

A WAVELET TRANSFORM APPROACH TO DISCRIMINATE INTER-TURN FAULTS FROM MAGNETIZING INRUSH CURRENTS IN TRANSFORMERS

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Abstract: The transformer protection is critical issue in power system as issue lies in the accurate and rapid discrimination of magnetizing inrush current from different internal faults. This paper describes a new method to discriminate the magnetizing inrush current and inter-turn fault using the wavelet transform. Method is independent of setting any threshold for discrimination amongst these. Practical results over the custom built transformer are presented with detailed description of proposed criterion. A discriminating function and feature extraction is defined in terms of difference of two-peak amplitude of wavelet coefficients in a specific band. This discrimination will aid in development of an automatic detection method shall give information to predict the failure ahead of time so that the necessary corrective actions are taken to prevent outages and reduce down time.

Keywords: Magnetizing inrush, inter-turn fault, wavelet transform, discriminating function

1. Introduction

As an essential element of electric power systems, the transformer plays a key role in the safe operation of power system. Differential protection established is the main protection of the transformer for many years because of its simple principle of operation and sensitivity [1]. However, a key problem of differential protection is how to discriminate magnetizing inrush from an internal fault. The conventional approach uses the second harmonic component of differential currents to restrain operation of differential relay to avoid tripping during magnetizing inrush conditions [2]. It is well known that some aspects of this method do not satisfy the requirement of modern power transformers protection. Moreover, for the modern power system, high performance relays are required, especially in terms of operating speed. Magnetizing inrush also exhibit a characteristic of peaked wave, which is caused by asymmetric saturation of transformer core. Identifying magnetizing inrush by these characteristics opens a new avenue of research for improving the operating speed of relays.

Today the world is gradually moving towards a deregulated power sector. The number of utilities supplying power is also increasing leading to a stiff competition. Consumers are demanding a 'Quality' electric supply. Hence, in this scenario minimization of frequency and duration of unwanted outages of distribution transformers is very important.

The presence of second harmonic component in the magnetizing inrush current can no longer be used as a means to discriminate between magnetizing inrush current and internal fault, since the second harmonic component may also be introduced during internal fault due to variety of other factors such as current transformer saturation or presence of a shunt capacitor etc [2],[10].

Previous work on transformer protection includes transformer inductance during saturation, flux calculated from the integral of voltage, and the differential current. New methods have been adopted which include ANN, and fuzzy logic. Also, some techniques have been adopted to identify the magnetizing inrush and internal faults [8]. In a modal analysis in conjunction with a microprocessors-based system was used as a tool for this purpose. In [11] a wavelet-based system is used. A wavelet-based signal processing technique is an effective tool for power system transient's analysis and feature extraction [2]. Some applications of the technique have been reported for power quality assessment, data compression, protection, analysis of power quality problem solution, and fault detection.

Paper [11] proposes a new wavelet-based method to identify inrush current and to distinguish it from internal faults. The second harmonic component is used as a characteristics component of the asymmetrical magnetization peculiar to the inrush. In [15] the active power flowing into transformer is used as a discrimination factor, which is almost zero in the case of energization

In this paper the property of multi resolution in time and frequency provided by wavelets is described, which allows accurate time location of transient components while simultaneously retaining information about fundamental frequency and its lower order harmonics, which facilitates

the detection of transformer inrush currents. The technique detects the inrush currents by extracting the wavelet components contained in the line currents using data window less than half power frequency cycle. The results prove that the proposed technique is able to offer the desired responses and could be used as a fast, reliable method to discriminate between inrush magnetizing and power frequency faults.

a wavelet-based scheme is developed to identify inrush current and to distinguish it from internal faults. A custom-built single-phase transformer was used in the laboratory to collect the data from controlled experiments. In these controlled experiments, a great variety of different fault scenarios on both primary and secondary windings of transformer were intentionally introduced. A schematic algorithm is developed for achieving the objective and proposed scheme do not require any threshold settings.

2. Discrete Wavelet Transform and Multiresolution Analysis

Wavelet analysis is about analyzing the signal with short duration finite energy functions. They transform the considered signal into another useful form. This transformation is called Wavelet Transform (WT).

Let us consider a signal $f(t)$, which can be expressed as-

$$f(t) = \sum_l a_l \phi_l(t) \quad (1)$$

Where, l is an integer index for the finite or infinite sum. Symbol a_l are the real valued expansion coefficients, while $\phi_l(t)$ are the expansion set.

If the expansion (1) is unique, the set is called a basis for the class of functions that can be so expressed. The bases are orthogonal if-

$$\langle \psi_l(t) \psi_k(t) \rangle = \int \psi_l(t) \psi_k(t) dt = 0 \quad k \neq l \quad (2)$$

Then coefficients can be calculated by the inner product as-

$$\langle f(t), \phi_k(t) \rangle = \int f(t) \phi_k(t) dt \quad (3)$$

If the basis set is not orthogonal, then a dual basis set $\phi_k(t)$ exists such that using (3) with the dual basis gives the desired coefficients.

For wavelet expansion, equation (1) becomes-

$$f(t) = \sum_k \sum_j a_{j,k} \phi_{j,k}(t) \quad (4)$$

In equation (4), j and k are both integer indices and $\phi_{jk}(t)$ are the wavelet expansion function that usually form an orthogonal basis. The set of expansion coefficients a_{jk} are called Discrete Wavelet Transform (DWT).

There are varieties of wavelet expansion functions (or

also called as a Mother Wavelet) available for useful analysis of signals. Choice of particular wavelet depends upon the type of applications. If the wavelet matches the shape of signal well at specific scale and location, then large transform value is obtained, vice versa happens if they do not correlate. This ability to modify the frequency resolution can make it possible to detect signal features which may be useful in characterizing the source of transient or state of post disturbance system. In particular, capability of wavelets to spotlight on short time intervals for high frequency components improves the analysis of signals with localized impulses and oscillations particularly in the presence of fundamental and low order harmonics of transient signals. Hence, Wavelet is a powerful time frequency method to analyze a signal within different frequency ranges by means of dilating and translating of a single function called Mother wavelet.

Formulation of DWT is related to filter bank theory in many of the good references. It divides the frequency band of input signal into high and low frequency components by using high pass $h(k)$ and low pass $g(k)$ filters. This operation may be repeated recursively, feeding the down sampled low pass filter output into another identical filter pair, decomposing the signal into approximation $c(k)$ and detail coefficients $d(k)$ for various resolution scales. In this way, DWT may be computed through a filter bank framework, in each scale, $h(k)$ and $g(k)$ filter the input signal of this scale, giving new approximation and detailed coefficients respectively. The filter bank framework is shown in fig 1. The down pointing arrow denotes decimation by two and boxes denote convolution by $h(k)$ or $g(k)$.

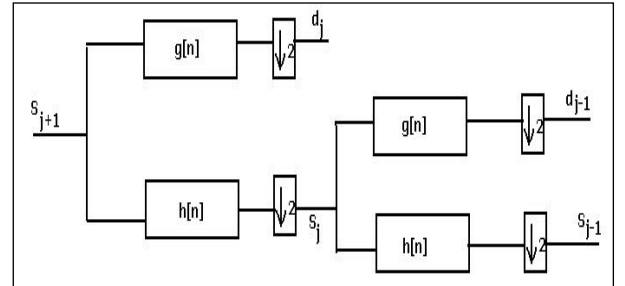


Fig. 1: Two band Multi-resolution analysis of Signal. The coefficients of filter pair are associated with the selected mother wavelet. Daubochies wavelet family is mostly used for analysis of transients. The sampling frequency in this paper is taken to be 10 kHz and Table I shows the frequency levels of the wavelet function coefficients.

Table I: Frequency levels of Coefficients

Decomposition Level	Frequency Components Hz
d1	5000-2500
d2	2500-1250
d3	1250-625
d4	625-312.5
d5	312.5-156.25
A5	0-156.25

3. Experimental setup

The setup for experiments has a custom built 220V/220V, 2KVA, 50Hz, single-phase transformer with externally accessible taps on both primary and secondary to introduce faults. The primary winding and secondary winding has 272 turns respectively. The load on the secondary comprises of static and rotating elements. Data acquisition card by Tektronix Instruments was used to capture the voltages and current signals. These signals were recorded at a sample rate of 10,000 samples/sec.

Different cases of inrush current and inter turn short circuit were staged on the custom built transformer by varying the parameters, which significantly affects the characteristics of these currents. These parameters are the residual core flux, the voltage angle at the time of switching. Different cases of inter turn short circuit are staged, considering the effect of number of turns shorted on primary and secondary and load condition. The following experiments were conducted on the custom built transformer.

1. Inrush current without load was acquired ..
2. Four percent (10 turns) of primary turns were kept short circuited on load and then the transformer was energized and differential current acquired.
3. The same procedure was repeated for secondary winding short-circuited.

The experimental circuit and experimental set up is as shown in Fig. 2(a) and Fig. 2(b).

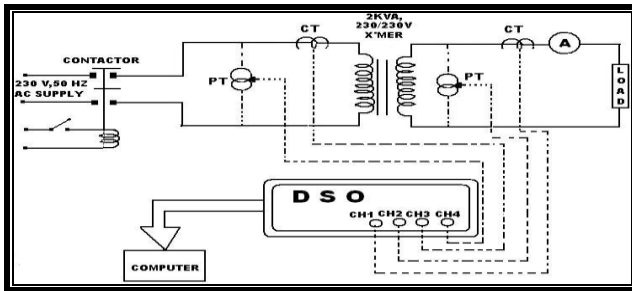


Fig.5: (a) Experimental Circuit

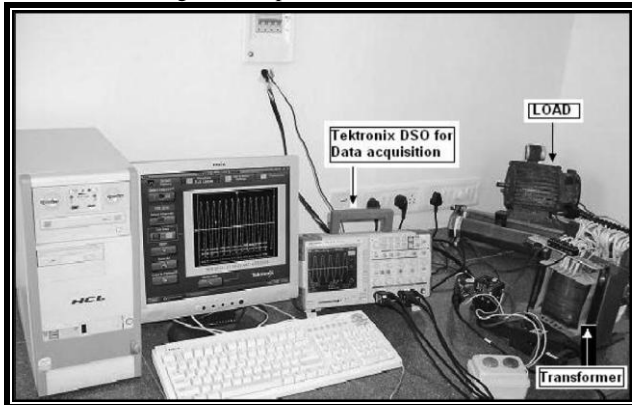


Fig.2: (b) Experimental Setup

4. Proposed Method

In Fig. 3, looking at the waveform of inrush differential current it is quite clear that its initial slope is less then it increases where as for fault differential current the initial slope is large and it start decreasing. A high value of slope indicates the presence of high frequency components. These features are independent of the connected power system and depend on the different nature of current and parameters of transformer.

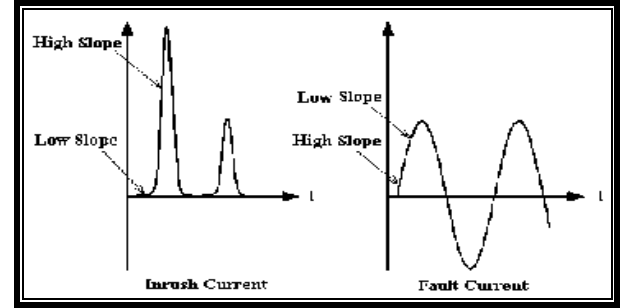


Fig. 3: Different behavior of fault and inrush current

In this paper this significant marked difference between the initial slope of the differential current due to fault and that due to magnetizing inrush current has been used to discriminate between inter-urn fault and magnetizing inrush current.

As per the proposed method for internal fault (inter-urn short circuit) the amplitude of high frequency is large initially and then it decreases. Hence high frequency components are captured in first two levels i.e. d1 and d2, as shown in Fig.4. Where as, in case of inrush current the amplitude of high frequency component initially is less and then increases. Therefore, in the first two levels that is d1, d2 nothing is seen where as in d3 high amplitude is observed in Fig.4.

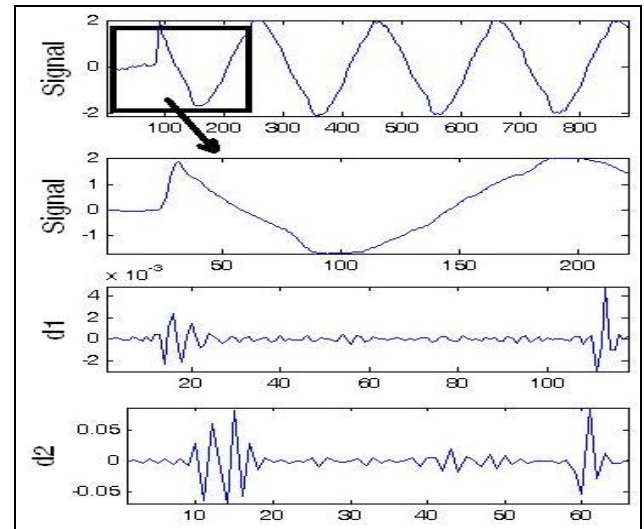


Fig. 4: Illustration of Wavelet decomposition of fault differential Current

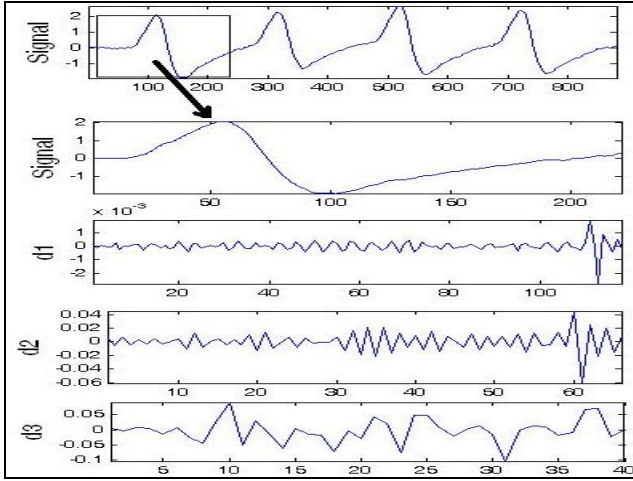


Fig. 5: Illustration of Wavelet decomposition of inrush Current.

5. Results and Discussions

Fig.6 shows the differential current (represented as 'Signal') due to inter-urn short circuit of 4% winding near to neutral in primary winding, with their detailed coefficients from Wavelet Transform up to d5 level. Here, the daub- 4-mother wavelet is used to obtain the desired wavelet coefficients.

In this figure, d1-d5 represents detailed coefficients of decomposition levels 1 to 5 respectively against sample numbers, while a5 is approximate coefficients of level 5. At the bottom of this figure absolute value of d5 is given. The detailed description and interpretation of Fig.6 is given below-

- Original Differential current signal is captured with data acquisition system discussed previously, and represented as 'Signal' in the figure. The fault is initiated at sample number 39 (Approx.) and it is marked as 'x' in figure. First negative peak of differential current is observed at sample number 50, denoted by 'Y' in figure.
- In decomposition level 'd1', peaking of wavelet coefficient is observed from sample number 39-64 approximately. Afterwards, magnitude of these oscillations decays.
- In 'd2' level, more clear vision of these abrupt changes in signal during samples 39-64 appears and maximum positive peak found at sample number 45.
- In 'd3' level high frequency components present in d2 are filtered out. Here again, peak of waveform observed at sample no. 45.
- In d4 level, first peak positive peak appears at sample 39 with magnitude 0.3571 and first negative peak reproduced at sample 50 with magnitude -0.3651 .

This is the approximate reproduction of curve between 'x' and 'y'.

- In d5 level, the first positive peak appears at sample 39 having magnitude 0.4041, while first negative peak appears at 59 with magnitude -0.5657 . Therefore, the d5 level represents precise measure for the slopes of fault and inrush currents.
- Hence, taking the absolute value of $|d5|$ as shown in figure, the first two consecutive peak values after the fault instant are the good approximations for the initial slope changes in the fault and inrush current.

Therefore, the discrimination function for fault and inrush current can be chosen as-

$$\Delta M = \frac{A - B}{A + B} \quad \left. \begin{array}{l} \text{First Peak after fault initiation} \\ \text{Second Peak after fault initiation} \end{array} \right\} \quad (2)$$

Hence, for inrush current $\Delta M < 0$ and for fault current $\Delta M > 0$.

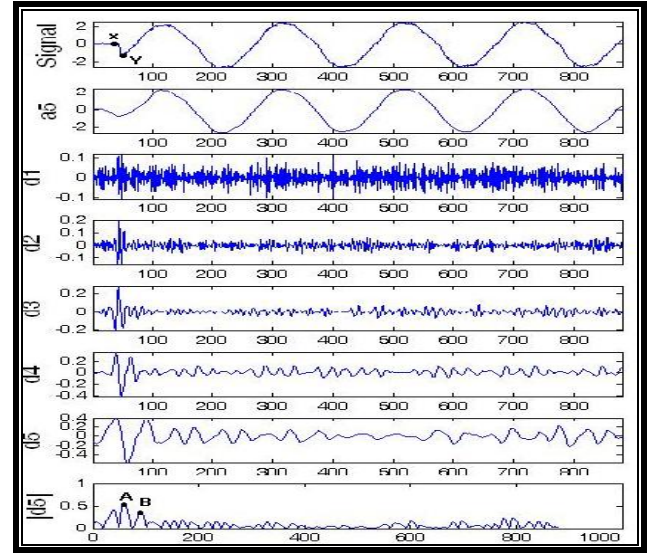


Fig. 6: Wavelet decomposition of differential current for fault in primary winding

Figure 7, shows wavelet decomposition of differential current acquired during inter turn fault of 10 turns in secondary winding. Nearly, same high frequency components were observed in such faults like fault in primary winding.

The high frequency components were observed in decomposition level d1-d4 for high initial slope of fault current. As discussed previously, fault current starts with high initial slope and slope decreases as fault progresses. From time-frequency localization in d1-d3 levels, high frequency components with high amplitudes at instant of fault and with decaying trends afterwards are clearly visible.

Filtration of this high frequency up to d5 level leads very interesting discriminating criterion of fault and inrush

current. The absolute value of the coefficients of d5 waveform is shown at the bottom of this figure. In this, A and B are the amplitudes of first two peaks following the disturbance. From the fig., It is seen that for inter-turn fault $A > B$. In the event of $A > B$ trip command can be issued in quarter cycle. The features used for diagnosis normally are seen in the high frequency range and not in lower frequency. From figure, it is obvious that the amplitudes of wavelet coefficients in D5 are larger than that of D1-D4. Many wavelets were tried as an analyzing wavelet, but finally Daubochies 4 (Db4) gave encouraging and distinguishing features.

Here also, magnitude of two consecutive peaks A and B, follows the same relation i.e. $A > B$.

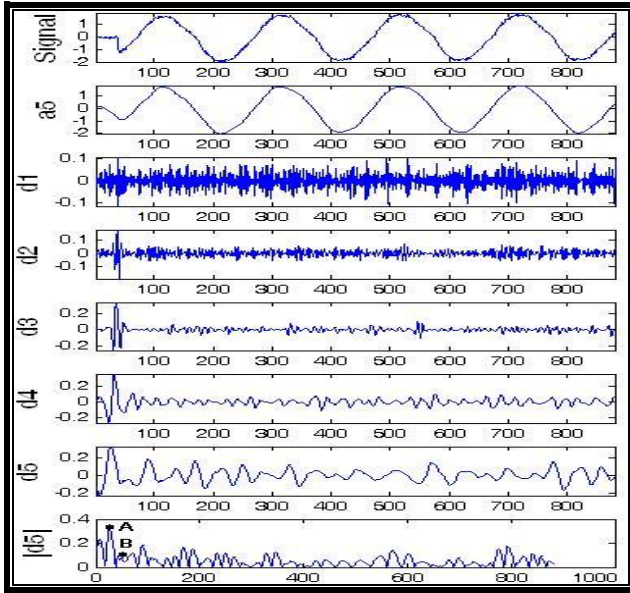


Fig. 7: Wavelet decomposition of differential current for fault in secondary winding

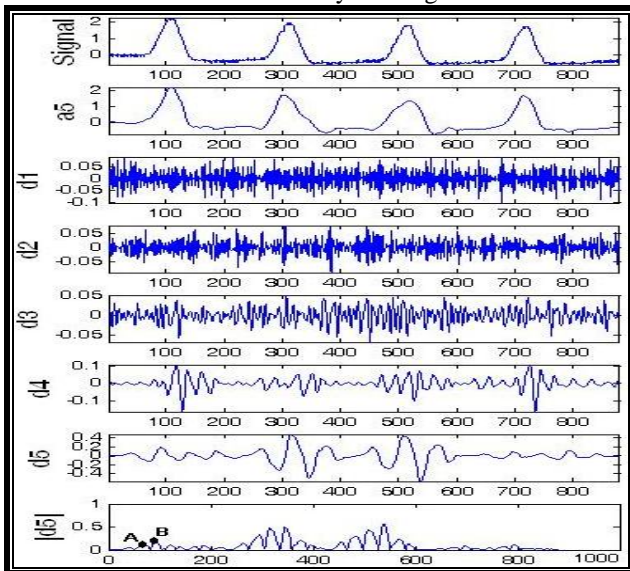


Fig. 8: Wavelet decomposition of differential current during Inrush

Inrush current exhibit different behavior or feature than the fault current, though their amplitude are comparable. Inrush current starts with low slope and increase rapidly afterwards. This characteristic is demonstrated in fig.8. The acquired inrush current signal is decomposed into five levels. No peaking was observed at the starting instant in d1-d2 level, as appeared in inter-turn fault. But high frequency oscillations can be noted in these levels, as high slope follows the low slope in inrush current. Therefore, repeated oscillations are reported in d4 level matching the high slope of inrush current, unlike the previous case. From the d5 and |d5|, the consecutive peaks A and B can be obtained and compared. For inrush, it can noted that $A < B$.

Following the previous discussion, proposed technique does not require any threshold value for discrimination amongst the magnetizing inrush and inter-turn faults in the transformer. The algorithm for the discrimination is presented below-

1. Capture the differential current with appropriate sampling frequency under the previously said conditions.
2. Apply MRA technique to obtain the discrete wavelet transform up to 5th decomposition level.
3. Obtain |d5|
4. Find the first two peak values A and B of |d5|
5. Calculate $\Delta M = A - B$
6. If $\Delta M < 0$ then it is Inrush Current
7. If $\Delta M > 0$ then it is Fault and provide trip signal or alarm.

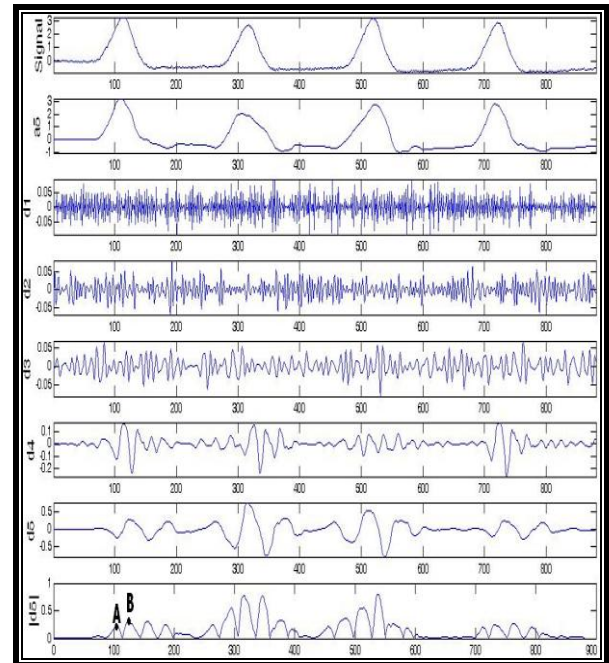


Fig. 9: Wavelet decomposition of inrush current

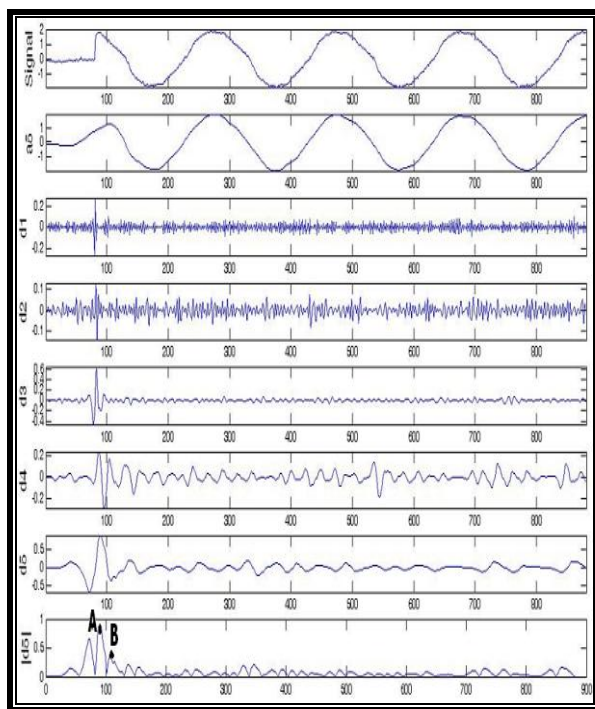


Fig. 10:- Wavelet decomposition of differential current during fault

Figure 9 and 10, shows the wavelet decompositions of inrush and fault differential currents for different switching instants.

6. Conclusion

In this paper, a new algorithm was presented which discriminate between the inter-turn fault and magnetizing inrush current. The algorithm used wavelet coefficients as a discriminating function. Two peak values corresponding the $|d5|$ level following the fault instant are used to discriminate the cases studied. As criterion compare the two peak values, hence no threshold settings are necessary in this algorithm. Proposed technique is discussed in depth and validated through the practical obtained on custom-built transformer.

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