FFT SPECTRUM AND MRA BASED IDENTIFICATION AND STRATIFICATION OF ROOT CAUSES OF CURRENT TRANSFORMER SECONDARY CURRENT DISTORTION

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ARTICLE INFO

***Article history*:**
Received: 26. 3. 2025.
Received in revised form: 6. 7. 2025.
Accepted: 7. 7. 2025.

Keywords:
Multi Resolution Analysis
Current Transformer
Discrete Wavelet Transform (DWT)
Fast Fourier Transform (FFT)
Harmonics
Signal Distortion

DOI: 10.30765/er.2871

Abstract:

Current Transformer (CT) secondary current waveform gets distorted if the CT core is saturated or owing to the distortion of CT primary current itself. This article presents a unique approach to ascertain and classify the reason of CT secondary signal distortion under various conditions. At first secondary current signal of CT is sampled and stored and then Fast Fourier Transform (FFT) is done on the captured signal to find out the presence of harmonics or distortion in the signal. To classify the reasons of distortion, Discrete Wavelet Transform (DWT) based Multi-Resolution Analysis (MRA) was performed on the captured signal. Based on it, analysis has been prosecuted to nose out the reason why the distortion has appeared. Numerous cases were considered to establish the uniqueness and clarity of the presented technique.

1 Introduction

Complexity and diversity of power network is increasing rapidly as a consequence of galloping needs of electricity in our society. It requires proper measuring and protection scheme to maintain the proper operation of the whole power network. In this context CT plays a significant role in measurement and monitoring a system.

In all conditions faithful reproduction of CT primary current is utmost required and for this CT characteristic (exciting current versus flux) must lie in its linear zone. Appearance of decaying dc factor in primary current saturates CT core and for that malformed CT secondary current creates problem in measuring and protection system. Several studies had been observed in this field.

A simulation was developed to estimate transient flux excursions, current wave shapes (secondary) and residual flux vales in saturated condition of a CT made by steel core considering eddy current effects and hysteresis [1]. CT errors and its transient performance were assimilated with direct laboratory test under this condition [2]. CT saturation detection is crucial for secure operation of power system. Different techniques already used by different researches to detect saturation. The prime reason of saturation is appearance of decaying DC constituent in primary current. In [3], partial sum and multistage least-squares based method applied for assessing phasor in saturation and DC offset condition. To accurately measure the fundamental component of fault current, saturation and decaying DC component creates the difficulty. Least squares error technique was proposed by the researchers to detect saturation by extracting fundamental component of current from distorted current signal [4]. Zero crossing technique and second order differentiation based technique was proposed to determine the starting of saturation [5]. In numerical differential protection of feeder, saturation was identified by symmetrical component based analysis, where simulation was carried out

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in EMTP/ATP platform [6]. In [7], three (first, second, third) difference functions of secondary signals are used by the researchers to detect saturation. In this work, saturation in every cycle of CT secondary waveform has been detected by first - difference function and others two difference functions were used to convert the discontinuities into pulses at inflection points. The main function of CT is faithful reproduction of secondary waveform for proper protection of system, but secondary signal gets distorted due to saturation and at this condition proper protection is hampered due to this distortion. In [8], mathematics based approach was suggested for compensating distorted CT secondary current. Another approach was also recommended for compensating the distorted secondary signal due to remnant flux in CT core, where magnetizing characteristic of that CT was applied for compensating purpose [9].

M. M. Haji et al. proposed 'Gaussian Mixture Models' for CT saturation detection [10]. In this analysis 132 kV network was simulated in PSACD/EMTDC software and different fault inception angles (0^0 to 90^0 and 90^0 to 180^0) have been considered to create CT saturation. Jiles Atherton (JA) theory was applied for ferromagnetic hysteresis of CT. An integrated filtering approach which is established on empirical mode decomposition (EMD) and Savitzky-Golay (SG) filter has been introduced to ascertain CT saturation in noisy environment [11]. In this analysis 220 kV power system was simulated in PSCAD and different conditions were created to create CT saturation. B. M. Schettino et al. proposed Savitzky-Golay (finite impulse response) filter based approach to identify saturation in noisy environment [12].

In [13], 'extended Kalman filter' has been used to determine and compensation of saturation. In this analysis, error estimation of the mentioned algorithm is employed to identify the starting and ending point of saturation. The limitation of this technique is that, the implied algorithm has not been executed in presence of different inter – harmonics. Digital algorithm based compensation and detection of saturation has been discussed in [14], where state space technique was used for compensating secondary current in CT saturated condition. Another mathematical technique was developed to faithfully reconstruction of primary current in CT saturated condition, where starting point and terminating point of saturation has been detected first for this purpose [15]. Error compensation algorithm was proposed in CT saturated condition [16], where magnetizing component current was considered to compensate saturated current of CT and EMTP based model was employed to validate the proposed algorithm. Y. C. Kang et al. proposed differential relay scheme for busbar protection where relay is capable to identify CT saturation [17]. In this work, initiation and termination of each saturation is detected by third difference function. This relay is also able to discriminate external and internal fault conditions of the system. Behaviours of CT were analyzed by FFT based technique under variable power scenario (active and reactive) and for this FFT spectrum was used for flux, secondary and primary signal of the CT [18]. Core saturated condition the secondary waveform of CT gets distorted and it contains lot of harmonics. Harmonic analysis for signal in any condition proposed in [19] – [23]. Signal processing and some optimization based techniques also used by different researches to ascertain and compensation of saturation [24] – [29]. 'Empirical Wavelet transform (EWT)' based waveform decomposition technique has been used in [30] to detect CT saturation. In this work, the proposed method is tested in IEEE 39 bus system with the help of 'DIg SILENT' software and MATLAB for all unbalanced conditions. In [31], saturation is detected by cross correlation of measured signal with respect to independent signal. Kalman filtering is also applied here to obtain primary current in that condition though the limitation of this work is that, its effectiveness decreases with the increase of noise levels. Decision Tree (DT), Artificial Neural Network (ANN) and Support Vector Machine (SVM) based Machine Learning techniques are used in [32], for binary classification of CT saturation detection. In these mentioned techniques maximum accuracy has been achieved using ANN based method. A moving window and stacked denoising auto-encoder based technique was used to identify the exact interval of saturation in every cycle of CT secondary current [33]. In [34], an unsupervised feature extraction technique along with auto-encoder and deep neural network has been used to identify saturation at different levels. Bayesian optimization and Deep Neural Network based (Bayesian Deep Neural Network) method used in [35], to compensate CT saturation. The constraint of this technique is that, the suggested approach has been tested for those CTs which are having similar characteristics. Data driven model and physical model used in [36], to identify saturation and compensation. In this analysis the eminence is that, integration of data model and physical model but the limitation is slight time delay.

All the reviewed works, described the algorithm to ascertain and compensate CT saturation, but none of these papers described the reasons of distortion of secondary waveform of CT. Without core saturation CT secondary signal gets distorted due to power quality problem in CT primary current.

This motivated authors to do the work. In this analysis, 'Fast Fourier Transform (FFT)' and 'Discrete Wavelet Transform' (DWT) based MRA technique has been discussed to identify and classify the reasons for distortion of secondary current (signal) of CT. The rest portion of this manuscript has been structured as follows: In section 2, one of the analytical tools such as FFT has been discussed. In section 3, second analytical tool which is 'Wavelet transform based multi resolution analysis' has been discussed thoroughly. In section 4, computer modeling of the proposed network has been discussed. In section 5, computer simulation has been discussed. Results and discussions are discussed in section 6. Section 7 and 8, are the analytical comparison and final conclusion of this work respectively.

2 Fast Fourier Transform (FFT)

The applications of FFT are in the diverse field. FFT is a mathematical tool to convert time domain data of a waveform in frequency realm [34] – [35]. In FFT, analyzed signal is broken down in the form of series of sinusoids. FFT is much faster than 'Discrete Fourier Transform (DFT)'. Presence of different frequency and correspondingly its magnitude can be extracted using FFT. Fourier Transform (FT) can be done in continuous time domain and discrete time domain. In continuous time, FT of a function y(t) is Y(ω), where, [37] – [38].

$$\mathrm{Y}(\omega) = \int_{-\infty}^{\infty} y(t)e^{-j\omega}\ dt \tag{1}$$

Where, $j = \sqrt{-1}$ and ω=frequency. Inverse FT of Y(ω) is y(t) which can be written as,

$$\mathrm{y}(t) = \frac{1}{2\pi}\int_{-\infty}^{\infty} Y(\omega)e^{j\omega t}dt \tag{2}$$

Where, Y(ω) is the signal's spectrum. For a discrete time domain signal y(n), the DFT is,

$$Y(l) = \sum_{n=0}^{N-1} y(n)e^{-2\pi jln/N} \quad \text{for } 0 \le l \le N-1 \tag{3}$$

Where, n=0, 1, 2, …, N-1 and N is number of samples. Equation (3) is called as N-point DFT. Cooley and Tukey in 1965 proposed 'Fast Fourier Transform (FFT)' algorithm which alleviates the evaluation time and complexity of DFT. FFT can be calculated using two algorithms. One is decimation in time (DIT) another is decimation in frequency (DIF). To compute 'N' point DFT, total number of N2 complex multiplications are required where as to calculate FFT, N/2 log2N complex multiplication are required. These are the predominance of FFT over DFT.

3 Wavelet-Transform (WT) and Multi-Resolution Analysis (MRA)

To excerpt the time-frequency information from non-stationery waveform in superior way WT is generally used which was the constraint of FFT analysis. Using WT, different aspects of a waveform or signal can be anatomized. Aspects of a signal can be categorized as breakdown point, notch, discontinuity, trends etc. WT is categorized as (i) 'Continuous Wavelet Transform (CWT)' and (ii) 'Discrete Wavelet Transform (DWT)' [39] – [40].

3.1 Continuous Wavelet Transform (CWT)

To In CWT, convolution is done in between analyzed signal and mother wavelet. Every time mother wavelet is translated and convolution is done accordingly. CWT gives three dimensional information of analyzed signal. Three dimensions of CWT results are scale (which is inverse of frequency), translational value (which is inverse of time) and coefficient. CWT expression of analyzed signal y(t) can be defined as [39] – [40],

$$Y_{WT}(e,g) = \frac{1}{\sqrt{|e|}}\int_{0}^{\infty} y(t)\varphi^{*}\left(\frac{t-e}{g}\right)dt \tag{4}$$

In the above equation, e represents translation; 'g' represents scale value and $\varphi^{*}(t)$ is the complex conjugate of mother wavelet. Complex conjugate of mother wavelet is considered to calculate complex wavelet. Here, in this analysis 'dB4' is considered as mother wavelet as it is well suited. In CWT and DWT analysis, the analyzed signal has to be discretized by maintaining the Nyquist criterion.

3.2 Discrete Wavelet Transform (DWT)

Radial Lots of data are generated in CWT analysis and not only that, CWT calculation is time consuming because at each scale significant work has to be done. This restraint of CWT can be surmounting by DWT analysis. Anatomization of signal in redundant form can be done using DWT analysis. DWT analysis is based on sub-band coding algorithm. DWT expression of any discrete signal y(n) can be expressed as [39] – [40],

$$z_{low}(n) = \sum_{m=-\infty}^{\infty} y[m]h[2n-m] \quad (5)$$

$$z_{high}(n) = \sum_{m=-\infty}^{\infty} y[m]g[2n-m] \quad (6)$$

In expressions (5) and (6), g and h is ‘high pass filter’, ‘low pass filter respectively.

3.3 Multi –Resolution Analysis (MRA)

WT provides multi-resolution analysis (MRA) with detailed windows [39]-[40]. MRA technique, first proposed by S. Mallat in 1988, where a multi-resolution frequency characteristic of a signal was accomplished by DWT. Decomposition of signal in different frequency level is recognized as ‘Mallat algorithm’. In wavelet analysis, MRA is achieved using dilated windows. For narrow window, time resolution is better than frequency resolution but for wide window it is reverse. Fig. 1(a) delineates the time-frequency relation and Fig. 1(b) depicts three layers MRA in Wavelet analysis. Signal is analysed with various frequencies with varied resolutions in MRA. ‘Down sampling’ and ‘up sampling’ is the important concept in MRA. Detail frequency information can be fetched by MRA analysis based on down and up sampling. In MRA, analysed signal passes through high and low pass filter in each DWT decomposition level. In this fermentation process, detail level coefficient is the output of high pass filter and approximation or approximate coefficient is the output of low pass filter respectively. This decomposition can be proceeding up to desired level. Here, down sampling is used for decomposition where ‘factor two (2)’have been considered for analysis. Reconstruction of signal is the over- turn procedure of decomposition. In this technique, signal is reconstructed through a synthesis filter bank where up sampling by a ‘factor two (2)’ is practiced for this intention. In this analysis, output of filter bank is called as ‘sub-band’ and filter bank technique is called ‘sub-band coding’. In this approach, decomposition of analysed signal is comprehended as ‘Mallat Algorithm’. Decomposition and reconstruction of a signal by down and up sampling has been depicted respectively in Fig. 1(c) and Fig. 1(d).

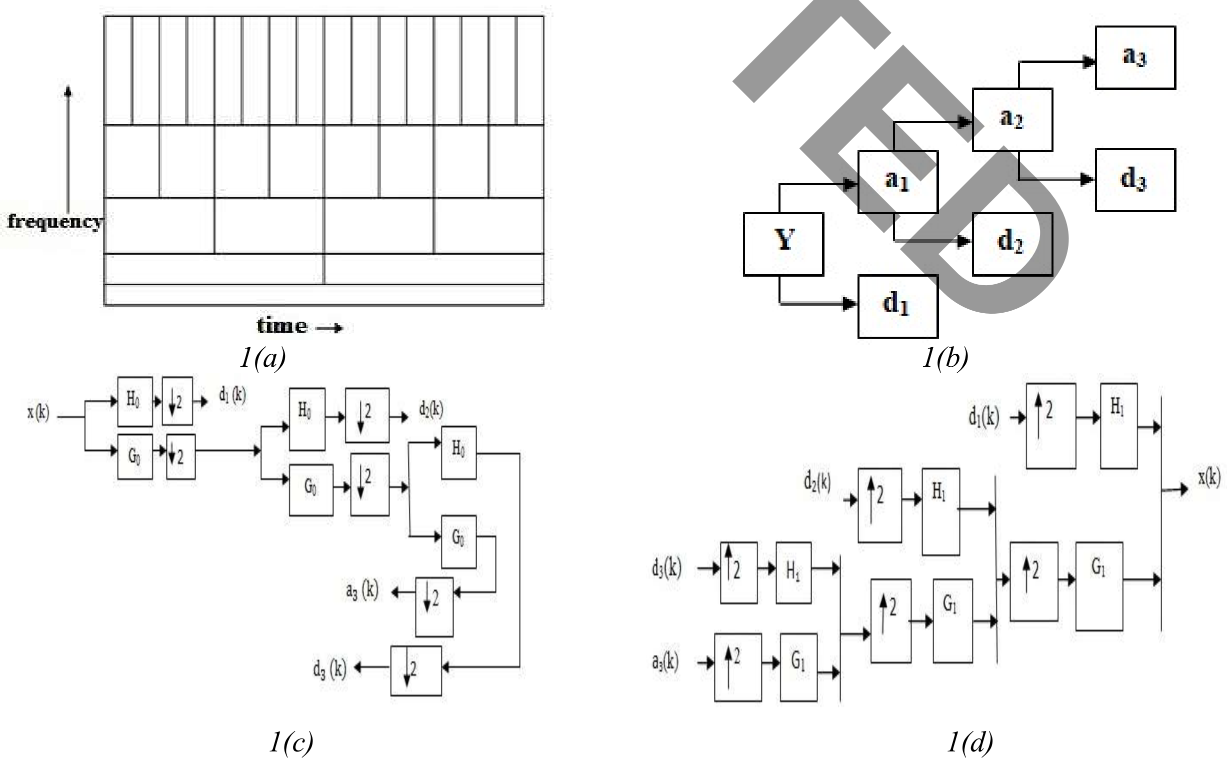


Figure 1. (a) Time-frequency representation in multi resolution analysis, (b) Multi-resolution analysis in three layers, (c) Decomposition structure by down sampling, (d) Reconstruction structure by up sampling.

4 Wavelet-Transform (WT) and Multi-Resolution Analysis (MRA)

4 Modeling

In this analysis, variable inductance to resistance (L/R) ratio (as load) is connected to a source for simulation. Different conditions have been created in simulink environment, like (i) normal condition (ii) varying breaker switching time (switching transient) to create CT saturation (iii) injection of high primary current to create CT saturation (iv) injection of sixty percent (60%) 2nd harmonic with hundred percent (100%) fundamental harmonic component to create distorted secondary waveform (CT) without core saturation and (v) injection of thirty percent (30%) 3rd and fifty percent (50%) 5th harmonic with hundred percent (100%) fundamental harmonic component to create distorted non-sinusoidal secondary waveform of CT without core saturation.

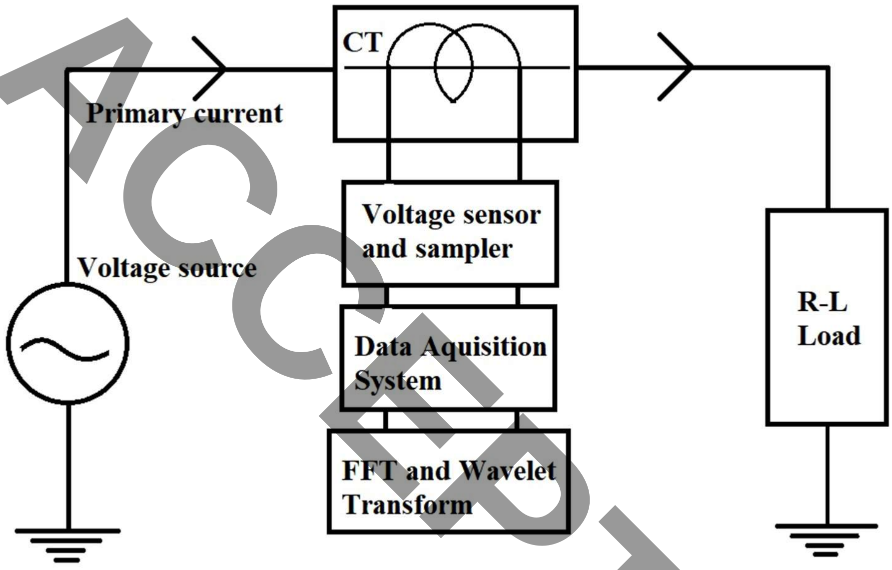


Figure 2. Simulation model of CT

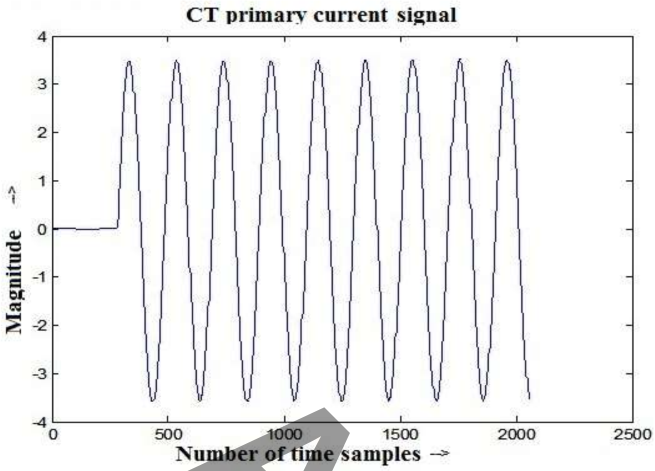
5 Computer Simulation

The circuit portrayed in Fig. 2 was simulated in MATLAB Simulink for the analysis. In 120 kV network, 2000/5 Amp and 25 VA burden CT is applied to find out the current in the network. Primary turns and secondary turns (CT) are single (1) and four hundred (400) respectively. By one (1) ohm load resistance, secondary side of the CT has been short circuited. CT core flux value 10 p.u. is considered at the knee point. Using the depicted network in Fig. 2, above mentioned five non-identical cases were simulated and thereafter FFT and MRA were done on the CT secondary signal to identify and classify the distortion of the signal.

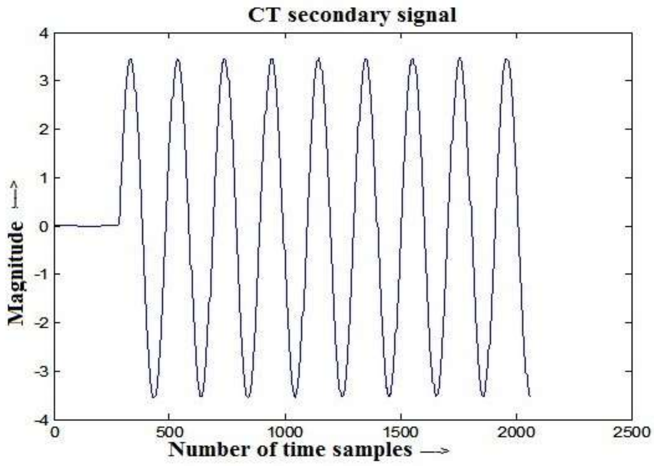
6 Results and Discussions

6.1 1000 Amp. Primary Current (normal condition)

At first 1000 Amp CT primary current is considered as the normal condition. Fig. 3(a) and 3(b) depict primary and secondary waveform respectively, though in practice primary signal is not used. After capturing the secondary waveform with proper sampling frequency FFT has been performed and also ‘db4’ based DWT have been executed for ‘Multi Resolution Analysis’ which is delineated in Fig. 4 and 5 respectively.



3(a)



3(b)

Figure 3. (a) Primary current signal of CT, (b) secondary current signal of CT

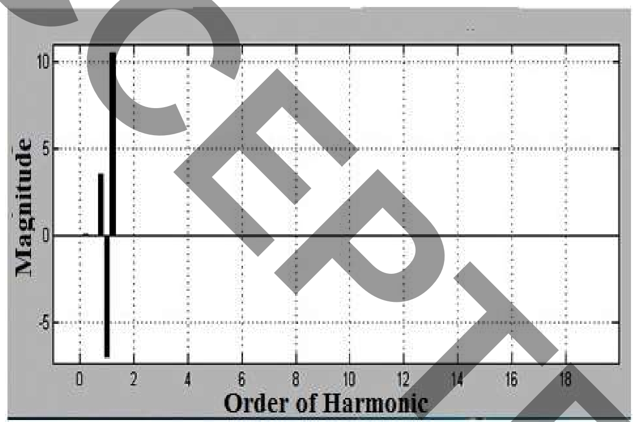


Figure 4. CT secondary signal FFT spectrum

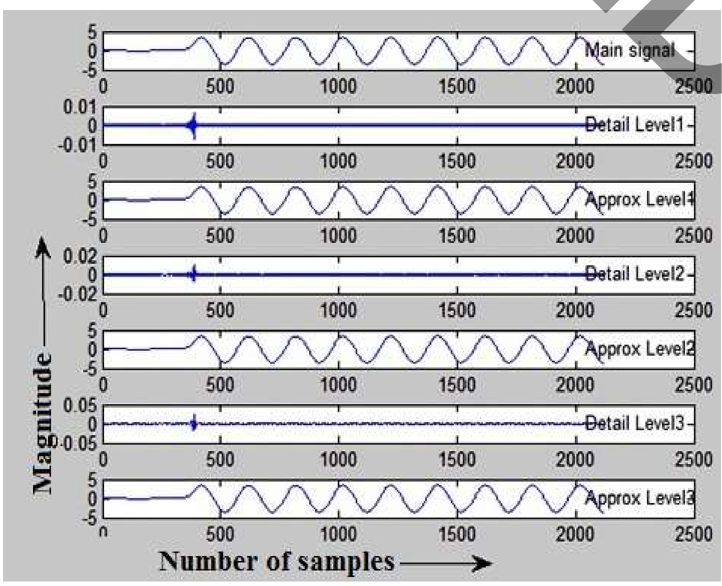
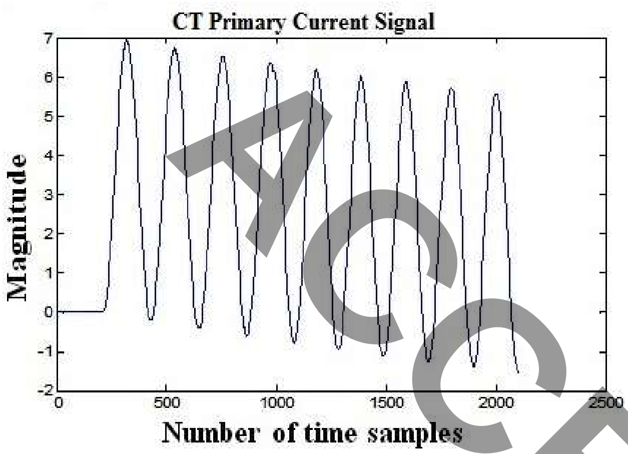


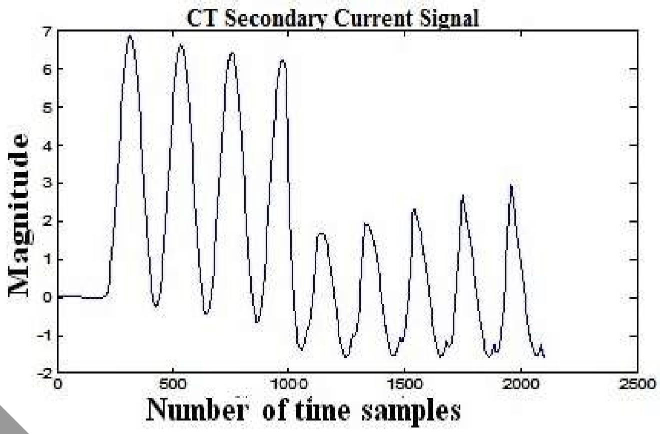
Figure 5. DWT of CT secondary signal

6.2 Saturation for switching transient

Here core saturation was considered by primary side breaker switching time. Breaker time (switching) was considered here as 1/50 second, as at that time voltage is at zero crossing position. Full current asymmetry has been observed due to this switching and as a result of that saturation is occurred in the CT core. Due to this CT saturation, secondary waveform (current) is distorted. CT primary and secondary current, FFT and Wavelet decomposition of CT secondary waveform is limned in Fig. 6(a), 6(b), 7and 8 respectively.



6(a)



6(b)

Figure 6. (a) Primary current signal of CT, (b) secondary current signal of CT

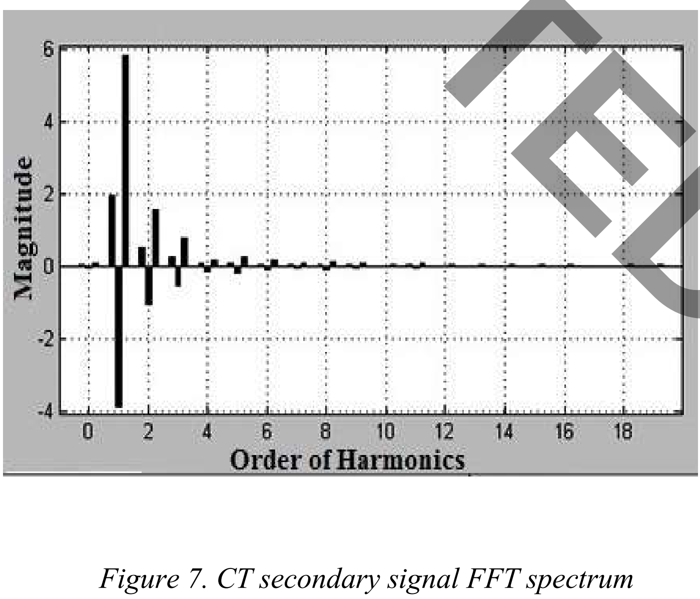


Figure 7. CT secondary signal FFT spectrum

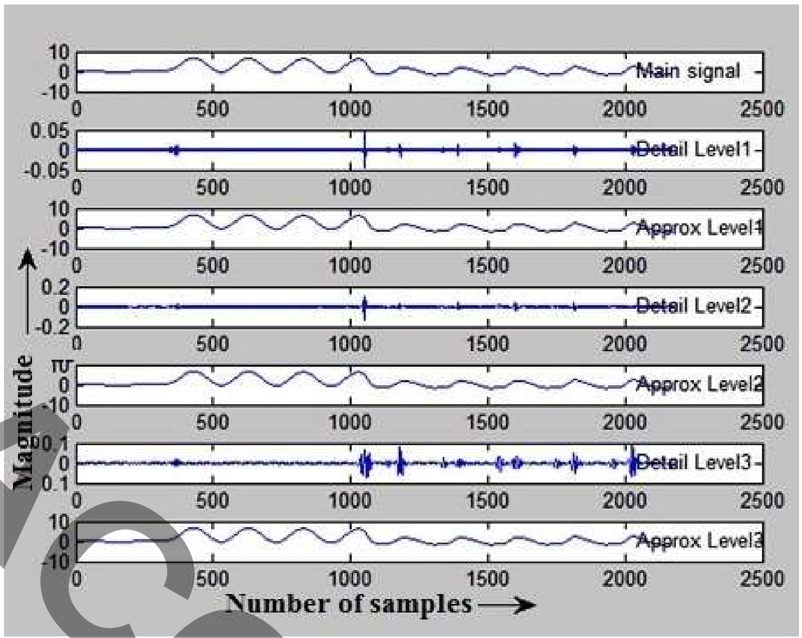


Figure 8. DWT of CT secondary signal

6.3 25kAmp primary current (high)

In this case CT secondary signal is considered as distorted due to saturation for high primary current. In the primary side for fault, high current (25 kAmp) was pondered and due to this, CT core is saturated which is reflected at FFT and DWT result of secondary waveform which is shown in Fig. 9 and 10 respectively.

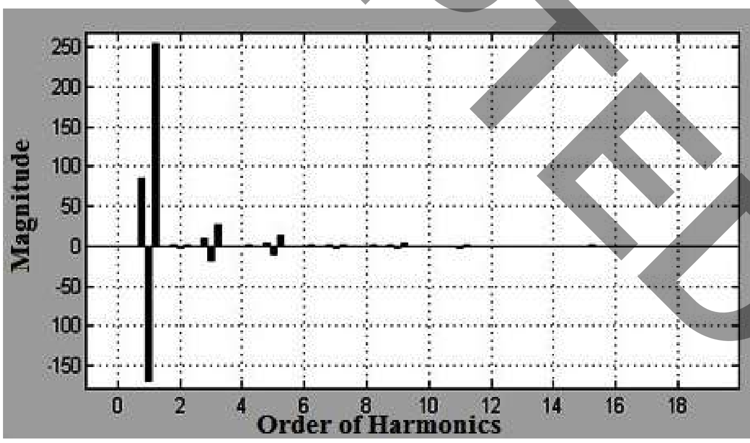


Figure 9. Spectrum analysis (FFT) of CT secondary signal

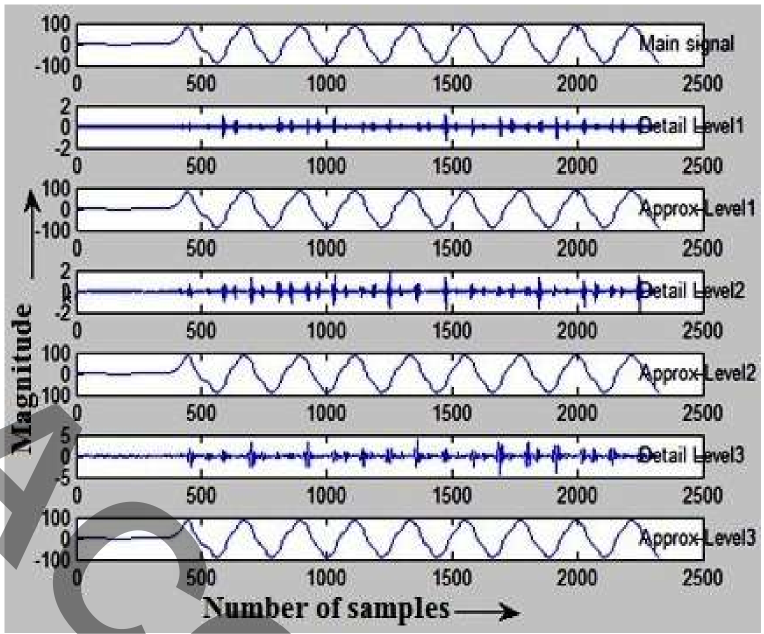


Figure 10. DWT of CT secondary signal

6.4 Primary current with 100%of 50 Hz and 60% of 2nd harmonic component (when primary current 1080 Amp and secondary current 2.67Amp)

Here, CT secondary signal is distorted but it is not an effect of core saturation. Injection of 2nd harmonic component with fundamental (50 Hz) component of frequency in primary current is the reason. Now, primary current itself is distorted and secondary current is a reflection of it, though primary current rms value is low (1080 amp). Results (FFT and MRA) are shown in Fig. 11 and 12 respectively.

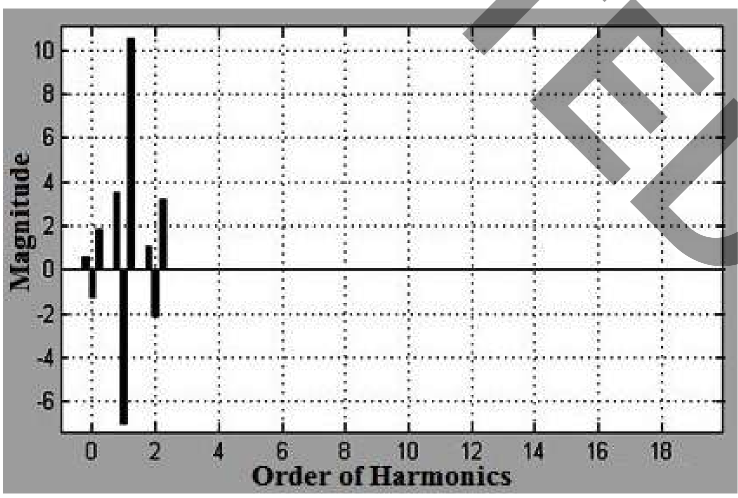


Figure 11. Spectrum analysis (FFT) of CT secondary signal

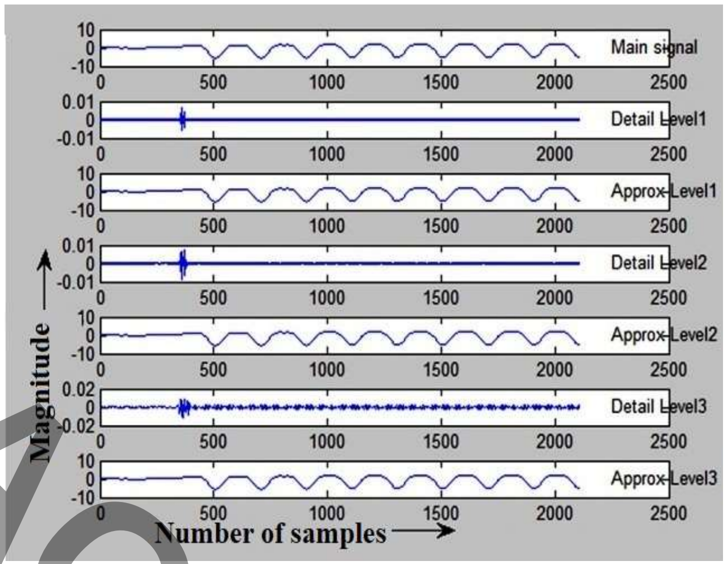


Figure 12. DWT decomposition of CT secondary signal

6.5 Primary current with 100% of 50 Hz and 30% 3rd harmonic and 50% of 5th harmonic component (When primary current 1010 Amp and secondary current 2.5 Amp)

Primary current is distorted because it contains 30% of 3rd and 50% of 5th harmonic. Here, FFT and MRA result is portrayed in Fig. 13 and 14 respectively.

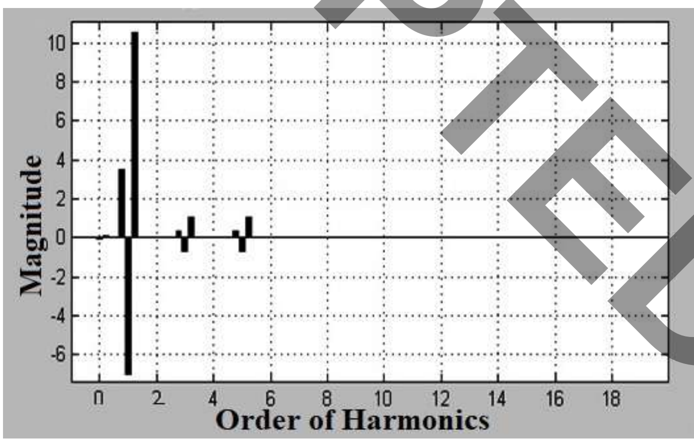


Figure 13. FFT spectrum of CT secondary waveform

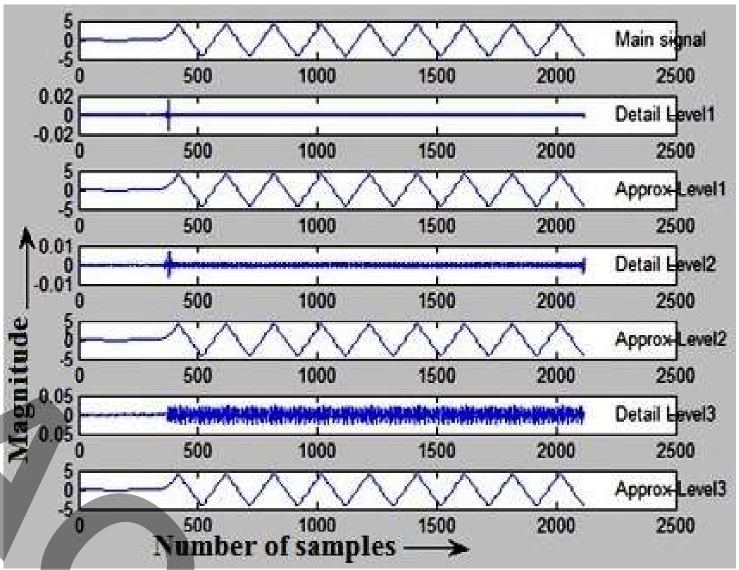


Figure 14. Wavelet decomposition upto third level of CT secondary signal

6.6 Primary current with 100% of 50 Hz and 30% 3rd harmonic and 50% of 5th harmonic component (When primary current 8077 Amp and 20.17 secondary current)

CT secondary is also distorted because of the distorted primary current. Distorted primary current has 30% of 150 Hz and 50% of 250 Hz frequency component though it is higher (8414Amp) than the previous case. Secondary signal is proper reflection of primary signal. Here, FFT and MRA result is given in Fig. 15 and 16 respectively.

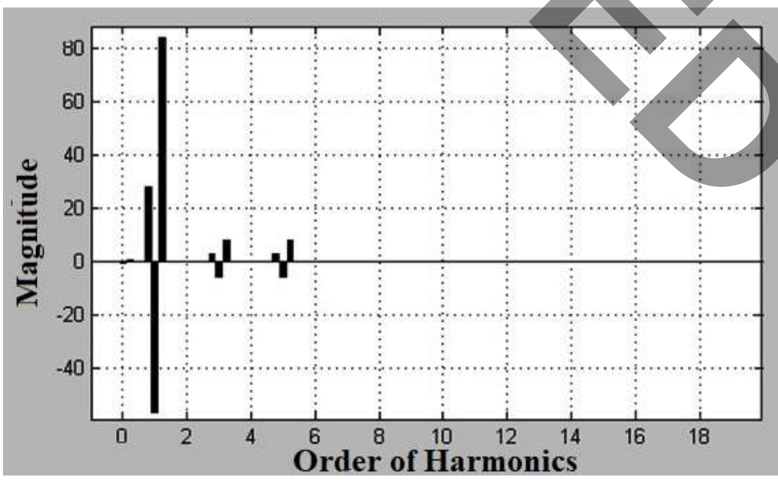


Figure 15. FFT spectrum of CT secondary waveform

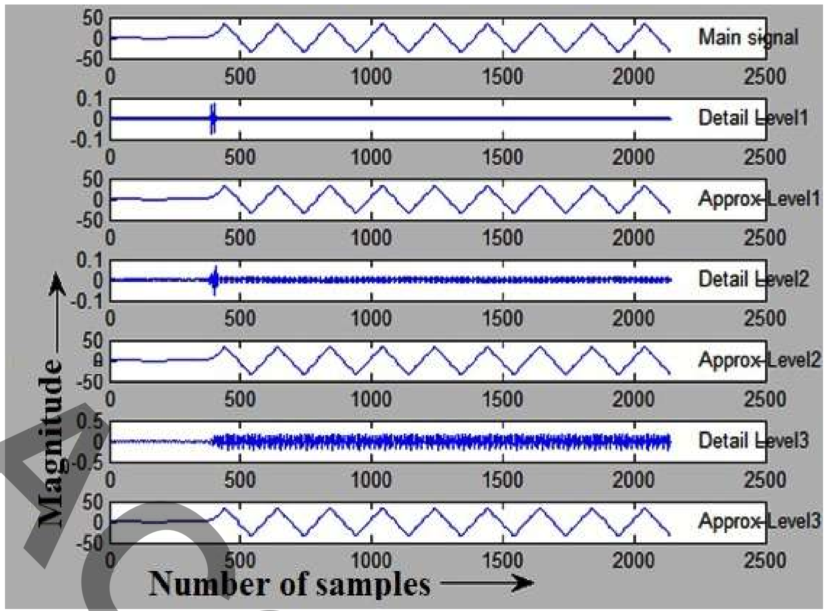


Figure 16. Wavelet decomposition upto third level of CT secondary signal

7 Analytical Comparison of Detail Level One Coefficients at Different Situations

Distorted CT secondary signal is caused by saturation or harmonics content of CT. Contortion of secondary signal can be identified by FFT result but reason for distortion can be classified by 'Multi Resolution Analysis'. Amongst MRA results maximum changes observed at detail level one coefficients. Different notches have been noticed in MRA results of DWT detail level one coefficient when CT core saturated (Fig. 17 b and 17c), but in ideal condition (Fig. 17a) and distorted secondary instance due to harmonics content of primary current signal, no notches have been observed in detail level one coefficients (Fig. 17 d, 17 e and 17 f). So using FFT results and DWT detail level one coefficients, distortion and reason of distortion can be identified and classified respectively.

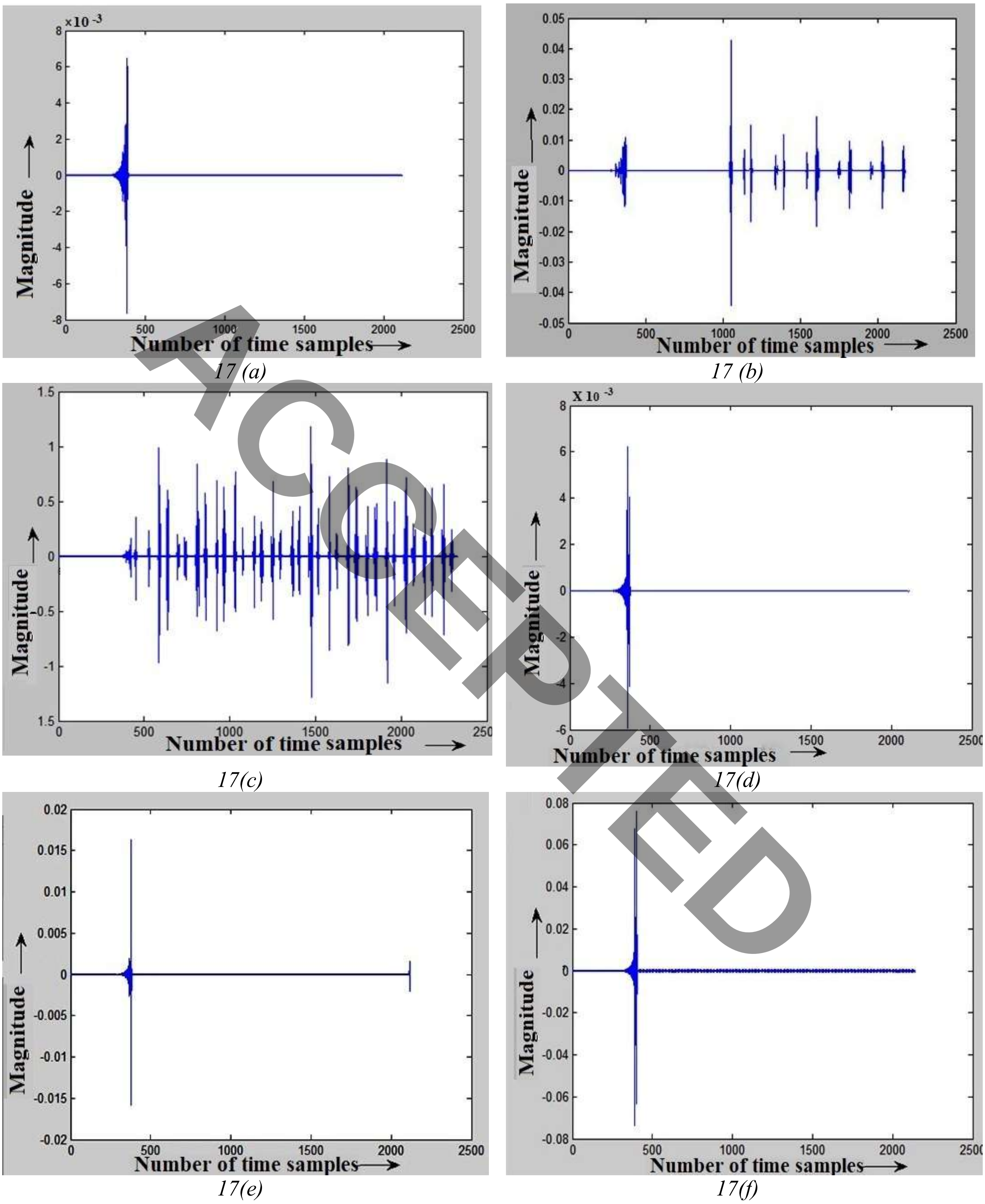


Figure 17. DWT first level (decomposition) detail coefficients at (a) normal condition, (b) switching transient (saturation) condition, (c) saturation at 25 kAmp, (d) primary current (1080 Amp) contains 60% 2nd harmonic (e) primary current (1010 Amp) contains 30% 3rd and 50% 5th harmonics (f) primary current (8077 Amp) contains 30% 3rd and 50% 5th harmonics.

8 Effect of Unbalanced Load on the CT

In this section CT performance has been analyzed due to unbalanced loading. In unbalanced loading condition, when X/R (reactance/resistance) ratio is 0.47 and primary current is 6732.35 Amp (in normal condition, X/R ratio is 3.142 and primary current is 1000 Amp), the CT primary, secondary signal, core flux, spectrum analysis (FFT) and DWT decomposition of secondary waveform are depicted in Figure 18 (a), (b), (c), (d) respectively. Due to unbalanced loading and high primary current, CT core gets saturated and distoted secondary waveform is not able to follow the primary current as it was in ideal condition. High CT flux is also shown in Fig. 18(b). Fig. 18(c) is the spectrum analysis of secondary waveform where presence of different harmonics is very clear. Fig. 18(d) depicts the DWT level three (3) decomposition of CT secondary waveform. In this figure different notches have been observed at detail levels, which indicates starting and ending of saturation in each cycle. From the spectrum analysis and DWT results, it is very much clear and it can be identified that, secondary signal distortion (CT) in unbalanced condition due to CT core saturation, is not the power quality problem of primary current (CT). Apart from starting notches, different notches have been observed in detail level coefficients (level 1,2 and 3) whose maximum value is 0.36 in detail level 1, 0.51 in detail level 2 and 0.89 in detail level 3.

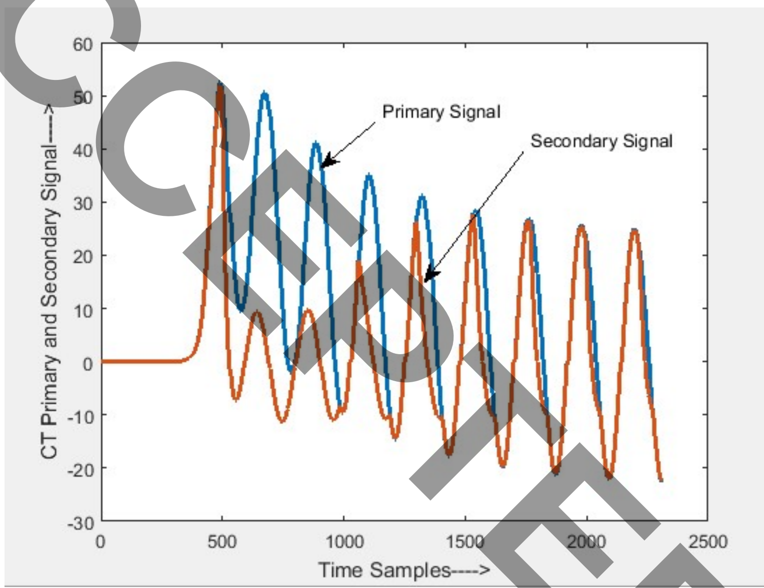


Figure 18(a). Primary and secondary waveform of CT

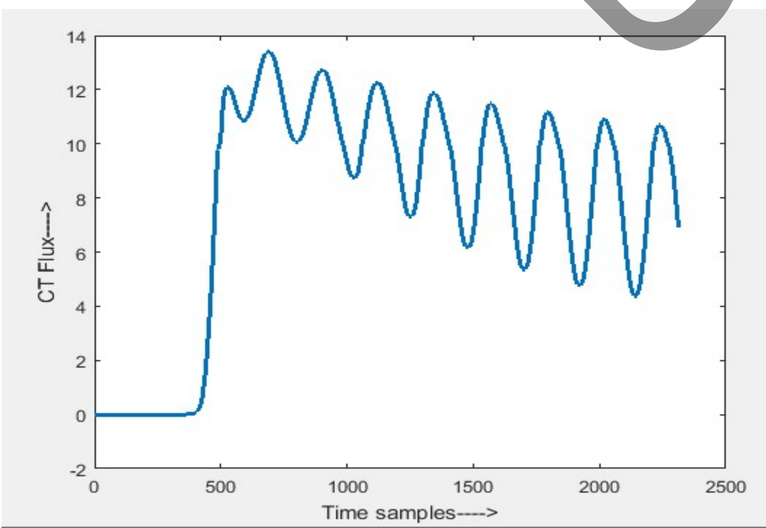


Figure 18(b). CT flux

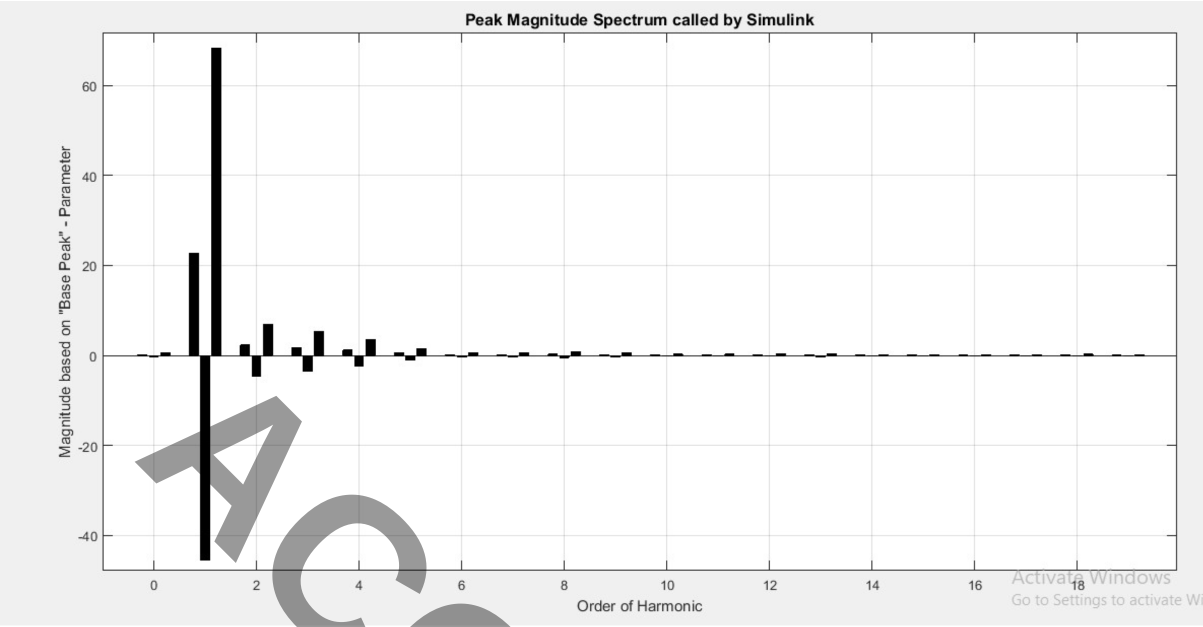


Figure 18(c). Secondary signal spectrum (FFT) analysis

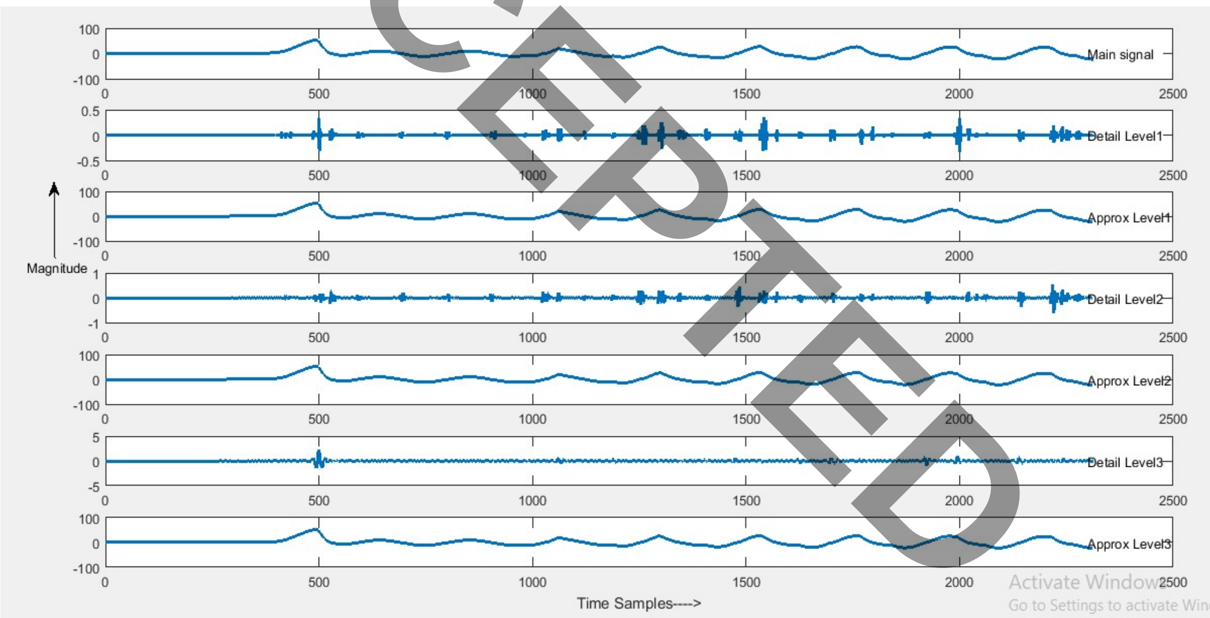


Figure 18(d). Level 3 Wavelet decomposition of secondary waveform

9 Conclusions

In this study, distortion of CT secondary was identified, and the cause was categorized using DWT-based MRA analysis. For this purpose, secondary waveform (CT) was recorded at the appropriate sampling frequency. At First, an FFT was executed on the recorded signal to identify any distortion in the waveform, and then DWT-based Multi - Resolution - Analysis was applied to determine the reason of the distortion. This method is capable enough for the accurate detection and classification of CT secondary signal distortion. This method yields incredibly positive results for the identification and classification of CT secondary signal distortion, which can then be applied to a suitable relaying algorithm.

Declaration of competing interest
The authors declare that they have no any known financial or non-financial competing interests in any material discussed in this paper.

Funding information
No funding was received from any financial organization to conduct this research.

Author contribution
The contribution to the paper is as follows: Aveek Chattopadhyaya: study conception and design; Aveek Chattopadhyaya: data collection; Sagnik Datta, Surajit Chattopadhyay: analysis and interpretation of results; Sagnik Datta: draft preparation. All authors approved the final version of the manuscript."

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Annexure

In this work, core material of CT is contemplated as silicon iron alloy. For this core material, current versus flux characteristics of above mentioned CT is delineated in Fig. A1. From this picture it is clear that 10 p.u. flux is the 'knee point' estimation of core flux..

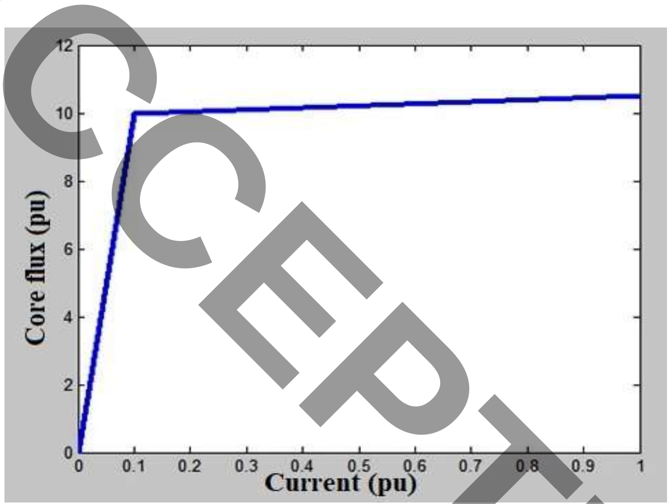

Figure A1. Current versus flux characteristics of CT