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Design of On-Site Calibration Device for Electricity Meter Based on Pulse Detection

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Abstract: At present, the error calibration of electricity meters in operation generally adopts an off-site method; that is, the electricity meter is taken out of operation and then calibrated in the laboratory. Off-site calibration, while beneficial, may not fully capture the operational error of the electricity meter due to potential differences in environmental conditions. An on-site calibration device for electricity meters based on pulse detection is designed, which obtains the error of the electricity meter under calibration by comparing the energy pulses of the standard electricity meter with those of the electricity meter under calibration. High-precision voltage and current sampling channels are designed, with a voltage measurement error of less than 0.02% and a current measurement error of less than 0.03%. In response to the non-synchronous sampling problem caused by frequency fluctuations in the on-site verification environment, a fast optimal frequency estimation algorithm is applied to accurately calculate the signal frequency within two cycles. The sampling time interval is adjusted to achieve lock-frequency synchronous sampling, and ensure the accurate calculation of electrical parameters. In order to reduce the complexity of the device circuit structure and equipment cost, a standard electric energy pulses generation method based on digital integration-to-frequency is proposed, which uses software to generate electric energy pulses, with a maximum output frequency of up to 10 kHz. Tests conducted in the laboratory on the developed on-site calibration device for electricity meters show that its accuracy is better than the 0.05 accuracy class, meeting the application requirements for on-site verification of electricity energy meters.

Keywords: electricity energy meter; on-site calibration; optimal frequency estimation; lock-frequency synchronous sampling; digital to frequency; electric energy pulse

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1. Introduction

With the development of smart grids, the application of smart electricity meters is becoming more and more widespread, and has become one of the important forces driving the intelligent development of power systems [1]. The coverage rate of smart electric energy meters in developed countries around the world is already very high, and the coverage rate of smart meters in the State Grid of China has reached 99.03% [2]. The widespread application of smart electricity meters has brought higher efficiency and better services, as well as new challenges. Since smart electricity meters are a type of trade-settlement-measuring instrument, according to relevant regulations in China, periodic calibration is required [3]. With the large number and wide coverage of smart electricity meters, it is time-consuming and laborious to remove them back to the laboratory for calibration, making on-site calibration inevitable.

Recently, there have been many studies published on on-site calibration technology for electricity meters. A multifunctional on-site calibration system with 0.2 accuracy for electricity meters has been designed [4]. Zeng et al. proposed an electricity meter calibration method based on a pulse virtual power source, which cannot be applied on-site [5]. A remote electricity meter calibration system has been developed, which calculates standard electric energy based on sampled waveform data and compares it with the electric energy pulse of the meter being tested to achieve a metering error, but it is greatly affected by the synchronous clock [6]. A rapid on-site electricity meter calibration method has been proposed, which uses a DSP to output high-frequency standard electric energy pulses, of which the frequency is up to 2 kHz [7]. With the promotion and application of digital input electricity meters, there are also many studies on calibration methods for digital electric energy meters [8–11], among which the electric energy calculation method and pulse-based calibration method provide a reference for research. In recent years, many researchers have studied error estimation methods for electricity meters based on data-driven approaches. E. E. Rizqi and C. Safitri used machine learning to model calibration test data, realizing intelligent error testing for electricity meter in smart manufacturing, improving test efficiency and reducing costs [11]. B. Danilevich and V. V. Tretyak studied the automation testing and calibration procedures of electricity meter and proposed an optimized algorithm for checking meter functions [12]. L. Chen et al. studied the error estimation method for smart electricity meters based on remote data analysis and proposed a truncated singular value decomposition regularization L-curve optimization (TSVD + L) method, obtaining better error estimation accuracy [13]. Data-driven error assessment methods can be used as a supplement to calibration, but cannot completely replace it.

In this paper, an online calibration device for electricity meters based on pulse detection has been designed. By designing high-precision voltage and current signal measurement units, improving electrical parameter calculation algorithms, and designing good pulse generation software, the accuracy of the designed calibration device of electricity meter is satisfactory. The remainder of this paper is organized as follows: Section 2 describes the principle of electricity meter calibration based on pulse detection, Section 3 details the design of the signal measurement units, Section 4 introduces the synchronous sampling method, Section 5 discusses the generation of electrical energy pulses by software, Section 6 presents laboratory calibration and on-site application results, and the last section is the conclusion.

2. Principle of Electricity Meter Calibration Based on Pulse Detection

The principle of on-site electricity meter calibration based on pulse detection is shown in Figure 1. The standard electricity meter and the electricity meter under calibration measure voltage and current at the same time, the standard electricity meter outputs high-frequency electrical energy pulses, and the electricity meter under calibration outputs relatively low-frequency electrical energy pulses. The error of the electricity meter under calibration can be obtained by comparing the number of electrical energy pulses of the two meters with the error calculator.

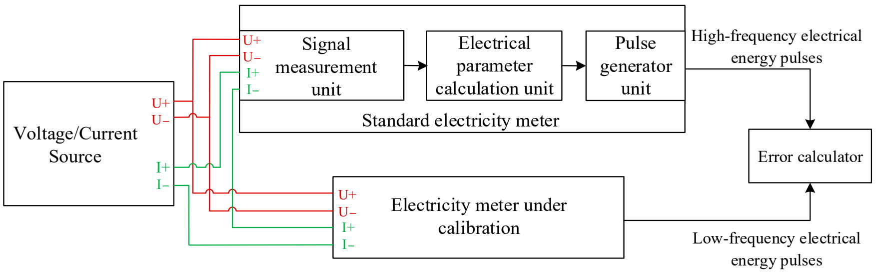

Figure 1. Schematic diagram of electricity meter calibration based on pulse detection.

The error calculator receives pulses output from the standard meter and the calibrated meter. Assuming that during the same period of time, the output pulse number of the calibrated meter is m_1 and that of the standard meter is m_0, the metering error of the calibrated meter is calculated as follows:

$$\varepsilon = \frac{m_1 K_0 - m_1 K_0}{m_0 K_1} \tag{1}$$

In Formula (1), K_0 and K_1 are the pulse constants of the standard meter and the calibrated meter, respectively. For example, if the pulse constant of the electricity meter is 2000, then in the absence of measurement error, 2000 pulses will be output when measuring 1 kWh of electrical energy. Usually, errors introduced by error calculator are very small.

As can be seen from Figure 1, the main factors affecting the accuracy of calibration include the signal measurement of the standard electricity meter, electrical parameter calculation, and pulse generation. The design of the above three parts is introduced below.

3. Design of Signal Measurement Units

3.1. Voltage Measurement Circuit

Voltage measurement circuit employs resistance voltage divider, which features good linearity and minimal temperature drift. After the voltage is divided by high-precision and high-stability resistors, it is followed by a differential amplifier, as shown in Figure 2.

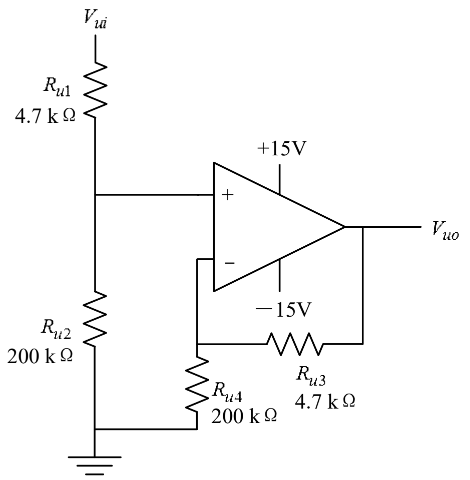

Figure 2. Voltage signal measurement circuit.

In Figure 2, the resistance divider uses ultra precision metal film resistors with an accuracy of 100 ppm and a temperature drift of less than 2 ppm. The output voltage is calculate as follows:

$$V_{uo} = \frac{R_{u2}}{R_{u1} + R_{u2}} \times \frac{R_{u3} + R_{u4}}{R_{u3}} \times V_{ui} \tag{2}$$

In Formula (1), R_{u1} and R_{u2} are the resistance values of the voltage divider resistors, R_{u3} and R_{u4} are the resistance values of the feedback resistors, and V_{ui} is the input voltage. The output voltage is converted into a digital signal using a 24-bit analog-to-digital converter.

3.2. Current Measurement Circuit

The current measurement circuit employs a current shunt, which features good linearity and minimal temperature drift. After the current is shunted by a high-precision and high-stability current shunt, it is followed by a differential amplifier, as shown in Figure 3.

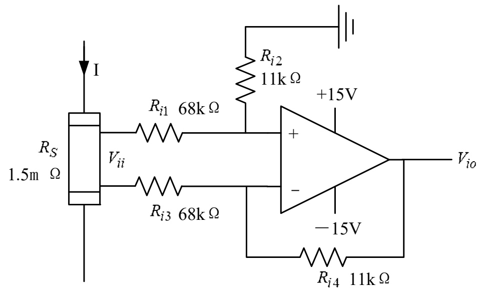

Figure 3. Current signal measurement circuit.

In Figure 3, the stability of the current shunt can reach 20 ppm and a temperature drift of less than 0.5 ppm. If $R_{i1} = R_{i3}$, and $R_{i2} = R_{i4}$, then the output voltage of the circuit is as follows:

$$V_{io} = V_{ii} \times \frac{R_{i1}}{R_{i2}} \tag{3}$$

In Formula (2), V_{ii} is the voltage output of the shunt and also the input voltage of the differential amplifier. The output voltage of the circuit V_{io} is converted into a digital signal using a 24-bit analog-to-digital converter.

3.3. Accuracy Testing of Voltage and Current Measurement

In order to verify the measurement accuracy of voltage and current signals, comparative tests were conducted using an Agilent 8.5 digit digital multimeter 3458A. The standard signal converter was selected as 220 V/5 V and 50 A/5 V, with a converting error of less than 0.005%. The voltage measurement error was tested at 80% Ur, 100% Ur, and 120% Ur, and the current measurement error was tested at 5% Ir, 20% Ir, 100% Ir, and 120% Ir. The rated voltage is 220 V and rated current is 50 A. The average values of the 10 test results are shown in the following two tables.

From Tables 1 and 2, it can be seen that at the above test points, the voltage measurement error does not exceed 0.02%, and the current measurement error does not exceed 0.03%.

Table 1. Voltage measurement error test results.

Test Point (%Ur)	**Error (%)**
80	0.02
100	0.01
120	0.01
Uncertainty: 1.3×10^{-4} (k = 2)	

Table 2. Current measurement error test results.

Test Point (%Ir)	**Error (%)**
5	0.03
20	0.02
100	0.01
120	0.01
Uncertainty: 1.7×10^{-4} (k = 2)	

4. Synchronous Sampling Method Based on Frequency Tracking

4.1. Error Analysis of Asynchronous Sampling

The electrical parameters of a standard electricity meter are calculated with the discrete voltage and current sampled values. When the sampling frequency is an integer multiple of the frequency of the sampled signal, regardless of the calculation method used, the calculation result is unbiased. However, when the frequency of the power system deviates, the sampling frequency is not equal to an integer multiple of the frequency of the sampled signal, causing calculation errors, which is called the asynchronous sampling problem.

Taking the calculation of the effective value of a periodic signal as an example, the calculation formula is as follows:

$$\overline{x(\omega t)} = \sqrt{\frac{1}{2\pi}\int_{\alpha_0}^{\alpha_0+2\pi}[x(\omega t)]^2 d\omega t} \tag{4}$$

In Formula (3), $x(\omega t)$ is the signal expression, $\overline{x(\omega t)}$ is the effective value of the signal, 2π is the signal period, and α_0 is the initial phase of the signal. It can be inferred that when the frequency fluctuation causes a periodic change in the signal of Δ, the calculation error is as follows:

$$\varepsilon = \sqrt{1 - \frac{2\cos(2\alpha_0 + \Delta) sin\Delta}{2\pi + \Delta}} - 1 \tag{5}$$

From Formula (4), it can be seen that the calculation error is a function of the initial phase α_0 and the amount of frequency variation Δ. The relationship between Δ with the frequency variation is

$$\Delta = 2\pi \times \frac{\Delta f}{f_0} \tag{6}$$

In Formula (5), Δf represents the frequency variation and f_0 represents the rated frequency of the signal. If the signal frequency can be measured in advance, the discrete sampling time interval can be adjusted according to the actual frequency to avoid asynchronous sampling problem.

4.2. Optimal Frequency Estimation Algorithm

Based on the above analysis, it can be concluded that the key of synchronous sampling method based on frequency tracking is to quickly and accurately calculate the signal frequency. By adjusting the signal sampling time interval to keep the signal integration period of 2π, the calculation error caused by asynchronous sampling can be reduced or even eliminated. Therefore, an optimal frequency estimation algorithm is employed in this article.

Assuming the mathematical formula for a sine signal is as follows:

$$x(t) = A_m \sin(2\pi(f_0 + \Delta f)t + \alpha_0) \tag{7}$$

In Formula (6), A_m is the signal amplitude, α_0 is the initial phase, Δf is the frequency variation, and f_0 is the rated frequency of the signal. The actual frequency is as follows:

$$f_{actual} = f_0 + \Delta f \tag{8}$$

Without knowing f_{actual}, using $T_0 = \frac{1}{f_0}$ as the integration period, the Fourier transform coefficients of the first period can be obtained as follows:

$$\begin{cases} a_1 = \frac{2U_m f_0}{\pi T_0 \Delta f(2f_0+\Delta f)} \cos(\pi \Delta f T_0 + \alpha_0)\sin(\pi \Delta f T_0) \\ b_1 = \frac{2U_m (f_0+\Delta f)}{\pi T_0 \Delta f(2f_0+\Delta f)} \sin(\pi \Delta f T_0 + \alpha_0)\sin(\pi \Delta f T_0) \end{cases} \tag{9}$$

Similarly, the Fourier transform coefficients for the second cycle can be obtained as follows:

$$\begin{cases} a_2 = \frac{2U_m f_0}{\pi T_0 \Delta f(2f_0+\Delta f)} \cos(3\pi \Delta f T_0 + \alpha_0)\sin(\pi \Delta f T_0) \\ b_2 = \frac{2U_m (f_0+\Delta f)}{\pi T_0 \Delta f(2f_0+\Delta f)} \sin(3\pi \Delta f T_0 + \alpha_0)\sin(\pi \Delta f T_0) \end{cases} \tag{10}$$

Let $A = \frac{a_1}{a_2}$, $B = \frac{b_1}{b_2}$, it can be deduced that

$$\cos(2\pi \Delta f T_0) = \frac{AB+1}{A+B} \tag{11}$$

Finally, Δf can be estimated as follows:

$$|\Delta f| = \frac{1}{2\pi T_0} \arccos\left(\frac{a_1 b_1 + a_2 b_2}{a_1 b_2 + a_2 b_1}\right) \tag{12}$$

The positive and negative signs of Δf can be determined based on the positive and negative signs combinations of a_1, a_2, b_1, b_2.

4.3. Adjustment Amount of Sampling Time Interval

Assuming the sampling time interval at the rated frequency is T_s, when the frequency variation is Δf, the sampling time interval should be adjusted as follows:

$$T_s{}' = \frac{f_0}{(f_0 + \Delta f) f_s} T_s \tag{13}$$

Because the power grid frequency is nearly stable within two power frequency cycles, it is possible to reduce asynchronous sampling errors to near zero by adjusting the sampling time interval.

5. Generating Electrical Energy Pulses Using Software Methods

The standard electricity meter needs to generate electric energy pulses based on the amount of measured electrical energy, which is a key point in the design of the calibration device. A digital quantity/frequency conversion (D/F conversion) method is proposed that uses software methods to generate standard electrical energy pulses with high accuracy and good uniformity. The specific method is explained as follows.

Assuming that the instantaneous power measured by the standard electricity meter at time i is P_i and the measurement time interval is ΔT, when ΔT is small enough, the amount of electrical energy during the time interval T is as follows:

$$W = \sum_{i=1}^{N} P_i \Delta T, N = \frac{T}{\Delta T} \tag{14}$$

When W reaches the set value, an electrical energy pulse is output. Assuming that the highest frequency of the electrical energy pulse that the standard electricity meter can output is f_h and the pulse constant is C_p—that is, the amount of electrical energy represented by one pulse is C_p kWh—then the relationship between f_h and C_p is

$$P_{\max} = 3600\, f_h C_p \tag{15}$$

In Formula (12), $P_{\max}$ is the maximum power that the standard electricity meter can measure, and the unit is kW.

A software accumulation unit is designed for accumulating P_i, and the storage unit that stores the accumulated value is denoted as $\sum P$. The software program reads the accumulated value of $\sum P$ every interval $T_c = \frac{1}{f_h}$. If $\sum P \geq C_p$, an electrical energy pulse is output and the $\sum P$ is updated to $\sum P - C_p$ as the new accumulation starting value. The above process can be represented as follows:

In Figure 4, the process of generating two electrical energy pulses is illustrated. Assuming $\sum P$ accumulates from 0 and after $3T_c$, the accumulated value exceeds C_p, Pulse1 is output at time $3T_c$, and $\sum P$ changes from $\sum P_{3T_c}$ to $\sum P_{3T_c} - C_p$. Similarly, after $2T_c$, the accumulated value exceeds C_p again, and at time $5T_c$, Pulse2 is output. The higher the power measured by a standard electricity meter, the higher the frequency of the output pulse, up to a maximum of f_h.

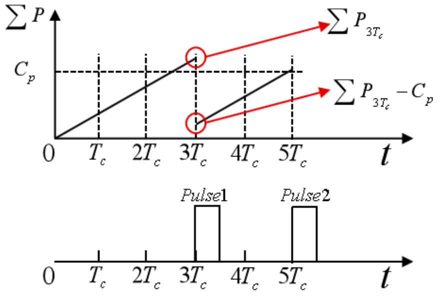

Figure 4. Schematic diagram of a standard electrical energy pulse generation process.

In the electricity meter calibration device designed in this paper, the maximum output frequency f_h and pulse constant C_p of standard electrical energy can be flexibly set and combined according to the actual calibrated electricity meter to reduce the errors introduced by the calibration device. According to the principle of pulse generation, the smaller the value of T_c, the smaller the error caused by the uniformity of electrical energy pulses. The calibration device designed in this paper has a minimum T_c of 100 us and a maximum output frequency of 10 kHz. The calibration error introduced by electrical energy pulses does not exceed 0.01%.

6. Laboratory Calibration and On-Site Application

The on-site calibration device for electricity meters adopts a portable design scheme, with a Cortex-TM-A7 as the processor core, a 32-bit floating-point DSP as the electrical parameter calculation core, and an FPGA as the measurement sampling control core. It achieves high-speed real-time independent sampling and the calculation of three voltage and three current channels, with a user-friendly human–computer interaction interface. The accuracy calibration of the designed on-site calibration device for electricity meters was performed in the laboratory, as shown in Figure 5.

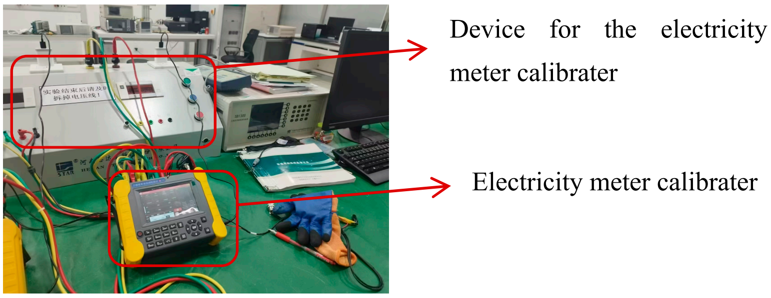

Figure 5. Accuracy calibration of on-site calibration device for electricity meter.

The calibration current points are selected according to the JJG 1085 "Verification Regulation of Reference Meters for Electrical Energy" [14]. The connection mode is a three-phase 4four-wire system, with a rated voltage of 220 V, a reference current of 5 A, and a reference power factor of 1.0. The calibration results of some current points are listed in Table 3.

Table 3. Calibration results of some current points.

Current Point (%In)	Error (%)	
	$\cos\phi$=1.0	$\cos\phi$=0.5(L)
100	0.010	0.015
50	0.015	0.015
20	-	0.010
10	0.025	-

The laboratory calibration results show that the electrical energy measurement error of the designed electricity meter calibration device is less than 0.05% with an uncertainty of 0.016% (k = 2), achieving the accuracy class of 0.05. According to the power supply quality standard of China, the harmonic distortion rate of the power grid below 400 V shall not exceed 5%. Setting the harmonic distortion rate to 10%, the measurement error of the device was tested under this condition, and the results showed that the measurement error of the device did not change significantly. This indicates that the device meets the requirements for applications under harmonic conditions in practical calibration work.

As shown in Figure 6, the developed on-site calibration device was applied to an on-site calibration for a three-phase electricity meter of a certain power user. The on-site calibration results were consistent with the laboratory verification results.

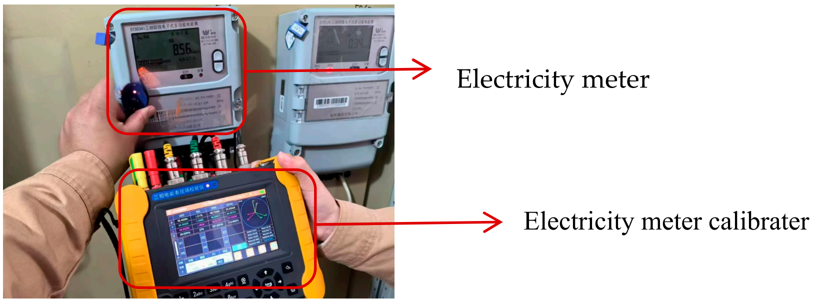

Figure 6. Scene of on-site calibration of electricity meter.

7. Conclusions

A pulse detection-based on-site calibration device for electricity meters has been designed. A high-precision resistor voltage divider sampling circuit and a shunt current sampling circuit were designed, with voltage and current measurement errors of less than 0.02% and 0.03%, respectively, at the specified measurement points. By using the optimal frequency estimation algorithm and frequency tracking synchronous sampling technique, the calculation error caused by the asynchronous sampling is reduced to nearly zero. The electrical energy pulse generation method using digital-to-frequency conversion can achieve a maximum output frequency of 10 kHz, and the calibration error introduced by the power pulse does not exceed 0.01%. The laboratory calibration tests of the developed on-site calibration device were conducted, and the results showed that the electrical energy measurement error was less than 0.05% (k = 2), meeting the application requirements for on-site calibration of electricity meter with the accuracy class of 0.2 and below.

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Data Availability Statement: The data presented in this study are available on request from the corresponding author due to the large amount of test and calibration data.

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