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This section of the magazine offers a vehicle that speeds publication of new results, discoveries, and developments. The section affords authors the opportunity to publish contributions within a few months of submission to ensure rapid dissemination of ideas and timely archiving of developments in our rapidly changing field. Original and significant contributions in applications, case studies, and research in all fields of power engineering are invited. Of specific interest are contributions defining emerging problems and special needs in specific areas. Brief notes may also comment on published areas of established power topics.

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Wavelet Packet Transform for RMS Values and Power Measurements

Effrina Yanti Hamid, Zen-Ichiro Kawasaki

Author Affiliation: Department of Electrical Engineering, Graduate School of Engineering, Osaka University, Osaka, Japan.

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filtering are not used for further decomposition, only the approximation coefficients (or the output from low-pass filtering) at each level are treated to yield further approximation and detail coefficients. In the WPT algorithm, both the detail and approximation coefficients are decomposed into lower levels to produce further coefficients (hereafter, both detail and approximation coefficients are called wavelet coefficients).

Wavelet packet decomposition is depicted in Figure 1. Let the original waveform contain $2^N$ sampling points. The wavelet coefficient at the level $j$, $k$th sampling point, and node $i$, $h$, is $d_{i,h}^{j,k}$. This coefficient is obtained by convolving the sequence $d_{i,h}^{j-1,k}$ with low-pass filter $h_{i,j}$, and then down-sampling by a factor of two. Similarly, the wavelet coefficient at node $i$ is $1,3,2^{2j-3}-1$ (odd) is obtained by convolving the sequence $d_{i,h}^{j-1,k}$ with high-pass filter $g_{i,j}$ and down-sampling by a factor of two. The number of nodes at level $j$ is $2^{2j-1}$, and the node at level $N$ is the original waveform. The filters $h_{i,j}$ and $g_{i,j}$ are a pair of conjugate mirror filters (QMF), meaning that both filters use the same set of coefficients, but with alternating signs and in reverse order. The Vaidyanathan filter is used in this study and the filter coefficients can be found in [4].

The time resolution of $d_{i,h}^{j,k}$ is half that of $d_{i,h}^{j-1,k}$ due to the down-sampling. As a result, if $d_{i,h}^{j-1,k}$ has $2^{j-1}$ sampling points ($k = 0, 1, ..., 2^{j-1}-1$) for the entire observation period, then $d_{i,h}^{j,k}$ will have $2^j$ sampling points ($k = 0, 1, ..., 2^j-1$) for the same observation period. Each node at level $j$ has $2^j$ sampling points or wavelet coefficients.

**RMS Values and Power Measurements:** The derivation of both the rms values of voltage or current and power equations using the discrete wavelet-based algorithm can be found in [3]. The following equations are extended forms from the DWT algorithm. The measurements consist of $I_{rms}$, $V_{rms}$, and active power ($P$). The definitions of these parameters are as follows (IEEE Std. 100-88):

$$I_{rms} = \frac{1}{T} \int_0^T i^2 \, dt, \quad V_{rms} = \frac{1}{T} \int_0^T v^2 \, dt, \quad P = \frac{1}{T} \int_0^T i v \, dt,$$

where $i$, and $v$, are, respectively, the analog current and voltage waveforms, which are periodic during the observation period $T$. In practice, the analog waveforms are digitized. Here, $i_n$ and $v_n$ will be the digitized waveforms of $i$ and $v$, respectively, with $n = 0, 1, 2, ..., 2^N - 1$.

**RMS Calculations:** rms of current or voltage in wavelet domain can be written as follows:

$$I_{rms} = \frac{1}{2^N} \sum_{n=0}^{2^N-1} (d_{j,j}^{1,n})^2 = \frac{1}{2^N} \sum_{i=0}^{2^j-1} \sum_{k=0}^{2^j-1} (d_{j,i}^{j,k})^2 = \frac{1}{2^N} \sum_{i=0}^{2^j-1} \sum_{k=0}^{2^j-1} (I_{j,i}^{k})^2,$$

$$V_{rms} = \frac{1}{2^N} \sum_{n=0}^{2^N-1} (v_{j,j}^{1,n})^2 = \frac{1}{2^N} \sum_{i=0}^{2^j-1} \sum_{k=0}^{2^j-1} (v_{j,i}^{j,k})^2 = \frac{1}{2^N} \sum_{i=0}^{2^j-1} \sum_{k=0}^{2^j-1} (V_{j,i}^{k})^2,$$

(1)

where $d_{j,i}^{j,k}$ and $v_{j,i}^{j,k}$ are the wavelet coefficients of $i_n$ and $v_n$, respectively. $I_j$ and $V_j$ are, respectively, the rms values of current and voltage for the frequency band at node $i$ and level $j$. In the WPT algorithm, only the wavelet coefficients at a certain level $j$ are used for the rms and power calculations.

**Power Calculation:** The power calculation in wavelet domain is done simply by multiplying the wavelet coefficients of current to those of voltage for every node at the same level, as follows:

$$P = \frac{1}{2^N} \sum_{n=0}^{2^N-1} \sum_{n=0}^{2^N-1} d_{j,i}^{j,k} v_{j,i}^{j,k} = \sum_{i=0}^{2^j-1} \sum_{k=0}^{2^j-1} (P_{j,i}^{k})^2,$$

(2)

where $P_j$ is the power for frequency band at node $i$ and level $j$.

**Evaluation:** To test the performance of rms values of voltage and current power measurements using the WPT algorithm, simulated current and voltage waveforms will be analyzed. Each waveform has $128 \times N = 7$ sampling points per 60-Hz fundamental cycle and contains first, third, fifth, seventh, eleventh, thirteenth, and seventeenth harmonics. The definitions of these parameters are as follows (IEEE Std. 100-88):

$$\hat{i}(t) = 1.0 \times \sqrt{2} \sin(2\pi 60 t + 10^\circ) + 0.1 \times \sqrt{2} \sin(2\pi 180 t + 20^\circ) + 0.08 \times \sqrt{2} \sin(2\pi 300 t) + 0.08 \times \sqrt{2} \sin(2\pi 420 t + 30^\circ) + 0.07 \times \sqrt{2} \sin(2\pi 660 t + 45^\circ) + 0.08 \times \sqrt{2} \sin(2\pi 780 t + 120^\circ) + 0.05 \times \sqrt{2} \sin(2\pi 1020 t + 45^\circ)$$

and

$$v(t) = 1.0 \times \sqrt{2} \sin(2\pi 60 t) + 0.2 \times \sqrt{2} \sin(2\pi 180 t + 30^\circ) + 0.2 \times \sqrt{2} \sin(2\pi 300 t + 150^\circ) + 0.1 \times \sqrt{2} \sin(2\pi 420 t + 60^\circ) + 0.1 \times \sqrt{2} \sin(2\pi 660 t + 20^\circ) + 0.1 \times \sqrt{2} \sin(2\pi 780 t) + 0.08 \times \sqrt{2} \sin(2\pi 1020 t + 45^\circ).$$

All calculations in this algorithm use Matlab and WaveLab v.802 software package [5].

First, both current and voltage waveforms are decomposed via the WPT algorithm as described in the section “WPT.” Next, only the wavelet coefficients at level 2 are used to calculate rms values of voltage, current, and power because each frequency band (or each node) at level 2 completely covers a respective harmonic component. Figure 2 shows the wavelet coefficients of current, voltage, and power for selected nodes. Level 2 has 32 nodes and each node has four coefficients. The wavelet coefficients at all nodes are then fed into (1) and (2) to compute the rms values and power, respectively.
Table 1 shows the calculation results based on using the WPT algorithm along with the true rms and power values. The true values are derived from analytical calculations. The table shows that the WPT algorithm can compute the rms values and power of each harmonic component. The total results of rms values and power are the same in all cases. This proves that rms values and power measurements using the WPT algorithm are valid. Leakage occurs to the measurement results at some frequency bands, however. These errors are due to the roll-off characteristics of the low-pass and high-pass filter pairs.

Conclusions: A WPT-based approach has been proposed to improve the DWT-based approach for the rms values and power measurements. The algorithm can separate harmonic components of power system waveforms and measure the rms values and power of each harmonic component. The test using a simulated current-voltage pair shows that the total results of rms values and power are the same as those derived from analytical calculations. The leakage occurs to the rms values and power at some frequency bands due to the roll-off characteristics of the wavelet filter, however. Hence, further study will be intended to find a suitable wavelet filter, which is able to minimize the error of rms values and power for all frequency bands.

References:

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Figure 1. Cylinder over plane