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Power Quality Disturbance Detection Using DSP Based Continuous Wavelet Transform

Mohammed E. Salem, Azah Mohamed and Salina Abdul Samad
Department of Electrical, Electronic and Systems Engineering, University Kebangsaan Malaysia,
43600 Bangi, Selangor, Malaysia

Abstract: This research presents a Digital Signal Processor (DSP) based prototype instrument to provide real-time detection of power disturbances that can be used to perform quick power quality monitoring. The proposed instrument uses the Texas Instrument TMS320C6711DSP starter kit (DSK) with a TI ADS8364EVM 250-kHz, 16-bit, 6-channel analog digital converter mounted on the daughter card. For real-time detection of power disturbances, the continuous wavelet transform is used to detect different types of disturbances such as voltage sag, swell, transient, interruption and harmonics. The results of analysis show that the implementation of continuous wavelet transform algorithm in DSP-based system provide accurate and fast detection of power disturbances.

Key words: Digital signal processor, instrumentation, power quality, real-time, wavelet signal processing

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INTRODUCTION

Electric Power Quality (PQ) has captured increasing concern in recent years and has led to the development of various types of PQ monitoring instruments. However, there is a need for a PQ monitoring instrument that can be used to perform fast and accurate detection of power disturbances. A real time PQ monitor should be able to acquire voltage and current waveforms, identify the disturbances from the abnormalities detected and thereby understand the causes of the disturbances. To perform all these functions in real time, there is a need for special hardware with massive computing power, sophisticated software to analyze data and advanced signal processing techniques for analyzing the PQ disturbance signals.

Due to the different types of PQ disturbances and signals encountered in power systems, various signal-processing techniques have been applied for analyzing the signals. Among the different signal-processing techniques, the most widely used are, the Fast Fourier Transform (FFT) and the Short Time Discrete Fourier Transform (STFT) (Moussa *et al*., 2004). Both the FFT and STFT techniques are most often used for analyzing power disturbance signals which are of stationary in nature. But for non-stationary signals, the FFT and STFT do not track the signal dynamics properly because FFT only shows the existence of certain frequency component and STFT has the limitation of having to choose a fixed window width. While the FFT based analysis is ideal for the calculation of magnitudes of the sinusoidal signals in their steady state, it does not have the temporal characteristics to cope with sharp changes and discontinuities in the signals. Fourier based analysis therefore cannot accurately detect the onset and the end of sustained events such as voltage sags or swells or transients such as interruptions and capacitor switching (Moussa *et al*., 2004). Due to the limitation of FFT, it has been used mainly for analyzing harmonic signals in real-time (Mohammed *et al*., 2005; Gherasim *et al*., 2004). Although the modified version of the FFT, which is the STFT, can resolve some of the problems introduced by the FFT analysis, the STFT still have some technical problems. In the STFT technique, the resolution is greatly dependent on the width of the window function. If the window is of finite length, thus it covers only a portion of the signal and causes the frequency resolution to get poorer. On the other hand, if the length of the window in the STFT is considered as infinite so as to get a perfect frequency resolution, then all the time information will be lost (Moussa *et al*., 2004). Owing to the limitations of the FFT and STFT in analyzing PQ disturbances, the Continuous Wavelet Transform (CWT) is used as an alternative approach for analyzing stationary, non-stationary and non-periodic wide band signals because of its capability in focusing on short time intervals for high frequency components and long intervals for low frequency components. The use of CWT to analysis stationary and non-stationary has been proposed on

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Corresponding Author: Mohammed E. Salem, Department of Electrical, Electronic and Systems Engineering,
University Kebangsaan Malaysia, 43600 Bangi, Selangor, Malaysia

offline analysis by (Malabika and Biswajit, 2004) for detect and characterise Power quality disturbances. A wavelet transform is used (Rafael, 2002) to review the state of the art techniques in signal processing for automatic classification of power quality events and to give a sign of the next trends. Reciprocally, the CWT provides accurate time location and bad frequency resolution at high frequency. This characteristic is appropriate for real signals such as voltage sags and transient over voltages (Olivier *et al.*, 2000).

This research, presents the real-time implementation of CWT using the Digital Signal Processor (DSP) hardware system for detecting various types of PQ disturbances, namely, voltage sag, swell, transient and harmonics. The DSP is distinct from the general-purpose microprocessor in which it has a far higher computing power. The proposed hardware system architecture uses the Texas Instrument TMS320C6711 DSP Development Starter Kit (DSK) with an ADS8364EVM 250-kHz, 16-bit, 6-channel, simultaneous sampling Analog Digital Converter (ADC) mounted on its daughter card. The experimental results displaying a CWT analysis of several PQ disturbances in real time are compared with the results obtained from processing the signals in MatLab with respect to speed and accuracy.

CONTINUOUS WAVELET TRANSFORM THEORY

The CWT provides an approach that can be more flexible than the STFT. The CWT uses a time-window function that changes with frequency, as opposed to the STFT for which the window function is fixed. This adaptive time window function is derived from a prototype function called a mother wavelet. The mother wavelet is scaled and translated to provide information in the frequency and time domains, respectively (Poularikas, 2000).

The continuous wavelet transform is defined as follows:
The Fourier transform of a signal x (t) is

$$X(f) = \int_{-\infty}^{\infty} x(t)e^{-i2\Pi ft}dt \qquad (1)$$

$$CWT_X(t,s) = \int_{-\infty}^{\infty} x(\tau)\psi_{t,s}^{*}(\tau)d\tau \qquad (2)$$

where x (t) is a signal and $\Psi_{t,s}$ (τ) is the wavelet basis function set which can be defined as follows:

$$\psi_{t,s}(\tau) = \frac{1}{\sqrt{s}}\psi\left(\frac{\tau - t}{s}\right) \qquad (3)$$

where s is the scaling variable (s > 0) and defined by

$$s = \frac{f_o}{f} \qquad (4)$$

where f_0 is the frequency of the chosen mother wavelet. The factor $1/\sqrt{s}$ in Eq. 3 is a scale-dependent normalization factor, employed so that all wavelets have the same energy. For large values of s the window function becomes a stretched version of the mother wavelet. Therefore large values of s provide a broad time-width windowing function located in the low frequency region of the frequency domain. On the other hand, small values of s provide a narrow time-width windowing function located in the high-frequency region of the frequency domain.

The parameter s in the wavelet analysis is similar to the scale used in maps. As in the case of maps, high scales correspond to a non-detailed global view (of the signal) and low scales correspond to a detailed view. Similarly, in terms of frequency, low frequencies (high scales) correspond to a global information of a signal (that usually spans the entire signal), whereas high frequencies (low scales) correspond to a detailed information of a hidden pattern in the signal (that usually lasts a relatively short time).
By substituting Eq. 3 into Eq. 2

$$CWT_X(t,s) = \frac{1}{\sqrt{s}}\int_{-\infty}^{\infty} x(\tau)\psi^{*}\left(\frac{\tau - t}{s}\right)d\tau \qquad (5)$$

As seen in the above equation, the transformed signal is a function of two variables, t and s, the translation and scale parameters, respectively. Psi (t) is the transforming function and it is called the mother wavelet.
The CWT has a frequency-domain integral:

$$CWT_x(t,s) = \int_{-\infty}^{\infty} X(f')\psi_{t,s}^{*}(f')e^{i2f'f''t}df' \qquad (6)$$

and represents the decomposition of x (f)' into a set of wavelet basis functions, $\Psi^*_{t,s}$ (f'), defined by

$$\psi^{*}_{t,s}(f') = \sqrt{s}\psi\ [s(f' - f)]e^{-i2\Pi ft} \qquad (7)$$

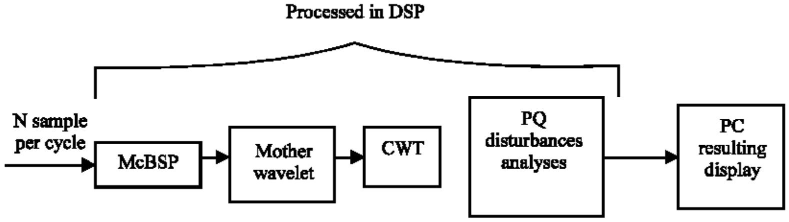

Fig. 1: Data flow through the system

Consequently the CWT can now be written as

$$\mathrm{CWT}_X(t,s) = \sqrt{s}\int_{-\infty}^{\infty} X(f')\psi^*(f'-f)e^{i2f'f''t}df' \qquad (8)$$

The CWT has a filter-bank interpretation in which each wavelet basis function can be thought of as a filter through which the original signal is passed. Each filter, however, has a fixed relative bandwidth as opposed to the fixed absolute bandwidth of the STFT (Poularikas, 2000).

In this study, all processing of the CWT algorithm has been done in the DSP. 1024 samples of a PQ signal are applied to the mother wavelet in DSP via external memory interface and multichannel bi-direction serial port (McBSP) as shown in Fig. 1. The McBSP sends interrupt to the DSP core whenever a new completed sampled data has arrived from ADC and then the analyses of this data will be carried out using CWT in DSP. The output of the analyses will then appear on the PC.

DSP BASED HARDWARE ARCHITECTURE

The PQ disturbance detection hardware is designed by considering the DSP hardware, a data acquisition device using an ADC converter and signal-conditioning module to interface it with the voltage and current probes. The system is DSP based because it offers several advantages such as software upgradeable, low cost and with low power consumption. The architecture of the system hardware is shown in Fig. 2 in terms of a block diagram. The prototype uses a signal-conditioning module for mains input isolation, a TMS320C6711DSP in the DSK evaluation board and a high performance 16-bit ADC, ADS8364 EVM. A PC running on Windows XP is interfaced with the DSK through a parallel port, DB25.

The DSK is a complete DSP system with a powerful (150 MHZ, max. 900 MFLOPS) processor and it comes with all the necessary hardware and software support tools for real-time processing [], including the Code Composer Studio (CCS) software. The TMS320C6711DSP processor is a floating-point DSP with very-long-instruction-word architecture, which is ideal for mathematical processing (Chassaing, 2002).

For the required accuracy and resolution, a 12-bit ADC is sufficient to measure the voltage variation and harmonic distortion. However, for measuring voltage fluctuations and current harmonic distortions, at least a 16-bit ADC is needed (Shiun, 2003). Therefore, a 16-bit ADC, which is ADS8364EVM, is used for all the functions.

The ADS8364EVM has the features of high-speed, low power, 6-channel simultaneous sampling ADC, analog inputs (0-5V) configurable as single-ended or differential, direct connection to the C5000 and C6000 DSK platforms through the 80-pin interface connectors and a high-speed parallel interface. The conversion time for the ADS8364 is 3.2 μs with a 5-MHZ external clock and the acquisition time is 0.8 μs, in which both are fast enough for working in real time. To maximize the output rate of 250 KSPS, the read function is performed at the start of the next conversion (ADS8364EVM User's Guide, 2002).

Programming in DSP is by means of using the Code Composer Studio (CCS) software developed by Texas Instruments and the C language. The CCS provides an integrated development environment which incorporates the software tools for code generation, such as a C compiler and assembler. It has graphical capabilities and supports real-time debugging. CCS is used in this application because it offers the following advantages (Gherasim *et al.*, 2004):

- The code is easily ported to DSP without having to substantially modify the source code.
- It offers a pre-emptive multitasking environment. Software expansion is easy and the real-time analysis module provides detailed real-time information on the algorithms being run.
- It has a real-time data exchange module transferring data in real-time between the DSP and PC.

The implementation of CWT analysis based on DSP is described as shown in Fig. 3. Both the CCS and the C languages are used in this work to interface the DSK with PC and display the results.

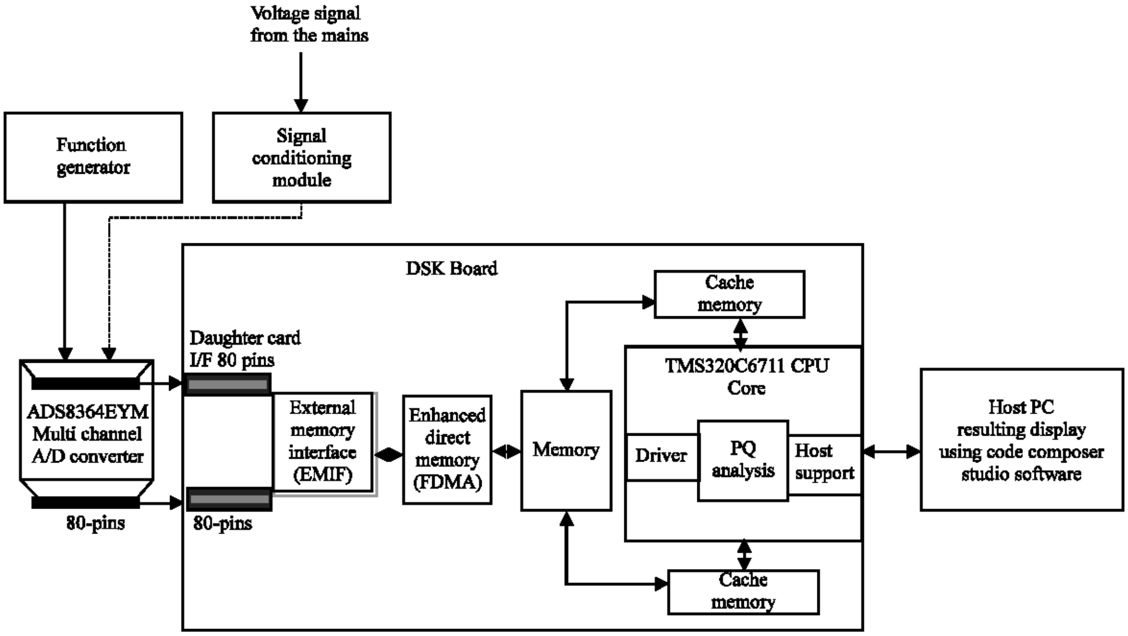

Fig. 2: DSP based hardware architecture

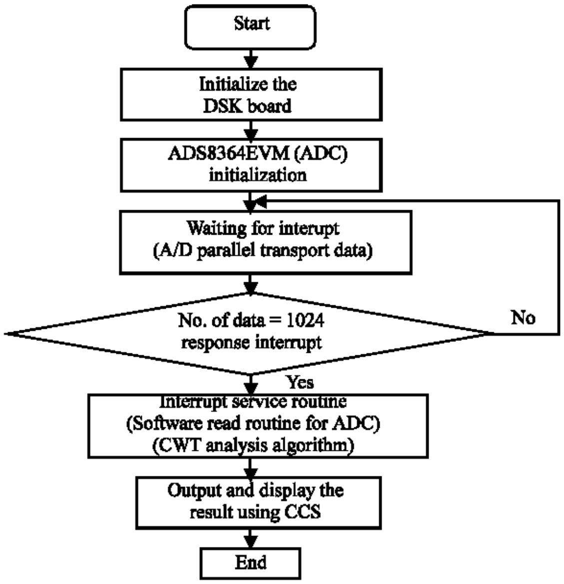

Fig. 3: Implementation of CWT analysis

POWER QUALITY DISTURBANCES DETECTION

Power quality analysis considers various types of PQ disturbances such as transient, harmonic distortion, voltage sag, voltage swell, noise, notching, interruption and voltage fluctuation. Using the CWT programmed in the DSP hardware system, some of the above-mentioned disturbances are analyzed. The results of CWT analysis in DSP are compared with that the results of off-line CWT analysis using the MatLab program in PC, from the point of CPU processing time. The comparison of results in terms of CPU processing time is shown in Table 1, where it is clear that CWT algorithm takes less processing time in DSP than in MatLab. On the other hand, Table 1 shows that the CPU processing time is same for all disturbances processed either in DSP or MatLab because, the data size and the execution clock cycle are the same.

Off-line of PQ disturbances were carried out using MatLab based CWT codes implemented in personal computer and C language based CWT codes implemented in DSP, respectively. The results obtained from both analyses are presented and compared.

For real-time analysis of PQ disturbances, analyses was carried out using C language based CWT implemented in DSP.

Offline analysis of PQ disturbances: Figure 4a shows a pure sine waveform whereas Fig. 4b shows the

Table 1: Processing time in DSP and MatLab

Power quality Disturbance	DSP processing Time (sec)	MatLab processing Time (sec)
Voltage sag	0.4338	4.2500
Voltage swell	0.4338	4.2650
Transient	0.4338	4.2660
Multiple disturbance	0.4338	4.2660
Voltage notching	0.4338	4.2650
Voltage interruption	0.4338	4.2650

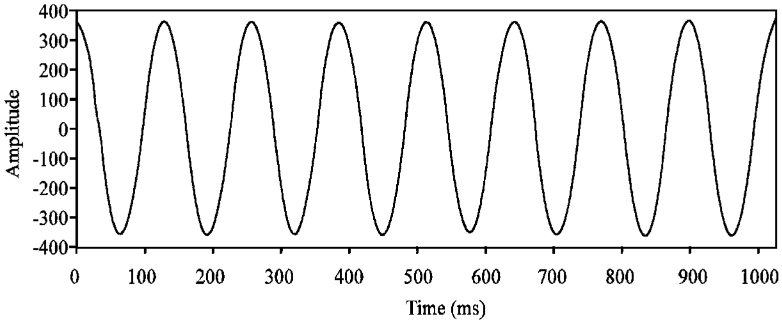

Fig. 4a: Pure sine waveform

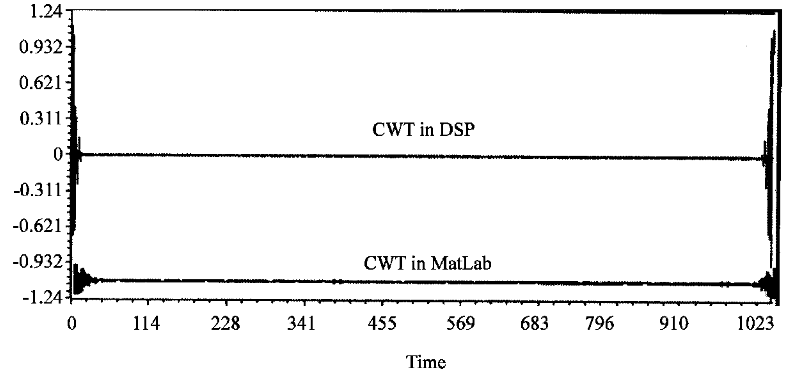

Fig. 4b: CWT analysis of pure sine waveform

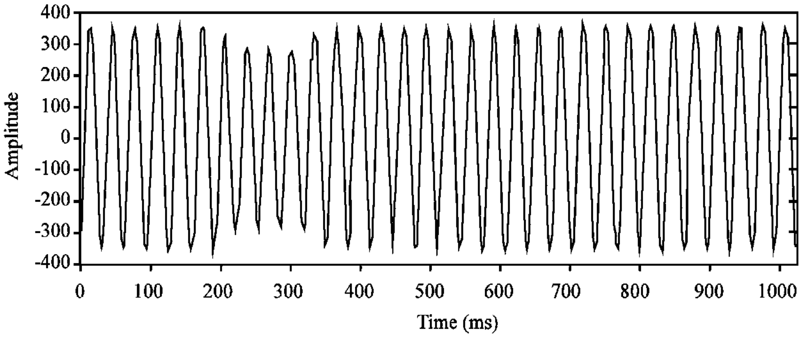

Fig. 5a: Voltage sag waveform

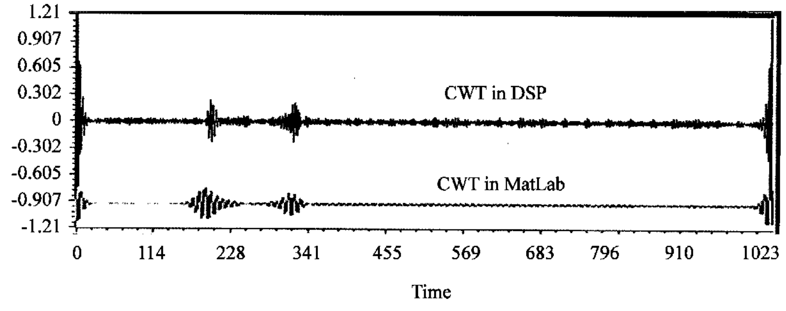

Fig. 5b: CWT analysis of voltage sag

corresponding CWT analysis of the waveform. From Fig. 5, it is seen that the CWT analysis show straight lines which indicate clearly that there are no disturbances in the waveform.

Figure 5a shows a voltage sag waveform obtained from PQ monitoring. The result of CWT analysis of the voltage sag is shown in Fig. 5b, in which the CWT is capable of localizing the voltage sag by determining the

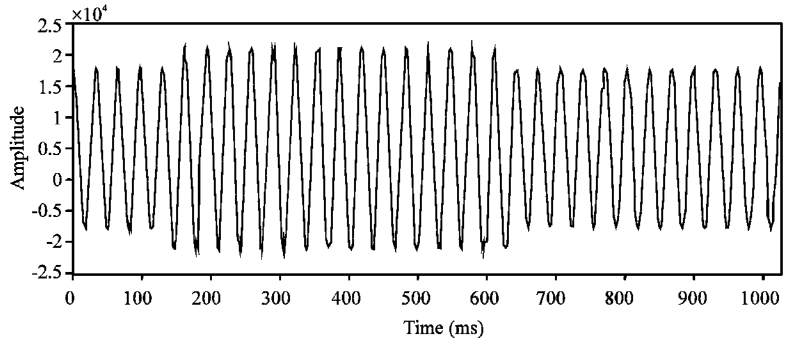

Fig. 6a: Voltage swell waveform

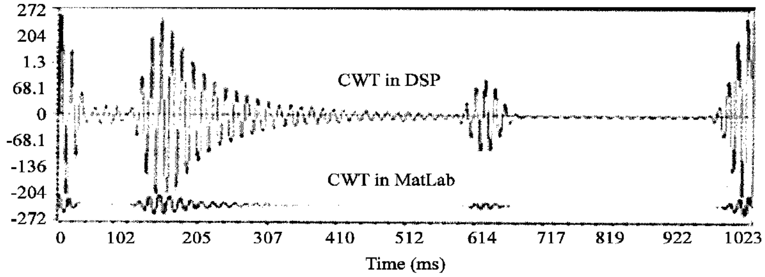

Fig. 6b: CWT analysis of voltage swell

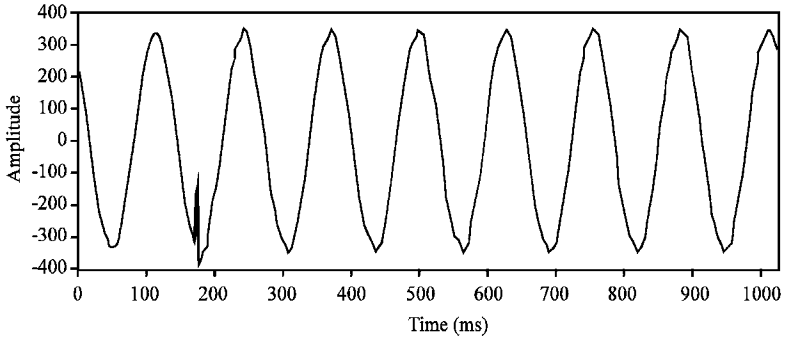

Fig. 7a: Transient waveform

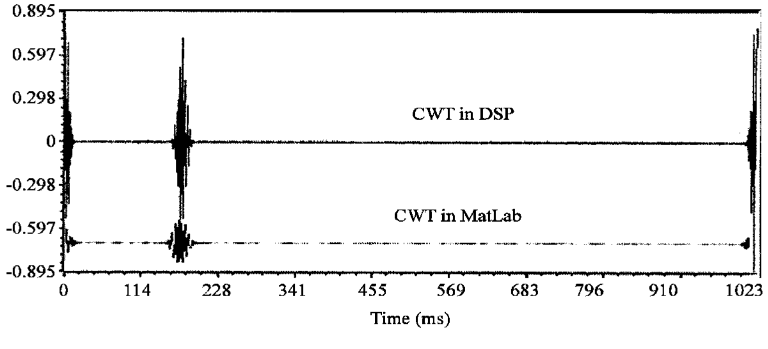

Fig. 7b: CWT analysis of transient

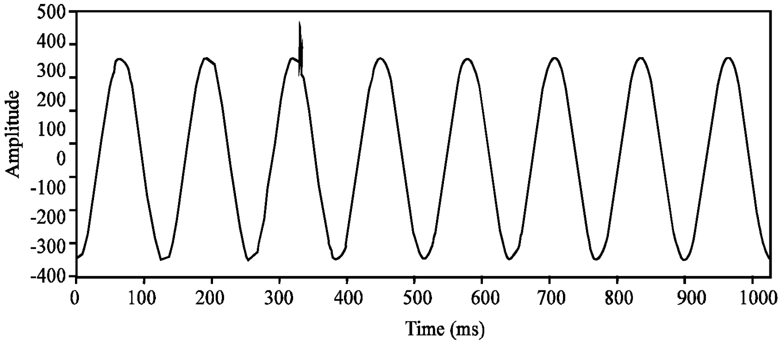

Fig. 8a: Transient waveform

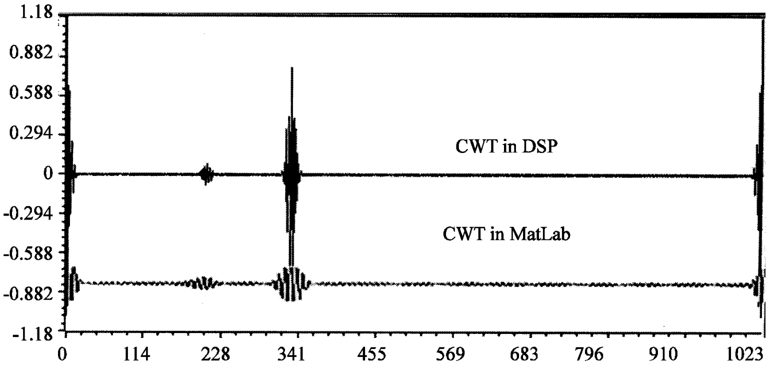

Fig. 8b: CWT analysis of transient

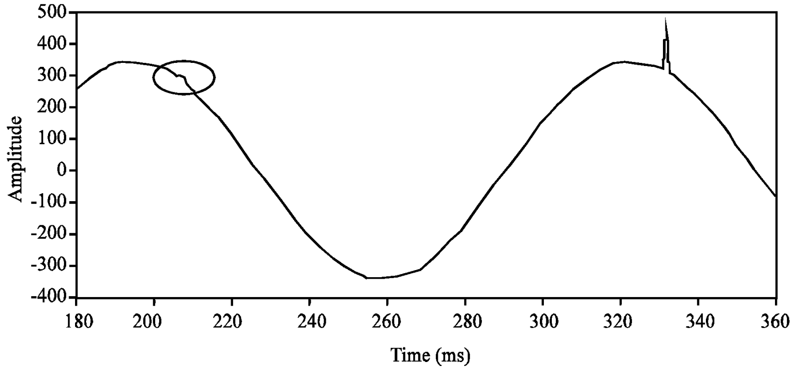

Fig. 8c: Two transients at 207 and 335 ms

starting and ending times of voltage sag as well as its duration. In DSP, precisely can get the duration of voltage sag using cursor in CCS and in this disturbance the duration occurs between 198 up to 321 ms.

Figure 6a shows a voltage swell waveform and the analysis using CWT of this disturbance is shown in Fig. 6b. The shape of CWT analysis in Fig. 6b appears according to the amplitude of the cycles.

From the Fig. 6b it can be seen the duration of voltage swell which is started from 152 up to 633 ms.

Figure 7a shows a transient waveform in which the disturbance has time duration shorter than voltage sag or voltage swell. The transient disturbance can be detected by using CWT analysis in which it can detect the exact time of occurrence of a transient at 175 ms as shown in Fig. 7b.

Another transient waveform is analyzed as shown in Fig. 8a. It is obvious from the figure that a transient occurs at 335 ms, in which the CWT analysis of this disturbance indicates another hidden disturbance at 207 ms as shown in Fig. 8b. After enlarging the portion of the waveform between 100 to 360 ms of Fig. 8a, a notching is shown at 207 ms as indicated in Fig. 8c in the circle.

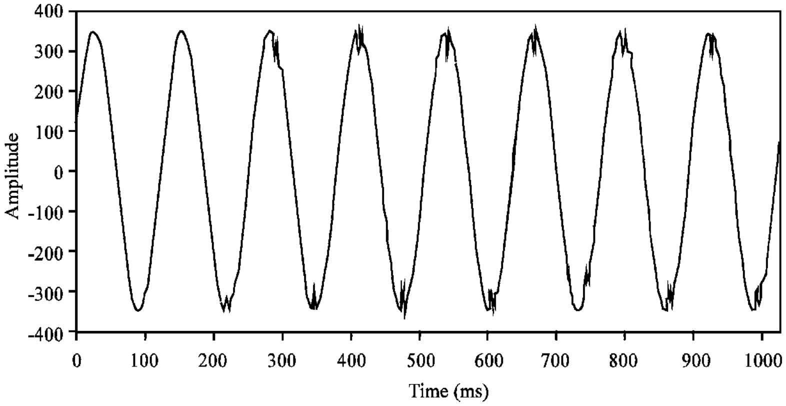

Fig. 9a: Voltage notching

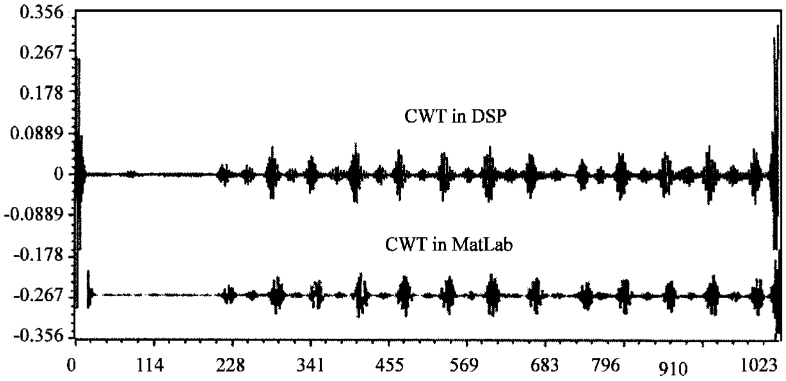

Fig. 9b: CWT analysis of voltage notching

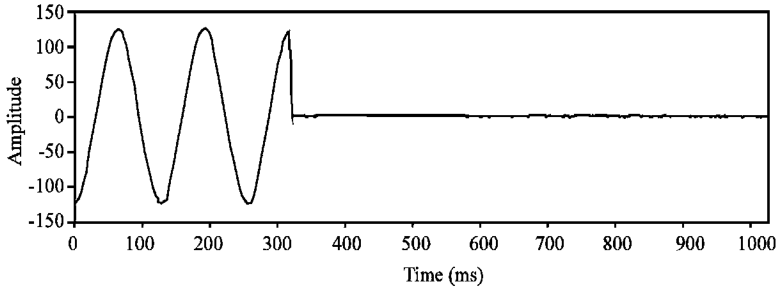

Fig. 10a: Interruption waveform

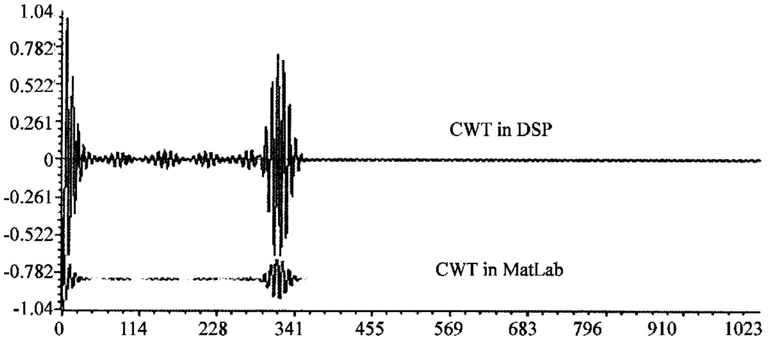

Fig. 10b: CWT analysis of interruption waveform

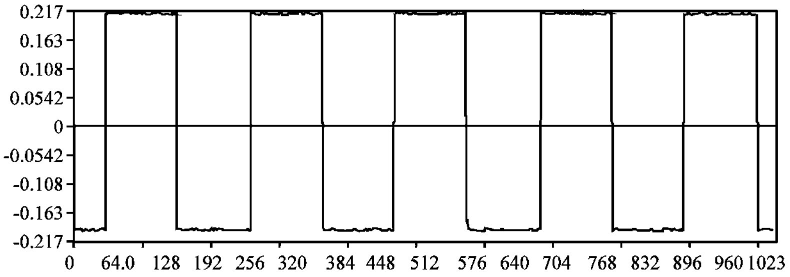

Fig. 11a: Harmonics from function generator

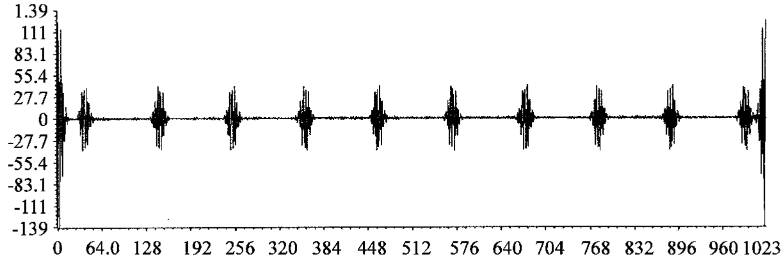

Fig. 11b: CWT analysis of Harmonics in DSP

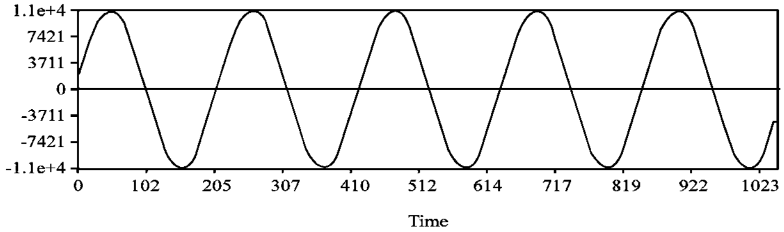

Fig. 12a: Voltage signal from mains supply

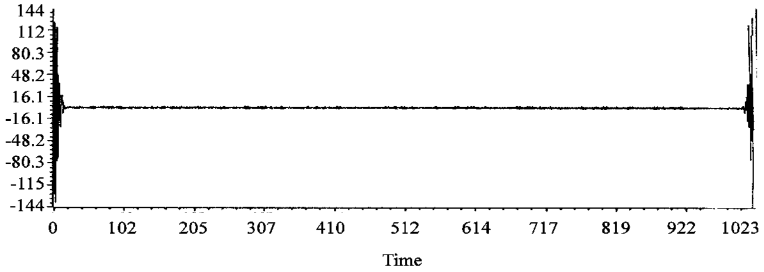

Fig. 12b: CWT analysis of mains voltage in DSP

Notching can be defined as a periodic voltage disturbance caused by the normal operation of power electronic devices when current is commutated from one phase to another (Jaya *et al*., 2004). Figure 9a shows a voltage notching disturbance obtained from monitoring. The result of CWT analysis on the voltage notching indicates that the notches in the mains signal occur from 216 up to 988 ms and the precise time of these notches are shown in Fig. 9b.

Power interruption is a related power quality problem and it is usually due to occurrence of faults in power systems. The interruption waveform is shown in Fig. 10a where the interruption starts at 320 ms. The CWT analysis result of this waveform is shown in Fig. 10b.

The Code Composer Studio (CCS) is used to download the CWT code in DSP memory and also can be used to get the exact time of any point in the analyzed waveform using data cursing, which means can obtained the time of any disturbance precisely. This facility gives DSP with CCS more accurately than MatLab.

Real-time analysis of PQ disturbances: For real-time analyses of PQ disturbances, a square wave signal obtained from a function generator and CWT analysis of this signal in real-time is shown in Fig. 11a and b, respectively. The fundamental frequency is 50 Hertz and other odd harmonics are shown in Fig. 11b.

The next signal considered for real-time analysis of signals in DSP is a voltage signal from the mains supply, which is shown in Fig. 12a. The signal was applied to the ADS8364EVM ADC and the output of the analysis in real-time using CWT is shown in Fig. 12b. From the Fig. 12b, it is clear there is no harmonic in the signal.

CONCLUSIONS

A real-time and offline implementation of CWT using the DSP hardware system is carried out to detect various types of PQ disturbances, namely, voltage sag, voltage swell, transient, voltage notching and harmonics. The hardware system architecture consists of the Texas Instrument TMS320C6711 DSP development starter kit with 16-bit, 6-channel, 250-kHz, ADS8364EVM analog digital converter mounted on its daughter card. The results of the CWT analysis of disturbances in offline was compared with the results of analysis implemented using MatLab in terms of processing time and accuracy and the processing time of CWT in DSP is less than that in MatLab. The CWT in the DSP-based system provides an accurate and fast detection of power quality disturbances as obtained in results.

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