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Full Length Research Paper

An alternative approach for calculation/measurement of fundamental powers based on wavelet packet transform

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In order to calculate/measure the fundamental harmonic power values, the wavelet transform based methods have been proposed in the literature. However, the fundamental harmonic of voltage and current signals cannot be decomposed into real and imaginary components in any of these methods based on only wavelet packet transform. It is required to decompose voltage and current signals with harmonics to real and imaginary components in a power system for power quality and control. In this study real and imaginary components are obtained by using the wavelet packet transform. Furthermore, the fundamental active-reactive-apparent powers are determined with two different methods and accurateness of the proposed methods is demonstrated via simulations.

Key words: Wavelet packet transform, fundamental powers, power factor.

INTRODUCTION

The number of nonlinear loads in the energy systems has been increasing rapidly in parallel to developing technology. Nonlinear load characteristics lead to harmonics in voltage and current signals in the power systems. Definitions belonging to the components in power analysis for signals consisting of harmonics are included in IEEE Work Group's source (Arseneau et al., 1996).

In the literature, classical power calculations/measurements based on windowing methods are carried out by means of the Fourier transform. The power analyses in the systems, where the static current and voltage signals are present, are performed with great accuracy in the frequency domain. Power measurement based on the wavelet transform was seen first in the works of W. K. Yoon and M. J. Devaney who used the discrete wavelet transform and 90° phase shift circuits (Yoon and Devaney, 1998, 2000). On the other hand an algorithm was presented which can simultaneously identify all harmonics. In the first step of this approach, the frequency spectrum of the waveform is decomposed into subbands using discrete wavelet packet transform filter banks. In the second step, continuous wavelet transform is applied to nonzero subbands to evaluate the harmonic contents (Pham and Wong, 1999). Root-mean-square (RMS) and active power calculations by using wavelet packet transform are given in Hamid et al. (2002).

Methods given above requires phase shift circuits and two transforms (discrete wavelet packet and continuous). In this study, the RMS values and phase angle of the fundamental harmonics of the voltage and current signals in the power system are determined based on only the wavelet packet transform and their real and imaginary components, are calculated active-reactive-apparent power values belonging to the fundamental harmonics and the displacement power factor are found with two different methods by using the calculated values. Accuracy and effectiveness of the proposed methods are demonstrated via simulation results for various voltage and current signals with harmonics.

The paper is organized as follows: Wavelet packet transform and Hilbert transform are discussed in Section "Materials and Methods". The proposed methods

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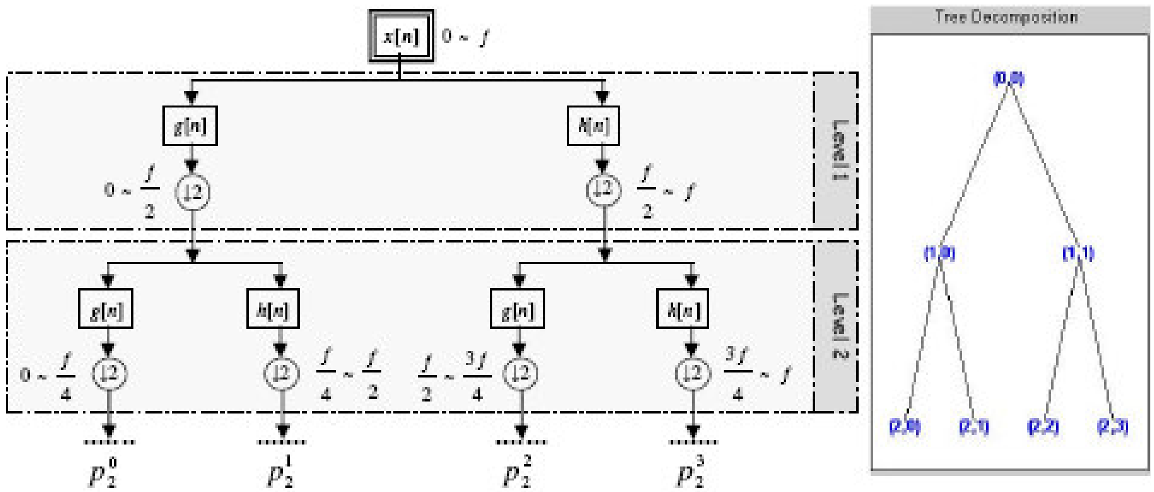

Figure 1. 2-level discrete wavelet packet transform/tree decomposition.

together with simulation results are provided in Section "Results and Discussion".

MATERIALS AND METHODS

Wavelet packet transform

Wavelet transform has been widely used in various fields for almost twenty years. In general, the discrete wavelet packet transform (DWPT) is given by the following iterations:

$$W_{2n}(t)=\sqrt{2}\sum_{k=0}^{2N-1} g[k]W_n(2t-k) \quad , \quad W_{2n+1}(t)=\sqrt{2}\sum_{k=0}^{2N-1} h[k \qquad (1)$$

In Equation 1, $g[n]$ and $h[n]$ are low-pass and high-pass filters of length $2N$, $W_0(t)=\varphi(t)$ is the scaling function and $W_1(t)=\psi(t)$ is the wavelet function. If a signal $x(t)$ with $N=2^L$ samples is subjected to the discrete wavelet packet transform up to the level s, we obtain 2^s nodes/packet or frequency bands and each frequency band has 2^{L-s} or $N/2^s$ wavelet packet coefficients (Figure 1). If the wavelet packet coefficients of the s th decomposition level at $2m$ th node and k th point is denoted by $p_s^{2m}[k]$, the analog signal $x(t)$ can be reconstructed by:

$$x(t)=\sum_{k=1}^{N/2^s} p_s^0[k].\varphi_{s,k}(t)+\sum_{m=1}^{2^s-1}\sum_{k=1}^{N/2^s} p_s^m[k].\psi_{s,k}^m(t) \qquad (2)$$

In Equation 2, $p_s^m[k]$ are the wavelet packet coefficients of $x[n]$ and $p_s^0[k]$'s are the scaling function coefficients or the coefficients at the 0th node (Wickerhauser, 1994; Goswami and Chan, 1999; Mathworks, 2000).

Hilbert transform

One of the popular transform in signal processing is the Hilbert transform. For a signal $x(t)$, its Hilbert transform is given by:

$$\mathcal{H}[x(t)]=\frac{1}{\pi}\int_{-\infty}^{\infty}\frac{x(\tau)}{t-\tau}d\tau = x(t)*\frac{1}{\pi.t} \qquad (3)$$

As a result of this transformation, the amplitude of $x(t)$ doesn't change, the phases of all frequency components are shifted by $\pi/2$.

RESULTS AND DISCUSSION

The proposed calculation/measurement methods

In this study, the proposed calculation/measurement methods are based on our approach in (Vatansever and Ozdemir, 2008). Calculation of RMS and phase angle values of the fundamental harmonics of any voltage or current signal are provided in detail in Vatansever and Ozdemir (2008) and are repeated here for convenience:

$$X_{RMS}^0=\frac{1}{\sqrt{2}}.\sqrt{\frac{1}{N}\sum_{k=1}^{N/2^s}\left|p_{\mathcal{H},s}^0[k]\right|^2} \qquad (4)$$

$$\theta_0=\angle p_{\mathcal{H},s}^0[1]-27.734+90^{\circ} \qquad (5)$$

By using these values, real and imaginary components of the fundamental harmonics of the voltage or current signal are calculated as:

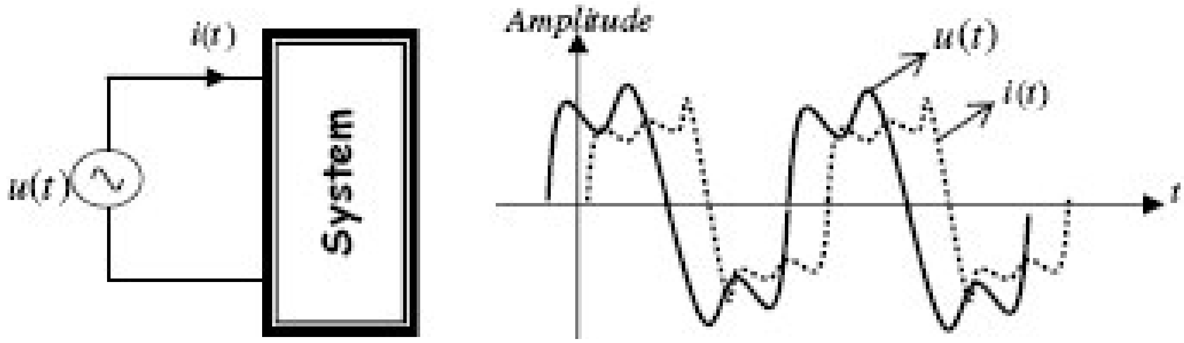

Figure 2. Sample power system and voltage-current graphics.

$$\begin{rcases} \text{Real part} \rightarrow X^0_{RMS}.Cos(\theta_0) \\ \text{Imaginary part} \rightarrow X^0_{RMS}.Sin(\theta_0) \end{rcases} \quad (6)$$

In this study, power values belonging to the fundamental harmonic are determined with two different ways.

The first method

Voltage and current signals with harmonics for a single phase power system are shown in Figure 2. In this power system, voltage and currents are:

$$\begin{rcases} u(t) = U_1.Sin(\omega_0 t + \alpha_1) + U_2.Sin(2\omega_0 t + \alpha_2) + ... + U_k.Sin(k\omega_0 t + \alpha_k) \\ i(t) = I_1.Sin(\omega_0 t + \beta_1) + I_2.Sin(2\omega_0 t + \beta_2) + ... + I_k.Sin(n\omega_0 t + \beta_k) \end{rcases} \quad (7)$$

From Equation 7, calculation of the fundamental harmonic power expressions are (Arseneau, 1996).

Fundamental active power:

$$P_1 = \frac{U_1.I_1}{2}.Cos(\alpha_1 - \beta_1) = \frac{U_1.I_1}{2}.Cos(\phi_1) \quad (8)$$

Fundamental reactive power:

$$Q_1 = \frac{U_1.I_1}{2}.Sin(\alpha_1 - \beta_1) = \frac{U_1.I_1}{2}.Sin(\phi_1) \quad (9)$$

Fundamental apparent power:

$$S_1 = \frac{U_1.I_1}{2} = \sqrt{P_1^2 + Q_1^2} \quad (10)$$

Displacement power factor: $dpf = \frac{P_1}{S_1}$ (11)

It is clear from Equation 8-11 that for calculation of P_1, Q_1, S_1 and dpf, we need to determine values of U_1, I_1, α_1 and β_1. There exist several classical studies for calculation of these values in the literature. In this study, these values are determined based on the wavelet packet transform as shown in Figure 3. To the best of our knowledge, this type of calculation is an alternative approach.

Simulations based on this method were performed with a graphical user interface (GUI) by using Matlab (Math-works, 2000) and WaveLab v.802 (Donoho, 1999) (Figure 4). In the GUI, it is possible to choose voltage and current signals with harmonics or load them from files. For signals of interest, 128 samples are taken in each pe-riod. Then, samples of the voltage and current signals are subjected to wavelet packet decomposition up to the 5th level. RMS and phase angle values of fundamental har-monics of the signals are computed from obtained wave-let coefficients. The calculated values are shown numeri-cally as well as visually in the GUI. Finally, fundamental powers are calculated by using Equation 8-11. Simulation results are provided in Table 1 from which it can be seen that the true values and those obtained by the proposed method are in good agreement showing the effectiveness of the proposed wavelet packet based approach. Small deviations between the true and calculated values are due to the non-ideal characteristics of the filters used in the wavelet packet decomposition.

The second method

Classical power calculation expressions by using fundamental real and imaginary components of the voltage and current signals with harmonics are given below. Expressions for voltage and current signals with harmonics at the power system, whose block diagram and sample waveform are provided in Figure 2 are

$$\begin{rcases} u(t) = U_0 + \sum_{k=1}^{m}\{a_k.Cos(k\omega_0 t) + b_k.Sin(k\omega_0 t)\} = U_0 + \sum_{k=1}^{M} u_k.Sin(k\omega_0 t + \alpha_k) \\ i(t) = I_0 + \sum_{k=1}^{n}\{c_k.Cos(k\omega_0 t) + d_k.Sin(k\omega_0 t)\} = I_0 + \sum_{k=1}^{n} i_k.Sin(k\omega_0 t + \beta_k) \end{rcases} \quad (12)$$

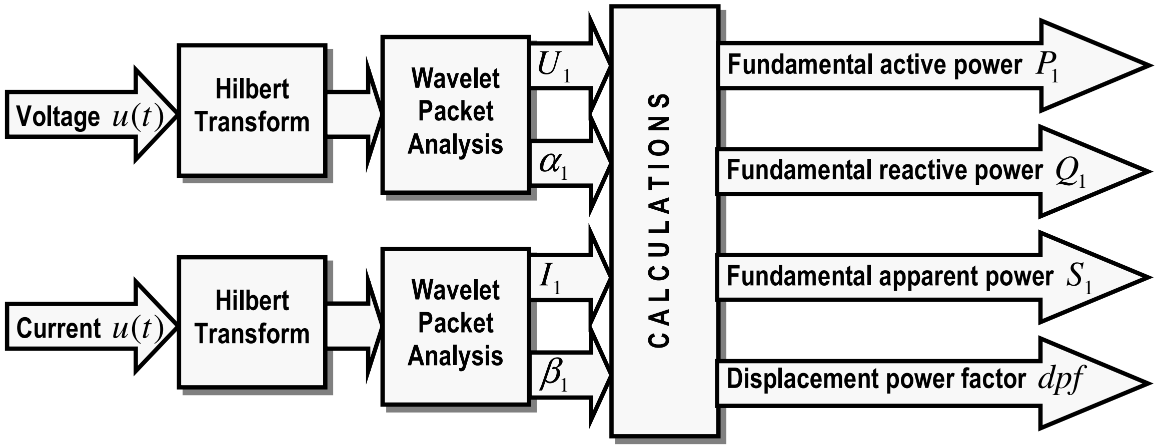

Figure 3. The block diagram of the first proposed method.

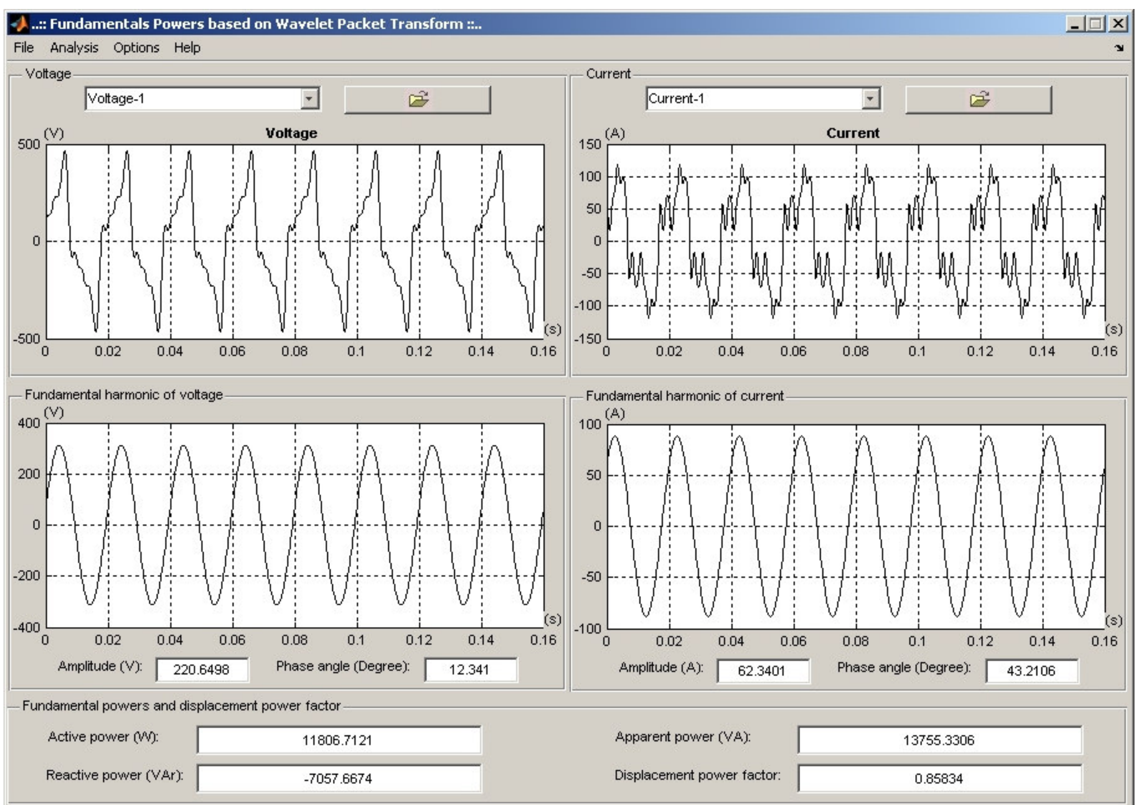

Figure 4. Screenshot of simulation program for the first method.

From Equation 12, the apparent power S, active power P and reactive power Q is given by (Marganitz, 1992).

$$S = U_{RMS} I_{RMS} = \sqrt{U_0^2 + \frac{1}{2}\sum_{k=1}^{m}\left(a_k^2 + b_k^2\right)}\sqrt{I_0^2 + \frac{1}{2}\sum_{k=1}^{n}\left(c_k^2 + d_k^2\right)} \quad (13)$$

$$P = \frac{1}{T_0}\int_0^{T_0} u(t).i(t).dt = U_0.I_0 + \frac{1}{2}\sum_{k=1}^{\min(m,n)}\left(a_k.c_k + b_k.d_k\right) \quad (14)$$

$$Q = \frac{1}{T_0}\int_0^{T_0} u(t).\mathcal{H}\{i(t)\}.dt = \frac{1}{2}\sum_{k=1}^{\min(m,n)}\left(a_k.d_k - b_k.c_k\right) \quad (15)$$

Table 1. Comparative simulation results for the first method.

				$\omega = 2\pi 50$	$\omega = 2\pi 60$
Voltage				$\sqrt{2}\left\{\begin{matrix} 220,65Sin(\omega t+12,34^o)+80Sin(3\omega t+135^o)+ \\ 50Sin(5\omega t-110^o)+25Sin(7\omega t+10^o)+ \\ 10Sin(9\omega t+40^o) \end{matrix}\right\}$	$\sqrt{2}\left\{\begin{matrix} 220,34Sin(\omega t-34,89^o)+75Sin(5\omega t+145^o)+ \\ 30Sin(7\omega t+105^o)+10Sin(11\omega t-10^o) \end{matrix}\right\}$
Current				$\sqrt{2}\left\{\begin{matrix} 62,34Sin(\omega t+43,21^o)+27Sin(3\omega t-153^o)+ \\ 14Sin(7\omega t+112^o)+10Sin(9\omega t-155^o)+ \\ 4Sin(13\omega t+28^o) \end{matrix}\right\}$	$\sqrt{2}\left\{\begin{matrix} 50,25Sin(\omega t-40,56^o)+30Sin(3\omega t+123^o)+ \\ 15Sin(5\omega t+162^o)+10Sin(7\omega t-175^o)+ \\ 6Sin(9\omega t+15^o) \end{matrix}\right\}$
FUNDAMENTAL HARMONIC	Voltage	Amplitude (V)	True	220.650000	220.340000
			Wavelet	220.649812	220.339988
			Error (%)	0.000085	0.000005
		Phase (º)	True	12.340000	-34.890000
			Wavelet	12.341008	-34.889104
			Error (%)	0.008169	0.002568
	Current	Amplitude (V)	True	62.340000	50.250000
			Wavelet	62.340096	50.250117
			Error (%)	0.000154	0.000233
		Phase (º)	True	43.210000	-40.560000
			Wavelet	43.210614	-40.559937
			Error (%)	0.001421	0.000155
FUNDAMENTAL POWERS		Active power (W)	True	11806.655261	11017.914129
			Wavelet	11806.712063	11017.923211
			Error (%)	0.000481	0.000082
		Reactive power (VAr)	True	-7057.743786	1093.907895
			Wavelet	-7057.667444	1094.070523
			Error (%)	0.001082	0.014867
		Apparent power (VA)	True	13755.321000	11072.085000
			Wavelet	13755.330585	11072.110106
			Error (%)	0.000070	0.000227
		Displacement pf	True	0.858334	0.995107
			Wavelet	0.858337	0.995106
			Error (%)	0.000350	0.000100

If the above equations are referred to the fundamental harmonic powers, we obtain

$$S_1 = U_{1_{RMS}} I_{1_{RMS}} \quad , \quad P_1 = \frac{1}{2}(a_1c_1 + b_1d_1) \quad , \quad Q_1 = \frac{1}{2}(a_1d_1 - b_1c_1) \qquad (16)$$

As seen in Figure 5, in the second method the real and imaginary compo-nents of the fundamental harmonics of the voltage and current signals to be analyzed are the same as those in the first method up to calculations of U_1, I_1, α_1 and β_1. After U_1, I_1, α_1 and β_1 are calcula-ted, the real a_1, c_1 and the imaginary b_1, d_1 components are obtained using Equation 6. a_1, b_1, c_1, and d_1 values substituted in Equation 16 in order to calculate the funda-mental harmonics powers.

Several simulations were carried out by using the desi-gned GUI. Results are provided in Figure 6 in which in-stantaneous variations of the real and imaginary compo-nents of the fundamental frequency of the voltage and current signals with harmonics are illustrated. In addition, effective values of the real and imaginary components are available numerically. Comparative results are provi-ded in Table 2. As was the case in the first method, the results in Table 2 demonstrate the effectiveness of the proposed method.

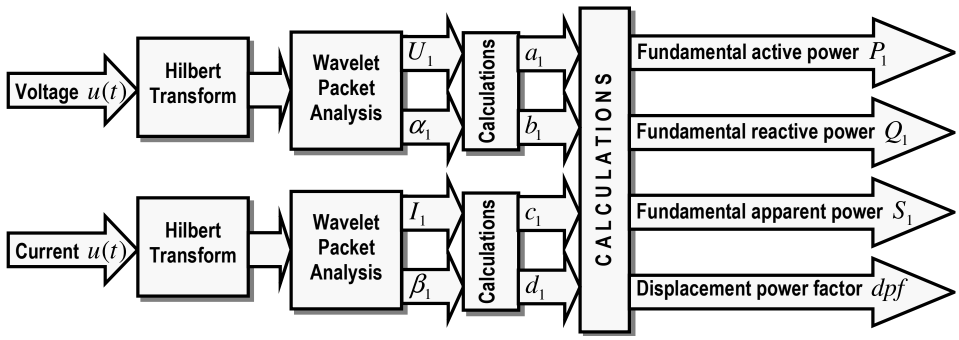

Figure 5. The block diagram of the second proposed method.

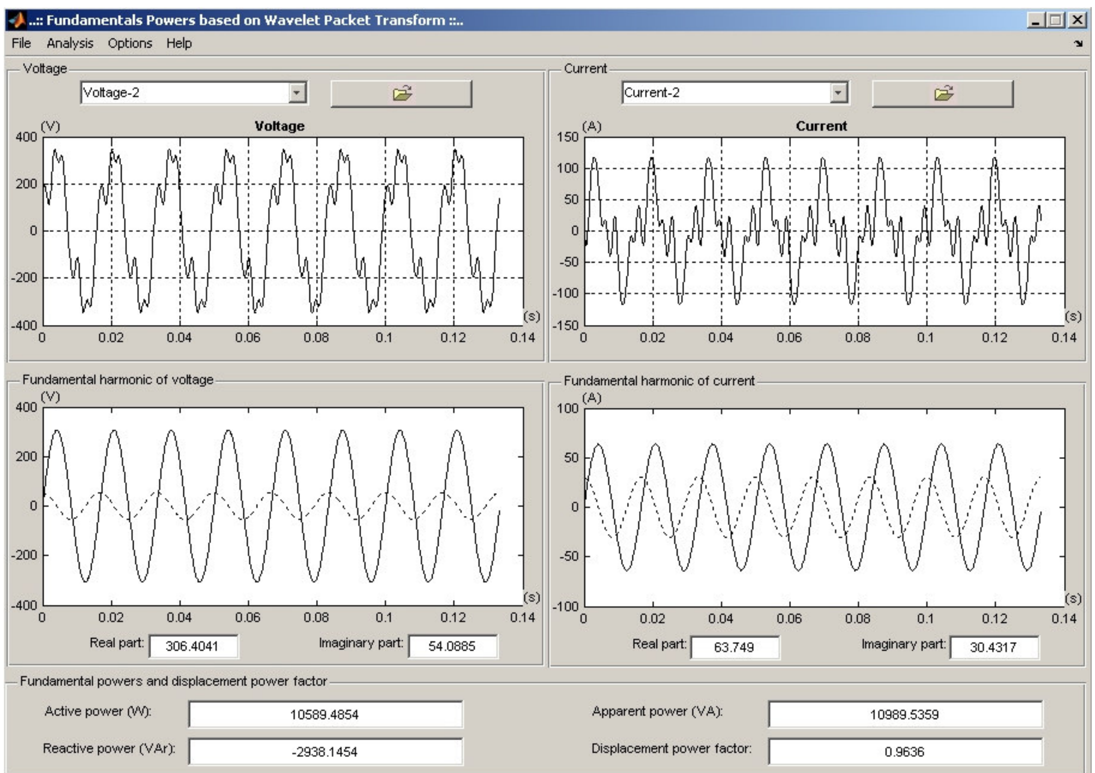

Figure 6. Screenshot of simulation program for the second method.

In Table 3, comparative results of the traditional FFTmethod, the method used (Yoon and Devaney, 2000) and the proposed methods are shown. The power measure-ment results shown in Table 3 are obtained by using the following voltage and current signals ($\omega = 2\pi 60$), which are given in (Yoon and Devaney, 2000) (Equation 17-18):

$$u(t) = \sqrt{2}\begin{cases} 1.0Sin(\omega t) + 1.0Sin(5\omega t + 150^{\circ}) + 1.0Sin(11\omega t \\ +1.0Sin(23\omega t - 45^{\circ}) + 1.0Sin(45\omega t + 45^{\circ}) \end{cases} \quad (17)$$

$$i(t) = \sqrt{2}\begin{cases} 1.0Sin(\omega t + 60^{\circ}) + 1.0Sin(5\omega t) + 1.0Sin(11\omega t) \\ +1.0Sin(23\omega t) + 1.0Sin(45\omega t - 45^{\circ}) \end{cases} \quad (18)$$

Comparison of the results in Table 3, show that almost all performances of the methods are the same. But in Yoon and Devaney (2000), discrete wavelet transform is used and measurement of the reactive power requires complex filter design for both voltage and current signals.

Again, the results of the traditional FFT method, the

Table 2. Comparative simulation results for the second method.

				$\omega = 2\pi 50$	$\omega = 2\pi 60$
Voltage				$\sqrt{2}\begin{Bmatrix} 220{,}12Sin(\omega t - 34{,}56^{o}) + 72Sin(3\omega t + 125^{o}) + \\ 41Sin(5\omega t - 140^{o}) + 23Sin(7\omega t + 42^{o}) \end{Bmatrix}$	$\sqrt{2}\begin{Bmatrix} 220{,}01Sin(\omega t + 10{,}01^{o}) + 58Sin(3\omega t + 111^{o}) + \\ 33Sin(5\omega t + 97^{o}) + 18Sin(7\omega t - 52^{o}) \end{Bmatrix}$
Current				$\sqrt{2}\begin{Bmatrix} 51{,}15Sin(\omega t - 44{,}44^{o}) + 33Sin(3\omega t + 103^{o}) + \\ 17Sin(5\omega t - 12^{o}) + 7Sin(7\omega t + 67^{o}) \end{Bmatrix}$	$\sqrt{2}\begin{Bmatrix} 49{,}95Sin(\omega t + 25{,}52^{o}) + 28Sin(3\omega t - 122^{o}) + \\ 17Sin(5\omega t + 153^{o}) + 9Sin(7\omega t - 174^{o}) \end{Bmatrix}$
FUNDAMENTAL HARMONIC	Voltage	Real part	True	256.362971	306.404758
			Wavelet	256.363791	306.404081
			Error (%)	0.000320	0.000221
		Imaginary part	True	-176.588946	54.082568
			Wavelet	-176.586951	54.088529
			Error (%)	0.001130	0.011022
	Current	Real part	True	51.647481	63.747976
			Wavelet	51.649002	63.749044
			Error (%)	0.002945	0.001675
		Imaginary part	True	-50.647633	30.433544
			Wavelet	-50.646232	30.431654
			Error (%)	0.002766	0.006210
FUNDAMENTAL POWERS		Active power (W)	True	11092.156885	10589.303651
			Wavelet	11092.198800	10589.485407
			Error (%)	0.000378	0.001716
		Reactive power (VAr)	True	1931.901691	-2938.664227
			Wavelet	1931.660119	-2938.145394
			Error (%)	0.012504	0.017655
		Apparent power (VA)	True	11259.138000	10989.499500
			Wavelet	11259.137846	10989.535911
			Error (%)	0.000001	0.000331
		Displacement pf	True	0.985169	0.963584
			Wavelet	0.985173	0.963597
			Error (%)	0.000406	0.001349

Table 3. Comparison of FFT, Ref. 3, first proposed method and second proposed method.

	FFT	**(Yoon and Devaney, 2000)**	**First proposed method**	**Second proposed method**
P_1 (W)	0.500	0.500	0.500	0.500
Q_1 (VAr)	-0.866	-0.866	-0.866	-0.866
S_1 (VA)	1.000	1.000	0.999	0.999
dpf	0.500	-	0.500	0.500

the method used (Hamid et al., 2002) and the proposed methods are given in Table 4 for comparison. The results of the power measurement are obtained using the following voltage and current signals ($\omega = 2\pi 60$) which are given in (Hamid et al., 2002) (Equation 19-20):

$$u(t) = \sqrt{2}\begin{Bmatrix} 1.0Sin(\omega t) + 0.2Sin(3\omega t + 135^{o}) + 0.2Sin(5\omega t + 150^{o}) + \\ 0.1Sin(7\omega t + 140^{o}) + 0.08Sin(9\omega t + 40^{o}) + \\ 0.1Sin(11\omega t + 15^{o}) + 0.1Sin(13\omega t + 150^{o}) \end{Bmatrix} \quad (19)$$

Table 4. Comparison of FFT, Ref.4, first proposed method and second proposed method.

	FFT	(Hamid et al., 2002)	First proposed method	Second proposed method
P_1 (W)	0.9848	0.9848	0.9848	0.9848
Q_1 (VAr)	-0.1736	-	-0.1736	-0.1736
S_1 (VA)	1.0000	-	1.0000	1.0000
dpf	0.9848	-	0.9848	0.9848

$$i(t) = \sqrt{2}\begin{cases} 1.0Sin(\omega t + 10^{o}) + 0.1Sin(3\omega t + 150^{o}) + 0.08Sin(5\omega t + 135^{o}) + \\ 0.008Sin(7\omega t - 22.5^{o}) + 0.09Sin(9\omega t + 20^{o}) + \\ 0.07Sin(11\omega t + 45^{o}) + 0.08Sin(13\omega t + 120^{o}) \end{cases} \quad (20)$$

Examination of the results shown in Table 4, reveals that the reactive power of the fundamental component can not be measured with the method given in Hamid et al. (2002). Therefore, in Table 4 just active power and power factor comparisons are made.

Conclusion

In this study, real and imaginary parts of the fundamental component of the voltage and current signals with harmonics are calculated based on only wavelet packet transform. By using these values, active-reactive-apparent powers for the fundamental component and the displacement power factor are determined by using two different methods. The accurateness of the proposed method was demonstrated by using simulations and comparative results. The method can be easily applicable in industrial applications using digital signal processors or microcontroller since presented study does not need trigonometric and complex number calculations.

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