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Design and Verification of AC/DC Comparator Based on A/D Sampling

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***Abstract*—There is an important significance of AC/DC comparator with high precision for the precision measurement in electric power industry. An AC/DC comparator based on the non integer period Sampling and rapid data refactoring is designed. The AC/DC comparator consists of the input buffer， A/D change， DC reference standard， magnetic isolation and sampling control chip. AC/DC comparator is used to sample the AC Magnitude and realize the AC traceable to DC with the reference of the high precision DC reference standard. Through the error analysis of the AC/DC comparator for each part， the Maximum error of voltage amplitude measurement is $\pm 8\times 10^{-6}$.The experimental results show that the accuracy of frequency， amplitude and phase is respectively 10^{-6}、10^{-6}、10^{-5}，and the stability is 10^{-6}、10^{-6}、10^{-5}. It proves that the AC/DC comparator can accurate measurement the fundamental magnitude of AC.**

Keywords- AC/DC comparator; non integer period Sampling; data refactoring; A/D

I. INTRODUCTION

With the development of smart grid, the promoting of power grid information technology, the continuous application of high and new technology in electric power and the fine management of electric power, the electric power measurement technology and standards are increasingly more high requirements[1-3]. It is a practical significance to develop an AC/DC comparator which can compare AC voltage to DC voltage with high precision, because Voltage References are stored in the form of DC. The most commonly used AC/DC comparator are electric system AC/DC comparator, electrostatic AC/DC comparator and thermoelectric AC/DC comparator[4]. The relative error of electric system AC/DC comparator is level of 10^{-4} because of the residual charges, the inductance that exists between coils, swirl and electrostatic. The relative error of electrostatic AC/DC comparator is level of 10^{-5} because of the lifting wire impedance, the contact thermopower, the residual reactance of shunt, the surface charge and the different field strength. The thermoelectric AC/DC comparator is based on the principle of the same thermal effects between the AC voltage and DC voltage, but it must work with a high stability temperature environment, and the relative error of thermoelectric AC/DC comparator is level of 2×10^{-6}.

A AC/DC comparator is designed, which use a high precision and high stability DC reference voltage as standard, and the AC traceable DC is based on A/D's non integer period Sampling and rapid data refactoring. The AC/DC comparator's dependability is verified with experiment.

II. NON-INTEGER-PERIOD SAMPLING AND DATA RECONSTRUCTION

The sampling period Ts with A/D is given by

$$T_S = \frac{K(1-\Delta)T_0}{N} \tag{1}$$

Where Δ is the random number between -1 and 1 , T0 is the period of the measured signal, K is the number of signal cycle in a sampling period and N is the number of sampling in a sampling period.

In the ideal situation, the periodic signal can be reconstructed at full period sampling to continuous periodic signal when Δ is 0, K and N are coprime number and N=L+1[5-6]. Assumes that the sampling interval is Δt radians, and a cycle sampling points is Δt radians, and a cycle sampling points is N, then Δ=tn. But Δt is not always zero. .Commonly used method is to adopt the method of phase lock loop dynamic tracking of measured signal to achieve the purpose of the whole cycle sampling[7] , but frequency tracking also appears a certain lag, cannot achieve high accuracy of measurement. Also some scholars put forward use the source table with bell technology, but the source being measured is not fixed, so it is hard to be totally with the lock. That is completely integral period sampling is done, but there's always some errors. Jiangqiu Zhang etc is theoretically proved that the innovation from the cycle model of a whole cycle sampling[8].According to the principle, continuous signal is proposed using a whole cycle sampling strategy. Using liner interpolation method to a synchronous sampling sequence into a sequence of synchronous sampling, insert 2^N points into a cycle. Using polynomial mathematical methods to piecewise polynomial fitting of the originnal sampling data, reconstruct fast Fourier transform of signal cycle integer point sequence.

III. AC/DC COMPARATOR

A. The structure of AC/DC comparator

An AC/DC comparator based A/D sampling and data processing technique is designed. AC instantaneous values are sampled by A/D, and the effective value, average value and etc can be acquire though calculating according to the definition of AC voltage. The structure of AC/DC comparator is as shown in Figure 1.

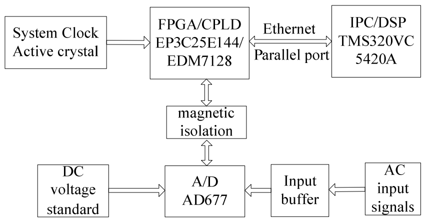

Figure 1. The structure of AC/DC comparator

The AC/DC comparator is composed of input buffer, A/D conversion, the DC voltage standard, magnetic isolators, the processor and the system clocks, and it can link to IPC by Ethernet and parallel port. The AC input signals compare with DC voltage reference through A/D after input buffer and the signal is collected and processed by data capture system, and AC voltage trace to the DC voltage though in this way. The A/D AD677 is 16 bit which has self-calibration function. Its sample frequency is 50Hz. The valid value of AC voltage U_{AC} is given by:

$$Y_{AX}=\kappa\cdot Y_{\Delta X} \tag{2}$$

Where the U_{DC} is DC reference voltage, k is the conversion factor of AC/DC.

B. Experimental verification system

Experimental verification system is composed of DC reference voltage reference, AC voltage source, Precision resistors, current transformer, AC/DC comparator and DSP (digital signal processor). As shown in Figure 2.

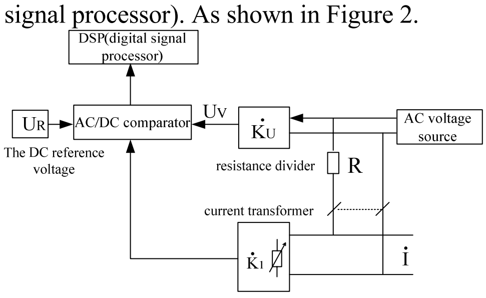

Figure 2. The composition of experimental verification system

And the DC reference voltage reference, AC voltage source, precision resistors are standard component. The precision resistor is designed with No inductance and capacitance. The AC/DC comparator is zero calibration and full-scale calibration. DC reference standard of AC/DC comparator compare to DC reference voltage reference by eight semi-digital digital multimeters. Temperature Coefficient of precision resistors is 0.1ppm/℃.

IV. Error Analysis

The main sources of error is voltage measurement error. And it is composed of the error by DC reference voltage, sampling method, input buffer and A/D converter.

A. The error by DC reference voltage

The error by DC reference voltage is caused by measurement error which is internal of AC/DC comparator. The DC reference voltage is saved by Fluke732B with standard group. The uncertainty of DC reference voltage measurement is 5.0×10^{-7}, and the measurement error E_{rr1} of 7V DC voltage is 1.75×10^{-6}V.

The DC reference which is internal of AC/DC comparator is LTZ1000ACH, and its annual variation of technical index is 0.83×10^{-6}. So the maximum error E_{rr2} which is caused by DC reference changes is 5.81×10^{-6}V. When E_{rr1} and E_{rr2} are limit value, though line synthesis, the quantity transfer error of DC reference voltage Err is 7.56×10^{-6} V calculated by $E_{rr1}+E_{rr2}$. And the relative error E is 1.1×10^{-6}.

According to the principle of A/D converter, AC 4V measurement error ΔU_1 which compare to DC reference voltage is calculated by:

$$\Delta U_1=4\text{V}\times E=4\text{V}\times1.08\times10^{-6}=4.32\times10^{-6}\text{V}$$

B. The error of Sampling algorithm

According to the principle of non integer period Sampling[9], In a period of N=1000 points, the relative error δ_{rms1} of sampling algorithm is 6.6×10^{-6} .

According to the principle of backlash compensation algorithm, in the condition of continuously sampling ten period, the relative error δ_{rms2} is 0.07×10^{-6}.

In conclusion, at the full-scale input 4V, the error of arithmetic ΔU_2 is calculated by:

$$\Delta U_2=4\text{V}\times0.1\times10^{-6}=0.4\times10^{-6}\text{V}$$

C. The error of input buffer

The AC input buffer of AC/DC comparator is an in-phase follower which is composed of High Precision Operational Amplifiers OP27E, and the error of input buffer E_{buf} is given by:

$$E_{\beta\upsilon\phi}=-1/(K+1) \tag{3}$$

Where K is Open-loop gain of Operational Amplifier.

The K is 1.8×10^{6}, according to manufacturer of OP27E., the error of input buffer E_{buf} is -0.56×10^{-6} by form (3).

But the Open-loop gain K is a changed value, the changing ranges is set to 10%. According to the form(3), the Open-loop gain of Operational Amplifier K is 1.8×10^{6}, K_1 which is after changing 10% is 1.62×10^{6}. The modulus of changing of input buffer error ΔE_{buf} is 0.06×10^{-6}calculated by $\|[-1/(K_1+1)]-[-1/(K+1)]\|$.

From Above Analysis and considering converted quantity of Operational Amplifiers, When ΔE_{buf} are limit value, the error of input buffer E is -0.62×10^{-6}.

In conclusion, at the full-scale input 4V, the error of input buffer ΔU_3 is calculated by:

$$\Delta U_3=4\text{V}\times(-0.62\times10^{-6})= -2.48\times10^{-6}\text{V}$$

D. The error of A/D converter

The A/D of AC/DC comparator is 16 bit, the resolution error of AC sampling E_n is 0.12×10^{-6}. The DC calibration target of A/D standard deviation is a fixed value, and it is 1/4LSB. Reducing the converter error to 1/12 LSB(1.25×10^{-6}). the error of the DC voltage calibration E_d is 1.25×10^{-6}.

When E_n and E_d are limit value, though line synthesis, the resolution error of AC sampling E_{nd} is 1.37×10^{-6}calculated by E_n+E_d.The system error of AC sampling E_s is estimated at half of the energy levels which is 3×10^{-6} after it is corrected.

The error of A/D convert E_{AD} consists of the resolution error of AC sampling E_{nd} and the system error of AC sampling E_s, and the E_{nd} and E_s is independent. When E_{nd} and E_s are limit value, though line synthesis, the error of A/D convert E_{AD} is 4.37×10^{-6}calculated byE_{nd}+E_s.

In conclusion, at the full-scale input 4V, the error of A/D convert ΔU_4 is calculated by:

$$\Delta U_4=4V\times(4.37\times10^{-6})= 1.748\times10^{-5}V$$

E. The total error

From above error analysis, when the error of input buffer is not corrected by the algorithmic, the AC measuring error of AC/DC comparator ΔU is given by:

$$\otimes Y=\otimes Y_1+\otimes Y_2+\otimes Y_3+\otimes Y_4 \qquad (4)$$

According to equation (4), the ΔU is 24.32×10^{-6}V.In conclusion, at the full-scale input 4V, the relative error of AC voltage measuring Δ is 6.08×10^{-6}.

Thinking about the effect of the board layouts and the testing circuit, when all values is limited, the error estimate of AC/DC comparator voltage measuring is not over 2×10^{-6}. So the maximum error of AC voltage measuring with AC/DC comparator is $\pm8\times10^{-6}$.

V. TESTING AND ANALYSIS

The stability and accuracy of AC voltage, phase and frequency is tested in a constant temperature and humidity environment(the temperature is 20℃, the relative humidity is 60%rh).Standard AC 4V signal of 50Hz, 52.45Hz, 54.94Hz, 57.4Hz, 59.88Hz, 62.34Hz and 64.8Hz is respectively input to AC/DC comparator, and the phase of input signal is respectively 0°、60°、180° and 300°. The AC voltage is measured by AC/DC comparator, as shown in Figure 3.

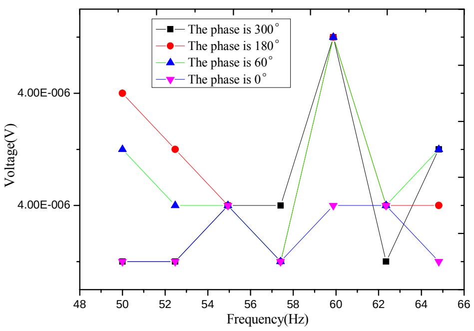

Figure 3. Measuring 4V under different phase and frequency

In figure 3, the maximum difference of voltage measurement is 4×10^{-7}V when the input voltage is at different phase, and the maximum difference of voltage measurement is 3×10^{-7}V when the input voltage is at same frequency and different phase.

A. Stability test

The frequency stability of input voltage is tested by AC/DC comparator. The data is recorded once every hour, and every time record five data. The mean value of five data is as the measuring value, and there are seven sets of data. The frequency stability curve is draw through calculation, as shown in Figure 4.

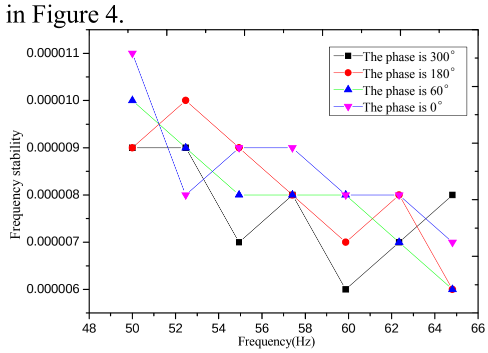

Figure 4. Frequency stability curve under different frequency and different phase

In figure 4, Frequency stability of AC/DC comparator is gradually drop off with increasing frequency. Frequency stability of AC/DC comparator is the level of 10^{-6} as a whole.

Voltage magnitude stability is tested in the same way, and the voltage magnitude stability curve is draw, as shown in figure 5.

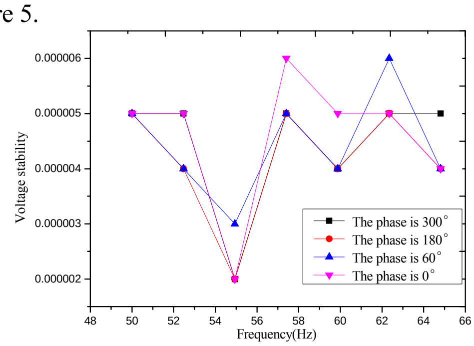

Figure 5. Voltage magnitude stability curve under different frequency and different phase

In figure 5, the voltage magnitude stability has an obviously minimal value in 55Hz at every phase. Voltage magnitude stability value of AC/DC comparator is the level of 10^{-6} as a whole. The maximum value is 6×10^{-6}, and the minimum value is 2×10^{-6}.

Phase stability of AC/DC comparator is tested in the same way, and the phase stability curve is draw, as shown in figure 6.

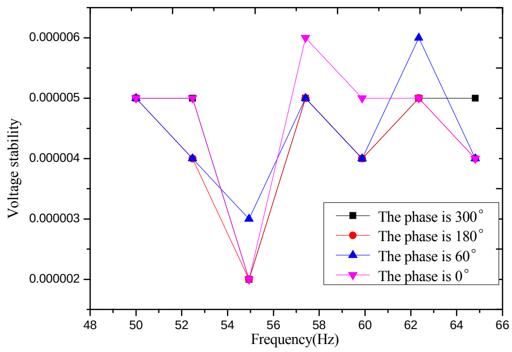

Figure 6. Phase stability curve under different frequency and different phase

In figure 6, the phase stability has an obviously minimal value in 55Hz at every phase, and the maximum value is 5×10^{-5}, and the minimum value is 2×10^{-5}°.

B. Accuracy test

The accuracy of AC/DC comparator is test with different phase and different frequency voltage. Standard AC 4V signal of different phase and different frequency is generate by a standard source. The data tested by AC/DC comparator is recorded once every hour, and every time record five data. The mean value of five data is as the measuring value at that point, and there are seven sets of data. The frequency accuracy curve is draw through calculation, as shown in Figure 7.

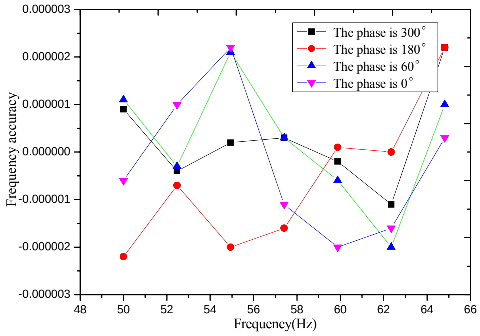

Figure 7. Frequency accuracy curve under different frequency and different phase

In figure 7, the different value is minimum at 65Hz, frequency accuracy of AC/DC comparator is the level of 10^{-6} as a whole, and the maximum value is 2.3×10^{-6}, and the minimum value is -2.2×10^{-6}.

Voltage magnitude accuracy of AC/DC comparator is tested in the same way, and the voltage magnitude accuracy curve is draw, as shown in figure 8.

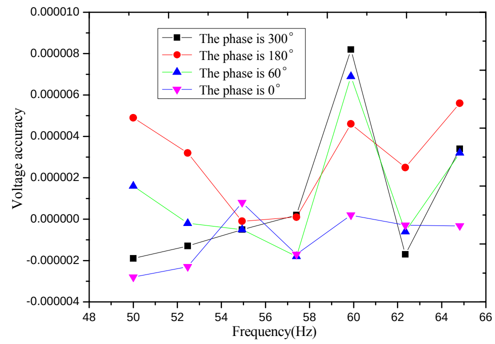

Figure 8. Voltage magnitude accuracy curve under different frequency and different phase

In figure 8, and the maximum value of voltage magnitude accuracy is 2.3×10^{-6}, and the minimum value of voltage magnitude accuracy is -2.2×10^{-6}.

Phase accuracy of AC/DC comparator is tested in the same way, and the phase accuracy curve is draw, as shown in figure 9.

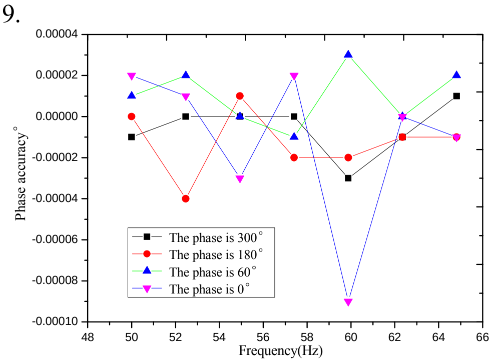

Figure 9. Phase accuracy curve under different frequency and different phase

In Figure 9, the different value is maximum which is 12×10^{-5}° at 60Hz, and the maximum value of phase accuracy is 3×10^{-5}°, and the minimum value of phase accuracy is -9×10^{-5}°.

VI. SUMMARY

Structure of the AC/DC comparator are introduced, and the voltage error of AC/DC comparator is $\pm8\times10^{-6}$ in theory. The stability and accuracy of phase, frequency and voltage magnitude is tested. Tests show that the stability of phase, frequency and voltage magnitude are respectively the level of 10^{-6},10^{-6},10^{-5}, and the accuracy of phase, frequency and voltage magnitude are respectively the level of 10^{-6},10^{-6},10^{-5}.It proves that the AC/DC comparator can reach high-precision measurement of basic electrical parameters.

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