Research on the Influence of Sampling Frequency on Energy Measurement Precision of Electronic Instrument Transformer

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ABSTRACT

Digital metering system, the electronic energy meter analog-to-digital conversion sampling function moved to the electronic instrument transformer, and electronic instrument transformer sampling frequency compared with the electronic energy meter is low, the sampling frequency will be insufficient in the analog-to-digital conversion process Introduce quantization error. In this paper, the measurement error model of electronic instrument transformer based on analog-to-digital conversion sampling principle is established, and the influence of sampling frequency on energy measurement error is quantitatively analyzed. The analysis shows that the accuracy of electronic instrument transformer measurement is related to oversampling rate.

Keywords: electronic instrument transformer, sampling frequency, energy measurement, error model, over sampling rate

INTRODUCTION

Digital metering technology is one of the main features of intelligent substation. As shown in Figure 1, the digital metering system is mainly composed of electronic instrument transformers, merging units and digital electric energy meters [1-2]. Due to the problems of traceability and reliability, the digital measurement system has not yet been officially applied to the trade settlement threshold, and the accuracy of measurement has been the focus of research.

In the digital measurement system, the analog-digital conversion sampling function of the electronic watt-hour meter has been moved to the electronic instrument transformer. The electronic instrument transformer converts the voltage and current signals into digital signals through the analog-to-digital sampling module and transmits the digital electric energy through the merging unit table, thus completing the entire measurement process. Because the digital watt-hour meter only accepts the digital signal and carries on the operation, the

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theoretical error is 0 [3], the actual error is also basically 0, so the main error of the digital measuring system concentrates on the electronic mutual inductor. According to the national standard requirements[1-2], the electronic instrument transformer sampling rate can choose 4kHz, 2.4kHz, 1kHz, industry standards[4] also provides for protection, fault recording measurement and measurement of electronic mutual inductance. The sampling frequency of the data output interface should be 4kHz. At present, most manufacturers of electronic instrument transformers installed at various digital stations are configured with 4kHz sampling frequency [5]. At present, the sampling frequency of analog to digital conversion of electronic watt-hour meter is generally higher than that of electronic instrument transformers. For example, 0.1-level single-phase energy metering chip ADE7755 has an over-sampling frequency of 900 kHz [6]. The higher sampling frequency ensures that the resulting digital signal is closer to the original signal, while the lack of sampling frequency introduces quantization error [7].

Compared with relay protection and monitoring and recording, electric energy measurement requires higher accuracy of electronic instrument transformers [8]. Therefore, whether the electronic instrument transformer based on 4kHz sampling frequency meets the accuracy requirement of electric energy metering is a worthwhile research problem.

**ENERGY MEASUREMENT ALGORITHM**

Electric energy refers to the electric energy absorbed or emitted by the circuit elements or equipment within a certain period of time, which is equal to the integral of the instantaneous power in time [9]. Integral method is currently the most widely used energy measurement algorithm, the mainstream of energy metering chips such as AD's ADE7755, ADE7752, Zhuhai Moment Company ATT7021, ATT7022 are calculated by the integral method [10]. In analogue measurement, the average active power standard value in the period is [11]:

![Figure 1. Digital Metering System.](image-url)
\begin{equation}
\begin{aligned}
P_0 = \frac{1}{T_0} \int_{0}^{T_0} u(t) i(t) dt = \frac{1}{T_0} \int_{0}^{T_0} \sqrt{2} U \sin(\omega t) \sqrt{2} I \sin(\alpha t - \phi) dt \\
= \frac{UI}{T_0} \int [\cos \phi - \cos(2 \alpha t - \phi)] dt = UI \cos \phi
\end{aligned}
\end{equation}

In the digital measurement system, the electronic instrument transformer sampling frequency is \( f_c \), the power system voltage is \( u \), the current frequency is \( f_0 \), the angular frequency is \( \omega_0 \), the sampling interval is \( \Delta t \), the sampling start angle is \( \theta \), the power factor angle is \( \phi \), such as Figure 2 shows the voltage and current sampling expression is:

![Figure 2. Voltage and Current Waveform Sampling.](image)

\begin{equation}
u(n\Delta t) = \sqrt{2} U \sin(\omega_0 n \Delta t + \theta)
\end{equation}

\begin{equation}
i(n\Delta t) = \sqrt{2} I \sin(\omega_0 n \Delta t + \theta - \phi)
\end{equation}

Where, \( U \) and \( I \) for the voltage and current RMS, \( n \) is a positive integer, \( u(n\Delta t) \) and \( i(n\Delta t) \) were \( n\Delta t \) moment of voltage and current. Period \( T \) sampling points for the \( N \), then the average active power:

\begin{equation}
P = \frac{1}{T} \sum_{n=1}^{N} u(n\Delta t)i(n\Delta t) \Delta t
\end{equation}

Substituting (2) and (3) into (4) gives:

\begin{equation}
P = \frac{2UI}{T} \sum_{n=1}^{N} \sin(\omega_0 n \Delta t + \theta) \sin(\omega_0 n \Delta t + \theta - \phi) \Delta t
\end{equation}

The formula (5) trigonometric function of the product and the difference can be obtained:

\begin{equation}
P = \frac{UI}{T} \cos \phi \sum_{n=1}^{N} \Delta t - \frac{UI}{T} \sum_{n=1}^{N} \cos(2\omega_0 n \Delta t + 2\theta - \phi) \Delta t
\end{equation}

Since \( T = N\Delta t, \Delta t = 1/f_c, \omega_0 = 2\pi f_0 \), into (6):

\begin{equation}
P = UI \cos \phi - \frac{UI f_0}{f_c} \sum_{n=1}^{N} \cos(n \frac{4\pi f_0}{f_c} + 2\theta - \phi)
\end{equation}

Compared with Eqs. (1) and (7), the power value integrated by A/D conversion sampling is not equal to the standard power value, that is, the error of analog-digital conversion sampling algorithm of digital measurement is introduced.
Multiplying \( \sin(2\pi f_0/f_c) \) by both sides of Eq. (7) gives:

\[
P \sin \left( \frac{2\pi f_0}{f_c} \right) = UI \cos \varphi \sin \left( \frac{2\pi f_0}{f_c} \right) - UI f_0 \sum_{n=1}^{\infty} \cos \left( \frac{4\pi f_0}{f_c} + 2\theta - \varphi \right) \sin \left( \frac{2\pi f_0}{f_c} \right)
\]

(8)

On the type (8) trigonometric function of the product of the expansion and spread, eliminating the positive and negative were:

\[
P = UI \cos \varphi - UI \frac{f_c}{f_0} \sin \left( \frac{2\pi f_0}{f_c} \right)
\]

(9)

The sampling energy measurement error \( \eta \) is:

\[
\eta = \frac{W - W_0}{W_0} = \frac{PT - P_0T}{P_0T} = \frac{P - P_0}{P_0} - \frac{\sin \left( \frac{2\pi f_0}{f_c} + 2\theta - \varphi \right)}{\frac{f_c}{f_0} \sin \left( \frac{2\pi f_0}{f_c} \right) \cos \varphi}
\]

(10)

From equation (10) shows that the analog-digital conversion sampling algorithm introduced measurement error and the sampling start angle, power factor, system frequency, sampling frequency and so on.

ALGORITHM ERROR ANALYSIS

Sampling initial angle

In (10), the numerator is a trigonometric function with a range of [-1,1]. Theoretically, as long as the sampling phase angle \( \theta \) is properly controlled, \( \sin(2\pi f_0/f_c + 2\theta + \varphi) = 0 \), that is, the error is 0, but the initial sampling angle is random and cannot be accurately controlled. Caused by the maximum error to consider[12], that \( \sin(2\pi f_0/f_c + 2\theta + \varphi) = 1 \), too:

\[
|\eta| = \frac{1}{\frac{f_c}{f_0} \sin \left( \frac{2\pi f_0}{f_c} \right) \cos \varphi}
\]

(11)

Power factor angle

From (11) shows that the power factor is inversely proportional to the error, the larger the power factor, the smaller the error caused by energy metering, when the power factor is close to 1, the error mutation to infinity. However, in practical situations, the power factor cannot be very small. At the gateway measurement, the power factor of the load is generally close to 1, so considering the power factor equal to 1[13], we can get:

\[
|\eta| = \frac{1}{\frac{f_c}{f_0} \sin \left( \frac{2\pi f_0}{f_c} \right)}
\]

(12)

System frequency

In formula (12), take the sampling frequency is 4kHz, have:
\[
|\eta| = \frac{1}{\frac{2\pi f_0}{4000} \sin\left(\frac{2\pi f_0}{4000}\right)}
\]  

(13)

Effect of System Frequency on Measurement Error Figure 3:

As can be seen from Figure 3, as the system frequency increases, the measurement error increases.

**Sampling frequency**

Formula (12), take the system frequency of 50Hz, have:

\[
|\eta| = \frac{1}{\frac{f_c}{50} \sin\left(\frac{100\pi}{f_c}\right)}
\]  

(14)

Sampling frequency and measurement error as a function of the relationship shown in Figure 4:

As can be seen from Figure 4, as the sampling frequency increases, the measurement error decreases, but the decreasing trend becomes slower.
Oversampling rate

According to Nyquist's sampling law, the sampling frequency must be greater than twice the system frequency (i.e., the oversampling rate is 2), and the sampled digital signal can completely preserve the information in the original signal [14].

To make (12), the error and the sampling frequency, the system frequency of the three-dimensional surface map, shown in Figure 5:

![Figure 5. Error, Sampling Frequency, System Frequency Three-Dimensional Surface Map.](image)

In the Figure 5, X-axis sampling frequency, Y-axis system frequency, Z-axis measurement error. The error surface is divided into two parts, the left half is the error anomaly area, the oversampling rate is less than 2, and the error anomaly is fluctuant; the right half is the error normal area, the oversampling rate is greater than 2, and the error is stable and undulating.

By (12) available:

\[ |\eta| = \frac{1}{N \sin\left(\frac{2\pi}{N}\right)} \]

where

\[ N \]

is the over-sampling rate, and \( N = f_c/f_0 \), when the oversampling rate tends to infinity:

\[ \lim_{N \to \infty} |\eta| = \lim_{N \to \infty} \frac{1}{N \sin\left(\frac{2\pi}{N}\right)} = \frac{1}{2\pi} = 0.1592 \]

From (16), we can see that increasing the oversampling rate can reduce the quantitative error of the energy measurement introduced in the A/D conversion process, but it cannot be completely eliminated. Once the oversampling rate is increased to a certain extent, the reduction of quantization error is no longer effective. Table 1 shows the correspondence between oversampling rate and the degree of approach to the limit.

<table>
<thead>
<tr>
<th>Over-sampling rate</th>
<th>8</th>
<th>26</th>
<th>80</th>
<th>210</th>
</tr>
</thead>
<tbody>
<tr>
<td>Approaching the limit (%)</td>
<td>90</td>
<td>99</td>
<td>99.9</td>
<td>99.99</td>
</tr>
</tbody>
</table>

Table 1. Over-Sampling Rate and Proximity to the Limit Value of the Corresponding Relationship.
Based on the 4kHz electronic instrument transformer, when only the fundamental wave is considered, the sampling frequency has reached 80 times of the system frequency of 50Hz, that is, the over-sampling rate is 80, and the introduced quantization error value is close to 99.9% of the limit value. The ADE7755 Metering chip over-sampling frequency of 900kHz, oversampling rate of 18000, measurement quantization error has been seen as a limit, compared with the electronic instrument transformer, due to its oversampling rate, harmonic measurement ability is strong [15-16].

CONCLUSION

In this paper, an energy metering error model of electronic instrument transformer based on analog to digital conversion sampling principle is established. The impact of sampling frequency on the quantization error introduced in the analog to digital conversion process is analyzed. The analysis shows that there is a quantization error introduced in the analog to digital conversion process. This value cannot be reduced by increasing the sampling frequency. Compared with electronic watt-hour meter, the electronic instrument transformer based on the sampling frequency of 4kHz has the same quantization error on the measurement of fundamental energy but relatively poor measurement capability on harmonic energy.

REFERENCES

1. GB/T20840.7-2007 Instrument transformers-Part 7: Electronic voltage transformers[S].
2. GB/T20840.8-2007 Instrument transformers-Part 8: Electronic current transformers[S].
5. ADE7755 Workbook[Z].

