Detection and Analysis of Power System Harmonics Based on FPGA*

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Abstract. With the development of technology, the power quality detect devices become more and more powerful and the measure accuracy increase quickly. This paper analyses frequency and harmonics signal of power system based on the theory of all-phase FFT spectrum by FPGA which has powerful processing function. All-phase time-shifting phase difference correcting spectrum algorithms is used to correct the measurements of power parameters quickly. The paper analyze the real-time data of power harmonics and frequency with high accuracy, the precision of frequency is 10^{-10} which can detect harmonic component under 20 degree correctly.

Keywords: All-phase FFT, Harmonic Analysis, FPGA.

1 Introduction

Power system harmonic and power system frequency are the important power quality parameters in China's power systems. The power frequency is 50Hz which regulated by GB/T15945-1995 "power quality-power system frequency deviation allowable". Power frequency allowing deviation value is 0.2Hz. When the capacity is lesser, deviation value can be extend to 0.5Hz. The waveform distortion and noise interference can reduce the precision of frequency measurement, especially the noise interference is the main reason.

The harmonics in power system produce additional spectrum leakage. Harmonic can cause power line aging, it even can cause a fire on power line. The harmonics produce mechanical vibration on electrical motor and cause physical damage to power electronic devices. When transfer signals in power system the background signal contains a large number of harmonic components. It caused the transmission difficult and the information lost in some seriously situation.

Power voltage and frequency is not stability due to the random power load. For the voltage and frequency instability, a mount of electrical energy lost during the

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transmission process. According to science statistics, power supply coefficient is just 70% or 80% in some place which shows the serious phenomena.

The theory of all-phase spectrum with good suppression of spectral leakage has high accuracy estimation by consider the input signal divided by all circumstances. In case of no disturbance, all-phase FFT analysis spectral can retain phase information. Due to the frequency and amplitude is liner to phase correction, this character provides a guarantee for frequency and amplitude accuracy measure. In this paper, time shifting and phase difference correction method is used to measure the harmonic and frequency precisely [2].

2 Basic Principle of All-Phase Spectrum

The China power supply is three-phase AC which frequency is 50Hz. The actual current has higher harmonics component except fundamental 50Hz. The third harmonic is larger compare with other harmonic component and it is the most harmful harmonic. Harmonic detection is the basic of harmonic management, the harmonic accuracy measure is prior to the harmonic management.

All-phase spectrum analysis need preprocess the sequence data which contain sample point x_0 and the length is N, then take the window comprehensive treatment and traditional FFT spectrum analysis. It improved the performance of spectral analysis by weight average offsetting the spectrum leakage[3] [4].

All-phase digital signal data pre-processing can be described as: Suppose a discrete signal's data length is (2N-1), divide this data into the length of N, then get the N data segment. Alignment each piece of data circular by centre point N which function as triangular window. Then overlap and normalize the corresponding phase and obtain a sample of data which length is N. Thus, all-phase method take account of all the possible chance of center sample data. The method can cut off to reduce the error caused by signal truncation [5].

All-phase FFT double window spectrum has better capability of data processing compared to non-window or single- window, it has less leakage and increases the measurement precision.

Frequency spectrum resolution precision and amplitude estimation precision is contradictory, window function can improve the amplitude spectrum estimation errors but it reduce the frequency spectrum resolution. In order to design a window function both has small amplitude estimation error and does not reduce the frequency resolution, we adopted double window function approach in practical applications.

The process as:

A. Sample signal of single-frequency and get the sequence:

$$\begin{aligned} X_{0=}&[X(N), X(N+1),\ldots, X(2N-1)]^T \\ X_{1=}&[X(N-1), X(N),\ldots, X(2N-2)]^T \\ &\vdots \\ X_{N-1=}&[X(1), X(2),\ldots, X(N)]^T \end{aligned} \tag{1}$$

B. Move the sample point first, shift each vector circular. We get the other N data which is N-Dimensional

$$X'_{0=}[X(N), X(N+1),\ldots, X(2N-1)]^T$$

$$X'_{1=}[X(N), X(N+1),\ldots, X(N-1)]^T \quad (2)$$

$$\vdots$$

$$X'_{N-1=}[X(N)\ X(1),\ldots, X(N-1)]^T$$

C. The All-Phase data vector can get by added sample points then average the Sum

$$X_{ap} = [NX(N),(N-1)X(N+1),\cdots,X(2N-1)+(N-1)X(N-1)/N]^T \cdot \quad (3)$$

3 Use Time Shifting and Phase Retardation Correction Method Based on All-Phase FFT

Sample two signals with same length consecutively and get the sequence. The sampling data should be preprocessed before FFT spectrum analyze. Then use the difference between the phase Sine signal and its delay signal to correct the spectral.

$$X_1(t)=A\cos(2ft+\boldsymbol{\theta}) \quad (4)$$

$$X_2(t)=A\cos(2f\ (t-t_0)\ +\boldsymbol{\theta})$$

A is signal amplitude, f is frequency, $\boldsymbol{\theta}$ is the original phase.

Sample the signal with f_s , do Fourier transform and get a sequenced spectrum $X_{ap}(k)$

$$X_{1ap}(k)= C_1(\omega_0,k)\cos(\boldsymbol{\theta}+2\pi k_0 *n/N)+ \quad (5)$$

$$jC_2(\omega_0,k)\sin(\boldsymbol{\theta}+2\pi k_0 *n/N)$$

$$X_{2ap}(k)= C_1(\omega_0,k)\cos(\boldsymbol{\theta}+2\pi k_0 *(n- n_0)/N)+$$

$$jC_2(\omega_0,k)\sin(\boldsymbol{\theta}+2\pi k_0 *(n- n_0)/N)$$

use $\boldsymbol{\varphi}_1$ describe the phase of $X_1(k)$

$$\boldsymbol{\varphi}_{1=}\boldsymbol{\theta}+2k_0 *n/N \quad (6)$$

use φ_2 describe the phase of X_2 (k)

$$\varphi_{2=} \theta + 2k_0 * (n-n_0)/N$$

$$\Delta \varphi = \varphi_1 - \varphi_{2=} 2\pi k_0 * n_0/N \quad (7)$$

the corresponding frequency correction value is :

$$k_{0=} \Delta\varphi * N/(2\pi * n_0) \quad (8)$$

Amplitude spectrum of all-phase FFT is the square of amplitude spectrum of traditional FFT.

4 Hardware Design

4.1 Acquisition Hardware Description

According to the character of the power system and consideration the real time detection, choose Cyclone II 2C35F672C8FPGA as the central processor. It is support a broad range of external memory interfaces, such as SDR SDRAM, DDR SDRAM, DDR2 SDRAM. The chips has 33,216 LES. The eight-channel 12 bits ADC MAX1308 is used to acquire high accurate power sampling signal. Eight channel's fast conversion time is 1.98 μs.The results can be transformed by RS232 and displayed in PC. Initial angle of current signal usually fluctuated, so the paper choose voltage signal as detect data can get a high-precision[5]. The paper design power parameter detection equipment to analysis harmonic wave and frequent by using FPGA and ADC1308 , meet the needs of power system measurement and have the practical value. This instrument measurement precision of frequency is 10^{-10}, can analyze harmonic component under 20 degree correctly [6] [7].

4.2 The Structure of the Hardware System

This paper adopt FPGA as the main processing chip, it has the character of the programmable components and prospect in digital signal process [8]. For the algorithm design, adopt the superiority of all phase FFT algorithm compare to some other power harmonic detection algorithm, it has high precision [9].

The paper present the whole system framework and how to complete each module. High power voltage signal has been changed into -5 ~ +5V low voltage signal through the conditioning circuit. The signals is sampled by AD and translated into FPGA which has great digital processing capability. For the current signal has some interference the system choose voltage signal as sampling data, processed in all phase pretreatment module, floating point FFT processing modules and so on, we get higher harmonic amplitude, RMS voltage and other power quality parameters, the results can be stored in the data storage module or translated to PC through communication module, it also

can be stored in LABVIEW waveform for real-time display, the detector will generate an alarm signal to inform people when the data exceed the national standard.

The harmonic analysis system based on FPGA can be divided into data disposal module, data acquisition module, signal analysis module, communication module, and the PC display module.

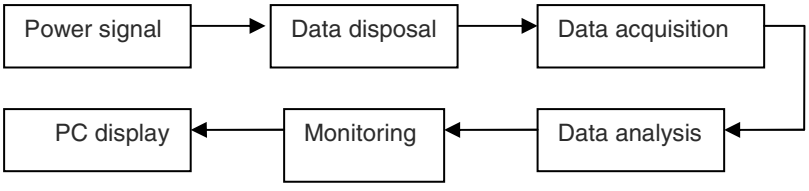

Fig. 1. The system structure diagram

The data disposal, data acquisition, pc display are the periphery design of the system. The data analysis and communications monitoring which process internal in FPGA are the core part of the system.

4.3 Key Module

4.3.1 FIFO Module

FIFO (First In First Out) is a kind of advanced data buffer, FIFO is used as the data transfer between the different clock speed interface or different data width interface, it also used as data buffer between data acquisition module and data processing module. FIFO can establish a connection between data processing module and the corresponding circuit. In this system it not only can change 50Hz low-speed sampling data into a continuous N point high-speed data, also can used as buffer between two processing module. The data buffer transport a group of data into to data processing modules, transfer the result to next processing module after be completely calculated.

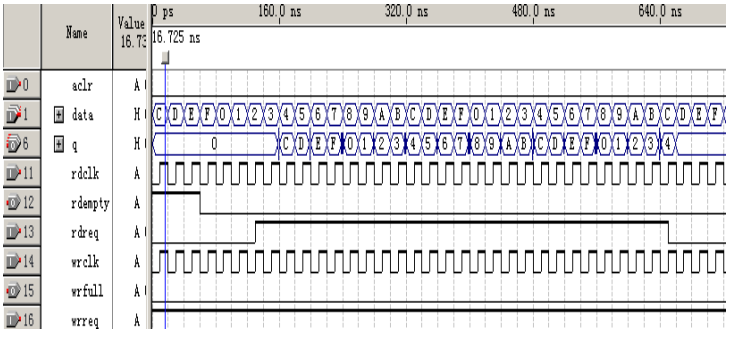

Fig. 2. FIFO QUARTUS simulation

4.3.2 FFT Module

Fixed-point FFT has a simple structure, but the effective signal could be submerged because of the noise disturb. Sometimes the data could be cut off for this reason. The floating-point FFT has high accuracy, the floating-point structure which each number is represented by single index and digit, but it consumed supreme resources and its speed is low. This paper adopt the floating-point mode to insure the harmonic detection accuracy, QUARTUS FFT is using flow pattern, ALTERA ATLANTIC interface use I/O agreement, eight road 256 point of FFT operations can be completed within 1 ms by multilayer parallel pipelines technique. The simulation as follows, the Sink Master as input interface, Source Master as output interface.

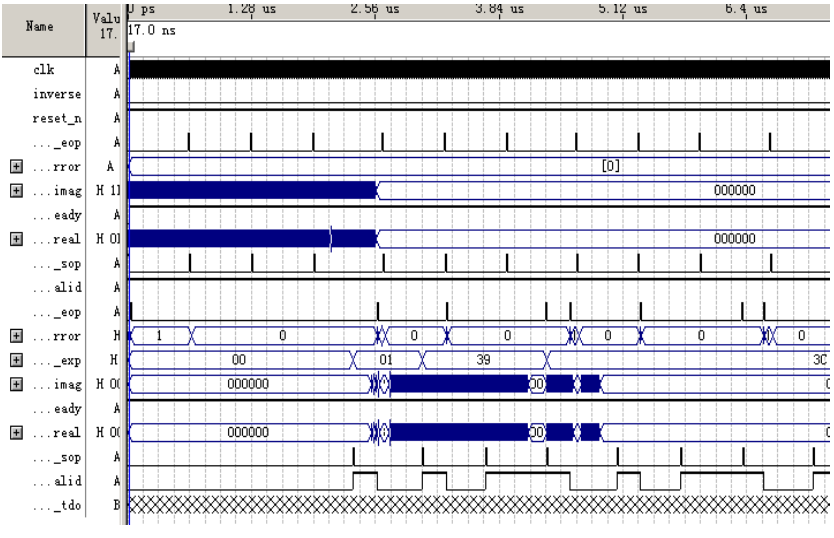

Fig. 3. FFT QUARTUS simulation

4.3.3 RMS Algorithm Module

Voltage RMS is one of the important power parameters, voltage deviation is a symbol of the power supply system operation whether normal or not. RMS algorithm adopts a discrete algorithm processing module, the formula as follows:

$$Urms = \sqrt{\frac{1}{N}\sum_{i=1}^{N} u^2(n)} \tag{9}$$

N - sampling points of measured signal in a cycle;
U (n) - the instantaneous voltage of sample point;
Urms - the RMS voltage of measured signals

The algorithm is intuitive comparatively. It is compare of multiplier module, accumulator module. The module above adopt 32-bit floating-point mode so the data

precision is high. The shortcoming is it take too memory. The algorithm can share the same ALM module which generated by QUARTUS with the FFT algorithm processing module to save some resources and time, [10] [11].

5 Measuring the Frequency

The power frequency is measured by the acquisition sample data, the real power frequency is fluctuated all the time. The waveform distortion components in transient periodic process and the noise interference are the reason of low measure precision. In this paper, initial angle disturbance of voltage signal affect measure frequency precision. The frequency is fluctuated at different time in same places. The result shows the maximum deviation is in safe standard.

The maximal deviation is:
(50. 36785322-50) = 0. 36785322<0.5
The minimum deviation is:
(50.03545321-50)= 0.03545321<0.5

6 Detection of Higher Harmonics

The extensive use of rectifier device which is non-sinusoidal in China's power system can cause a large number of harmonic mixed in AC current. Harmonic will generate additional damage to load, result in power loss and line aging. Power Harmonic detect arithmetic can monitor and record the real-time parameters. The perfect harmonic power detect arithmetic can do real-time monitoring and analyzing .The accurate detection of harmonic is premise to maintain the power normal operation. The design of detect arithmetic has practical meaning and potential development.

The power signal is complicated. It is combine the fundamental signal of 50Hz and other higher frequency harmonic components. The harmonic cause the power factor is low. For the harmonic disturb, the quality of power supply is in low efficiency. The harmonic cause power lost in distribution system and high failure rate of equipment. Analysis the real voltage data to represent the power signal as follows. The wave is showed in MATLAB in figure 4.Despite the complicate harmonic, the waveform is not a smooth sine curve. Because of the noise disturb, UA,UB,UC are not display as the same waveform[12].

Analysis higher harmonic by classical way has spectrum leakage. The strength signal's frequency next line will override the weak signal's frequency main line. FFT can't detect the low frequency signal. So the suppression of spectral leakage trait in all-phase FFT spectrum can be used in detecting the higher harmonics in power system[13] [14].

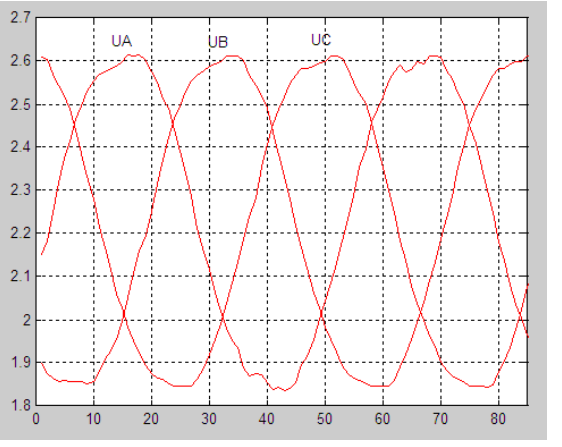

Fig. 4. Real three-phase voltage signal in power system

In this harmonic analysis of all-phase FFT can detect the 20th harmonic. We can see the contentment of 50Hz is high and the contentment of odd harmonics is large than the even harmonics. In some research , the universal simulation experiment consider the harmonic amplitude is decreased by harmonic random increased, but by this actual acquisition date, 9th harmonics amplitudes is slightly larger than the 7th harmonics amplitudes.Harmonic's amplitude are not always decreased by harmonic degree increased[15].

All-phase FFT improves the accuracy of higher harmonic analysis. After the treatment of all-phase FFT, the leakage of spectrum is reduced. Figure 5 is harmonics power amplitude spectrum based on all phase FFT. Figure 6 is partial enlargement of Figure 5. It is shows the higher harmonic component clearly. Pay attention to the point A, the same point in both figure 5 and figure 6. Figure 7 is the bar charts of content of harmonics in power system. The result is complied with national standards GB/T15945-1993 quality of electric energy supply [16] [17].

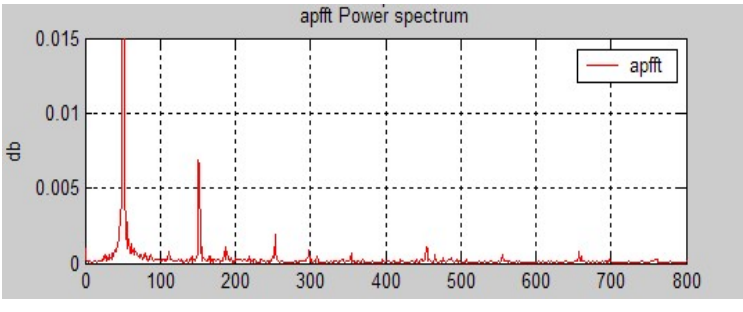

Fig. 5. Higher harmonics power amplitude spectrum based on All-phase FFT

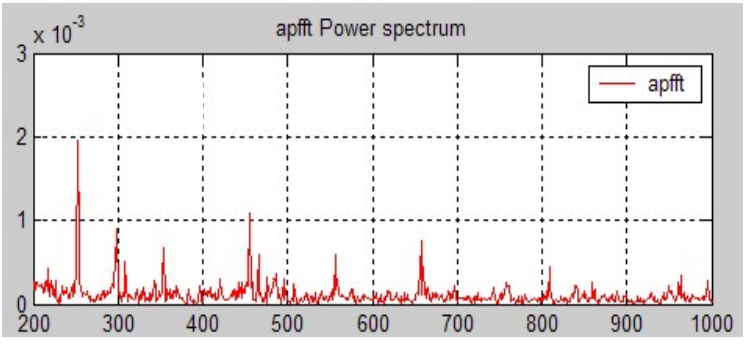

Fig. 6. Partial enlargement of Figure5

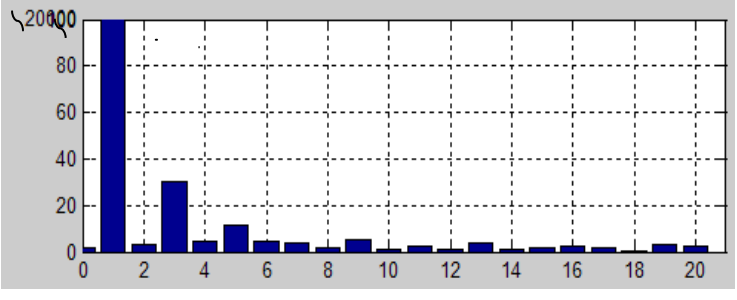

Fig. 7. The bar charts of amplitude content of harmonics based on All-phase FFT

7 Conclusion

Take the all-phase FFT algorithm to process the real power signal by FPGA, the power frequency and the higher harmonic could be measured accurately. All-phase FFT has the phase correction linear characters which increases the accuracy of the frequency and harmonics detection. The character of all-phase FFT restrain spectrum leakage can be used to detect the weak higher harmonic component in this equipment. Precise harmonic detection is the base of the normal operation of power system, the high accuracy of harmonic detection can monitor and analyze the real-time power signal in the electricity system[18].

Because of the large amounts of harmonics presence in power system, three-phase power frequency waveform is not the smooth sine curve. We measured the RMS voltage power is 386.425V, less than five percent of the require standard. It is visible the dominant part of spectrum is 50Hz frequency, the higher amplitude content is descend in turn, odd harmonic content is larger than the even harmonic content. Due to the all phase reprocess detection methods, spectrum analysis showed the harmonic precision is as high as 20 degree.

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