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Research and Realization of Transient Disturbance Detection Algorithm Based Coiflet Wavelets and FPGA

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Abstract

This paper proposes a Coiflet wavelet algorithm based on FPGA to realize the real-time detection of power quality transient disturbance. As to the real-time problem of wavelet algorithm software applications, the algorithm is realized on the FPGA. When Coiflet wavelet is taken as basic functions, the effect of the detecting signal singularity is good. Because of its symmetry in the time-frequency domain the algorithm could avoid the signal distortion during decomposition and reconstruction, which is convenient for subsequent signal processing. By simulating test of several kinds of signal source, the begin-end time of signal transient disturbance is contrasted. The test results show that the method is more accurate and feasible on real-time detection of power quality transient disturbance.

Keywords*: power quality, transient disturbance, wavelet algorithm, FPGA*

1. Introduction

With the use of more power electronics and precision instruments, the power quality problems are more concerned. The accurate detection of real-time power quality is the key to study and solve power quality problems [1-2]. In the power system, because of its serious harm to sensitive equipment, the transient disturbance signal is concerned and has become the focus of power quality analysis [3-4]. Mainly according to the duration and the nature of power quality disturbance, referring to IEEE (IEEE Std 1159-2009) standard and the standard of our country promulgated by relevant to five kinds of typical signal power system, the transient power quality disturbance can be divided into pulse transient oscillation, transient, voltage sag, voltage transient rise and voltage pulsation [5-6].

So far, the power quality detection methods widely used includes the Fourier transform, neural network, secondary transform, wavelet transform，Prony analysis and so on [7]. The traditional methods of signal spectrum analysis are based on Fourier transform. Fourier transform is a transformation of global time-frequency domain; it is suitable only to the stable periodic signal analysis, and can get more accurate results [8]. Neural network is possibly local convergence because of local minimum problems, which directly affects the system control precision; the secondary transform can't be analyzed in time domain. The calculate time of Prony analysis is too long. The wavelet transform is selected in this paper because of its good characteristics in time domain and frequency domain localization, as well as the good ability of processing mutations signal [9-10]. In this paper, to realize the construction of the wavelet algorithm, DSP Builder tool is used and the feasibility and the accuracy of the algorithm are validated by computer simulation. Then, the algorithm is transformed into HDL and implemented in FPGA. At the last, the realization of wavelet algorithm on hardware is tested by Modelsim simulation experiment.

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2. MALLAT Algorithm

The Discrete Wavelet Transform algorithm is mainly Mallat algorithm. In multi-resolution analysis, the two-scale equations of scaling function and wavelet function can be expressed as:

$$\varphi(t)=\sqrt{2}\sum_{k}h(k)\varphi(2t-k) \quad (1)$$

$$\psi(t)=\sqrt{2}\sum_{k}g(k)\varphi(2t-k) \quad (2)$$

During formula (1) and (2), the wavelet base is consists of the linear combination, which can be got by the scaling and translation of scaling function. The construction process of wavelet base is actually the designing process of the low-pass filter and high-pass filter [11]. Mallat algorithm can realize fast decomposition and reconstruction of the signal just according to the filter coefficients. The basic idea of Mallat filter algorithm implementation is to use a high-pass filter and a low-pass filter to process the original signal. By using the filter group to achieve Mallat algorithm the computation amount of wavelet transform can significantly be reduced.

3. Selection of Wavelet

The key to realize wavelet algorithm is the selection of wavelet base, which based on different characteristics and applications of wavelet functions. The problem of the transient power quality detection is one of many power quality problems, which in practical applications may be an intermediate process. So we must ensure that the signal processing has no distortion, and must select the wavelet base with better symmetry. The scaling function and wavelet function with the equal order vanishing moment is called Coiflet wavelets.

The condition that the vanishing moment of scaling function equals zero is defined as a following quintuple:

$$\int t^{l}\varphi(t)d_{l}=\begin{cases}1 & (l=0)\\ 0 & (l=1,2,3,...L-1)\end{cases} \quad (3)$$

The condition that the vanishing moment of wavelet function equals zero is defined as a following quintuple:

$$\int t^{l}\psi(t)d_{l}=0 \quad (l=0,1,2,...L-1) \quad (4)$$

From formula (3) and (4), we could know that Coiflet series wavelet has many characteristics such as orthogonality, double orthogonality and approximate symmetry. Meanwhile Coiflet wavelet has more symmetry and higher compressibility, which is able to detect signal singularity and mutation points. So it is suitable for the power quality disturbance signal detection [12]. Compared with other wavelet structure designed by Daubechies, the algorithm analysis about Coiflet filter is rarer [13]. Daubechies has proved that in order to construct a wavelet base with N order vanishing moment, the length of the scale filter group can't be less than 2N. When analyzing transient signal, in order to detect the singular point effectively, the selected wavelet base must have high enough vanishing moment. The CoifN wavelet function's vanishing moment order number is 2N, and the filter length is 6N, which has the very good effect for singularity detection. Research and analysis show that:

(1) Coiflet scaling function with integral or filter characteristics is similar to D Dirac function.

(2) Coiflet wavelet coefficients have the compact support nature, and are more suitable for real-time online calculation than the continuous wavelet.
(3) When Coiflet wavelet transform is used in the extraction of transient component information or numerical analysis, its large number coefficients is less. So it has good sparse features.
(4) Coiflet wavelet has better symmetry than Daubechies wavelet series, in other words, it has better reconfigurable property.

The study shows that Coiflet2 wavelet has good regularity, and is more suitable for the detection of transient power quality than other Coiflet wavelet.

4. Hardware Implementation of Wavelet Algorithm

DSP Builder is a system level design tools, which link two design tools: the Matlab/Simulink graphic design platform and QuartusII. The system level and RTL level simulation both can be done on the Matlab/Simulink platform. QuartusII is taken as the underlying design tools on the background. So DSP Builder can make full use of advantages of the various tools.

In this paper, firstly, system level modeling and simulation use DSP Builder tool according to the filter principle based on Mallat algorithm. Then the hardware module is transformed into VHDL language. At last, the simulation is completed by QuartusII and Modelsim.

The overall structure of wavelet algorithm implementation is shown in Figure 1, where A portion is the analog signal source of transient power quality disturbance; the result output section B is divided into three outputs to compare results. Wavelet processing module is the core design, which is shown in Figure 2.

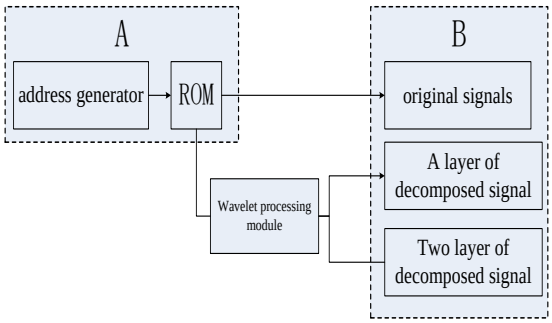

Figure 1. Structure Diagram

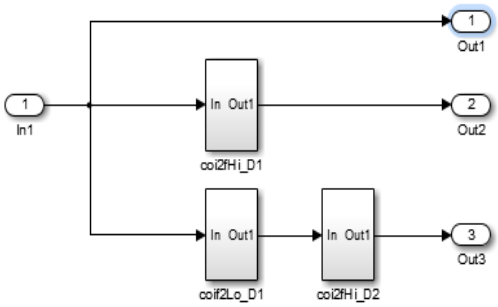

Figure 2. Wavelet Processing Module

Literature [13] proposed an improved intermediate coefficient to obtain Coiflet scale filter coefficients. Compared with the Coiflet filter coefficient designed by Daubechies, the result precision is higher. As shown in formula (5) and (6), they are high-pass and low pass coefficients of the wavelet decomposition filter:

Hi_D = [-0.0005, 0.0013, 0.0039, -0.0167,-0.0420, 0.0540, 0.2949,-0.5747,

0.2730, 0.0476,-0.0293,-0.0116] (5)

Lo_D = [0.0116,-0.0293,-0.0476, 0.2730, 0.5747, 0.2949,-0.0541,-0.0420

0.0167, 0.0040,-0.0013,-0.0005] (6)

To minimize the complexity of the operation, this paper selects 11 binary digits to represent the quantized coefficients. After quantification the results of filter coefficients are shown in formula (7) and (8).

Hi_D = [-1, 1, 4,-17,-43, 55, 302,-588, 280, 49,-30,-12] (7)

Lo_D = [12,-30,-49,280, 588, 302,-55,-43, 17, 4,-1,-1] (8)

According to above quantified low-pass and high-pass filter coefficient, the decomposition of high-pass filter and low-pass filter is constructed by delaying units, gain units and parallel adder. Its structure is shown in figure 3, figure 4, respectively.

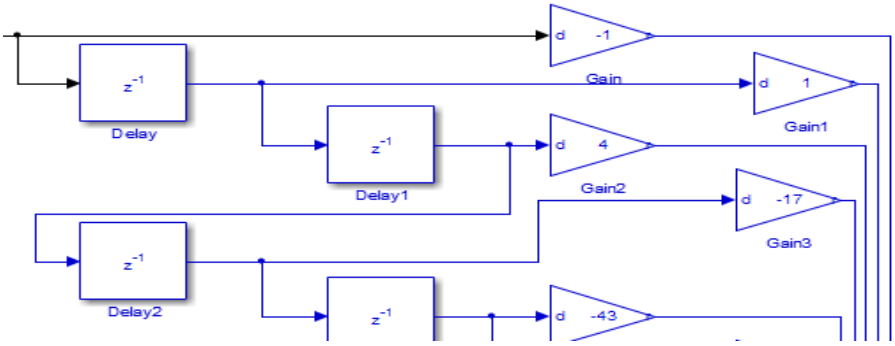

Figure 3. High Pass Filter

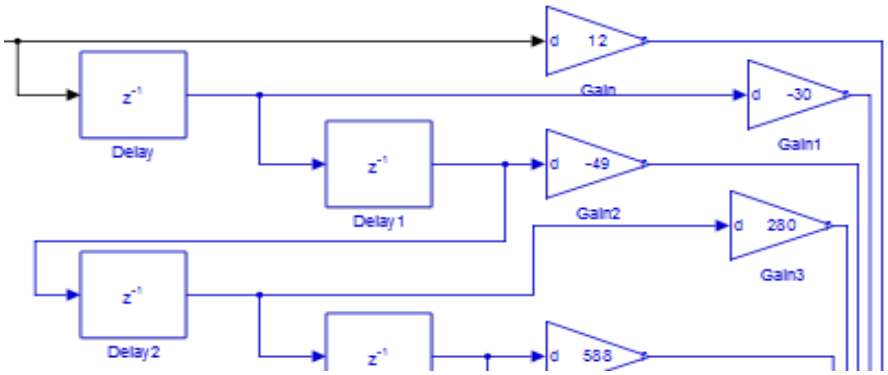

Figure 4. Low Pass Filter

5. Experiment and Analysis

The signal source can be simulated as the corresponding module in DSP Builder's toolbox, which has transient disturbance of power quality in power grid. We detect the mutation point using the transient disturbance detection system set up in this paper, to verify the correctness and accuracy of the signal detection system implemented with filter

method. These transient disturbance signals include voltage signals, voltage sag, the transient oscillation signal and the pulse signal.

5.1 Matlab / Simulink Simulation

For the five kinds of typical power quality disturbance signal: pulse transient, oscillation transient, voltage sag, voltage swell and voltage gap, in Matlab environment, the simulation results of the signal are given respectively. Using the Mallat algorithm, respectively, the original signal in first line l is processed with a layer of wavelet decomposition algorithm and two layer. Since this simulation experiment reads ROM data cyclically, and the original signal is composed of 8 cycles, at the same time, each cycle has 256 sampling points, so the mutation point of the original signal could be determined by the detected data singularity location in time domain.

Figure 5 shows the detection results of pulses transient disturbance of the original data which occurs at sampling point 283 and 899, and Figure 6 shows the detection results of the original data between sampling points 1012 and 1040 when voltage oscillation occurs. Figure 7 is the detection results of voltage interruption between 1049 and 1598. Figure 8 is the detection results of voltage swell between 939 and 1599. Transient voltage sag and voltage swell are similar and need not be repeated here.

As can be seen from Figure 5 and Figure 6, after original signal is processed with a layer of wavelet decomposition algorithm and two layer, the one layer and two layer of wavelet coefficients could be got respectively, which characterization of the transient signal mutation moment. According to the modulus maxima theory, the begin-end time of pulse transient oscillation and transient disturbance can be got also.

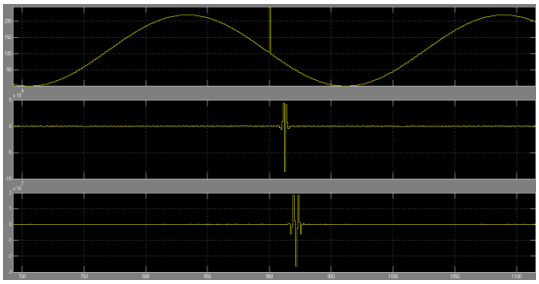

Figure 5. Pulse Transient Detection

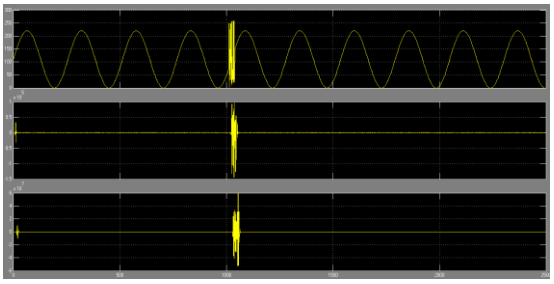

Figure 6. Oscillation Transient Detection

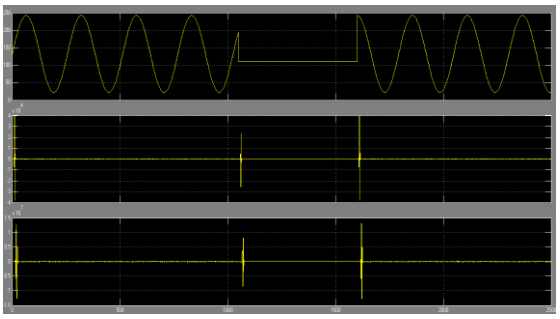

Figure 7. Voltage Interruption Detection

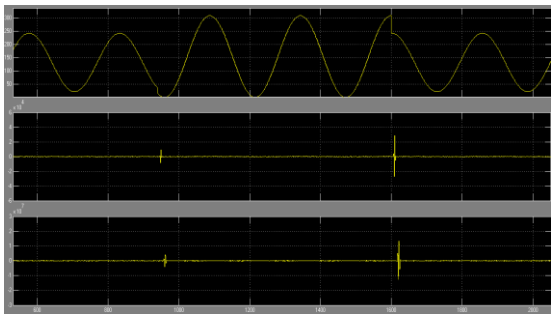

Figure 8. Voltage Swell Detection

As you can see in the above figures，at begin-end moment of voltage interruption and voltage swell, there are two very obvious mutation point, and the wavelet coefficients of other location is near to zero. So the begin-end moment of transient voltage disturbance can be easily got, to achieve the purpose of transient power quality disturbance detection. As can be seen from the diagram, this method is effective and feasible.

5.2 Modelsim Simulation Results in RTL Level

In Matlab / Simulink, the simulation of transient disturbance detection algorithm is system-level. There is no corresponding VHDL code for simulation in RTL-level, and the specific delay time can't be got. It is necessary to do function and timing simulation of algorithm based on FPGA. At the same time, due to excellent performance of FPGA, such as: high integration, high speed and parallel working, the delay caused by processing algorithm is also very small，which greatly improves the real-time performance of transient power quality disturbance detection.

As described above, we get the corresponding VHDL of Coiflet algorithm built in the DSP Builder at first, then generate the corresponding module in a project built in the QuartusII. In this article, the Cyclone IV of Altera Corporation is used to do related experimental verification. According to the FPGA development board we set the corresponding parameter, and do the function and timing simulation of Coiflet wavelet algorithm, to verify the accuracy and feasibility of the method.

As shown in figure 9~12, the first line is clock signal, the second is reset signal, and the third line is original voltage signal. In addition the fourth and fifth lines are respectively the test results of one layer and two layer wavelet decomposition of original voltage signal. As can be seen from the diagram, all kinds of disturbance signal can be seen clearly, and the detection results are consistent with the Simulink simulation waveform. There are obvious modulus maxima points in the wave of first layer decomposition, but two layer decomposition is clearer.

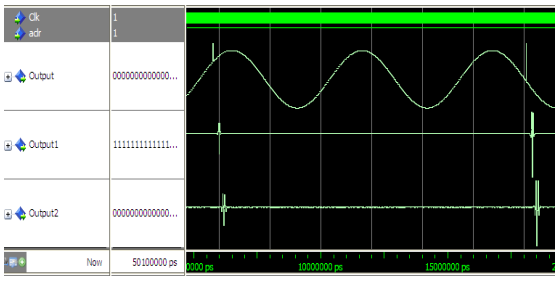

Figure 9. Pulse Transient Simulation

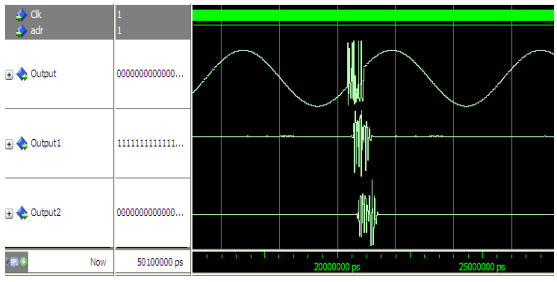

Figure 10. Oscillation Transient Simulation

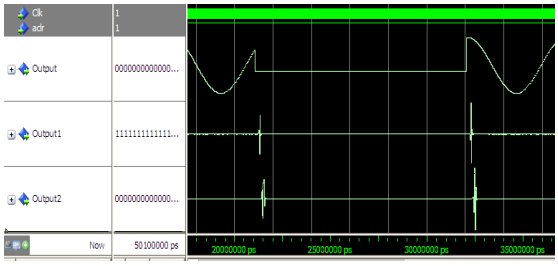

Figure 11. Voltage Interruption Simulation

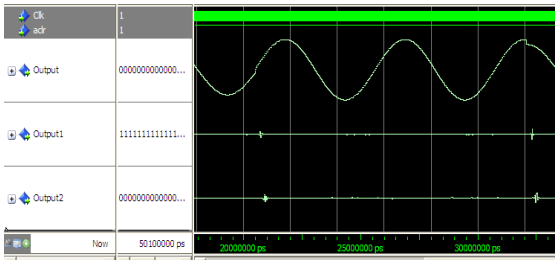

Figure 12. Voltage Swell Simulation

Take transient pulse as example, figure 13 shows the details of pulse transient simulation. As can be seen from the diagram, Coiflet wavelet has good symmetry, which avoids the signal distortion during wavelet decomposition and reconstruction, to ensure the accuracy of detection.

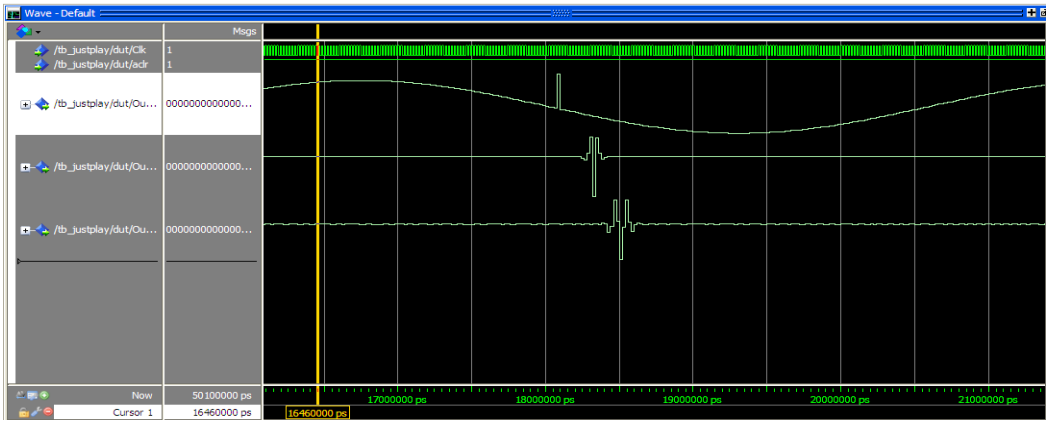

Figure 13. The Simulation Details of Pulse Transient

After analyzing simulation data, record the begin-end moment of all kinds of transient power quality disturbance signal, and compare the results with the original set disturbance time. As shown in table 1, the simulation result shows that this design of transient disturbance detection algorithm based on FPGA are in millisecond delay in the detection of all kinds of the transient disturbance signal, which can accurately locate signal mutation point of the moment.

Table 1.The Begin-End Time Comparison of Several Kinds of Disturbance Signal

Disturbance source	Actual begin time	actual end time	Begin time of detection	End time of detection
Voltage swell	0.0734s	0.1250s	0.0739s	0.1261s
Voltage sag	0.0797s	0.1250s	0.0801s	0.1261s
Voltage interruption	0.0820s	0.1248s	0.0824s	0.1253s
Oscillatory transients	0.0791s	0.0813s	0.0796s	0.0822s

6. Conclusion

Using DSP Builder tool for realizing Coiflet wavelet algorithm based on the FPGA, the transient power quality disturbance signal can be detected in real-time, which can make full use of FPGA's high speed, high flexibility, as well as the good characteristic of Coiflet wavelet in time-frequency domain. The simulation results show this method proposed in the paper can more accurately detect the starting and end time of the disturbance signal, and the range of error in the system is allowable. So the real-time detection of disturbance signal is achieved.

In this paper, the results obtained from improved intermediate coefficient method are more precise than the Coiflet coefficient designed by Daubechies.

Compared with the other transient disturbance detection methods, the FPGA realization method based on wavelet algorithm is faster, and the detection accuracy is higher. So the method has a great potential in transient disturbance detection of the power system.

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