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Original

Numerical overcurrent power relay enhancement based on integrated discrete wavelet transform

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Abstract: As electrical power demands increase, the need for advanced protection relays has surged as a vital element in the power distribution system. That is, to ensure the continuity of power supply and eliminate abnormal faulty status, relays with diverse types and functions play a significant role in electrical power system operation and protection as well. In the power system, current variation faults may accrue for many reasons, which may harm power system components, load, and jeopardize human safety. However, in now a day digital current relay, a large number of current waveform samples are collected and processed to continuously monitor and detect faults. This large number of samples needs a bigger storage data real state and longer time to compile. Therefore, optimization is needed to improve current relay reliability and accuracy with much fewer samples. As a result, in this work, the wavelet transform algorithm with its wide spectrum feature of waveform analysis and decomposition process will be evaluated as an enhancement tool in current relay performance. Using MATLAB/Simulink, a simulation of modern digital current relay and the unique characteristics of wavelet transform (de-noising, mining, and decomposition) will be executed to evaluate the ability of advance fault detection based on a smaller number of current waveform data with respect to conventional analysis algorithm. As a result, by comparing the performance of the new proposed setting with the conventional digital overcurrent relay compiling algorithm, a promising result in terms of less than half the data samples were collected for faster compiling process and shorter relay response time was achieved.

Keywords: Digital current relay, power system protection, faults detection, reliability, and discrete wavelet transform

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1. Introduction

With the significant increases in energy demands, power utility companies must continually improve their operating system to maximize efficiency by aggregate power protection (Gielen et al., 2019). Yet, as transmission line components are exposed to many open surrounding effects and subject to a high rate of fault occurrence (Dudhe & Waghmare, 2017), power system failure analysis and fault protection are required. That is, due to open environment effect such as strong wind, heat effect, cold weather, lighting, man-made accidents, and integrated renewable energy sources effect on power voltage, current and frequency intermittent changes (Alsaif, 2017; Ayadi et al., 2020; Radwan et al., 2019), transmission lines are highly subject to failure operation. As power faults occur, whether symmetrical or asymmetrical, an abnormality of electric current flow will arise as a result between phases or phase(s) and the ground.

Therefore, continuous monitoring for fault occurrence and fault classification is required, as per IEEE 1159 standards, to stabilize power distribution and prevent power disturbances (McTaggart et al., 2010). While in Abdelmoumene, and Bentarzi (2012), as a huge capital loss associated with power accidental and outage, relays operation and failure to detect abnormality has contributed to almost 70 % of blackouts (Phadke et al., 2016). As a result, many researchers have been investigating the reliability and enhancement of power relays. In Terzija et al., (2011), Wide Area Monitoring (WAM) was proposed as a technique to monitor power systems and update per cycle. However, due to the requirement of the primary relay high-speed response, a complicated computational process and communication infrastructure is required (Phadke et al., 2016), as well as the effect of retransmitting data by inheriting efficiency reduction (Alawady et al., 2021). Moreover, in Horowitz and Phadke (2006), 70% of WAM disturbances were due to deprived relay settings. Meanwhile, as in Jaworski et al. (2016), pilot protection techniques depend on the reliability of communication linkage, other work has been done by enhancing coordination among overcurrent relays in power distribution using a nature-inspired root tree algorithm (Wadood et al., 2018). In addition, some work has been done on the physical relay enhancement. In Khurshaid et al. (2019), optimization was proposed through adjusting directional overcurrent relay time-dial settings in a closed-loop power distribution system. Other work focused on identifying power faults by comparing the differences of sequential current cycles (Sidhu et al., 2002). However, this technique of spotting power faults is based on detecting mismatch in the signal by using Fourier transform to convert voltage and current signal into phasor (Wu et al., 2005). Yet, as disturbance caused by noise, harmonics, and frequency variation will be inherited as an error's factors into current waveform cycles calculations (Ray et al., 2017; Wei et al., 2020), and due to Fourier transform characteristics in localizing domain to provides magnitude and time, which is best used for stationary signals (Ahmad et al., 2018, Awada et al., 2016; Awada, 2021; Elmore et al., 2015; Toufiq et al., 2021) relay effectiveness can be jeopardized and mis-leaded. As a result, many researchers have been investigating the benefit of wavelet transform to overcome these issues and detect power faults based on wavelet special features algorithm for current waveform analysis (Awada et al., 2021; Costa et al., 2015). In Seo, (2019), wavelet transform was used in the neural network of relay protection to identify and isolate the fault, however, the proposed technique is based on network layers and hierarchy process.

In this work-study, an enhancement of current numerical relay performance was executed by implementing the discrete wavelet transform (DWT) to perform an instantaneous current waveform component analysis before numerical relay computation. That is, any potential changes, unexpected, in the current waveform will be detected with the elimination of noise disturbances and less computational process. Several types of (DWT) were investigated under different operating settings, to determine system reliability in extracting and identifying the current fault. As a result, based on wavelet transform special features of dilation and translation, noise filtering, and waveform decomposition property (Awada, 2021; Dudhe & Waghmare, 2017), this newly proposed technique will provide an effective current relay operation without any relay setting changes to distinguish between normal and faulty conditions.

2. Wavelet transform

While Fourier transform is used as a waveform visualizing tool, many other analysis applications are based on such algorithms. Yet, as Fourier analysis is localized in frequency domain and based on breaking the waveform into oscillations over the entire window analysis, local and temporal waveform data cannot be provided due to integral over time and limitation in frequency and bandwidth (Awada et al., 2021) especially for transient signals. In addition, as Fourier based on summation of cosine waves, noise, frequency distortion, harmonics and spectral impurity will be summed into the final waveform. On the other hand, wavelet transform has the advantage of stretching analysis window, adjustable for every cycle, to best fit each signal analysis in both time and frequency domain as shown in Figure 1. In addition, the special characteristics of wavelet signal decomposition have shown an advantage over the Fourier by localizing waveform components in specific time-frequency to define a signal pattern and hidden data.

Meanwhile, wavelet special property of extraction data through translation and dilation allow to analyze waveform in multi- scales of resolution analysis and multi-rate of filtering by dividing waveform into various frequencies (Rajabinezhad et al., 2021). With scaling coefficient energy, wavelet approximation and detail sub-band are divided into overlapped blocks coefficients were each used as an element block to the established feature vector of waveform component. This particular property helps in dropping the mandatory coefficients and produces a lesser mass of feature vectors. Therefore, based on dilation and translation and decomposition process, wavelet transform has shown more details by zooming into the waveform components by directionality approximately and detail analytic as defined as in Eq. (1), to help to identify any abrupt variations in the electrical waveform such as voltage, phase, current, frequency, etc.

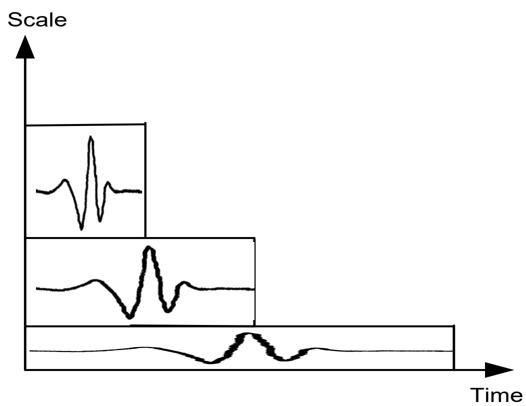

Figure 1. Wavelet windows analysis at various frequencies sectors (Awada, 2021).

$$\Psi c(s) = \Psi r(s) + j\Psi i(s) \tag{1}$$

Where the imaginary part j of wavelet ψi(t) is a Hilbert transform of the real part ψr(t). Since wavelet banks are based on predetermined filters (details h1(n) and approximation g1(n)) (Awada, 2021; Rajabinezhad et al., 2021), the decomposition process approximates half the sample as shown in Eq. (2).

$$g_0(s) = h_0\left(n - \frac{1}{2}\right) \tag{2}$$

That is, two channels of filter banks will be constructed of down-sampling in each decomposition level as shown in Eq. (3) and Eq. (4) and Figure 2.

$$H_0(z)F_0(s) + H_1(s)F_1(s) = 2s - 1 \tag{3}$$

$$H_0(-s)F_0(s) + H_1(-s)F_1(s) = 0 \tag{4}$$

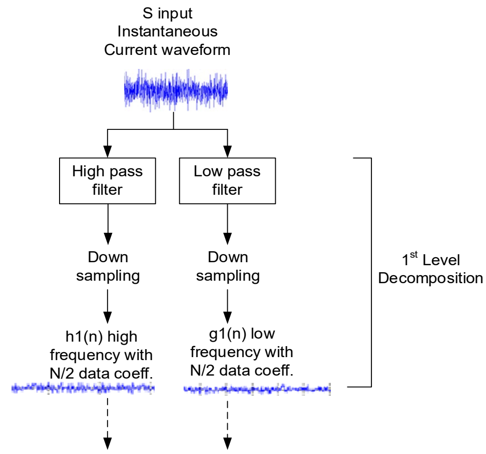

Figure 2. Wavelet transform decomposition.

As a result, modern technology of power protection system based on a numerical relay, waveform component analysis has become a major aspect in relay operation. Therefore, DWT will be used to examine current waveform instantaneous amplitude variation based on low-pass approximation coefficients to eliminate impeded noises and obtain an accurate overcurrent relay outcome.

3. Overcurrent relay

The power system is subject to many exposures and excessive overload that led to overcurrent phenomenon as shown in Figure 3.

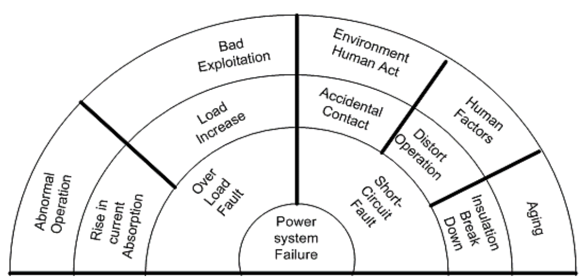

Figure 3. Overcurrent fault causes.

As a result, overcurrent protection relay acts as a protection element to prevent stresses and damages to power system components and load equipment as well (Bougouff et al., 2021). That is, overcurrent is a condition where an amount of current passing through (conductor or bus bar for example) is larger than the planned design. This may lead to extreme heat generation and equipment destruction. Therefore, to distinguish between a surge charge and short circuit condition, overcurrent relay typically operates on time delays of few milliseconds and current between 10% to 50% above rated current (Ji et al., 2020) as shown in Figure 4 for Definite-time characteristics.

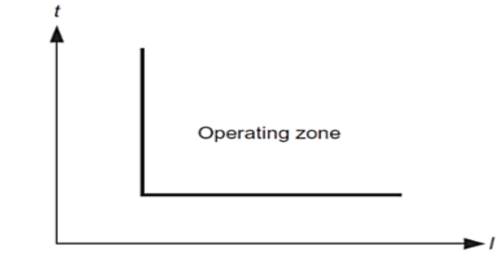

Figure 4. Definite-time characteristic (Ji et al., 2020).

As the relay time delay is lower than instantaneous current setting and higher than standard fault flow, the relay operates as failure occurs with time delay. That is, the standard operation time (T) of the relay as in IEC 60255 is as shown in Eq. 5.

$$t = TDS \times \left(\frac{a}{\left(\frac{I_f}{CT_r \times I_p} \right)^B - 1} \right) \quad (5)$$

4. System under-study for fault detection using wavelet transform

In this work, a power system based on 400 KV and 50 Hz was modelled as a subject to overload (short circuit) failure and single phasing failure, as shown in Figure 5, to evaluate numerical overcurrent relay performance in conventional compiling algorithm and newly proposed DWT analysis for error detection.

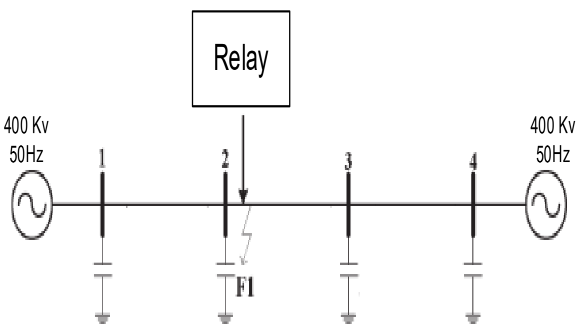

Figure 5: Power System Modulation

The new proposed protection system is intended to simplify the enhancement of overcurrent relay operation by adding wavelet transform algorithm as a tool to define current waveform component with de-noising interference and interleave waveform into multi-level analysis before overcurrent relay operation that meets IEEE standard C37.112-1996 characteristics as seen in Figure 6.

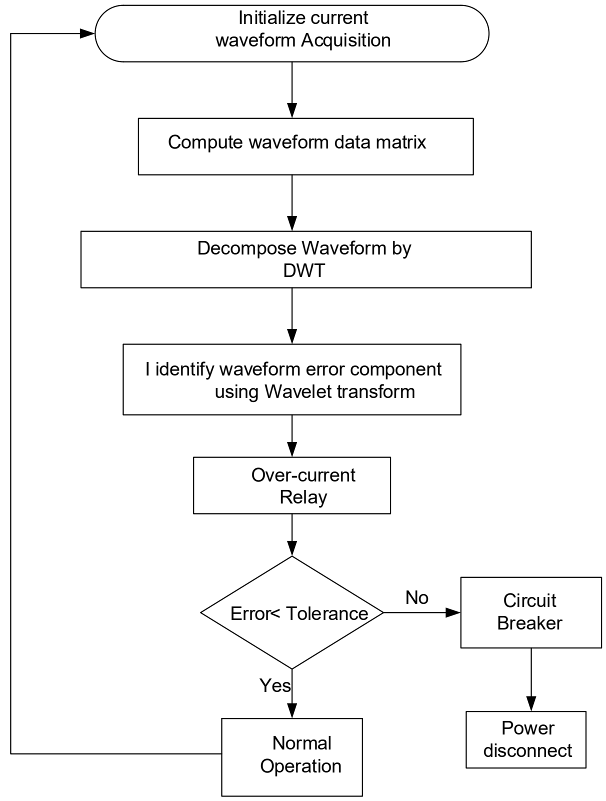

Figure 6. Overview of proposed new overcurrent protection scheme.

By interleaving instantaneous current waveform, amplitude (A) will be defined as a function of wavelet coefficients as in Eq. 6.

$$f \cong \left(A, \left| s[1] \right|, A, \left| s[2] \right|, \ldots, A, \left| s[n] \right|, \ldots \right) \quad (6)$$

Meanwhile, by applying wavelet transform scaling and decomposition as in Eq. 7.

$$\begin{bmatrix} \frac{\sqrt{2}}{2} & \frac{\sqrt{2}}{2} & & & \\ \frac{\sqrt{2}}{2} & -\frac{\sqrt{2}}{2} & & & \\ & & \frac{\sqrt{2}}{2} & \frac{\sqrt{2}}{2} & \\ & & \frac{\sqrt{2}}{2} & -\frac{\sqrt{2}}{2} & \\ & & & & \ddots \end{bmatrix} * f = \begin{bmatrix} \frac{\sqrt{2}}{2}(A+|s(1)|) \\ \frac{\sqrt{2}}{2}(A-|s(1)|) \\ \frac{\sqrt{2}}{2}(A+|s(2)|) \\ \frac{\sqrt{2}}{2}(A-|s(2)|) \\ \vdots \\ \vdots \end{bmatrix} \Rightarrow \begin{bmatrix} \frac{\sqrt{2}}{2}(A+|s(1)|) \\ \frac{\sqrt{2}}{2}(A+|s(2)|) \\ \vdots \\ \frac{\sqrt{2}}{2}(A-|s(1)|) \\ \frac{\sqrt{2}}{2}(A-|s(2)|) \\ \vdots \end{bmatrix} \quad (7)$$

The high pass components of wavelet decomposition [($\frac{\sqrt{2}}{2}(A-|s(1)|)$, $\frac{\sqrt{2}}{2}(A-|s(2)|)$, $\cdots, \frac{\sqrt{2}}{2}(A-|s(n)|)$] will be used as numerical current relay input to determine abnormality with respect to a predetermined threshold.

5. Simulation and result discussion

MATLAB/Simulink was used as a tool to model a real-time numerical overcurrent relay of a power system network operation and fault simulation. However, as proposed, the wavelet transform algorithm was added to the numerical overcurrent relay to form the wavelet base relay. That is, as intended for this work, wavelet-based and conventional Fast Fourier Transform (FFT) overcurrent numerical relays were simulated and compared in terms of operation time and number of samples required to determine current disturbances as shown in Figures 7 and 8.

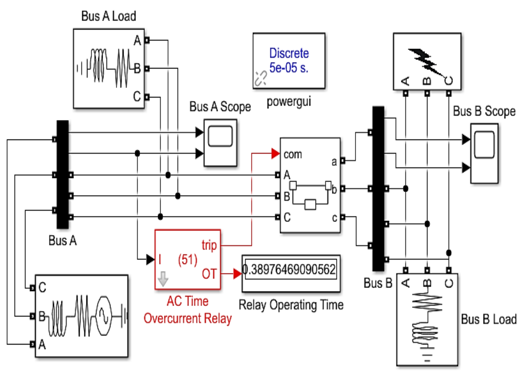

Figure 7. Power system-overcurrent conventional relay operation.

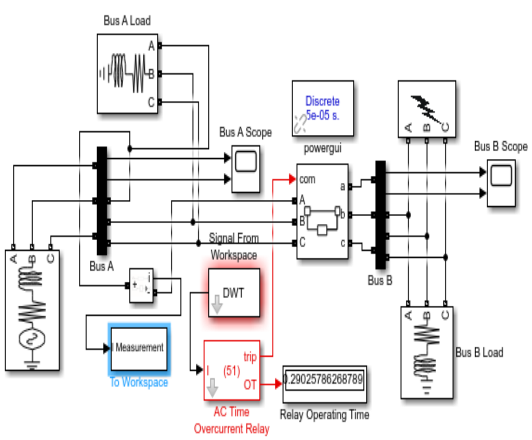

Figure 8. Power system-overcurrent wavelet base relay operation.

As current waveforms were monitored in all three phases, the system was able to detect current disturbance due to single phasing, overload, and short-circuit as shown in Figures 9, 10, and 11 for asymmetrical and symmetrical phases fault.

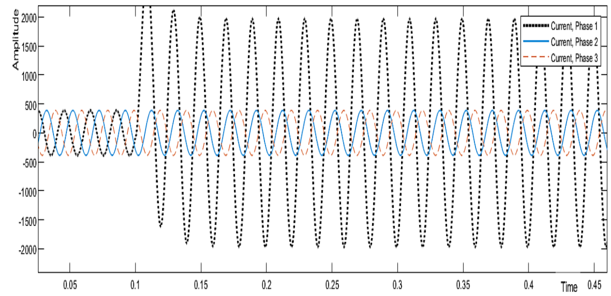

Figure 9. Overload, asymmetrical over current phase fault.

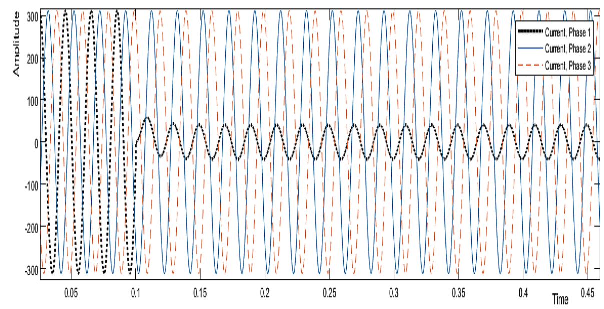

Figure 10. Single phasing asymmetrical under current phase fault

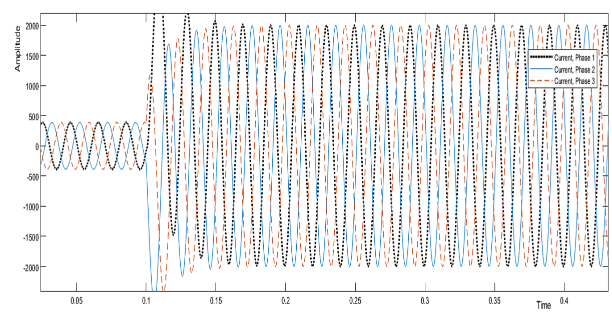

Figure 11. Overload, short-circuit, symmetric current phase fault.

As a result, by applying conventional numerical relay algorithm, operation time to trip circuit breaker was around 0.395 second as shown in Table 1 and Figure 12. Meanwhile, several types of wavelet transform were used in evaluating the response time of the numerical overcurrent relay. As a result, relay operation time dropped to 0.29 second as shown in Table 1 and Figure 12.

Table 1. Numerical overcurrent relay operation time.

Algorithm	Operation time
dB4	**0.290257863**
Db1	0.297271946
Haar	0.299272977
Sym1	0.301273987
Coif2	0.305298593
FFT	**0.395043079**

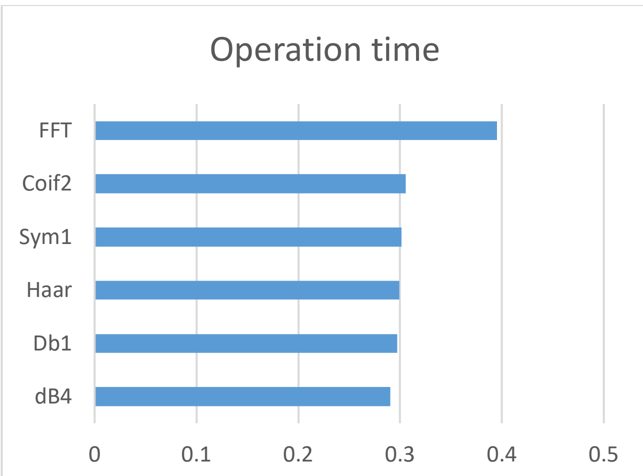

Figure 12. Numerical overcurrent relay operation time based on FFT and DWT.

Due to the special characteristics features of Daubechies wavelets as closest to sinewave (Awada, 2021), it has been recommended as best analytical tool for this type of integration. In addition, based on the wavelet transform level of decomposition process, the number of collected data was dropped from 7000 data samples for conventional numerical overcurrent relay to 3500 data samples at 1st level of decomposition and 1750 data samples at 2nd level of decomposition as shown in Figures 13, 14, and 15 respectively.

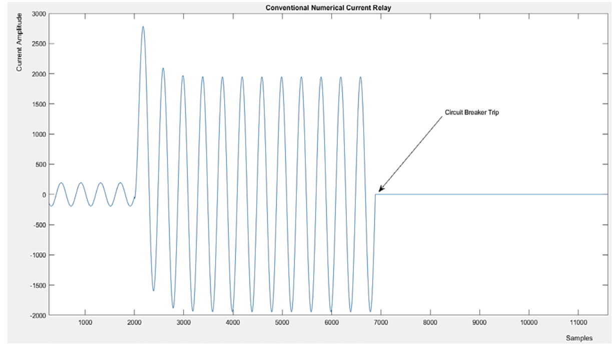

Figure 13. Number of data samples required by conventional relay to trip the circuit breaker.

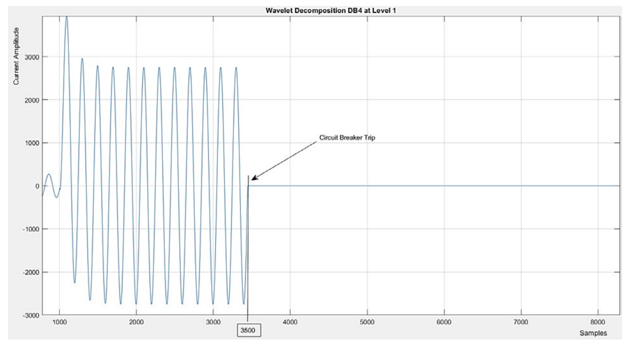

Figure 14. Number of samples used by numerical overcurrent relay based on 1st level wavelet decomposition.

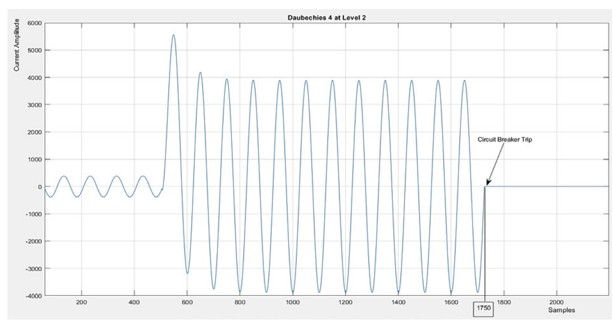

Figure 15. Number of samples used by numerical overcurrent relay based on 2nd level wavelet decomposition.

6. Conclusion

In this work, the main intention was to implement wavelet transform properties into numerical overcurrent relay data analysis and action process. By applying advanced signal processing to instantaneous power system current waveform, wavelet transform properties of de-noising and extraction components had shown a promising algorithm in enhancing the operation of numerical overcurrent relay. By eliminating noise interference from system generation, transmission, and load pre-fault, in addition to power swing, wavelet transform was able to identify current waveform fault components at diverse frequency bands by far fewer sample data (less than half of FFT) and less response time by 0.10 Sec. That is, only 1750 data samples were used in the 2nd stage of wavelet compiling Vs. 7000 for FFT compiling of overcurrent relay fault detection. In addition, the Daubechies wavelet had outperformed all other types of wavelets and FFT in fault detection duration due to its special characteristics of sinusoidal waveform. As a result, by comparing wavelet transform and Fourier transformation algorithms in terms of overcurrent relay operation, wavelet transform has shown a promising result based on selected mother wavelet transform.

Conflict of interest

The author has no conflict of interest to declare.

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