Design of high precision transient waveform measurement algorithm based on oversampling and mean filtering

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Abstract. In the transient impulse test of simulated lightning, the accuracy and reliability of digital impulse measurement secondary system has always been a research hotspot in industry and academia. In this paper, an oversampling mean filtering algorithm is proposed to overcome the disadvantages of high-resolution ADC and low-resolution ADC which are greatly affected by quantization noise in the secondary system of impact test measurement. By increasing the sampling frequency and mean filtering, this method can achieve the accuracy index that can only be obtained by expensive high-resolution chip using cheap low-resolution chip, and it is easy to implement. In this paper, the principle of the algorithm is analyzed in detail, and its implementation is described. On this basis, the performance of the algorithm is discussed through simulation analysis, and the effectiveness of the algorithm is verified through experiments.

1. Introduction
The transient impulse test of simulated lightning is widely used in the detection of power equipment. The accuracy of the test waveform directly affects the safety, economy and practicability of power equipment, so it has been paid more and more attention in related fields [1]. The impact measurement system of impact test is generally divided into primary measurement equipment and secondary measurement system. The secondary impact measurement system is mainly composed of waveform acquisition device (such as acquisition card, oscilloscope, etc.) and impact waveform processing software, which is an important part of the whole impact voltage measurement system [1]. In order to obtain accurate impulse waveform, iec61083-2:2013[2] specifies the waveform used to evaluate the impulse measurement software, including impulse voltage waveform, switching impulse voltage waveform, impulse current waveform, etc and also specifies the relevant error limits, which is the standard for the accuracy of transient impulse test measurement results.

Impulse voltage measurement software is the core part of the secondary impulse measurement system, and its calculation accuracy directly affects the overall measurement accuracy of the measurement system. The most direct way to improve the measurement accuracy of the system is to use analog to digital converter (ADC) with high resolution (such as 12 bits) [3]. However, 8-bit ADC oscilloscopes are widely used in the current measurement system, and the price of high-resolution and low-resolution ADC oscilloscopes at the same maximum sampling rate is quite different. Using high-resolution ADC oscilloscopes will greatly increase the experimental cost [4]. At the same time, abandoning the 8-bit oscilloscopes of the existing impact measurement system will cause waste. In addition, using multiple low-speed and high-resolution ADCs to realize parallel time alternating sampling can also improve the
accuracy, but in practical application, due to the inconsistency of time and amplitude of each channel, the measurement results will produce errors [5]. In addition, oversampling method can be used to improve the measurement accuracy of the system. Oversampling method is mainly to get a large amount of data by increasing the sampling rate, and then reduce the sampling rate and quantization noise by digital filtering and decimation, so as to improve the signal to noise ratio (SNR) of the system and improve the measurement accuracy of the system. This method can avoid the bottleneck of Nyquist sampling rate when directly amplifying and filtering the measured signal, and can give full play to the function of the secondary system of impulse measurement without adding additional hardware devices, obtain higher signal-to-noise ratio, achieve high-precision lightning impulse waveform measurement at low cost. In this paper, the over sampling method is used to process the collected data, and the sampling rate is 100 times higher than the original sampling rate. Then the mean filtering algorithm is used to de noise and de sample the data. Finally, the change of signal-to-noise ratio is used to analyze the data. The results show that the oversampling method can improve the measurement accuracy by 3.32 bits.

2. Error analysis of measurement system

When measuring the transient impulse voltage waveform, its work flow is shown in Figure 1. The high voltage generated by the impulse is attenuated by the voltage divider, and the low-voltage arm of the voltage divider transmits the attenuated voltage signal to the digital measuring instrument in the measurement system through the coaxial cable; the digital measuring instrument converts the collected data by ADC, and then sends it to the impulse measurement processing software program for subsequent calculation and processing [1].

In the transient impulse voltage experiment, according to the test objects of impulse voltage measurement system accepted by national high voltage metering station, the impulse voltage divider can meet the requirements of relevant national standards and power industry standards [6]. Therefore, the improvement of experimental measurement accuracy needs to be considered from the secondary measurement system.

![Figure 1. Impulse voltage measurement system](image)

There is a formula (1)[7]:

$$|e_q| \leq \frac{V_{ref}}{2^n}$$  \hspace{1cm} (1)
Among them: $V_{\text{ref}}$ is the reference voltage; $N$ is the number of ADC bits.

Assume that the maximum amplitude of the $N$ bit ADC input is $X_m$. The quantization noise has the formula (2):

$$\sigma_e^2 = \frac{2^{2(N-1)}X_m^2}{12}$$

![Figure 2](image.png)

**Figure 2.** Quantization noise diagram

But when the digital measuring instrument collects data at a lower sampling rate, quantization noise always exists [8]. If the quantization noise can be reduced, the signal-to-noise ratio will be improved, and then the resolution of ADC will be improved, so as to achieve high-resolution measurement; and with the reduction of noise, the measurement accuracy of the system will also be improved.

3. **Oversampling and mean algorithm design**

Oversampling technology is to use the sampling rate much higher than the initial sampling rate to sample the analog signal, and then combine with digital filtering and decimation to improve the resolution. The process of improving resolution by oversampling technology can be roughly divided into the following two parts [3]: (1) high speed sampling of input analog signal at a sampling frequency higher than Nyquist sampling frequency; (2) construction of digital decimation filter to realize low-pass filtering and downsampling. Figure 3 is the schematic diagram of the oversampling system.

![Figure 3](image.png)

**Figure 3.** Schematic diagram of oversampling system

From Nyquist theorem: sampling frequency $f_s$ allows the reconstruction of useful signals within half of the sampling frequency. If the sampling frequency is 100kHz, the signal whose frequency is lower than 50KHz can be reconstructed and analyzed, so the oversampling rate OSR can be expressed as (3):

$$OSR = \frac{f_s}{2f_m}$$

In the impulse secondary measurement system, the quantization noise power of ADC is fixed, which has nothing to do with sampling rate and sampling sample. Therefore, when the sampling rate is
increased, the power density of quantization noise becomes smaller in frequency domain. However, since the power of the measured signal remains unchanged, the overlapping part of the quantization noise and the signal in the frequency domain is reduced, which is equivalent to separating a large part of the quantization noise and the signal. As shown in Figure 4, the triangular part is the signal power spectrum, and the rectangular part is the noise power. It can be seen from the figure that after oversampling, the signal power remains unchanged, the noise power distribution is wider, and the overlap between noise and signal is less.

![Figure 4. Oversampling noise power](image)

It is assumed that \( N \cdot f_s \) oversampling the original signal (where \( N \) is called the oversampling rate and \( f_s \) is called the oversampling rate), because the output signal power and quantization noise power will not change with the change of sampling frequency, but with the increase of sampling rate, the distribution bandwidth of noise power spectrum will increase, which leads to the decrease of noise power spectrum density, and the oversampling rate is inversely proportional to the quantization noise power in the signal spectrum[3] and has the following formula (4):

\[
E(f) = e_{rms} \cdot \frac{2^q}{f_s}^{1/2}
\]

Among them, \( e_{rms} \) is the average noise power; \( f_s \) is the sampling frequency; \( E(f) \) is the energy spectral density in the band.

Since the quantization order of ADC is usually uniform, it is assumed that the noise is white noise, and the average value of the distribution of random variables representing noise among ADC codes is 0, then the variance is the average noise power, as shown in formula (5):

\[
\begin{align*}
e_{rms} &= \int_{-q/2}^{q/2} \left( \frac{e^2}{q} \right) de = \frac{q^2}{12} \\
q &= \frac{V_{ref}}{2^N}
\end{align*}
\]
The mean value of the measured data is to achieve downsampling and low-pass filtering. The process of digital signal processing for oversampling and low-pass filtering is usually called interpolation. Interpolation method has a good effect on most data sets. In this sense, it can be considered that: when using oversampling to achieve interpolation to calculate the mean value, the larger the number of samples to calculate the mean value, the stronger the selectivity of low-pass filter, and the better the interpolation effect. The calculation and extraction of mean value need to be processed by software, and the specific process is shown in Figure 5:

![Flow chart of oversampling and averaging](image)

Figure 5. flow chart of oversampling and averaging

Therefore, if the noise passes through the low-pass filter, that is, the average value of the sample is obtained, then the noise power in the output band has equation (6):

\[
\begin{align*}
n_0^2 &= \int_{0}^{f_m} e_{rms}(f)^2 df = e_{rms}^2 \left(\frac{2f_m}{f_s}\right) = e_{rms}^2 \left(\frac{2}{\text{OSR}}\right) = \frac{1}{12\text{OSR}} \left(\frac{V_{ref}}{2N}\right)^2 = \frac{V_{ref}^2}{12\text{OSR}4^N} \\
\end{align*}
\]

Among them: \(n_0\) is the output noise power; \(N\) is ADC significant digits; \(V_{ref}\) is the reference voltage. According to the definition of SNR, the relationship between SNR and bit is as follows (7):

\[
\text{SNR} = 6.02N + 1.76\text{dB}
\]

Therefore, it can be concluded that the improvement of signal-to-noise ratio and the increase of significant digits of measurement are completed at the same time, when the oversampling rate is increased by 4 times, the significant bit is increased by 1 bit, and the signal-to-noise ratio is increased by 6dB.

Therefore, for example, when the impact secondary measurement system uses an 8-bit ADC to output a value (1 Hz) per second, if it wants to achieve 12 bit measurement accuracy, it needs to add 4 bits. The oversampling frequency can be calculated according to the formula \(f_{os} = 4^4 \cdot f_s = 256(\text{Hz})\). When the sampling frequency is 256Hz, enough samples can be obtained. Then these samples are accumulated to get the mean value, and the data value in accordance with the data measured by 12 bit ADC can be obtained.

4. Experimental simulation

The oversampling method can reduce the in band noise and improve SNR. The simulation experiment is completed by MATLAB. The sinusoidal signal mixed with white noise is oversampling to calculate the mean value. The two methods are compared from the filtering effect picture and the change of signal-to-noise ratio. The simulation results are shown in Figure 6. In order to meet the actual test requirements, the MATLAB control system toolbox is used to simulate the lightning transient simulation waveform. It can be seen from Figure 6 that the oversampling averaging algorithm has obvious effect on improving the measurement accuracy of ADC. With the increase of sampling rate, the higher the oversampling rate, the weaker the noise, and the more obvious the real physical signal display, that is, the measurement accuracy is also improved.

In order to improve the resolution performance of impulse measurement system by comparing oversampling and averaging, SNR is introduced as the criterion in the program
\[ \text{SNR} = 10 \log \left( \frac{P_C}{P_x} \right) = 20 \log \left( \frac{A_C}{A_x} \right) \]  \hspace{1cm} (8)

Among them: \( P_C \) is the signal power after processing; \( P_x \) is the original signal power; \( A_C \) is the amplitude of the processed signal; \( A_x \) is the amplitude of the original signal.

(a). raw data after oversampling

(b). 4-fold mean filter processing
Figure 6. Results of over sampling mean value processing under different sampling rates

Under the above different oversampling rates, the change of SNR is shown in Table 1. From the data in Table 1 and equation (7), combined with Figure 6, it can be concluded that with the increase of the over sampling rate, the measurement resolution of the system is improved, and the measurement accuracy is also effectively improved.
| Oversampling rate (N) | 4     | 8     | 16    |
|----------------------|-------|-------|-------|
| Signal to noise ratio (SNR/dB) | 6.2695 | 9.3352 | 12.5902 |

5. Test verification
Based on the above, TDG (test data generator) attached to IEC 61083-2 is used to generate the corresponding test waveform according to the sampling rate of the hardware device used in the lightning transient impulse test. Figure 7 shows the signal data of L1-M12 normally sampled under 8-bit ADC, and the time domain waveform obtained after data processing with MATLAB; Figure 8 shows the signal data after 100 times oversampling.

From the experimental results, it can be seen that the data processed by oversampling mean is smoother than the untreated data, so under the condition of meeting the ADC conversion rate, the measurement accuracy of the measurement system can be effectively improved by oversampling the data signal and downsampling by means filtering.

6. Conclusion
Aiming at the problem that low resolution ADC can not achieve high precision measurement in secondary system of impulse measurement, this paper proposes an oversampling mean filtering algorithm:

1. The oversampling mean filtering algorithm can improve the measurement resolution of the secondary system and the measurement accuracy;
2. When the ADC noise is close to white noise, the effect of oversampling mean algorithm is better;
3. When increasing the sampling rate, it will occupy the storage space and increase the CPU running time, so the resolution and throughput of the system hardware need to be considered when using the oversampling mean algorithm.
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