Analysis and optimization of calibration method of digital energy meter

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Abstract. At present, the short of calibration of digital energy meter include deficiency of standard, inefficiency, and the lack of proper methods. In this paper, based on four commonly used methods (Watt-second method, standard digital meter method, standard digital power source method, standard analog meter method), the factors that cause the error of these calibration methods are introduced, and relevant measures of improvement and optimization are put forward.

1. Introduction
With the rapid development of intelligent substation, digital energy meter has gradually replaced the traditional electronic energy meter, becoming an important part of the energy measurement and trade settlement. At present, the commonly used methods of error calibration are standard digital meter method, standard digital source method, standard analog meter method[1-4] and watt-second method, which are still imperfect. Calibration experiments using analog sources can be used to trace the digital meter, but introduce new system errors such as A/D conversion, signal conditioning[5] and so on. Compared with the analog source method, the digital source method has the advantages of shorter calibration time and less error introduction[6]. This paper introduces the four commonly used calibration methods, and provides the technical reference for the basic error test scheme of digital energy meter to the standardization, systematization and specialization.

2. Error Analysis of Calibration Methods for Digital Energy Meter

2.1. Watt-Second Method
The watt-second method calculates the power of the calibrated meter by detecting the fixed number of electric pulses \( m \) and the fixed measurement time interval \( t \), and compare it with the power \( P_0 \) set by the standard digital power source to get the error. Its principle is as Figure 1. According to the principle of detection, the error expression is as formula (1).
Figure 1. Process of Watt-second calibration method

\[ y = \frac{P_L - P_0}{P_0} = \frac{K_{Cf} - P_0}{P_0} \]  

(1)

\( C_0 \) is the standard meter pulse constant and \( P_L \) is the power value of the calibration meter when it is converted to a digital source. \( K' \) is the coefficient. When the calibration meter works in the primary power mode, \( K' = 1 \); When the calibration meter works in the secondary power mode, \( K' = 10^{3/2} (K_I K_U) \), in which \( K_I \) and \( K_U \) are the virtual current ratio and the virtual voltage ratio of the digitized electric energy meter.

According the formula (1), we can see the source of error introduced from the watt-second method has three aspects: measurement time, the overflow error and power calculation in non-full period.

According to the formula (1), \( P_L = \frac{m}{K' C_0 t} \) is obtained, and it can be seen that the accuracy of the measurement time interval \( t \) will affect the measurement result of the watt-second method. Assuming that the actual measurement time is \( t + \Delta t \), the calibrated meter is accurate under ideal conditions, that is, \( \frac{m}{K' C_0 t} = P_0 \), we can get the relative error of this method is as follows:

\[ \varepsilon = \frac{m}{K' C_0 (t + \Delta t)} \frac{m}{P_0} = \frac{m}{K' C_0 P_0 (t + \Delta t)} \frac{m}{K' C_0 P_0 t} \]

\[ \approx \frac{\Delta t}{t} \]  

(2)

The measurement time error \( \Delta t \) is a fixed value related to the hardware circuit and the timing of the high frequency pulse. In general, the measurement time error \( \Delta t \) will not exceed 100us [7]. Therefore, when \( t > 1s \), the introduction error of the measurement time interval is less than 0.01%, so the introduction error brought by the uncertainty of the measurement time can be ignored.

Digital energy meter output power pulse by the way of the energy pool [8]. The energy meter calculates the corresponding power based on the data obtained \( E(k) = U(k)I(k)\Delta t \), and then put the \( Et(k) \) into the energy pool, when the energy pool is full, it emits a power pulse. But when the energy meter emits the last power pulse, the energy pool may "overflow". This part of the overflow of energy will eventually be remnants to the energy pool and cause system errors. And because \( \Delta t = 1 / f_c \), so the overflow error expression is:

\[ \triangle y = \frac{P(k)}{f_c P_0 t} = \frac{\frac{U_{m} I_{m} \sin(\alpha t + \alpha) \sin(\omega t + \alpha + \varphi)}{f_c U_{m} I_{m} \cos(\varphi) t}}{\frac{U_{m} I_{m} \cos(\varphi) t}{2}} \]

\[ = \frac{\cos(\varphi) - \cos(2\omega t + 2\alpha - \varphi)}{f_c \cos(\varphi) t} \]

(3)
Therefore, from the formula (2), we can see that when \( t = \varphi/2w - \alpha \), the maximum relative error is as follows:

\[
\Delta y_{\text{max}} = \frac{\cos(\varphi) + 1}{f_c \cos(\varphi)t}
\]

It can be seen that the relative system error of the digital energy meter is inversely proportional to the sampling rate \( f_c \), measurement time interval \( t \) and the offset angle \( \varphi \). The \( f_c \) in the digital meter is generally 4 kHz. If \( \cos\varphi = 0.5 \), the relative error calculated by the formula (3) is 0.01% when the measurement time \( t > 7.5 \) s, so the introduction error can be ignored.

When digital energy meter is calibrated, the time length corresponding to the calculated data frame is most likely not the entire period, resulting in a systematic error in the calculation of the average power [9]. The instantaneous power of the sine wave output from the standard power source is as formula (5).

\[
P(t) = 2UI \sin(\omega t) \sin(\omega t - \varphi)
\]

\[
= UI(\cos(\varphi) - \cos(2\omega t - \varphi))
\]

\[
\varepsilon' = \frac{\int_{t_0}^{t+60} P(t)dt - Pt}{Pt}
\]

\[
= \frac{-\int_{t_0}^{t+60} UI \cos(2\omega t + 2\alpha - \varphi)dt}{UIt \cos(\varphi)}
\]

Where \( \varphi, \alpha, t \) and \( t_0 \) respectively represent the power factor angle, the initial phase angle, the actual calculation time and the time when the timing is started. The formula (6) can be further reduced to the formula (7) as follows:

\[
\varepsilon' = \frac{\sin(2\omega t_0 - \varphi) - \sin(2\omega t + 2\alpha - \varphi)}{2\omega t \cos(\varphi)}
\]

Because of \( |\sin(2\omega t_0 - \varphi) - \sin(2\omega t + 2\alpha - \varphi)| \leq 2 \), the greatest error caused by single-phase non-periodic power calculation is:

\[
\varepsilon'_{\text{max}} = \frac{1}{2\pi f_N \cos(\varphi)}
\]

In equation (8), \( f_N \) is the fundamental frequency. Let \( \cos(\varphi) = 0.5 \) by equation (8) can be introduced, in \( U = U_N \), under the condition of \( I = 120\% I_N \), when \( t > 63.66s \), the error caused by non-full period power calculation is less than 0.01%, so it can be ignored, but when the load current is 5% of the rated current, calibration time is extended by 24 times. Therefore, the error in the calculation of the non-full period is the main error of the watt-second method in the single phase calibration.

When the three-phase symmetrical calibration is practiced, the error induced by the calculation of the non-periodic power is:
It can be seen from the formula (9) that the introduction error of non-periodic calculation is 0 when the three-phase symmetrical calibration is practiced. Therefore, it is only necessary to extend the calibration time to eliminate the overflow error and test the time interval error. Therefore, it is more efficient to use the watt-second method to perform three-phase symmetrical calibration.

From the above error analysis, it can be seen that the error effect caused by the non-periodic sampling is better than that of the digital energy meter and the error due to the inaccurate measurement time interval (which needs the longest measurement time to reduce the error effect). According to the error synthesis formula, the total relative error is:

$$\varepsilon_x = \sqrt{\varepsilon_0^2 + \varepsilon_r^2 + \Delta y^2}$$

(10)

According to the error theory and the definition of small error, when the system error introduced by the test method is less than the error limit of 1/10, then the error introduced by the test method can be ignored [10]. By the formula (2), (3), (8) we can see that all of the errors are related to the measurement time interval \(t\), so the most effective way to reduce the system error is to increase the measurement time interval. When the time \(t\) is large enough, the introduction error can be ignored.

2.2. Standard Digital Meter Method

The digital power source can send data packets containing voltage and current signals. It transmitted to the standard meter and the calibrated meter through the switch. The standard digital meter sends the high frequency pulse \(m\) according to the received data message. Pulse \(N\) converted to the standard digital meter for the \(m_0\) [11]. The principle is as Figure 2.

![Figure 2. Process of Standard digital meter method](image)

The error characteristics are as formula (11).

$$\gamma = \frac{m-m_0}{m} \times 100\%$$

(11)

According to the principle of digital power source and standard meter method, there is overflow error and pulse counting error, the maximum value of pulse count error is \(\pm 1\). So the introduction error of the method due to the pulse counting calibration is as follows:

$$\varepsilon_n = \frac{m \pm 1-m_0}{m \pm 1} - \frac{m-m_0}{m} \approx \frac{1}{m} = \frac{1}{c_0 p_0 t}$$

(12)
It can be seen from the formula (11) that the greater the pulse constant, the longer the measurement time interval, the smaller the error of this test method. For a given standard meter, the pulse time constant $C_0$ is constant, so only by increasing the measurement Time $t$ to increase the number of calculation of the number of pulses to reduce the relative reference error of the standard meter method. The relationship between precision of standard meter method and the number of calculated pulses is as follows:

Table 1. The relationship between the accuracy class and the pulse number

| Accuracy level | Pulse Number |
|----------------|--------------|
| 0.05           | 50000        |
| 0.1            | 20000        |
| 0.2            | 10000        |
| 0.3            | 6000         |

It can be seen from Table 1 that this method is very demanding on the number of pulses. When the number of calculated pulses reaches 10k, it can reach the precision level. The pulse frequency of the standard digital meter is generally not more than 1 kHz, so its detection demands long time, especially in the case of small load current, the test time will be extended.

2.3. Standard Digital Power Source Method

The standard digital power source sends out the high frequency pulse $m$ proportional to the electric energy, meanwhile the calibrated meter outputs the low frequency pulse $N$, and then converts $N$ into the pulse number $m_0$ of the standard source output using the conversion formula. Its principle is as Figure 3.

![Figure 3. Process of standard digital power source method](image)

The error characteristic is as formula (13).

$$\gamma = \frac{m-m_0}{m} \times 100\%$$

The main reference error of standard power source method is still overflow error and pulse counting error. Using it to test the accuracy of 0.2-level energy meter needs at least 10s, of which overflow error can be ignored, and using standard power source method, the test time can be adjusted for the pulse constant $C_0$ is adjustable, so that the credibility of calibration can be ensured in short calibration time. But when the power pulse constant $C_0$ set large, there will be a certain impact in the test system. When the overflow error $\Delta Y_{\text{max}}>3\varepsilon$, the overflow error becomes the main introduction error, and the synchronization pulse error is small and can be ignored. Similarly, when $\varepsilon_0>3\Delta Y_{\text{max}}$, the synchronization pulse error dominates, and the overflow error can be ignored. In other cases, the overflow error and the synchronization pulse error should be considered.
2.4. Standard Analog Meter Method

Analog signal source output standard sinusoidal signal, after A/D conversion, the data frame sent to the calibrated energy meter, and then it compares the power pulse output from calibrated meter and the power pulse converted by the is standard sinusoidal signal, to analyze the error characteristics of the calibrated meter.

The standard analog meter has a mature technical system and a clear means of traceability. It is a commonly used method to calibrate the digital energy meter at present. But compared with the standard digital source method, it introduces error \( \varepsilon_s \) of the signal conditioning and A/D conversion equipment, and calibration method of pulse output will cause overflow error \( \Delta y \), and the error \( \varepsilon_n \) caused by pulse counting. The synthetic error is:

\[
\varepsilon'_s = \sqrt{\Delta y^2 + \varepsilon_n^2 + \varepsilon_s^2}
\]  

(14)

As the A/D conversion circuit and other error modules can be controlled by technical means to reduce errors, and the using of analog source method can complete the traceability of digital energy meter, so this method currently is still more commonly used.

3. Optimization of Calibration Methods for Digital Energy Meter

For the watt-seconds method, its source of error is measurement time interval error, overflow error and non-full period sampling error. To improve the efficiency, we can increase the accuracy of the measurement interval with high-frequency pulse for the time counting, and the fixed pulse counting method is changed to the fixed time range to detecting the pulse number and pulse time interval, so that the working condition interference can be avoided. It applies to three-phase symmetric conditions.

For the standard digital meter method, its source of error is overflow error and sync pulse error. To improve the efficiency of calibration, interpolation can be used for standard meter to improve the pulse output frequency. Energy meter with larger pulse frequency constant can be used as standard energy meter. Its applicable condition is rated conditions with larger load current.

For the standard digital source method, its source of error is overflow error, synchronization pulse error and introduction error of standard digital power source. To improve the efficiency, we can increase the frequency of the pulse according to the actual working condition, and in the three-phase symmetry test, the average power method is used. Its applicable condition is rated conditions with larger load current.

For the standard analog meter method, its source of error is overflow error and synchronization pulse error and error caused by A/D conversion and other signal debug module. To improve the efficiency, we can select the analog standard meter with smaller error for comparison and reduce the system error form A/D conversion, signal conditioning and protocol group frame. It can be used in the requirement for traceability.

The principle of standard digital source method is basically the same as the standard digital meter method, so the introduction error of each is the same. Since the standard digital source method can adjust the pulse frequency constant, the standard digital source method is more efficient. Standard analog meter method is a mature method of calibration system, but because it contains modules of the introduction of error, in general, it is inferior to digital power source method. Watt-second method introduced a new non-integer period sampling error, in the case of single-phase meter calibration, Watt-second method required a longer time. Therefore, Watt-second method is most suitable for calibration in three-phase symmetrical working condition.

4. Conclusion

In this paper, the error analysis and comparison of four commonly used methods of calibrating digital energy meter are carried out. According to the error characteristics of each calibration method, some relevant improvement measures are given. Based on the above analysis, the choice of calibration scheme should be based on its error characteristics to take appropriate measures to improve the test accuracy and reduce error in the introduction of the error. In order to solve the problems such as slow
calibration speed and incomplete traceability chain, improvements are made to accurately and quickly calibrate the measurement accuracy of digital energy meter. It is important to promote the improvement of digital energy meter detection technology.

5. References

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