Error Self-Detection of Smart Electric Meter Base on DFT processing

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Abstract. The paper proposes a high frequency signal (975 HZ) through superposition method for error self-detection. The feasibility of 975Hz superposition signal is illustrated and verified. According to the Nyquist sampling theorem, the sampling data are processed by DFT theorem. And through the self-detection error and metering error analysis judgment, it is concluded that scheme design of the self-detection error can be used as report and the early warning mechanism of smart IoT electric meter. It lays a good foundation for realizing the transformation of smart electric meter from regular replacement to state replacement, and provides a theoretical basis for ensuring the accuracy of metering.

1. Introduction

The smart electric meter is not only an important part of the smart power grid, but also the basis for grid operation control and trade settlement between the supply and use of electricity. The result of metering is directly related to the security of the grid and the fairness and reasonableness of the trade settlement between the two sides, which is particularly important for determining the error state of the smart electric meter's operation. Therefore, in order to realize the change from regular replacement to state replacement of smart electric meter and to ensure the accuracy of metering, it is imperative to explore an efficient and accurate error self-detection method for smart electric meter operation.

With the construction and development of smart grids, especially the popularisation of advanced metering infrastructure (AMI), power companies are acquiring large scale metering data. In recent years, some results have been obtained in the application of large-scale metering data based on smart electric meter\(^1\)-\(^5\).

In the paper, the distribution characteristics of the integrated and influential error of digital electric meter are obtained through simulation and statistical characterisation. In reference\(^6\), a mathematical model for the variation of the metering error with temperature under different loads is derived by showing that the low temperature environment causes the metering error to drift in the negative direction. In reference\(^7\), a quantitative analysis of the metering error between full-wave and fundamental metering method of electric meter in a harmonic context is presented. In reference\(^8\), Variational Mode Decomposition (VMD) is proposed to analyse the data on the electric metering error caused by harmonics, (VMD). The method uses the band division capability of VMD to separate the harmonic modes effectively, which is applied to harmonic detection in power system.

The metering error of electric meter is mainly caused by two aspects. One is the harmonic effect of power frequency magnetic field, and the other is temperature and humidity, magnetic field, damage of electrical components, virtual welding of lines and wiring error. At present, the voltage metering part of single-phase smart electric meter generally uses voltage divider resistance network, and the wire under voltage current metering part mainly uses manganese copper shunt integrated with relay. The
null line current metering part uses common CT. Manganese copper piece has simple structure, small volume, cheap and good linearity. However, when the current is high, it generates more heat and has poor overload capacity. When the manganese copper piece is damaged due to self-heating or other reasons, resulting in changes in resistance, it will cause metering error and lead to inaccurate electric metering. Because the accuracy metering error of the smart electric meter operation in the field cannot be detected, even if the metering accuracy deviates, the maintainer cannot get error information in time. To address the above problems, this paper proposes an error self-detection scheme based on the high-frequency selection and superposition principle for real-time detection of metering error.

The method creates a periodically transformed signal by superimposing a high frequency alternating voltage of 975HZ on a 50HZ operating frequency voltage. The time domain signal sampling is transformed to sampling in the discrete time Fourier transform frequency domain by sampling a limited range of data. The method obtains the amplitude, frequency and phase of each waveform signal by Fourier transform decomposition. It is characterized by high metering accuracy, simplicity and ease of engineering implementation when sampling is synchronised and the sampling frequency satisfies Nyquist's sampling theorem. The linear relationship between the obtained error self-detection results and the metering error enables early warning and reporting when the error accuracy of the smart IOT electric meter changes.

2. High frequency signal selection and signal superposition scheme design based on ADC sampling principle

The high-frequency signal is selected according to the sampling frequency of the ADC and the original power frequency signal is a sinusoidal wave of 50Hz. In order to distinguish from the 50Hz sine wave power frequency signal, the selected high-frequency signal should be higher than the power frequency signal and less than the harmonic frequency limit of 1000Hz. Therefore, the optional range expression for high-frequency signal is as equation (1).

\[ s_{\text{add}} < f_{\text{add}} < f_{\text{ADCmax}} \]

Where \( f_{\text{add}} \) refers to the high-frequency signal that needs to be superimposed; \( f_{\text{ADCmax}} \) refers to the maximum sampling frequency within the ADC sampling capability. According to the Nyquist sampling theorem, when the sampling frequency is greater than 2 times the highest frequency in the signal in the process of analog/digital signal conversion, the digital signal after sampling can completely retain the information in the original signal. In general practice, the sampling frequency should be 2.56 ~ 4 times of the highest signal frequency.

In addition, the selected frequency is best within the range of non-odd and even harmonics. The frequency of the power frequency signal is 50HZ, and the error fluctuation is usually within 1%. Therefore, the power frequency signal frequency range is 49.5HZ-50.5HZ, and its odd harmonic range is 49.5k-50.5k (\( k \) is an odd number). The even harmonic range is 49.5k-50.5k (\( k \) is an even number), and the selected frequency should avoid this range, so the selected frequency range should be as expression (2).

\[ 50.5k \sim 49.5k(k+1) \quad (k \text{ is a positive integer greater than 1}) \]

According to the existing ADC equipment, The 975HZ signal is selected as the high-frequency. The amplitude, frequency and phase of the 975HZ high-frequency signal and the 50HZ power frequency signal have good distinguishability. ADC sampling is performed before being superimposed, and DFT processing is performed on the 50HZ time-domain waveform graph. The 50HZ signal spectrum graph is shown in Figure 1. The amplitude of the signal is 0 at the 975HZ frequency since the 975HZ signal is not superimposed.
After superimposing the 975HZ high frequency signal on the fundamental 50HZ, the superimposed waveform time domain graph is shown in Figure 2.

Chapter 3 will derive the discrete Fourier transform, analyze and process the 975HZ signal spectrogram, get the result of the error self-detection, and determine whether the metering resistance value is abnormal, which leads to metering error.

3. Hardware realization principle of double channel error self-detection.
Considering the independence of voltage and current loop, the scheme samples the voltage and current respectively, and inject sinusoidal current of specific frequency into both ends of the sampling resistor of the voltage path. The output data of the metering channel will be analyzed by DFT on at this frequency point, and conduct comparison analysis with the original value. Each phase provides two high-stability criterion current sources to cover different faults of the voltage link. The current injection principle of current path is the same as that of voltage path. The input signal is processed by using this principle and the self-detection error value is output. Its sampling circuit is shown in Figure 3 and Figure 4.
4. Design of high frequency and fundamental frequency signal separation scheme based on DFT

When the high-frequency alternating voltage of 975Hz is superimposed on the power frequency voltage of 50Hz, it can be inferred that this value is a rational value from the expression \( T1/T2 = 39/2 \), so the superposition signal is a non-sinusoidal signal with periodic transformation. Fourier series and Fourier transform are used to decompose the non-sinusoidal and superposed signal into the fundamental wave and the harmonic wave. By calculating the amplitude and phase Angle of the fundamental wave and harmonic wave of the periodic distortion waveform, the signal analysis is carried out. If \( x(t) \) is a continuous signal of period \( T \), the Fourier series is expanded as equation (3).

\[
x(t) = \sum_{k=-\infty}^{\infty} X(k\omega)e^{jkw t}
\]  
(3)

Where \( \omega \) is the fundamental frequency and \( k\omega \) is the kth harmonic frequency. Fourier series are of infinite length in the time-frequency domain, which is inconvenient for analysis and calculation. Therefore, DFT is used to discretize the frequency domain. The definition is as equation (4).

\[
X(k) = DFT[x(n)] = \sum_{n=0}^{N-1} x(n) e^{-j2\pi kn/N} \quad (0 \leq k \leq N - 1)
\]  
(4)

Where \( X(k) \) is the spectrum of \( x(n) \), and \( x(n) \) is one period of the periodic signal. The interval between adjacent frequencies is \( 2\pi/N \). To ensure the waveform of 50Hz and 975Hz can be obtained with this interval, the angular frequency resolution of the spectrum should be set suitably. The formula is as equation (5).

\[
\Delta\omega = \frac{2\pi}{T}
\]  
(5)

Where \( \Delta\omega \) is the angular frequency resolution of the spectrum, \( T \) is a period of \( x(n) \). And the output spectrum will only be an integer multiple of the fundamental frequency. The data length is set as \( pT \), and the frequency resolution is as equation (6).
\[ \Delta \omega = \frac{2\pi}{pT} = \frac{w}{P} \]  

(6)

The 975Hz inter-harmonic signal can be fetched. The above formula can be differentiated as equation (7) and (8).

\[ X(w) = \sum_{n=0}^{N-1} (x_1(w) + x_2(w))e^{\frac{j2\pi}{N} kn} \]  

(7)

\[ X(w) = \sum_{n=0}^{N-1} x_1(w)e^{\frac{j2\pi}{N} kn} + \sum_{n=0}^{N-1} x_2(w)e^{\frac{j2\pi}{N} kn} \]  

(8)

Where \( x_1(\omega) \) is one period of the power frequency signal, \( x_2(\omega) \) is one period of the high frequency signal, and \( X(\omega) \) is the spectrum of the superposition signal. When \( w_1 = 50 \), \( \sum x_1(w_1)e^{\frac{j2\pi}{N} kn} = 0 \); \( w_2 = 975 \), \( \sum x_2(w_2)e^{\frac{j2\pi}{N} kn} = 0 \).

The overall hardware implementation scheme is shown in Figure 5.

As a result, the filtered spectrum waveform in the case of actual signal superposition can be obtained as shown in Figure 6.
It can be seen from Figure 4.2, the frequency spectrum containing 975Hz is extracted after the processing of the superposed signal. When the metering resistance is accurate and without damage, its amplitude can be regarded as the standard amplitude. However, due to various external factors in the actual working process of the electric meter, its resistance will change and lead to the change of its amplitude, then the output error self-detection results will also change. Based on the relationship between error self-detection results and metering error, metering error of electric meter can be detected and warned, which provides a theoretical basis for realizing the transformation of smart electric meter from regular replacement to state replacement and ensuring the accuracy of metering.

5. Scheme testing and data analysis
Three electric meters are selected. Metering error and self-detection error values are obtained after calibration. The error data of voltage and current loop are measured under different working conditions (0.5L and 1.0L). And graphs are drawn as Figure 7 to Figure 10.

![Figure 7. Influence curve of voltage circuit sampling resistance on accuracy (1.0L)](image1)

![Figure 8. Influence curve of current circuit sampling resistance on accuracy (1.0L)](image2)
From above curves, it can be concluded that the metering error caused by hardware change under different working conditions is proportional to the self-detection error. With the increase of the metering error, the self-detection error also increases linearly. It can be learned that the relationship between metering error and self-detection can be used to quantitatively fit the error relationship of the voltage circuit. It can also be concluded that the metering error caused by hardware changes under different working conditions is proportional to the self-detection error. With the increase of the metering error, the self-detection error also increases linearly. In addition, it can be concluded from the experimental results that the self-detection error is similar as the metering error at work condition of 0.5L and 1.0L, which shows that the effect of phase angle is compensated by the treatment of the phase angle and the accuracy is improved.

6. Conclusion
This paper puts forward a kind of efficient and accurate smart electric meter operation error detection design, the method based on timing high frequency signal injection forms the superposition signal. According to the Nyquist sampling theorem, data information including amplitude and frequency is set up. Data are processed by using analysis methods such as DFT, and the self-detection error value under the high frequency selected signal is obtained. And through the error from the self-detection error results and metering error analysis judgment, it is concluded that they are proportional when the
hardware changes and the calibration of fundamental wave metering signal by external injection signal is realized. Therefore, the result is produced that the design of error self-detection scheme can realize the purpose of warning and reporting when the error accuracy of the smart IoT electric meter changes. The method presented in this paper has the characteristics of high metering accuracy, simple implementation and easy engineering implementation. According to the change relationship of metering error and self-detection error, which can determine if the running state of the electric meter is correct, and realize the conversion of self-detection error to metering error. It’s of great significance for the smart electric meter to use from periodic replacement to state replacement, and ensure the accuracy of metering. It also contributes to the construction of the national advanced metering system.

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