Research on time-division analog multiplier for 50ppm reference electrical energy meter

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Abstract. Time-division analog multiplier is the measurement core of reference electrical energy meter. The measurement accuracy of time-division analog multiplier is improved by using signal conversion and phase lock technologies and symmetrical triangle wave generator. Signal conversion and phase-locked technology will be measured signal and triangle wave generator of time division multiplier correlation processing, to achieve triangle wave generator of time division power multiplier and measured signal full cycle synchronization. A symmetrical triangle wave generator with reference level accuracy is developed, which makes the measurement accuracy of time-division analog multiplier reached 20ppm and meet the measurement requirements of 50ppm reference electrical energy meter.

1. Introduction
With the rapid development of the power industry, the development and production of reference electrical energy meters used in the electric power field are relatively successful and achieved remarkable social and economic benefits. At present, the principle of electric energy measurement at home and abroad is mainly included analog multiplier measurement technology and digital multiplier measurement technology. The analog multipliers are divided into time-division multiplier and Gilbert variable transconductance multiplier. Time-division multiplier (TDM) is widely used in electronic standard power or energy metering instruments because of its simple circuit, fast response, high-cost performance, high-precision, and wide measurement range. Time-division multiplier is an important part of reference electrical energy meter, and also the main source of measurement error. With the continuous improvement of the accuracy requirements of electric energy measurement in China, the requirements of electric energy meter are also improved, as an important component of analog electronic reference electrical energy meter, time-division multiplier needs more in-depth research[1].

2. Design principles and difficulties

2.1. Design principles
Time-division multiplier is mainly composed of pulse width modulation circuit, pulse amplitude modulation circuit, and low-pass filter circuit. According to the different principles of pulse width
modulation, the following typical types of time-division multiplier are developed, including clock triangle wave voltage comparison type, non-clock triangle wave voltage comparison type, clock square wave voltage integral type, non-clock square wave voltage integral type, non-clock square wave current integral type, etc[2-3].

2.2. Research difficulties
Many integrators are used in the time-division analog multiplier circuit, and the comparator is also used in pulse width modulation. Therefore, the offset voltage, zero drift, and temperature drift will inevitably be introduced into the circuit, affect the measurement accuracy.

The traditional triangle wave generator applies the characteristic of a hysteresis-comparison circuit or single analog chip that if the threshold voltage is exceeded, the output overturn. It forms an oscillation circuit with a peripheral triode, capacitor, and other devices. Although the circuit is simple, the poor frequency stability and large output offset voltage will cause poor linearity and slope symmetry of the triangle wave, which will produce a large error in the PWM circuit[4].

The multiplication value of the time-division multiplier is based on the concept of instantaneous, but in fact, it's impossible to be completely instantaneous. Therefore, modulation frequency F and division number n have an important influence on the measurement accuracy of the time-division analog multiplier. Under ideal conditions, if the modulation frequency F is higher and the division number n is larger, the measurement error will be smaller, the accuracy will be higher, and the recovery will be better. However, the components are limited by their high-frequency response characteristics, and considering the high price of high-frequency components and the need of cost control, the modulation frequency should not be too high. Moreover, high modulation frequency will bring other interference to the circuit[5].

3. Design of time-division analog multiplier for 50ppm standard electric energy meter

3.1. Circuit design of time-division analog multiplier
The Time-division analog multiplier adopts a clock triangle wave voltage comparison type. The circuit is mainly composed of voltage frequency conversion circuit, frequency multiplier circuit, triangular wave generator, comparator, inverter, an analog switch, low-pass filter, and other devices. The circuit design principle is shown in Figure. 1.

Figure. 1 circuit design principle block diagram of time-division analog multiplier
The phase error of the time-division multiplier is reduced and the measurement accuracy of power/electric energy is improved by adopting the time-division power multiplier which synchronizes the whole period with the measured signal and using the voltage analog signal and the triangular wave generator [6]. The voltage analog signal is processed by frequency multiplier and locking to generate a triangular wave, which in turn divides the input voltage analog signal.

The input current analog signal is also divided into forward and reverse signals, which are multiplied by the analog switch and the split voltage analog signal respectively. Finally, the power can be calculated by outputting the DC voltage through the low-pass filter, and then the frequency output can be obtained by V/F conversion so that the measurement result of electric energy can be obtained[7].

The voltage signal of the measured electric energy $E_v$ is applied to the comparator circuit and compared with the double frequency clock triangle wave signal $E_s$ to output a pulse that the width is $T_1$ (or $T_2$). At the same time, according to this pulse $T_1$ (or $T_2$), the switch SW which is used to convert the current signal $\pm E_i$ of the measured electric energy will modulate the pulse amplitude. Finally, the low-pass filter converts the instantaneous value to the average value and outputs the DC output $E_0$ which is proportional to the product of $E_v$ and $E_i$.

If the integral slope of the triangular wave is $K$ and the positive and negative amplitude is $\pm E_s$, the following relationship can be obtained:

$$\frac{KT_2}{2} = E_v - E_s$$
$$\frac{KT_1}{2} = E_v - (-E_s)$$
$$T_1 + T_2 = T$$

From the above formula, it can be concluded that:

$$E_v = \frac{(T_2 - T_1)E_s}{T}$$

(1)

It can be seen that the input voltage is proportional to the width difference ($T_2 - T_1$) of the triangular modulated pulse $E_s$. When the transfer switch SW is turned to $-E_i$ during $T_1$ and to $+E_i$ during $T_2$, the output power voltage value $E_0$ is:

$$E_0 = \frac{(E_1 - T_1)E_i}{E_s}$$

(3)

Combined with the former formula, we can get the following conclusion:

$$E_0 = \frac{E_1 E_i}{E_s}$$

(4)

Obviously, the output power voltage value $E_0$ is proportional to the product of $E_v$ and $E_i$.

3.2. Frequency multiplier circuit with phase-locked technology

The PLL frequency multiplier circuit is a closed-loop frequency feedback system, which is mainly composed of a V/F converter, a phase comparator, a low-pass filter, voltage-controlled oscillator, and counter. The principle of the PLL frequency multiplier circuit is shown in Figure. 2.

![Figure 2 phase locked frequency multiplier circuit principle](image-url)
The voltage signal \( u(t) \) of the measured electric energy is converted into frequency signal \( f_1 \), and then an error voltage signal \( U_\delta \) is generated by the phase difference between the two input signals through the phase comparator. After the harmonic component and high-frequency component are filtered by the low-pass filter, a voltage control signal \( U_d \) is output to the voltage-controlled oscillator to generate the output frequency signal \( f_0 \). \( f_0 \) is also used as the sampling signal enters the counter (or frequency divider) to form a feedback loop. The frequency multiplication factor \( n \) has been set, and the frequency generated by the voltage-controlled oscillator is multiplied by the n-fold frequency, to realize the synchronization with the measured signal and the frequency of \( n \) times the whole period.

3.3. Circuit design of symmetrical voltage triangle wave generator

Triangle wave generator is the driving source that supplies the modulation reference of the pulse width modulation circuit, which is one of the core circuits of the triangle wave comparison time division multiplier. Therefore, it is required to have enough accuracy, a stable integral slope, and also enough high frequency to provide the reference for the transformation. The circuit principle of the triangle wave generator is shown in Figure 3. To meet these requirements, first of all, a stable and accurate reference voltage input and a comparative converting level potential are required. The resulting voltage reference has two paths, one path \( +E_r \) is used as input to the integrator of the triangular wave, the other way \( -E_r \) is used for input to the comparator via a voltage divider as a comparison level. Besides, the super-servo circuit feedback is used in the triangle wave generator to optimize the influence of the input misalignment voltage on the output in the square-to-triangle wave circuit, to improve the symmetry of the output triangle wave and reduce the distortion of the output waveform.

3.4. Design of pulse width modulation circuit

The voltage signal \( E_v \) of the measured electric energy and the synchronous whole period triangle wave signal \( E_s \) output a width-modulated pulse through a comparator. The difference in width is the measured value. Considering the effect of current shunting caused by voltage transformer sampling, an input buffer is set up and compared in the comparator. Comparator circuit is an important part of the pulse width modulation circuit. It requires a stable comparison level and a fast response conversion rate without lag. It mainly consists of an operational amplifier and a second inverter. The output pulse of the second inverter is used as a switch signal for pulse amplitude modulation of another measured electric energy current signal \( E_i \). The principle of the pulse width modulation circuit is shown in Figure 4.
3.5. Design of pulse amplitude modulation circuit

The operation of the multiplier is achieved by pulse width modulation and pulse amplitude modulation circuits. The operation of the multiplier is achieved by pulse width modulation and pulse amplitude modulation circuit. The difference of pulse width in \((T_2-T_1)/T\), which is one of the multiplier factors, requires the polar transformation of another input to get the same amplitude voltage signal with positive and negative polarity. Therefore, a reverse circuit is needed in the pulse amplitude modulation circuit to complete 1:1 equal amplitude transformation. The pulse amplitude modulation circuit requires the converted voltage signal to have high amplitude symmetry, small phase deviation, and small inter-pole capacitance to reduce the amplitude modulation peak potential as much as possible. Also considering the shunt effect caused by current transformer sampling, an input buffer is set at the front of the modulation circuit. The principle of pulse amplitude modulation circuit is shown in Figure 5.

4. Research on error influence

4.1. Influence of modulation frequency and division number on measurement error of TDM

The output of TDM \(E_0\) is the product of the instantaneous average values of two input variables \(E_V\) and \(E_I\). The so-called "instantaneous value" of measurement is a relative term, it's actually a time-division period \(T\), it can only be finite small technically[8].

Let the amplitude of two input signals are \(E_v = A \sin \omega t\), \(E_i = B \sin (\omega t + \varphi)\), frequency of the input signal is \(f = 50\)Hz, frequency of time-division is \(F = 1/T\), number of segments measured in a single time-division period is \(n = F/f\), so, radian of each fraction is \(2\pi/n\).

In the k-th division number, the

\[
E_{vk} = \frac{2\pi}{2\pi} \int_{\frac{(k-1)n}{n}}^{\frac{kn}{n}} A \sin \omega t dt = \frac{\pi A}{2\pi} \left[ \cos \left( \frac{2(k-1)\pi}{n} \right) - \cos \left( \frac{2k\pi}{n} \right) \right]
\]

(5)

\[
E_{ik} = \frac{\pi B}{2\pi} \left[ \cos \left( \frac{2(k-1)\pi}{n} + \varphi \right) - \cos \left( \frac{2k\pi}{n} + \varphi \right) \right]
\]

(6)

Then the k-th time-division product is:

\[
E_{vk} \cdot E_{ik} = K \cdot E_{vk} \cdot E_{ik}
\]

In order to simplify the discussion, let the coefficient \(K = 1\), then the average value of instantaneous product in a \(2\pi\) period can be expressed as:
In theory, if \( n \) is infinite, that is, when the number of divisions is infinite, we can get the following results:

\[
E_p = \frac{1}{n} \sum_{k=1}^{n} E_{2k}
\]

\[
= \frac{nAB}{4\pi^2} \sum_{k=1}^{n} \left[ \cos \frac{2(k-1)\pi}{n} - \cos \frac{2k\pi}{n} \right] \times \left[ \cos \left( \frac{2(k-1)\pi}{n} + \varphi \right) - \cos \left( \frac{2k\pi}{n} + \varphi \right) \right]
\]

In theory, if \( n \) is infinite, that is, when the number of divisions is infinite, we can get the following results:

\[
E_p = \frac{1}{2} AB \cos \varphi
\]

However, in fact, \( n \) can't be infinite. But as long as \( n \) is large enough, it can meet certain accuracy requirements. Therefore, it is advisable to take the following values:

\[
E_p = E_t = \sqrt{2} \sin \omega t
\]

\[
E_0 = \frac{1}{2\pi} \int_{0}^{2\pi} \left( \sqrt{2} \sin \omega t \right)^2 \, dt
\]

Since the waveform is completely symmetrical, there are:

\[
E_0 = \frac{2}{\pi} \int_{0}^{\pi} \left( \sqrt{2} \sin \omega t \right)^2 \, dt = 1
\]

\[
E_p = \frac{8m}{\pi^2} \sum_{k=1}^{m} \left[ \cos \frac{(k-1)\pi}{2m} - \cos \frac{k\pi}{2m} \right]^2
\]

In the above formula, \( m \) is the number of equal divisions in \( 0 \sim \pi/2 \) period. The number of divisions in whole period \( n=4m \).

Through simulation calculation, the curve of measurement error under different modulation frequencies is shown in Figure 6.

![Figure 6. Curve of measurement error under different modulation frequencies](image)

We can see from the figure above, if modulation frequency is higher and number of divisions is larger, the uncertainty of measurement error will be smaller. So, in order to achieve 20ppm or better measurement uncertainty, we should choose at least 20kHz and above modulation frequency.
4.2. Influence of harmonics on measurement error of TDM

According to the working principle of the time-division analog multiplier, we can see that, when there are higher harmonics in the input signal of TDM, during the same time period, the variation range of higher harmonic is larger than the fundamental wave[9-10]. Therefore, when the order of harmonics is high, it can’t be regarded as DC signal, otherwise, it will produce principle error.

Similar to the reasoning above, at the same modulation frequency, the average power of the \( h \)-th harmonic is:

\[
E_{ph} = \frac{N}{4\pi} \sum_{k=1}^{N} \left[ \cos \left( \frac{2(k-1)\pi}{n_0} \right) - \cos \left( \frac{2k\pi}{n_0} \right) \right] \left[ \cos \left( \frac{2(k-1)\varphi}{n_0} \right) + \varphi \right] - \cos \left( \frac{2k\varphi}{n_0} + \varphi \right) \]

(13)

Take \( A_h = B_h = 1 \), by integrating and simplifying the \( h \)-th harmonic power in the power frequency period, the following results can be obtained:

\[
E_{ph} = \frac{N}{2\pi} \cos \varphi \sum_{k=1}^{N} \left[ \cos \left( \frac{2(k-1)\pi}{n_0} \right) - \cos \left( \frac{2k\pi}{n_0} \right) \right] \]

(14)

It can be seen from the above that the value of harmonic power is related to harmonic order and modulation frequency.

After the simulation calculation, take the modulation frequency is 1kHz, 10kHz, 100kHz, 1MHz and 10MHz respectively, take the fundamental frequency \( f = 50 \) Hz. So the equal divisions \( m \) in \( 0 \sim \frac{\pi}{2} \) period are 5, 50, 500, 5K and 50K respectively. The highest harmonic order is 30-th, the measurement error curve under each harmonic is shown in Figure 7.

![Figure 7. Measurement error curve of TDM under each harmonic](image)

We can see from the figure above, if the modulation frequency is constant, the harmonic order is higher, the measurement error will be larger. The measurement error decreases with the rise of modulation frequency. When the modulation frequency rises to a certain degree, such as 10MHz, the error of each harmonic is very small, almost negligible.
5. End
The measurement uncertainty of time-division analog multiplier is up to 20 ppm, it can be widely used in the development of high precision electric energy and power measuring instruments. Typical application is as the measurement core of reference electrical energy meter, used to calibrate low-grade electric energy meters, and the circuit structure of the system is relatively simple, high precision, good linearity, and wide measuring range. It can complete the calculation and display of voltage, current, and power under power frequency.

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