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Key Technologies Development of Transient Signals Based Protection Device Using DSP and S-Transform

LIU Xingmao¹,a and ZHENG Gao²
¹Control Engineering College, Chengdu University of Information Technology, 610225 Chengdu, China
²Department of Electromechanical Management, China Maritime Police Academy, 315801 Ningbo, China
liuxm2010@foxmail.com

Abstract. The correctness of new principle of transient signal based protection used to be verified by simulating. In order to further introduce the dynamic simulation experiments for the transient signal based protection algorithm, the key technologies of transient signal based protection device were developed. The hardware of the synchronous multi-channel data acquisition and high-speed data processing was designed with kernel of high-speed floating point digital signal processor TMS320C6748 and simultaneous sampling analog-to-digital converter. The sampling program reads the AD conversion data using DMA mode, which reduce the consumption of CPU time. The S transform was used to extract the fault traveling wave signals from the sampled data. The time consumption of algorithm which extract the traveling wave was analyzed when it ran on TMS320C6748. The test result shows that the hardware and software design is feasible.

1. Introduction
The extra-high voltage (EHV) transmission lines have become the backbone of the power transmission network. Rapidly removing the faulted EHV transmission line is one of the best measures, which can improve power system transient stability and increase the transmission capacity [1-2]. The protection principles based on transient signals can improve the relay operating speed. In addition to fast operation, the above principles are immune to power swing, current transformer saturation and distributed capacitance current of transmission line, which have been the difficulty confronted by the conventional protections. Therefore, a great number of the protection principles based on transient signals have been suggested since the 1970s, such as directional traveling-wave protection, traveling-wave distance protection and high frequency transient based protection[3-4].

At present, the above transient signals based protections were verified through applying the electromagnetic simulation software, and the simulation results showed that those suggested protections had the competence to identify all kinds of faults. To evaluate the hardware and software limitation in a real-time implementation of the proposed algorithms by using the methods of dynamic simulation, the protection devices based on transient signals were developed. The ultra-high speed traveling-wave based protection board was developed in [5]. The transient signals based non-unit protection device for high voltage direct current transmission lines was designed in [6].

There are two challenges faced during the implementation of the transient signals based protections. One of the challenges is capturing voltage and current signals at simultaneous multichannel signal
acquisition and high speed sampling rates required for the protection algorithms. The other one is real
time and high speed data processing. Therefore, the digital signal processor (DSP) based hardware was
designed in this paper. The specific sampling process and the extraction of transient signals were
described. The test results show that the design of the hardware and the transient signal extraction
algorithm can meet the requirement of transient signal based protection device.

2. The data acquisition and signal processing hardware based on DSP
The hardware is mainly constituted of three blocks that are signal transforming, analog to digital (A/D)
converting and digital signal processing block. A block diagram of hardware is displayed in Fig. 1.

![Diagram showing hardware blocks: transformer, OP2177, comparator, ADS8556, FPGA, DSP, TMS320C6748, EP1C6Q240C8, Simultaneous Sampling, filter, amplifier.](image)

**Figure 1.** The block diagram of ac sampling circuit.

The signal transforming block consists of six transformers, six low pass filters and six amplifiers. The voltages and the currents, which are the inputs of the hardware, are transferred to voltage signals by V/V and I/V transformers. The filters are applied to remove high frequency noises and the upper limit frequency of the filters is set as 250 kHz.

The digital (A/D) converting block is consisted by the zero crossing detect circuit and a 16-bit six-
channel simultaneous sampling A/D convertor (ADS8556). The zero crossing-detect circuit, which consists of a comparator, generated square wave whose frequency is the fundamental frequency, and FPGA locks the frequency and controls the converter. The A/D convertor contains six 16-bit, successive approximation register based ADCs with true bipolar inputs, and it supports data rates of up to 730 kSPS in parallel interface mode.

The digital signal processing block mainly contains high-speed fixed/floating point DSP (TMS320C6748) and FPGA. The DSP is used to run the algorithm and FPGA is used to control the periphery chips. The high-speed DSP can achieve data processing involved in the algorithm.

3. Multi-channel simultaneous and high speed sampling
In order to accommodate the high sampling rates, it was decided to read the A/D conversion data using the direct memory access (DMA) channels instead of using the processor. The block diagram of sampling process is displayed in Fig. 2. The sampling process can be described as:

Step 1: Enhanced high-resolution pulse-width modulator (eHRPWM) of DSP generates a pulse signal to initiate the conversion of the A/D convertor.

Step 2: The conversion synchronization is achieved by connecting the pin GP5_3 of the DSP to the pin BUSY/INT of the A/D convertor. When the conversion data of all six channels are latched to the output register the pin BUSY/INT of the A/D convertor transitioned low.

Step 3: A DMA transfer is initiated by the pin GP5_3 of the DSP when the pin GP5_3 transitions low from high.
Step 4: Performed by the DMA, the A/D conversion data are copied from the register of the A/D convertor to DDR2 SDRAM.

Figure 2. The block diagram of sampling process.

4. S-transform based transient signals extraction

4.1. S-transform

The S-transform provides a time-frequency representation of a signal. It uniquely produces a frequency-dependent resolution that maintains a direct relationship with the Fourier spectrum[7]. The S-transform has the superior properties owing to the fact that the modulating sinusoids are fixed with respect to the time axis, whereas the localizing scalable Gaussian window dilates and translates. Therefore, it is possible to apply notions of sinusoidal frequencies in interpreting and exploiting the resulting time-frequency spectrum[8].

The discrete S-transform is calculated by taking exploiting the efficiency of the discrete Fourier transform. Let \( h[kT] \) denote the discrete form of the continuous signal \( h(t) \), where \( k=0,1,\ldots,N-1 \), and \( T \) is a time sampling interval. The discrete Fourier transform of \( h[kT] \) is given as

\[
H \left[ \frac{n}{NT} \right] = \frac{1}{N} \sum_{k=0}^{N-1} h[kT] e^{-\frac{2\pi i nk}{N}}
\]

(1)

where \( n=0,1,\ldots,N-1 \).

Using (1), the discrete S-transform of the time series \( h(kT) \) can be expressed as (letting \( f \rightarrow n/NT \) and \( \tau \rightarrow jT \))

\[
S \left[ jT, \frac{n}{NT} \right] = \sum_{m=0}^{N-1} H \left[ \frac{m+n}{NT} \right] e^{-\frac{2\pi i (m+1)n}{n}} e^{-\frac{2\pi i m j}{n}}
\]

(2)

and for the \( n=0 \), it equals to the following constant

\[
S \left[ jT, 0 \right] = \frac{1}{N} \sum_{m=0}^{N-1} h \left[ \frac{m}{NT} \right]
\]

(3)

where \( j, m, \) and \( n=0,1,\ldots,N-1 \). The sampling

Equation (3) gives the zero frequency voice the constant average of the time series. The S-matrix is obtained as \( S[jT,n/NT] \), which contains the instantaneous phasor values for spectrums. Amplitude and phase of the spectrum explored are expressed as \( |S[jT,n/NT]| \) and

\[
\tan^{-1} \left\{ \frac{\text{imag} \left[ S[jT,n/NT] \right]}{\text{real} \left[ S[jT,n/NT] \right]} \right\}
\]

(4)
4.2. Transient signals extraction

4.2.1. The phase-modal transformation. The phase modal transformations are the useful analytical approaches which are often used to decouple a three phase system. Clarke transform, which is one of phase modal transformation methods, is adopted to achieve the same purpose in this paper. The modal voltage and current can be expressed as:

\[
\begin{align*}
    u_a &= (2u_α - u_β - u_γ) / 3 \\
    i_a &= (2i_α - i_β - i_γ) / 3 \\
    u_β &= (\sqrt{3}u_β - \sqrt{3}u_γ) / 3 \\
    i_β &= (\sqrt{3}i_β - \sqrt{3}i_γ) / 3 \\
    u_γ &= (u_α + u_β + u_γ) / 3 \\
    i_γ &= (i_α + i_β + i_γ) / 3
\end{align*}
\]

(5)

Where \(u_α, u_β, u_γ\) and \(i_α, i_β, i_γ\) are the voltage and current of phase \(a\), \(b\), and \(c\), respectively; \(u_α, u_β, u_γ\) and \(i_α, i_β, i_γ\) are \(α\) modal, \(β\) modal and \(γ\) modal of the voltage and current, respectively.

4.2.2. The superimposed component. A fault occurred on a transmission line can be regarded as superimposing a voltage to the fault point, which causes the post-fault voltages and currents to deviate from the pre-fault voltages and currents. The superimposed components of voltage and current are obtained by subtracting the pre-fault voltages and currents from the post-fault voltages and currents. Therefore, the superimposed voltage and current are given as:

\[
\Delta u_α = \sum_{y=k}^{y=N} \frac{x+y}{N} u_α \left( y - N \right) - \sum_{y=k}^{y=N} \frac{x+y}{N} u_α \left( y - N - 1 \right)
\]

(6)

\[
\Delta i_α = \sum_{y=k}^{y=N} \frac{x+y}{N} i_α \left( y - N \right) - \sum_{y=k}^{y=N} \frac{x+y}{N} i_α \left( y - N - 1 \right)
\]

(7)

Where \(u_α\) and \(i_α\) are \(α\) modal of the voltage and current, \(N\) is the sample number per cycle, \(y\) is sample number variable and \(k\) is the recent sample number.

4.2.3. Extracting transient signals based on S-transform. Superimposed components contain transient signals which consist of multiple frequency components. The explored frequency component of transient signals can be extracted while superimposed components undergoing a discrete S-transform. The algorithm of transient signals extraction based on S-transform can be expressed as:

Step 1: Apply fast Fourier transform (FFT) to the superimposed component and acquire the frequency spectrum \(H(m)\) where \(m\) is the frequency sample index.

Step 2: Rotated and concatenated \(H(m)\) with the \(n\) which is the explored frequency index and obtain \(H(m+n)\).

Step 3: Multiply \(H(m+n)\) with Gaussian window \(G(m+n)\) which can be expressed as:

\[
G(m,n) = \exp \left[ -a \left( \frac{2\pi^2 m^2}{n^2} \right) \right]
\]

(8)

Where \(a\) is the parameter to adjust the shape of Gaussian window.

Step 4: Use inverse fast Fourier transform on \(H(m+n) G(m+n)\). Then the discrete S-transform of superimposed component is obtained.

5. Laboratory experiment

In this section, laboratory experiments were conducted to assess the run time and verify the correctness of the algorithm, which was applied to extract transient signals, by using real standard signals. Voltage and current data were generated and recorded using PSCAD/EMTDC. Then, the record data were played back by applying the Real Time Playback (RTP), which produced the signals proportional to the recorded data. The output signals were the inputs of the designed hardware platform. The computer was used to debug the program and displayed the data in Code Composer Studio.
5.1. **The time complexity and the time consumption of the S-transform**

The DSP clock frequency was 456MHz, and the ADS8556 sampled the signals at 500kHz sampling rate. The routine and data were loaded in random access memory to reduce run time. The time complexity and the time consumption of the algorithm in section 4.2.3 were shown in Table 1. Step 1 and Step 4 take linearithmic time or \( O(N\log_2 N) \) time. Step 2 and step 3 take linear time, or \( O(N) \) time. Results show that the run time of the algorithm is 0.0388ms if the data window N is 128 sampling points and it is 0.2582ms if the data window N is 1024 sampling points. It can be seen that the hardware and algorithm satisfies the real time requirement for transient signals based protection device.

| Step         | The time complexity     | The time consumption/ms |
|--------------|-------------------------|-------------------------|
|              | \( O(N\log_2 N) \)     | 0.0093                  |
| Step 1       |                          | 0.0568                  |
| Step 2 and step 3 | \( O(N) \)            | 0.0213                  |
| Step 4       | \( O(N\log_2 N) \)     | 0.0082                  |
| Total        |                         | 0.0388                  |

5.2. **Test of transient signals extraction**

To test the correctness of the algorithm, which was applied to extract transient signals, the simulation model of 500 kV transmission system displayed in Fig. 3 in [9] and the apparent surge impedance based relaying method in [9] were used for the following simulation and analyse. The fault type explored here was A phase to ground fault. The fault location from the busbar A was 100 km. The fault resistance and the fault inception angle were 0 \( \Omega \) and 30°, respectively. The record data from the simulation were played back by RTP, and \( \alpha \) modal of superimposed voltages \( \Delta u_\alpha \) and \( \alpha \) modal of superimposed currents \( \Delta i_\alpha \) were obtained by the routine. Fig. 3 (a) and Fig. 3 (b) showed the

![Graph](image1)

(a) The superimposed voltage.

![Graph](image2)

(b) The superimposed current.

![Graph](image3)

(c) The magnitude of voltage traveling.

![Graph](image4)

(d) The magnitude of current traveling.

**Figure 3.** The superimposed components and the magnitude of traveling extracted.
waveforms of $\Delta u_\alpha$ and $\Delta i_\alpha$, respectively. The selected frequency in the discrete S-transform results was selected as $f_1=50$ kHz, the voltage and the current traveling were extracted and the magnitudes of them were shown in Fig. 3 (c) and Fig. 3 (d), respectively. The apparent surge impedance obtained by the method suggested in [9] was $-115.15+43.58\,\Omega$ and the method operated correctly.

6. Conclusion
The hardware for transient signals based protection was implemented on Texas Instruments TMS320C6748. The digital data of the voltages and currents were obtained using ADS8556, which was capable of providing multichannel simultaneous sampling at a high sampling rate. The DMA controller was used to transfer the A/D conversion data to reduce the workload of DSP. S-transform was applied to extract transient signals. Experiment tests were carried and results reveal the real-time ability with satisfactory transient signals extracting accuracy.

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