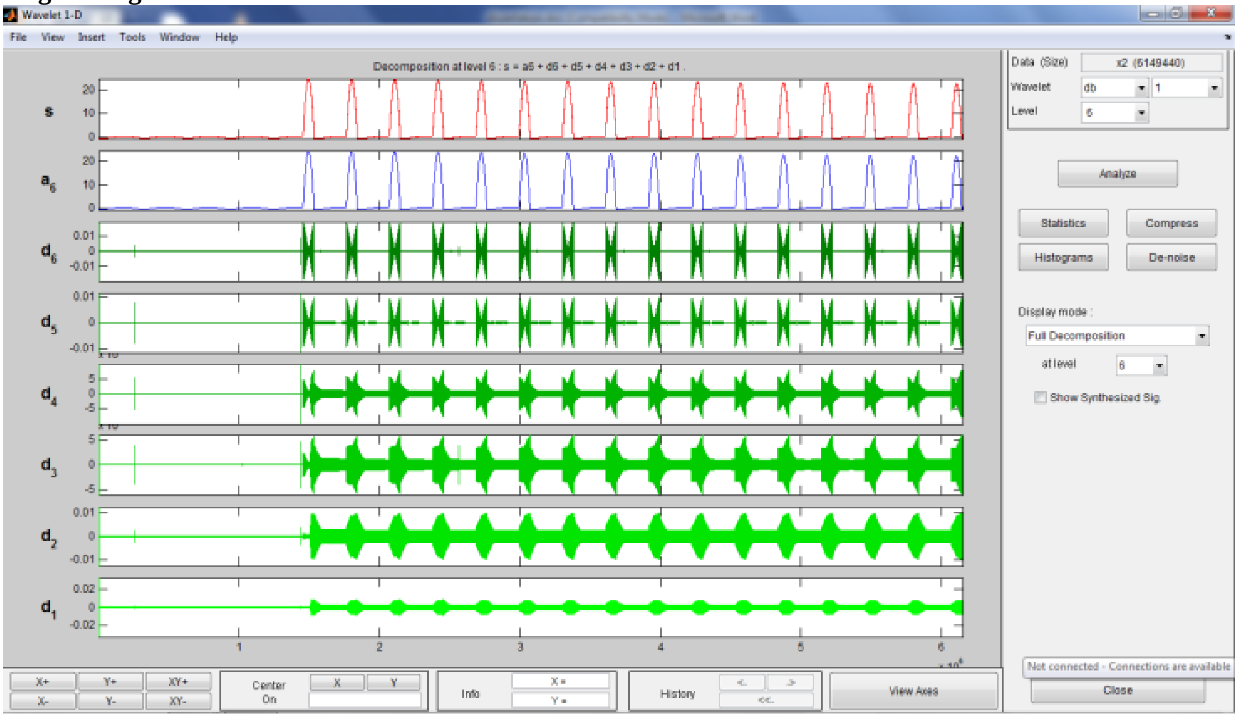

Fig.6 (a) WT of Diff. current for Magnetizing Inrush current at phase A.

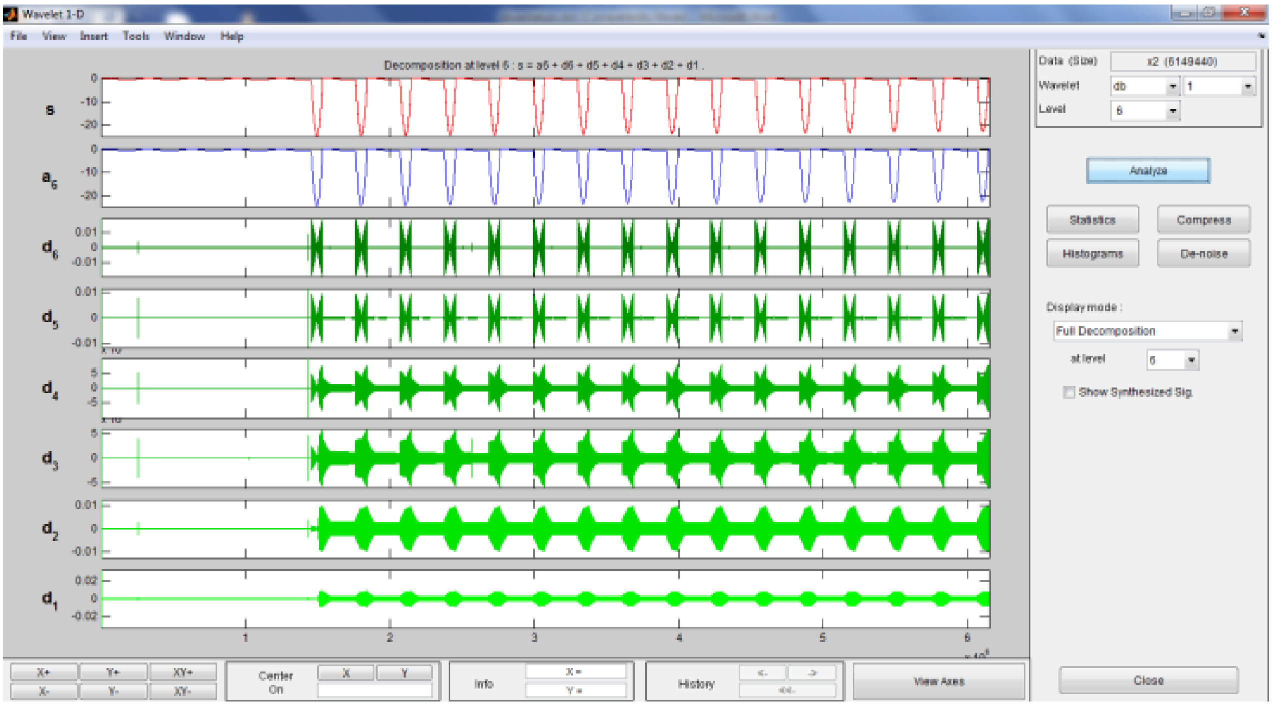

Fig.6 (b) WT of Diff. current for Magnetizing Inrush current at phase B.

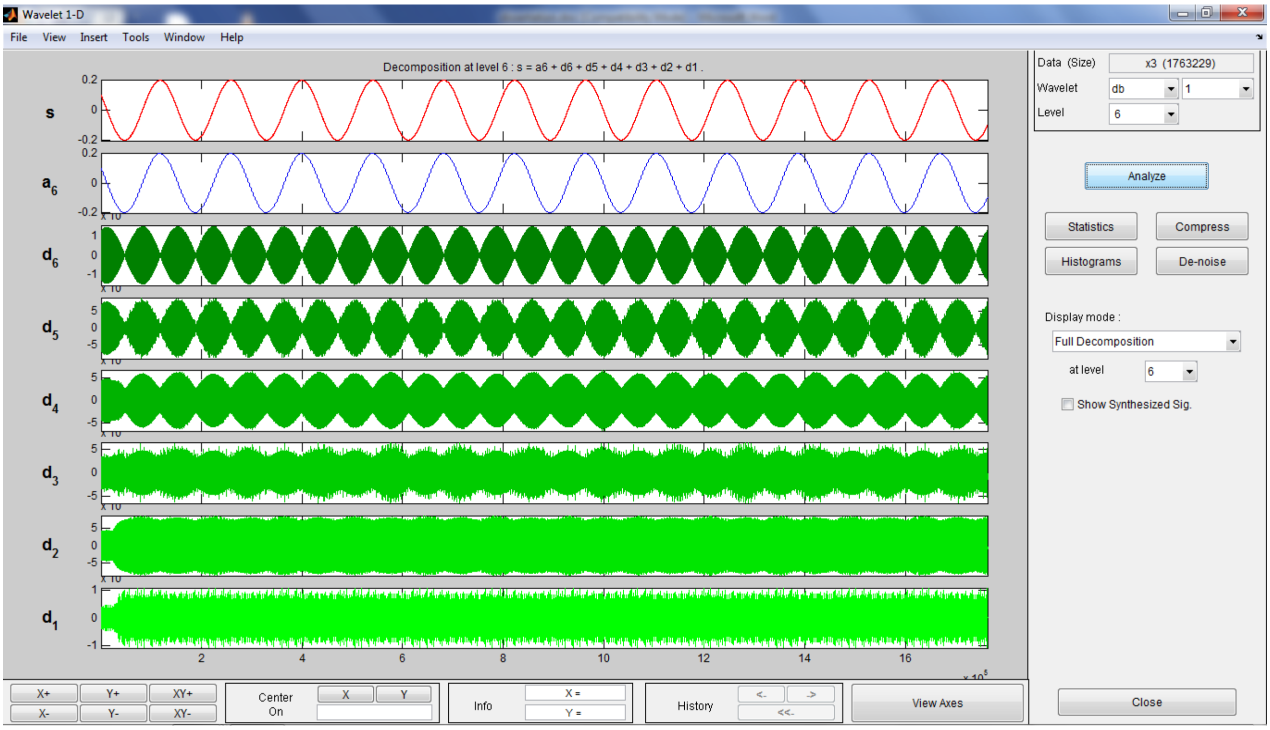

Fig.6 (c) WT of Difference current at phase C.

TABLE 2

Maximum, Minimum detail coefficient and energy level of three phases at Magnetizing Inrush current condition

Phases	Max. Current Dev. (A)	Min. Current Dev. (A)	Energy Level
A	**0.3097**	– 0.05197	**4.2×10^4** KJ
B	**0.05197**	– 0.3097	**4.2×10^4** KJ
C	0.0004199	– 0.0003606	6.14 KJ

For the case of magnetizing inrush current, the loaded transformer is energized at rated line supply line voltage. Three phase current signals at magnetizing inrush fault condition and detail coefficient are shown in above figure 6(a), 6(b) & 6(c) which indicated that there is an abnormal response in phase A & phase B. The detail coefficients of these signals have more current threshold than normal condition. We take normal condition as reference and compare this signal to abnormal one. Also energy level of Phase A and phase B are more than phase C, which is presented in table 2. On other hand, the perpendicular line at time axes in figure 6.(a) & 6.(b) indicate, when the fault inception began in phase A & phase B although phase C had no such fault indication

Over Excitation condition in phase C

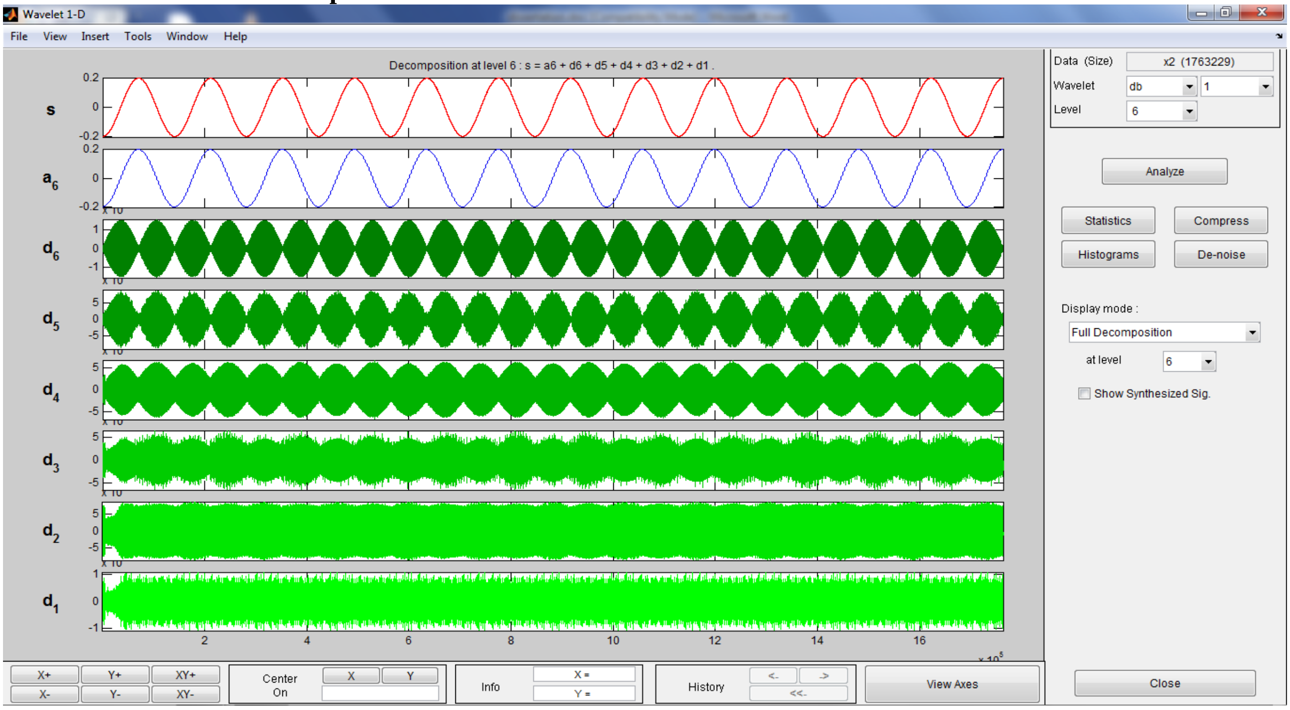

Fig.7 (a) WT of Differential current at healthy phase.

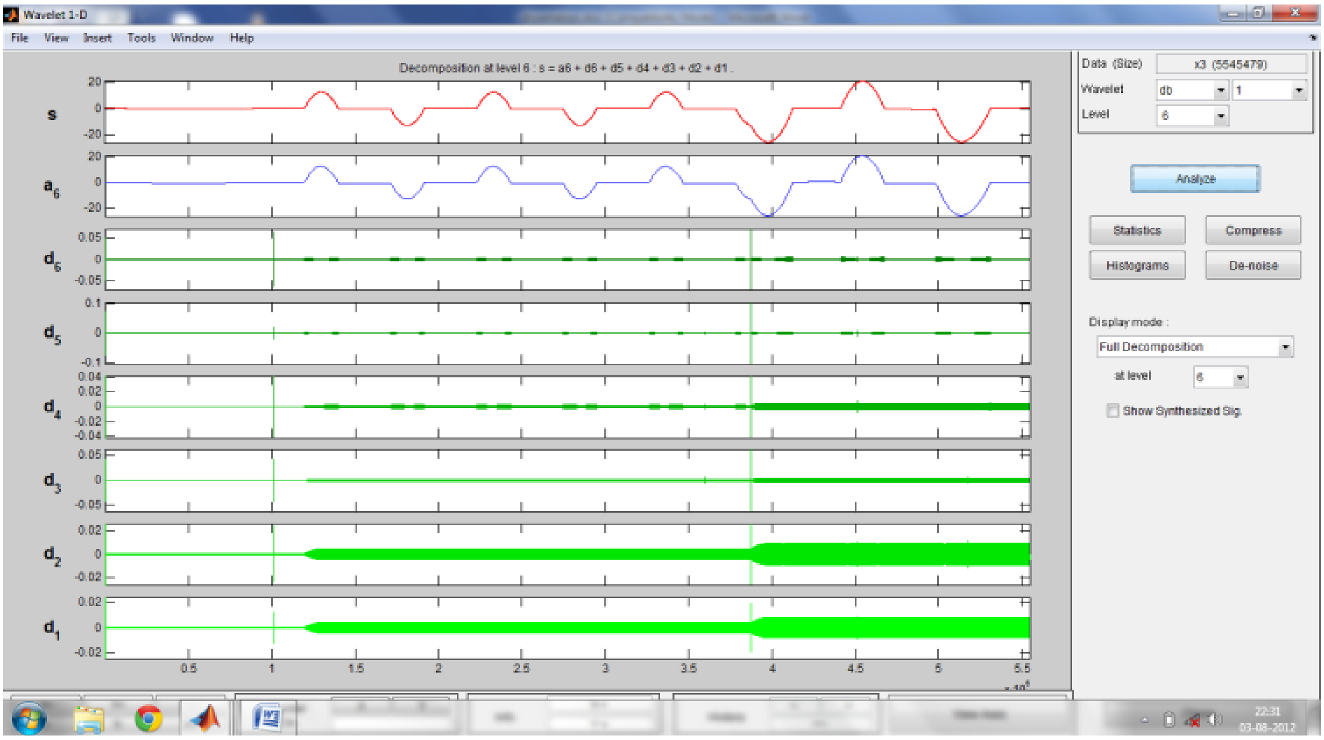

Fig.7 (b) WT of difference current for over excitation at faulty phase C.

After transformer has been energized, the above figure 7(a) and 7(b) show the three phase differential currents Ib, and Ic signals and their wavelet responses. After wavelet decomposition at the first level, maximum detail of wavelet coefficients were calculated for each signal waveform with and without fault condition as shown in above figure, which indicate that there is a fault in phase C. The detail coefficient of the faulty phase has more current deviation than phase, which represent in table 3. In over- excitated condition and perpendicular line at time axes in faulty phase indicated when the fault inception began although the healthy phase had no fault indication.

TABLE 3

Maximum, minimum detail coefficient and energy level of three phases at over excitation condition.

Phases	**Max. Current Dev. (A)**	**Min. Current Dev. (A)**	**Energy Level**
A	0.0004186	– 0.0003597	6.19 KJ
B	0.0004207	– 0.0003599	6.17 KJ
C	**0.08523**	– 0.2704	**7.9×10^4** KJ

Internal fault condition (L – L fault between phase A and B)

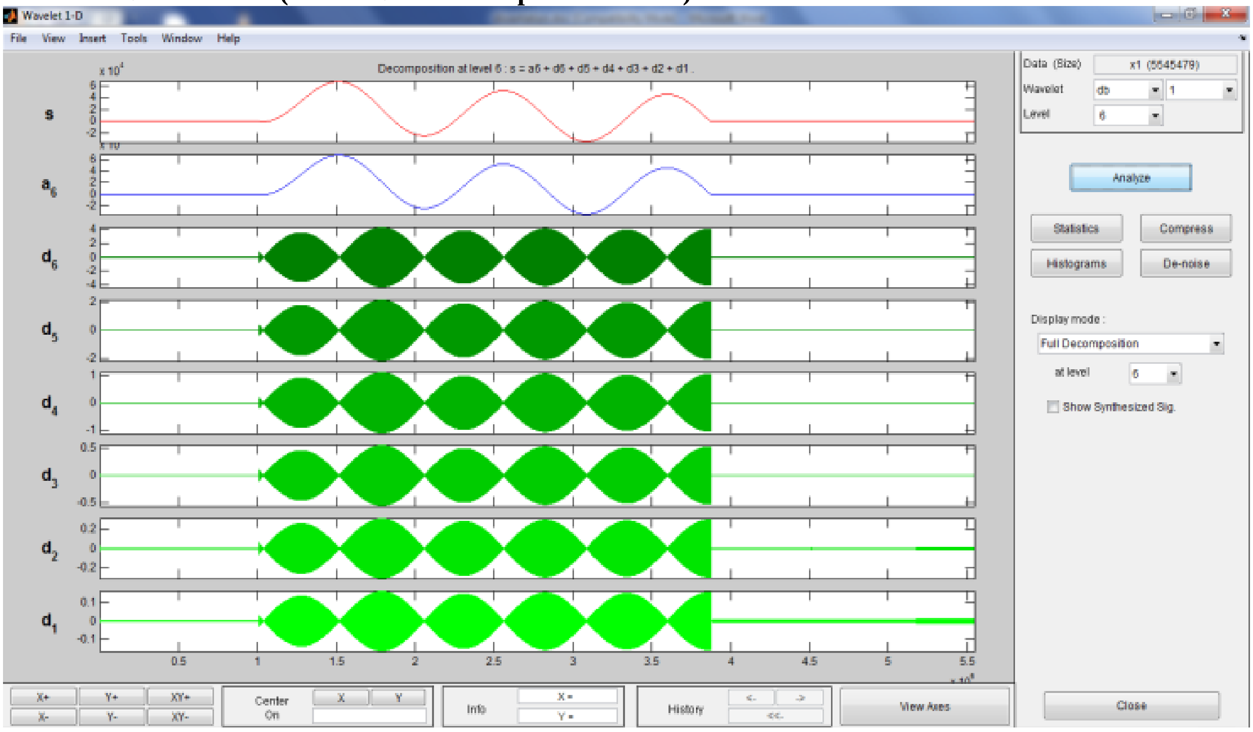

Fig.8. (a) WT of Differential current for internal fault at phase A.

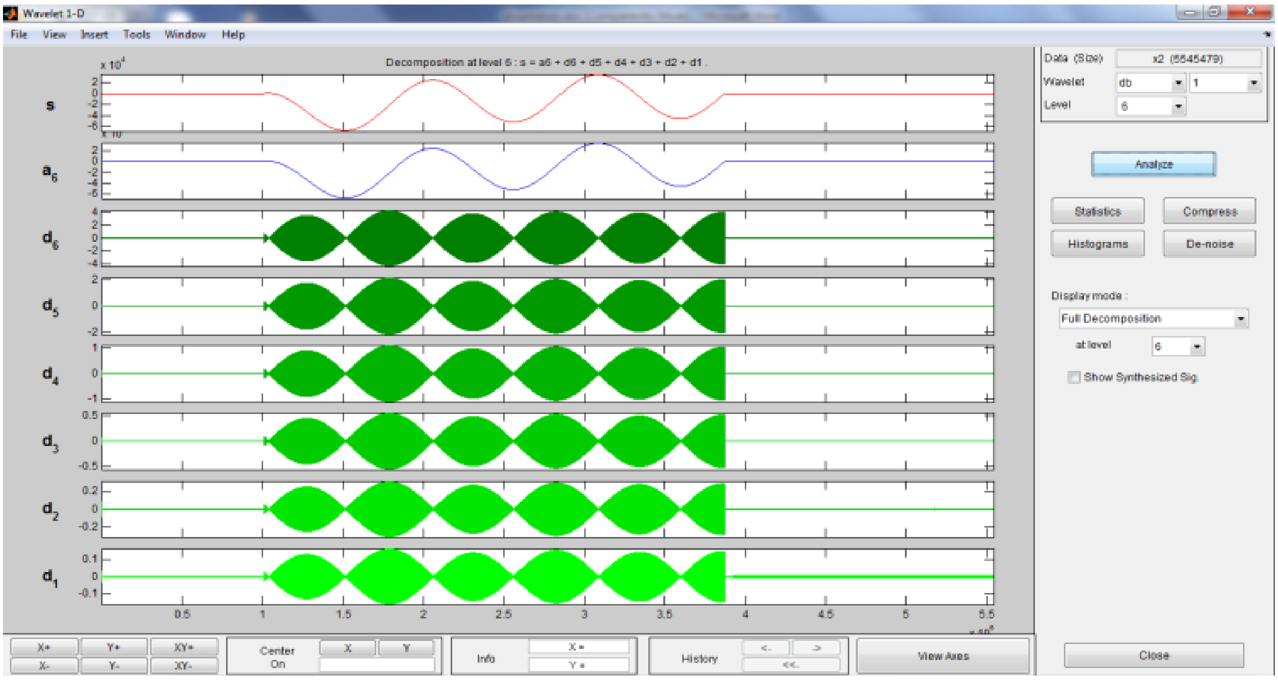

Fig.8. (b) WT of Diff. current for internal fault at phase B.

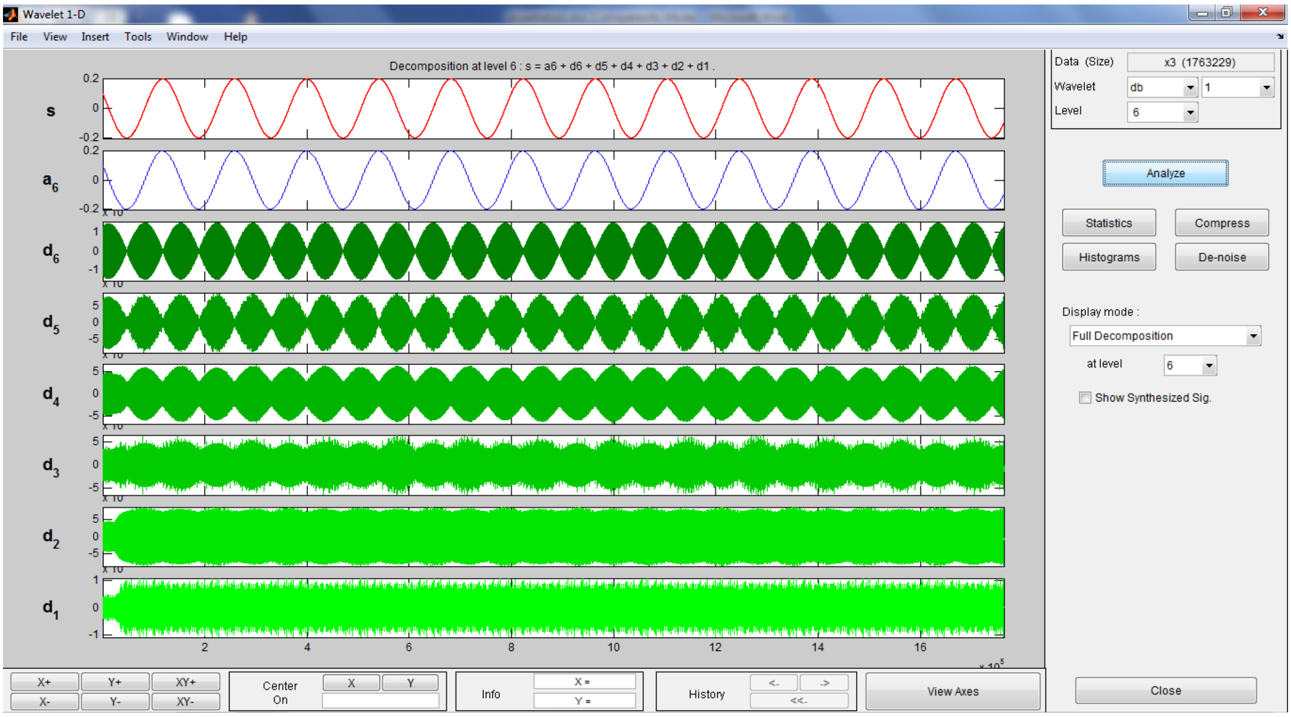

Fig. 8(c) WT of Differential current at healthy phase C.

TABLE 4
Maximum, Minimum detail coefficient and energy level of three phases at internal fault condition.

Phases	Max. Current Dev. (A)	Min. Current Dev. (A)	Energy Level
A	**3.73**	– 3.734	**11.9×10^{8}** KJ
B	**3.745**	– 3.736	**11.9×10^{8}** KJ
C	0.0004199	– 0.0003606	6.14 KJ

The occurrence of an internal fault creates a high frequency distortion in the current waveform. Figure 8.(a), 8.(b) & 8.(c) represents the differential current signal of three phases for internal fault corresponding to internally short circuited on A & B phases. A high frequency distortion in the current waveform is observed. The detail coefficients of these signal has current deviation which is extremely high as compared to phase C. The deviation energy level is also very high as compared to all above cases.

VI. CONCLUSION

The wavelet transform is a powerful tool for the analysis of current transient phenomena, due to its ability to extract information from transient signals simultaneously in the time and frequency domain. Different types of faults have been considered for the purpose of analysis. These faults are detected based on recognizing their wave shapes, more precisely from the fault current wave shapes using wavelet transform. The simulated results show that the fault current detection and classification scheme of three phase power transformer using wavelet transform is found to be precise and reliable.

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BIOGRAPHY

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