On-line Discrete Wavelet Transform in EMTP Environment and Applications in Protection Relaying

N. Perera, A.D. Rajapakse and R.P. Jayasinghe

Abstract--This paper describes the development of an on-line discrete wavelet transform tool for an electromagnetic transient simulation program. Multi-resolution properties of wavelet transform make it ideally suitable for analyzing power system transient signals which consist of non-periodic high frequency oscillations superimposed on power frequency signal. New power system devices such as power quality monitors and protective relays based on algorithms involving wavelet transformation are emerging. Thus, it is highly useful for power system electromagnetic transient simulation programs to have integrated capability for wavelet transformation. This paper also briefly presents several applications of wavelet transformation in power system protection and power quality monitoring.

Keywords: Electromagnetic transient simulation, Wavelet transforms, Applications of wavelet transform in power system, Power system protection, Power quality.

I. INTRODUCTION

Wavelets are mathematical functions that decompose a signal into different frequency components, and then study each component with a resolution matched to its scale [1]. They have added advantages over traditional Fourier methods because wavelet transformation localizes information in the time-frequency plane; and capable of trading frequency resolution with time resolution and vice-versa. These properties have made Wavelets transformation highly suitable for analyzing physical situations where the signal contains discontinuities and sharp spikes [1],[2].

Waveforms associated with fast electromagnetic transients are typically non-periodic and contains both high frequency oscillations and localized impulses superimposed on power frequency and its harmonics. These characteristics present a problem for traditional Fourier analysis because its use assumes a periodic signal and because a wide-band signal requires denser sampling and longer time periods to maintain good resolution in the low frequencies [3]. On the other hand, multi-resolution properties of wavelets transform make them well suited to analyze transient signal superimposed on a continuous fundamental.

Due to the wide variety of signals and problems encountered in power engineering, there are various applications of wavelet transform. These include detection, and analysis of power quality disturbances and power quality data compression [4], [5], high voltage insulation condition monitoring [6], fault detection [7], [8], and disturbance classification [9]. Several power engineering products based on wavelet transformation such as protective relays [10] and power quality monitors [11] are now emerging.

Electromagnetic transient programs (emtp-type programs) are widely used for power system studies involving power quality issues, protection system operation, etc. An integrated tool that can be used to perform wavelet transformation of the simulated waveforms is a highly useful feature for those studies investigating wavelet transformation based techniques. Although several wavelet transform programs such as MATLAB® wavelet toolbox are available, their use generally requires simulated waveforms to be saved in data files and then perform the analysis external to the emtp-type simulation. The novelty of the proposed component is that it can be used to perform the wavelet transform as the waveforms are generated by the simulation. Thus it is possible to simulate systems such as protective relays based on wavelet transformation in a closed loop manner.

This paper is organized as following. Section II gives a brief introduction to the wavelet transformation for the benefit of readers not familiar with wavelet transformation. Then the implementation of wavelet transformation using filter banks is explained in Section III. A brief description of the usage and capabilities of the wavelet tool developed is given in Section IV. Section V presents several application examples, and conclusions are given in Section VI.

II. WAVELET TRANSFORMATION

The wavelet transformations can be Continuous Wavelet Transformation (CWT) or Discrete Wavelet Transformation (DWT). If *f(t)* is a signal with a finite energy, its CWT is defined as

$$CWT_{\Psi} f(a,b) = \int_{-\infty}^{\infty} f(t)\Psi^{*}_{a,b}(t)dt \qquad (1)$$

where,

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$$\Psi_{a,b}(t)=|a|^{-1/2}\Psi\left(\tfrac{t-b}{a}\right) \qquad (2)$$

The function $\Psi(t)$ is the basis function or the mother wavelet, the asterisk denote a complex conjugate, and a ($\neq 0, \in \Re$) is the scale parameter and b ($\in \Re$) is the translation parameter. The mother wavelet function must satisfy several conditions: it should be short and oscillatory, i.e. it must have zero average and decay quickly at both ends. Several examples of wavelets are shown in Fig.1.

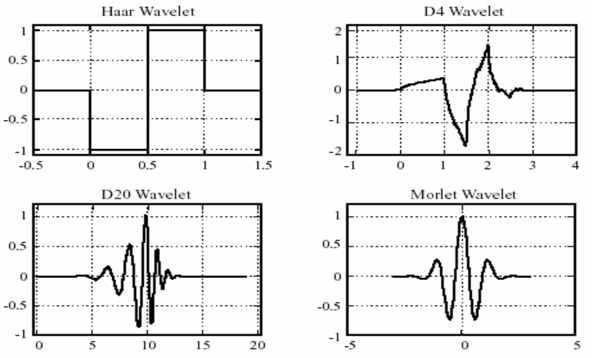


Fig. 1. Different types of wavelets

In discrete wavelet transformation, mother wavelet is dilated and translated discretely by selecting

$$a = a_o^m \quad ; \qquad b = nb_o a_o^m \qquad (3)$$

where a_o (>1) and b_o (>0) are fixed real values and m and n are positive integers. Then the discretized mother wavelet becomes

$$\Psi_{m,n}(t)=\frac{1}{\sqrt{a_o^m}}\Psi\left(\frac{t-nb_o a_o^m}{a_o^m}\right) \qquad (4)$$

The corresponding discrete wavelet transformation is given by

$$DWT_\Psi f(m,n)=\sum_k f(k)\Psi^*_{m,n}(k) \qquad (5)$$

DWT provides a decomposition of a signal into sub bands with a bandwidth that increases linearly with frequency. In the case of dyadic transform corresponding to $ao = 2$ and $bo = 1$, the result is geometric scaling, i.e. 1, $1/a$, $1/a^2$… and translation by 0, n, $2n$… This scaling gives the DWT logarithmic frequency coverage in contrast to the uniform frequency coverage of Fourier transformation.

III. FILTER BANK IMPLEMENTATION OF DWT

A. *Decomposition and Reconstruction*

DWT can be implemented efficiently as a filter bank as shown in Fig. 2 [1],[2]. This implementation is commonly known as Mallat tree algorithm and consists of series of low-pass filters and their dual high pass filters. H(n) denotes a high pass filter and L(n) is its dual low pass filter. The filter coefficients are determined by the type of mother wavelet selected. The circle with downward arrow behind 2 denotes down sampling by a factor of 2. The outputs d_1, d_2, d_3, etc. are called the detail wavelet coefficients while the output from the last low pass filter is referred to as the approximation wavelet coefficient.

It is possible to obtain the original signal $f(t)$ through wavelet series reconstruction. The reconstruction can also be carried out efficiently using a tree algorithm as shown in Fig. 3. The filters H'(n) and L'(n) are the inverse filters of H(n) and L(n) respectively. In Fig. 3, the circles with upward arrow behind 2 denotes up sampling by a factor of 2.

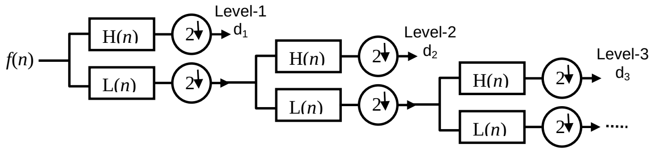


Fig. 2. Mallat tree algorithm for wavelet decomposition

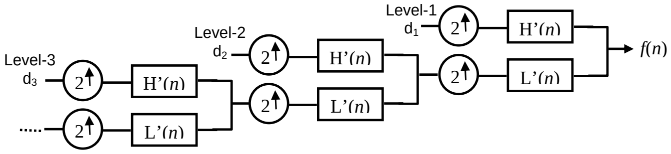


Fig. 3. Wavelet reconstruction

B. *Multilevel Decomposition and Reconstruction*

The reconstruction algorithm can be used to provide the wavelet coefficients of different scales a finer time resolution. Fig. 4 illustrates this process: decomposition of sampled signal *x(n)* for three levels and use of up sampling and filtering to obtain finer reconstruction wavelet coefficients. The original signal $x(n)$ can now be easily reconstructed simply by adding the reconstruction wavelet coefficients: the detail coefficients D1(n), D2(n), D3(n) and approximation coefficient A3(n). Note that all these coefficients now have the same sampling rate as the original signal.

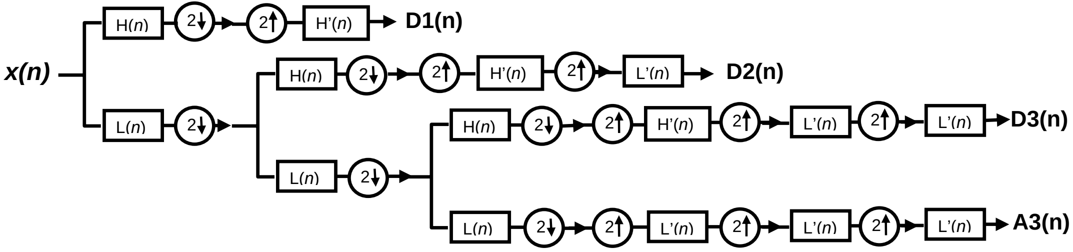


Fig. 4. Multilevel wavelet reconstruction

IV. WAVELET TRANSFORM TOOL IN EMTP ENVIRONMENT

Simulation of devices that use wavelet transform based techniques is essential for research and development as well as for validating the suitability of those new devices for practical applications. Since emtp-type programs are widely used for studies concerning power quality issues, protection, and transients in power systems, the capability of applying wavelet transformation in emtp environment itself will provide many advantages. Although there are several free/commercial software tools available for wavelet analysis, they can be used only for post simulation analyses using the waveforms saved to data files. This is not obviously a convenient way, especially when simulations are needed to carry out repetitively. On the other hand, since the analysis has to be carried out after completing the simulations, simulation of devices that use wavelet transform cannot be performed. The online wavelet transformation tool developed here enable simulating systems such as protective relays based on wavelet transformation in a closed loop manner.

A. *DWT Tool*

In the present study, an online wavelet transformation tool was developed in PSCAD/EMTDC® software. However, this can be implemented in any other emtp-type program. The block diagram in Fig. 5 shows the processing steps involved.

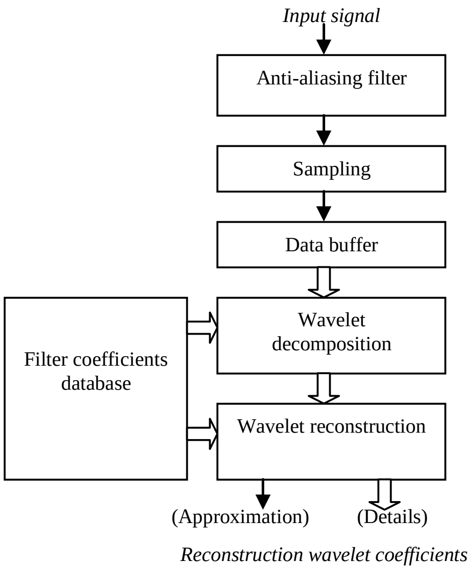


Fig. 5. Processing steps involved in the DWT tool

As applications may need signal sampling intervals that are different from the simulation time step, a provision is allowed for re-sampling the input signal at a frequency selected by the user. An anti-aliasing filter is also provided for filtering out high frequency noise. The cutoff frequency of the anti-aliasing filter is automatically determined based on the sampling frequency selected. A provision is provided to disable the anti-aliasing filtering if required. Sampled data is placed in a buffer before the decomposition and reconstruction is performed. User can specify the type of mother wavelet. Currently nine types of mother wavelets have been implemented: Harr, Daubechies (DB) (order 1, 2, 4, and 8), Symlets (Sym) (order 1, 2, 4, and 8), Coeiflets (order 1 and 2) (Harr, Daubechies order1, and Symlet order 1 are essentially the same). In addition, a user can specify the level of details computed. This selection requires a change in the dimension of the output. The total number of coefficients calculated is equal to the number of detail levels plus one (for the approximation component).

B. *Validation*

The accuracy of computation is validated by comparing with MATLAB® wavelet toolbox, which is one of the most widely used tools for wavelet analysis. Fig. 6 shows a sample of results which compares the wavelet coefficients of a signal with transient (top most graph) obtained through MATLAB and the DWT tool developed in PSCAD/EMTDC.

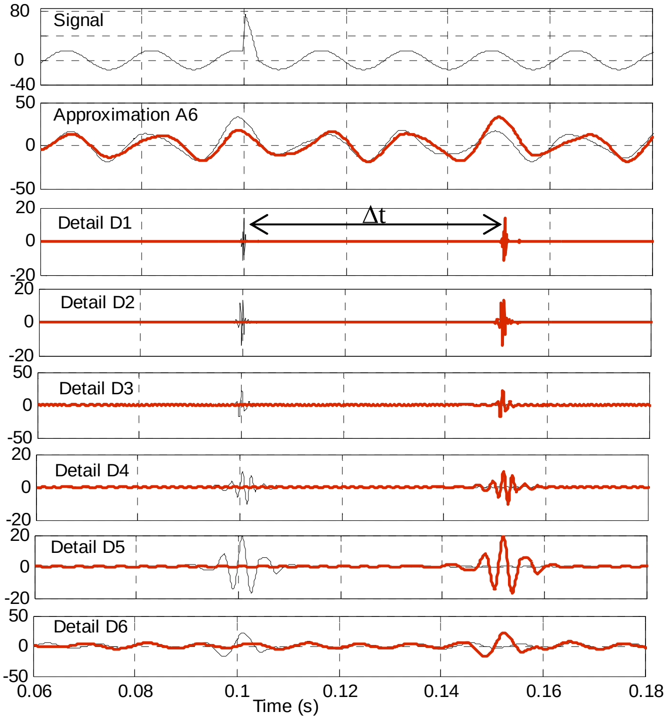


Fig. 6. Comparison of the wavelet coefficients calculated using MATLAB wavelet tool box (thin lines), and the PSCAD DWT tool (thick lines) for a sample waveform. The mother wavelet used is Sym8. Note that the online calculation in PSCAD results in a time lag (Δt).

TABLE I
DATA WINDOW SIZES (NUMBER OF SIGNAL SAMPLES) REQUIRED FOR ONLINE DISCRETE WAVELET TRANSFORM.

Level	Haar	Db2/sym2	Db4/sym4	Db8/sym8	Coif1	Coif2
1	2	6	14	30	10	22
2	4	14	34	74	24	54
3	8	30	74	162	52	118
4	16	62	154	338	108	246
5	32	126	314	690	220	502
6	64	254	634	1394	444	1114

For the case shown in Fig. 6, Sym8 mother wavelet was used. Shown in thicker lines are the results from the

PSCAD/EMTDC online DWT tool (transformation was performed as the signal being generated from the simulation). MATLAB results were obtained at the end of simulation by using a recorded waveform. Except for the time delay, both curves were found to be identical. Time delay, which cannot be avoided in online calculation, is dependent on the data window size (number of signal samples) required to perform the calculation. Table-1 gives the data window sizes required for different types of mother wavelets at different detail levels to perform online DWT.

V. APPLICATIONS OF WAVELET TRANSFORM TOOL

A. Rapid Isolation of Faults

Wavelet transform can be used to quickly identify the direction of fault currents using initial transients in the currents (or voltages) due to the fault [12]. In order to explain the principle, consider a relay installed at a busbar interconnecting three lines segments as shown in Fig.7.

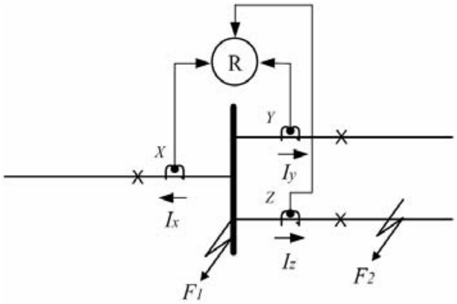


Fig. 7. Wavelet based relay at a busbar interconnecting three lines

Three sets of CTs measure the currents on each branch at *X*, *Y*, and *Z*. A fault in the region between the CTs, such as fault F_1, is an internal fault whereas a fault outside the CTs, such as fault F_2, is an external fault.

The measured three-phase currents are transformed to modal domain using the constant Clark's transformation matrix in (6) before applying wavelet transform.

$$\begin{bmatrix} I_1 \\ I_2 \\ I_3 \end{bmatrix} = \frac{1}{3} \begin{bmatrix} 1 & 1 & 1 \\ 2 & -1 & -1 \\ 0 & \sqrt{3} & -\sqrt{3} \end{bmatrix} \begin{bmatrix} I_a \\ I_b \\ I_c \end{bmatrix} \qquad (6)$$

In (6), I_a, I_b, and I_c are the phase currents and I_1, I_2, and I_3 are the modal components. Only the components I_2, and I_3 , which are known as aerial mode components, are used for the fault locations. By using these two components all types of ground and ungrounded faults can be handled. Thus the use of modal transformed quantities gives some computational advantage, in addition to providing decoupled signals. In the following analysis, Level-1 wavelet transform coefficients (WTCs) obtained with DB4 mother wavelet were used.

For an internal fault such as F1, WTCs of the currents measured at X, Y and Z will all have the same sign as shown in Fig. 8.

For an external fault such as F_2, wavelet coefficients of the transients currents measured on the non faulted branches are opposite in sign compared to those measured on the faulted branch. This sign difference can be clearly observed in WTCs shown in Fig. 9, and can be used to determine the direction of fault.

If such relays can be installed at strategic locations on a power network and communication is provided between the neighboring relays, faulted segments can be determined very fast: all the information required is obtained within half a cycle. Application of such a scheme for a 230 kV, 12 bus transmission network is shown in Fig. 10.

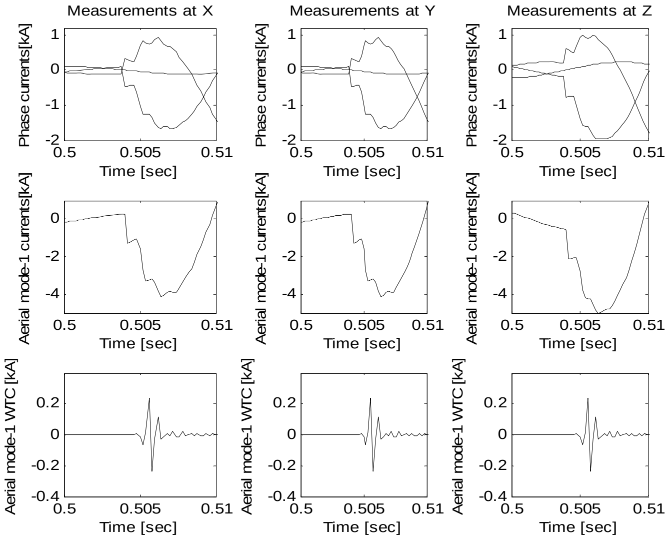


Fig.8. Phase currents, corresponding modal signals and their WTCs for an internal fault between phases A and B.

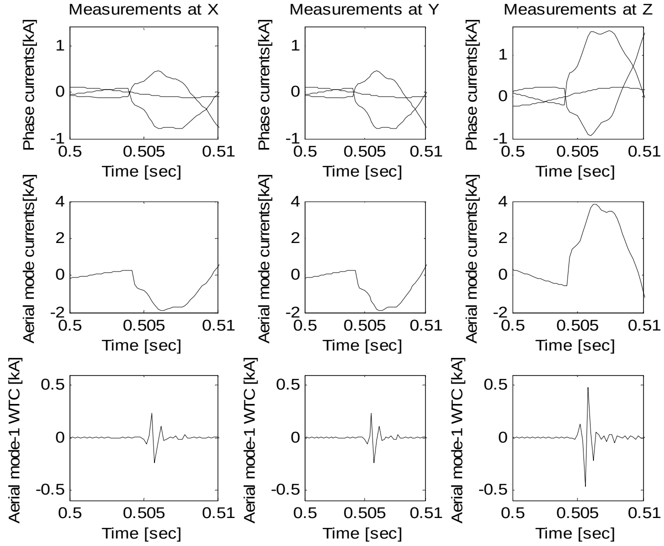


Fig. 9. Phase currents, corresponding modal signals and their WTCs for an external fault between phases A and B.

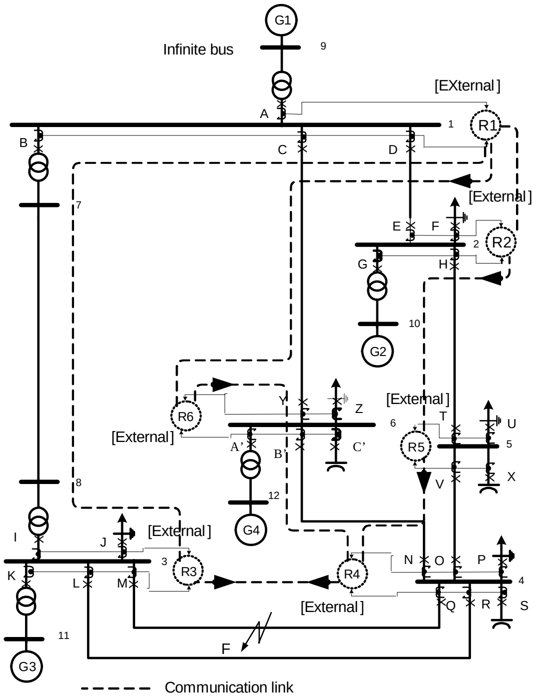


Fig. 10. Wavelet based protection scheme. Arrows indicate fault current directions identified by each relay

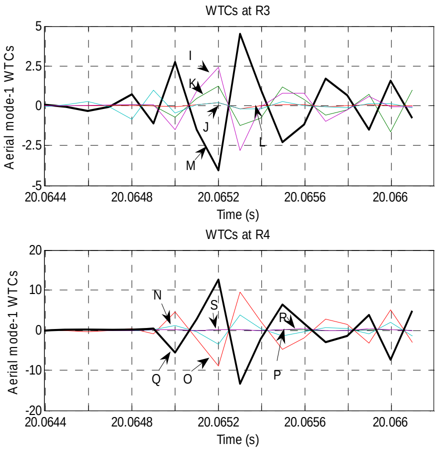


Fig. 11. Wavelet coefficients observed by R3 and R4

Fig. 11 shows the wavelet coefficients observed at bus-3 and bus-4. WTC of branch M has a sign opposite to those of the other branches connected to bus-3. Similarly, WTC of branch Q has a sign opposite to those of the other branches connected to bus-4. From the above information, R3 determines that the fault is in the direction of bus-4, while R4 determines that the fault is in the direction of bus-3. If communication is provided, R3 and R4 can jointly determine that the fault is in the line M-Q connecting them. In Fig. 10, fault type (internal/external) and fault direction as identified by each relay are also indicated.

B. Fault Location using Traveling Waves

Distance to a fault can be estimated using traveling waves originating from the fault [13]. Consider a fault locater installed at a busbar connecting three line segments A, B and C in Fig. 12.

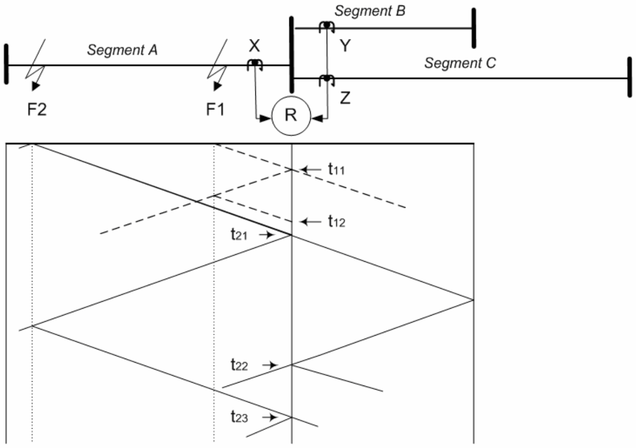
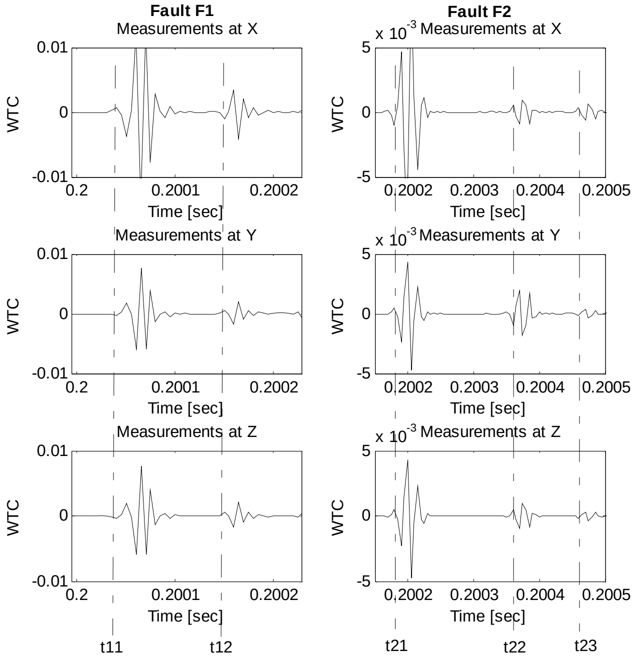


Fig. 12. Two faults F_1 and F_2 occur on a segment connected to a relay agent and their lattice diagrams

In order to explain the concept, consider two ungrounded faults; fault F_1 close to the near end of Segment-A and fault F_2 close to the remote end of the same segment. Fig. 12 also shows the lattice diagram for the resulting traveling waves; dotted lines correspond to F_1 and the dark lines correspond to F_2. In order to estimate the fault distance, it is necessary to find the time between the arrival of successive traveling wave fronts originating or reflected from the fault. For example, for fault F_1, t_{11} and t_{12} are the arrival times of the transient originating from the fault and its first reflection from the fault, respectively. Knowing the traveling time (t_{12} - t_{11}), and assuming the propagation speed to be that of light, the distance to the fault can be estimated. The time interval (t_{12} - t_{11}) can be estimated by using the WTCs of the currents as shown in Fig. 13a.



(a) (b)

Fig. 13. Transients observed at three measurement points for fault F_1 and F_2.

The situation is more complicated for a fault such as F_2, due to the arrival of reflections from other points before the arrival of wave front reflected from the fault. For example, t_{21} and t_{23} are the relevant transient arrival times required to estimate the distance to the fault. However, the transient arriving at time t_{22} (where $t_{22} < t_{23}$) should be ignored in order to correctly estimate the fault distance. This can be achieved with the help of fault direction finding method described in the previous section. As seen in Fig. 13b, for transients arriving from line Segment A, the WTC of the current measured at point X has a sign opposite to the WTCs of that measured at the other two points (Y and Z). This permits distinguishing the transient coming from the fault from the other transients.

C. Power Quality Disturbance Detection

Wavelets can also be used to detect the power quality events such as voltage sags and swells, transients, harmonics, etc. Detection of such disturbances is necessary for applications such as disturbance recorders: for example, change in wavelet coefficients can be used to trigger waveform recording. Fig. 14 shows an example voltage waveform with a swell and sag, and the corresponding wavelet coefficients. WTC shown in Fig. 14 is the level-1 detail coefficient obtained with DB8 mother wavelet.

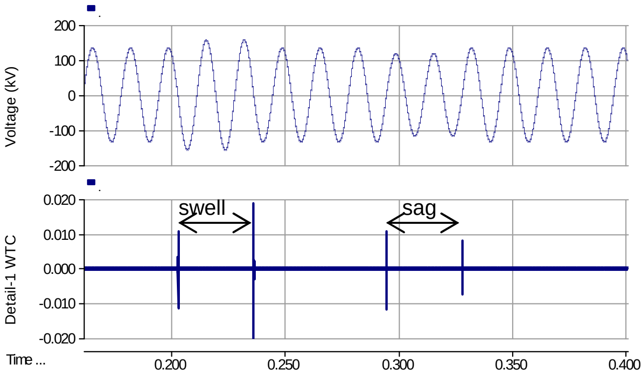


Fig. 14. Detection of power quality events using wavelets: a voltage swell and a voltage sag

VI. CONCLUSIONS

A tool for performing online discrete wavelet transformation in an emtp-type program (PSCAD/EMTDC) was developed. The online DWT tool handles nine different mother wavelet types, and incorporates an integrated anti-aliasing filter and a sampler. Accuracy of calculations was extensively validated against MATLAB® wavelet toolbox. Several applications of DWT in power system protection and power quality monitoring were presented. The new online DWT tool will stimulate the development of new wavelet applications in the field of power systems.

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VIII. BIOGRAPHIES

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