M.E. El-Hawary, Editor

Power Engineering Letters

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Editorial Board

In This Issue

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Wavelet Packet Transform for RMS Values and Power Measurements

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Abstract: This letter proposes an approach based on wavelet packet transform (WPT) for root mean square (rms) values of voltage and power measurements. The algorithm can simultaneously measure the distribution of the rms of voltage or current and power with respect to individual frequency bands from the wavelet coefficients associated with each voltage current pair. The advantage of the WPT is that it can decompose a power system waveform into uniform frequency bands, which are important for identification of harmonic components and measurement of harmonic parameters. The algorithm is validated using simulated waveforms.

Keywords: Power, rms value, harmonic, wavelets, wavelet packet.

Introduction: Power quality is an issue of increasing concern to utilities and their customers. One of the major power system problems is steady-state waveform distortion due to harmonics. Harmonics are produced by variable speed drives, arc furnaces, personal computers, and other nonlinear devices. Since harmonics can severely degrade the performance of power supplies and their connected equipment, it is necessary to always monitor harmonic parameters such as voltage, current, and power [1]-[2].

There has not been much work on applying wavelet transform for rms voltage and power measurements. The discrete wavelet transform (DWT) algorithm for rms value of voltage or current and active power measurements has first been introduced in the literature [3]. The results show that the discrete wavelet-based algorithm could quantify the rms value of voltage or current and power of several harmonics within each frequency band. The waveform decomposition results using the DWT provide nonuniform frequency bands, however. For instance, at a higher level of decomposition, the frequency band becomes wider. As a result, frequency bands at the higher levels cover more harmonic components than those at lower levels. Therefore, the discrete wavelet-based algorithm cannot be used to measure the rms value of voltage or current and power of individual harmonic components [3]. In practice, it is important to be able to identify the rms value of voltage or current and power of individual harmonic components in order to know the sources and thus to eliminate their effects [1]-[2].

To overcome the limitation, the DWT algorithm is expanded to WPT algorithm in this study. Similar to the DWT algorithm, in the WPT algorithm the input waveform is decomposed into wavelet coefficients, and frequency separation is achieved using a wavelet filter. The advantage of the WPT is that it can decompose a waveform into uniform frequency bands, so that this WPT algorithm has a capability to measure the rms value of voltage or current and power of individual harmonic components. In the wavelet transform, there are many types of wavelet filters. Here, we simply select the Vaidyanathan filter because of its good frequency selectivity [4].

WPT: While a detailed mathematical background of WPT can be found in [4], a brief summary is given in this section. The WPT is a direct expansion from the pyramid tree (or DWT) algorithm to a full binary tree. In the DWT algorithm the detail coefficients (or the output from high-pass

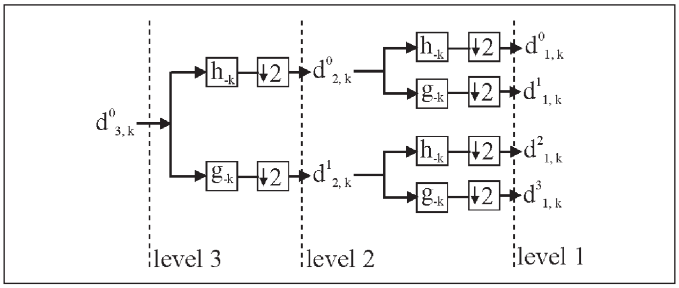

Figure 1. Wavelet packet decomposition with successive filterings and downsamplings

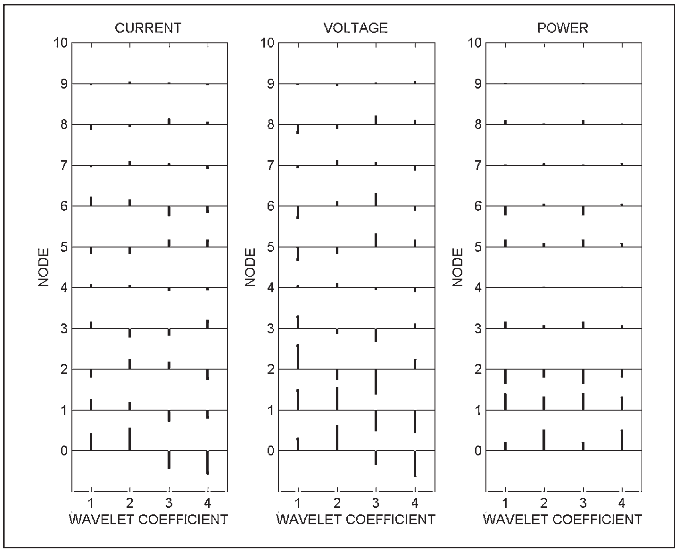

Figure 2. Wavelet coefficients of the current, voltage, and power at level 2 for the first eleven nodes. The rest of the nodes have very small or zero coefficients. (The ratios of node 0 and the other nodes are, respectively, 1:5, 1:5, and 1:50 for current, voltage, and power.)

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 jth, kth sampling point, and node ith, where $i = 0,2,...,2^{N-j}-2$ (even) and $j = 1,2,...,N$, is $d^i_{j,k}$. This coefficient is obtained by convolving the sequence $d^{i/2}_{j+1,k}$ with low-pass filter h_{-k}, and then down-sampling by a factor of two. Similarly, the wavelet coefficient at node $i = 1,3,...,2^{N-j}-1$ (odd) is obtained by convolving the sequence $d^{(i-1)/2}_{j+1,k}$ with high-pass filter g_{-k} and down-sampling by a factor of two. The number of nodes at level j is 2^{N-j}, and the node at level N is the original waveform. The filters h_{-k} and g_{-k} 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 $d^i_{j,k}$ is half that of $d^i_{j+1,k}$ due to the down-sampling. As a result, if $d^i_{j+1,k}$ has 2^{j+1} sampling points ($k = 0,1,...,2^{j+1}-1$) for the entire observation period, then $d^i_{j,k}$ 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):

$$I_{\text{rms}} = \sqrt{\frac{1}{T}\int_0^T i_t^2 dt}, V_{\text{rms}} = \sqrt{\frac{1}{T}\int_0^T v_t^2 dt}, P = \frac{1}{T}\int_0^T i_t v_t dt,$$

where i_t and v_t 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_t and v_t, respectively, with $n = 0,1,...,2^N-1$.

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

$$I_{\text{rms}} = \sqrt{\frac{1}{T}\int_0^T i_t^2 dt} \cong \sqrt{\frac{1}{2^N}\sum_{n=0}^{2^N-1} i_n^2} = \sqrt{\frac{1}{2^N}\sum_{i=0}^{2^{N-j}-1}\sum_{k=0}^{2^j-1}\left(d^i_{j,k}\right)^2} = \sqrt{\sum_{i=0}^{2^{N-j}-1}\left(I^i_j\right)^2},$$
$$V_{\text{rms}} = \sqrt{\frac{1}{T}\int_0^T v_t^2 dt} \cong \sqrt{\frac{1}{2^N}\sum_{n=0}^{2^N-1} v_n^2} = \sqrt{\frac{1}{2^N}\sum_{i=0}^{2^{N-j}-1}\sum_{k=0}^{2^j-1}\left(d^{*i}_{j,k}\right)^2} = \sqrt{\sum_{i=0}^{2^{N-j}-1}\left(V^i_j\right)^2}, \tag{1}$$

where $d^i_{j,k}$ and $d^{*i}_{j,k}$ are the wavelet coefficients of i_n and v_n, respectively. I^i_j and V^i_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:

$$P = \frac{1}{T}\int_0^T i_t v_t dt \cong \frac{1}{2^N}\sum_{n=0}^{2^N-1} i_n v_n = \frac{1}{2^N}\sum_{i=0}^{2^{N-j}-1}\sum_{k=0}^{2^j-1} d^i_{j,k} d^{*i}_{j,k} = \sum_{i=0}^{2^{N-j}-1} P^i_j, \tag{2}$$

where P^i_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 $128(N = 7)$ sampling points per 60-Hz fundamental cycle and contains first, third, fifth, seventh, eleventh, thirteenth, and seventeenth harmonics (odd integer harmonics), as follows:

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

and

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

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. Comparison results between calculated and true values of rms and power measurements; values of rms and power for the rest of nodes are very small or zero)								
Node	Frequency Band (Hz)	Harmonic Component	True I_{rms}	True V_{rms}	True Power	Calculated I_{rms}	Calculated V_{rms}	Calculated Power
0	DC-120	1st	1.0000	1.0000	0.9848	1.0000	1.0000	0.9848
1	120-240	3rd	0.1000	0.2000	0.0197	0.0941	0.2130	0.0197
2	240-360	5th	0.0800	0.2000	-0.0139	0.0870	0.1858	-0.0139
3	360-480	7th	0.0800	0.1000	0.0069	0.0756	0.0945	0.0062
4	480-600	9th	0	0	0	0.0263	0.0329	0.0008
5	600-720	11th	0.0700	0.1000	0.0063	0.0691	0.1050	0.0069
6	720-840	13th	0.0800	0.1000	-0.0040	0.0795	0.0935	-0.0044
7	840-960	15th	0	0	0	0.0260	0.0417	0.0011
8	960-1080	17th	0.0500	0.0800	0.0040	0.0427	0.0683	0.0029
9	1080-1200	19th	0	0	0	0.0138	0.0173	-0.0001
10	1200-1320	21st	0	0	0	0.0019	0.0013	0
11	1320-1440	23rd	0	0	0	0	0	0
12	1440-1560	25th	0	0	0	0	0	0
	Total		1.0181	1.0566	1.0039	1.0181	1.0566	1.0039

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.

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Finite Elements for Electric Power Engineers

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Abstract: Finite element analysis of electric and magnetic fields is becoming more and more of an indispensable tool for power engineers. The necessary equations are derived here in an unconventional way, which is intended to be easy to follow and give students and users of commercial computer programs a better understanding of how the method works.

Keywords: Finite elements, electric fields, magnetic fields.

Introduction: Commercially available computer programs provide solutions, but in order to use them confidently and intelligently, it is highly desirable that the users understand how the field problems are solved by using the finite element method.

Unfortunately, textbooks on this subject are not easily accessible. They either explain the finite element method based on variational calculus or on the Galerkin weighted residual approach. Both are highly mathematical. They also generally describe calculations both in two and three dimensions, elements of different types, and not only linear variation of potentials within elements.

For two-dimensional fields (flat or axisymmetric) and linear variation of potentials within triangular elements, which cover most of the applications in power engineering, it will be shown here how the same

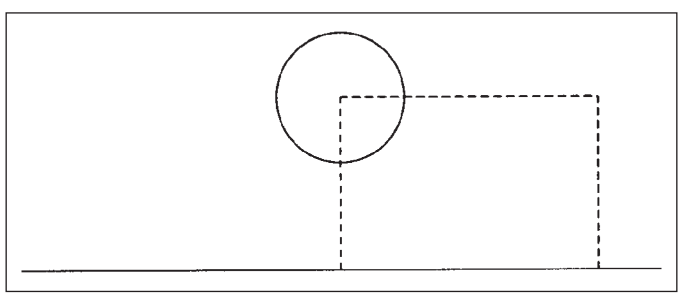

Figure 1. Cylinder over plane