Table 1. Application and comparative analysis					
S = 2 KVA; U = 220 V; I_{FNL} = 0.410 A; x_d^* = 1.01 pu					
I_{FD} (A)	0.25	0.30	0.35	0.55	0.60
I (A)	2.25	1.60	1.15	1.30	1.80
x_d (pu)	1.00	1.04	0.93	1.01	1.06
ε (%)	-0.99	2.97	-7.92	0	4.95

Table 2. Application and comparative analysis					
S = 28.9 MVA; U = 6900 V; I_{FNL} = 238.5 A; x_d^* = 1.82 pu					
I_{FD} (A)	160	187	302	336	392
I (A)	434	275	356	556	875
x_d (pu)	1.83	1.81	1.81	1.78	1.78
ε (%)	0,55	-0.55	-0.55	-2.20	-2.20

These same equations can be used to obtain the theoretical zero active power *V*-curve. It is important to note that there is a prohibited zone where the field current is near to I_{FNL}, leading to erroneous values of x_d. In practice, a 25% upper and lower security margin of field current over I_{FNL} is sufficient to stay out of this zone.

Application: The presented method was applied to a microalternator (2 kVA) and to a medium-sized synchronous machine (28.9 MVA). Direct-axis synchronous reactance values were obtained using no-load and short-circuit saturation curves (x_d^*). Tables 1 and 2 summarize the results for several excitation currents.

Conclusions: A simple method to estimate a value for the direct-axis synchronous reactance was presented. The method employs on-line data measurements, was applied to two synchronous machines, and give results with error smaller than 10% when compared with a standardized method.

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Instrument for the Quality Analysis of Power Systems Based on the Wavelet Packet Transform

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Abstract: This letter presents the design and implementation of a computer-based instrument to virtually monitor the quality of voltage, current, and power in electric power systems. The proposed instrument is capable of performing online measurement functions, including data acquisition, display, and analysis, as well as data archiving. The analysis of concurrent voltage and current waveforms is performed using the wavelet packet transform (WPT) technique to provide the value of power quality (PQ) indices. In particular, the instrument also enables us to display both the temporal and spectral relationship of the original waveforms. Results of actual data are reported to validate the performance of the developed instrument.

Keywords: Power quality, instrumentation, wavelet packet transform.

Introduction: Electric power quality (PQ) has captured increasing attention in power engineering in recent years. The general strategy to assure the power quality is to monitor the rms of voltage and current and, in some cases, the power of the supply and take appropriate countermeasures based on detection of disturbances, which exceed the load tolerance limits. Most of the common PQ monitoring methods are designed for periodic voltage and current waveforms. Unfortunately the loads are always dynamic in nature, and disturbances, such as harmonic distortion and short-duration variation, can occur occasionally. It is interesting in engineering practice to measure and express the PQ indices in terms of harmonics that are functions of time [1]. This kind of measurements can be realized by applying the wavelet transformation. This transform decomposes the original time-domain waveform into individual frequency bands, and each of these bands represents that part of the original waveform occurring at that particular time and in that particular band [2], [3].

Engineers are generally interested that the measurement results be available both in numerical and graphical forms. Preferably, all the necessary analysis and presentation functions are included in the measuring software, or the results must be available for export to other commercial analysis tools, such as statistics and graphics software packages. Moreover, it is desirable that the PQ monitoring instrument is portable, so that the engineers can carry it along for field tests.

In this letter, the online measurement for the PQ analysis by means of a portable instrument is considered. By incorporating a standard computer interface and utilizing the computational power of an ordinary PC/laptop as well as implementing a commercially available digitizer, the proposed instrument defines its specific functions through software programming. Concurrent voltage and current waveforms are acquired, and then they are processed by using the wavelet packet trans-

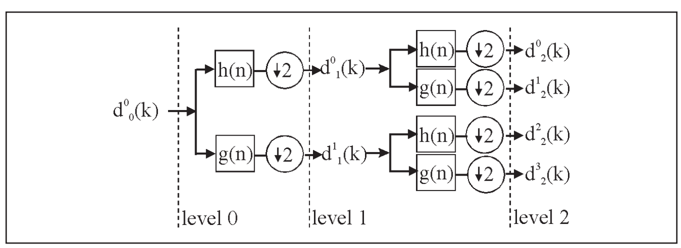

Figure 1. Wavelet packet decomposition tree

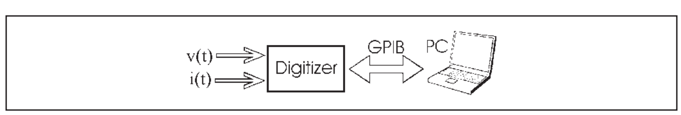

Figure 2. Block diagram of proposed instrument

form (WPT) technique. The PQ indices in terms of total rms, total power, and rms and power of individual frequency bands, as well as their dependent quantities such as power factor and total harmonic band distortion can be obtained. A brief description of both the WPT technique in PQ analysis and the measuring instrument as well as the experimental results are presented.

The WPT Technique In PQ Analysis: *Theory Of WPT*: WPT is a generalization of the commonly used conventional discrete wavelet transform. In practice, the transformation from original time-domain waveform to wavelet transform coefficients (WTCs) deals directly with the low-pass filter $h(n)$ and high-pass filter $g(n) = (-1)^{1-n} h(1-n)$. The WTCs at the jth level and kth point can be computed via the following recursion relations

$$d_j^{2i}(k) = \sum_n h(n) d_{j-1}^{i}(2k-n) \tag{1}$$

$$d_j^{2i+1}(k) = \sum_n g(n) d_{j-1}^{i}(2k-n) \tag{2}$$

where i is the node number or frequency band index. Level 0 is the original waveform.

The implementation of (1) and (2) is depicted in Fig. 1. Let the original waveform has 2^N points. The coefficient $d_j^{2i}(k)$ is obtained by convolving the sequence $d_{j-1}^{i}(k)$ with $h(n)$, and then downsampling by a factor of two. The coefficient $d_j^{2i+1}(k)$ is obtained in similar manner but by convolving with $g(n)$. Number of bands at jth level is 2^j, and every band has 2^{N-j} coefficients. The reconstruction of each band has a reversal process which includes upsampling by a factor of two and filtering.

Calculation of PQ Indices: Let $v(t)$ and $i(t)$ be respectively the analog voltage and current waveforms during the observation period T, and let $v(n)$ and $i(n)$ be the corresponding digitized waveforms of $v(t)$ and $i(t)$, respectively, with $n = 0,1,\ldots,2^N - 1$. The rms of voltage (V_{rms}) and current (I_{rms}) and active power (P) can be computed directly from the WTCs as follows [2], [3]:

$$V_{rms} = \sqrt{\frac{1}{T}\int_0^T v(t)^2 dt} \cong \sqrt{\frac{1}{2^N}\sum_{n=0}^{2^N-1} v(n)^2} = \sqrt{\frac{1}{2^N}\sum_{i=0}^{2^j-1}\sum_{k=0}^{2^{N-j}-1}(d_j^i(k))^2}$$
$$= \sqrt{\sum_{i=0}^{2^j-1}(V_j^i)^2},$$

$$I_{rms} = \sqrt{\frac{1}{T}\int_0^T i(t)^2 dt} \cong \sqrt{\frac{1}{2^N}\sum_{n=0}^{2^N-1} i(n)^2} = \sqrt{\frac{1}{2^N}\sum_{i=0}^{2^j-1}\sum_{k=0}^{2^{N-j}-1}(d*_j^i(k))^2}$$
$$= \sqrt{\sum_{i=0}^{2^j-1}(I_j^i)^2},$$

$$P = \frac{1}{T}\int_0^T v(t)i(t)dt \cong \frac{1}{2^N}\sum_{n=0}^{2^N-1} v(n)i(n) = \frac{1}{2^N}\sum_{i=0}^{2^j-1}\sum_{k=0}^{2^{N-j}-1} d_j^i(k) d*_j^i(k) = \sum_{i=0}^{2^j-1} P_j^i, \tag{3}$$

where $d^{i_j}(k)$ and $d^{*i_j}(k)$ are the WTCs of $v(n)$ and $i(n)$, respectively. V^{i_j}, I^{i_j}, and P^{i_j} are respectively the voltage rms, current rms and power of the frequency band at node i and level j.

Power factor and total harmonic band distortion (THBD) also can be computed from the WTCs. We add a word 'band' in the THBD because the WPT can not extract any single frequency component. Rather, the WPT brings a frequency band around the frequency of interest. The power factor (p.f.) is defined as the ratio of the active power to the apparent power,

$$p.f. = \frac{P}{V_{rms}I_{rms}} = \frac{\sum_{i=0}^{2^j-1} P_j^i}{\sqrt{\sum_{i=0}^{2^j-1}(V_j^i)^2}\cdot\sqrt{\sum_{i=0}^{2^j-1}(I_j^i)^2}}. \tag{4}$$

The THBD is defined as the ratio of the rms value of the frequency bands at nodes $i > 0$ to the rms value of the original waveform. The THBD of voltage and current is

$$THBD_v = \frac{1}{V_{rms}}\sqrt{\sum_{i=1}^{2^j-1}(V_j^i)^2},$$
$$THBD_i = \frac{1}{I_{rms}}\sqrt{\sum_{i=1}^{2^j-1}(I_j^i)^2}. \tag{5}$$

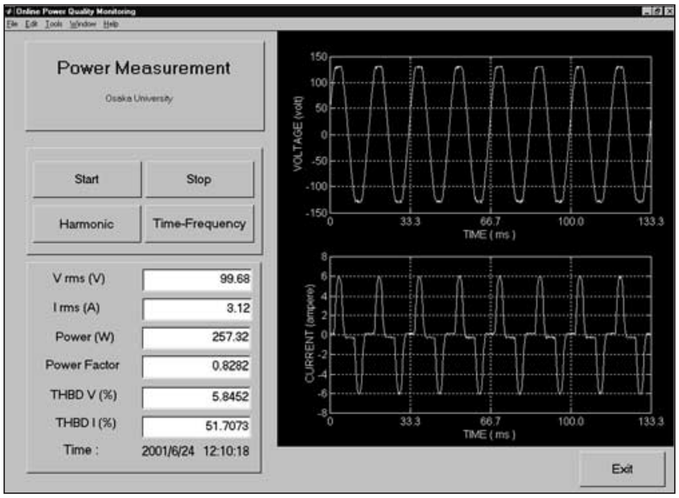

Figure 3. Main screen of PQ monitoring instrument

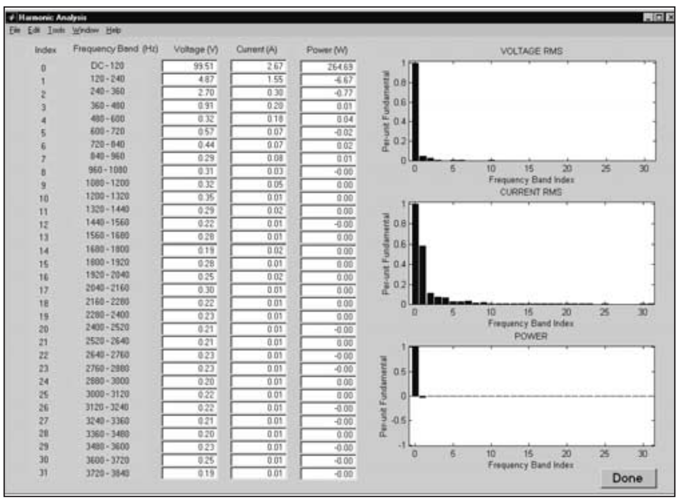

Figure 4. Detail PQ indices for harmonic analysis

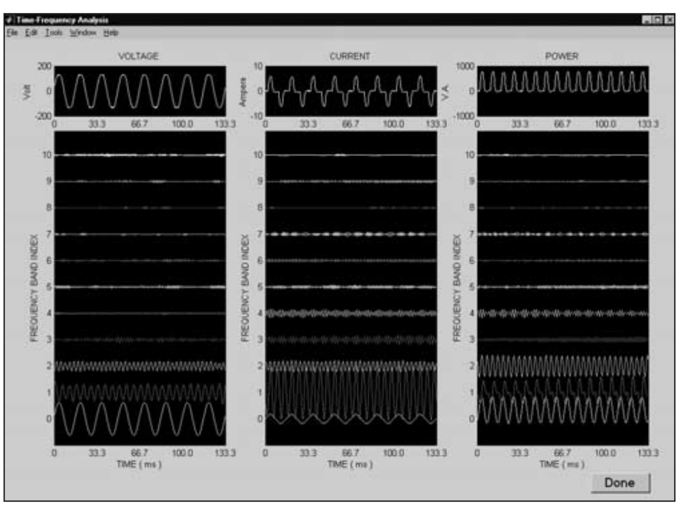

Figure 5. Time-frequency analysis screen (The ratios of band index 0 and the other bands are respectively 1:10, 1:10, and 1:2 for voltage, current, and power.)

Tabel 1. Comparison results between FFT and WPT techniques for the first nine bands								
Band Index	Frequency Band (Hz)	Band odd Harmonic	FFT V*rms*(V)	FFT I*rms*(A)	FFT Power(W)	WPT V*rms*(V)	WPT I*rms*(A)	WPT Power(W)
0	DC-120	1st	99.51	2.67	264.69	99.51	2.67	264.69
1	120-240	3rd	4.94	1.55	-6.65	4.87	1.55	-6.67
2	240-360	5th	2.57	0.34	-0.79	2.70	0.30	-0.77
3	360-480	7th	0.94	0.18	0.02	0.91	0.20	0.01
4	480-600	9th	0.26	0.19	0.05	0.32	0.18	0.04
5	600-720	11th	0.57	0.07	-0.02	0.57	0.07	-0.02
6	720-840	13th	0.42	0.07	0.02	0.44	0.07	0.02
7	840-960	15th	0.30	0.08	0.01	0.29	0.08	0.01
8	960-1080	17th	0.31	0.03	0.01	0.31	0.03	-0.00
TOTAL			99.68	3.12	257.23	99.68	3.12	257.32
Error(%)			-0.000360	-0.020498	0.036887	0.000000	0.000000	0.000000

Instrument Description: Figure 2 shows the block diagram of the measuring instrument. A 4-channel LeCroy 9374C digitizer with 8-bit resolution is used for signal acquisition. Only two channels are used. The digitizer is connected to a PC/laptop Pentium 300 MHz via a General Purpose Instrumentation Bus (IEEE488/GPIB) board. Each voltage or current waveform is digitized at rate of 100 KHz, and then it is digitally resampled every 13 points to fit the WPT requirement so that each 60 Hz fundamental cycle has 128 points. Eight fundamental cycles with a total length of 1024 (2^{10}) points, corresponding to $T = 8/60$ second, are further processed to compute the PQ indices. The PC works under Windows and is used to interface with the user, representing the measurement results and setting the parameters given by the user. The original data and graphic displays can be stored in the storage media for other purposes. Software for data acquisition and communication between the PC and digitizer is coded in C/C++ language. The graphical interface applications are programmed in MATLAB, which dynamically links the C/C++ codes via DLL (Dynamic Link Library) format.

Experimental Results: To evaluate the accuracy of rms and power measurements of the developed instrument, a representative example is given. Figure 3 shows the main screen of the PQ monitoring display. The waveforms on the right panels show the concurrent voltage and current recorded at a power supply point which was supplying several PCs and other electronic devices in our laboratory. Both waveforms are first decomposed using the WPT. In the wavelet transform, there are many types of wavelet filters. In this study, we apply the Vaidyanathan filter because it has good frequency separation [3]. Then, only the WTCs at level $j = 5$ are used to calculate the rms and power because each frequency band at level 5 completely covers a respective odd harmonic component. The values on the left screen show the PQ indices which are computed using (3), (4), and (5).

Figure 4 shows the distribution of rms and power with respect to individual bands, and their corresponding histograms are shown on the right panels. The rms values of each band are computed from their WTCs at each band using (3). The 5-level of decomposition yields $2^5 = 32$ bands which have the same width of 120 Hz, and each band has $2^{10-5} = 32$ WTCs. The bands cover up to the 63rd harmonic, which is sufficiently higher than the PQ standard recommendation (up to 50th or better). Band index 0 includes the fundamental frequency component, and the other bands include higher frequency components. Each of the bands also retains both the time and frequency relationship as demonstrated in Fig. 5. Top panels of this figure show the original waveforms, while the bottom panels show the reconstructed waveform associated with the WTCs of individual bands. The original power waveform is the product of the $v(t)$ and $i(t)$ pair, from which the total average power in time domain can be computed. The WTCs of power are the products of the voltage and current WTCs pairs registered at the same band and time. From this figure one can see the harmonic waveforms of both voltage and current as well as power. Table 1 compares the WPT results with the FFT results for the first nine bands of interest with the associated odd harmonics which are included in these bands. Power at each frequency of the FFT technique can be computed based on magnitudes and angles resulting from FFT analysis of voltage and current data. The table shows that the WPT results closely match the FFT results. The total results of rms and power of the WPT technique are almost the same in all cases. However, the relative errors indicate that the WPT technique provides the same total rms and total power values as the time domain reference, while the FFT technique provides small errors. The small discrepancies between the results of FFT and those of WPT are attributable to non-ideal wavelet filter characteristics since the filter pair has overlap spectral [2] and/or due to pitfalls in the FFT since the waveforms are not pure stationary and periodic. Table 2 shows the power factor and THBD of voltage and current. This table shows that the WPT results and the FFT results are not so different.

Tabel 2. Comparison results of power factor and THBD values		
	FFT	WPT
p.f.	0.8277	0.8282
THBDv (%)	5.8510	5.8452
THBDi (%)	51.6909	51.7073

Conclusions: An instrument for PQ analysis was designed, implemented, and evaluated. The proposed instrument can determine up to the 63rd harmonic of power frequency and provides important PQ indices, such as total rms, total power, rms and power of individual frequency bands, power factor, and THBD. The computation of PQ indices is based on the WPT technique. The advantage of applying the WPT technique is that the instrument enables to display both the temporal and spectral relationship of the original instantaneous rms and power. The instrument can be used to perform diagnostic PQ testing to evaluate waveform distortion (harmonics) and short-duration disturbances. Numerical and graphical results are available in real-time. The test shows that (1) the value of PQ indices closely matches the value obtained from the FFT technique, and (2) the result of total rms and total power is the same as that obtained from the time domain reference.

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