Broadband Phase Angle Calibration Device Based on Digital Sampling and DFT Interpolation Algorithm

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Abstract

Based on the digital sampling technology, a new broadband phase difference calibration device is developed. The DFT and interpolation compensation algorithms under non-integer period sampling are used. The construction, sampling strategy and compensation algorithm of the calibration device are introduced in detail. Its uncertainty is evaluated and verified by experiments. The frequency of the device covers 10Hz~100kHz and the best measurement uncertainty on the phase difference is 0.0006 °.

1. Introduction

Sine signal phase difference measurement is widely used in the field of power systems, industrial automation, intelligent control, communication, navigation, vibration analysis, analysis of material properties, network analysis and so on. The phase difference measurement commonly used digital phase meter, phase Angle voltmeter, the power analyzer, such as measuring equipment, and its value is accurate with the standard phase calibration source.

There are many kinds of phase difference measurement methods. The traditional methods are the analog device vector method, the diode phase detecting method and the pulse counting method. The measurement accuracy of these methods can reach to be 0.02°. At present, a method combining data acquisition hardware and signal processing algorithm software is more widely used [1-2] and the accuracy of related commercial instrument is close to be 0.005°. The singal processing methods of passing zero, sine curve fitting, time domain correlation, and frequency spectrum analysis are commonly used.

The early phase angle standard in NIST used sine curve fitting method [3], and the best measurement uncertainty is 0.001°.The time domain correlationand spectrum analysis have strong anti-interference ability. Their essences are the orthogonality of trigonometric functions. Under the condition of synchronous sampling or integer period sampling, both of them have higher accuracy. However, the phase obtained by spectrum analysis has reference characteristic in theory which is more suitable to be used as measurement standard [4]. The phase measurement uncertainty is about 0.0008°. But it is difficult to realize synchronous or integer-period sampling in sampling process. To improve the phase angle measurement accuracy the singal processing algorithm should be improved. This paper developed a new low-frequency phase Anglecalibration device based on DFT and interpolation compensation algorithm and its best uncertainty reachedto be 0.0006°.

2. Components of Calibration Device

The principle block diagram on calibration device is shown in Fig.1. The device consists of the broadband resistor voltage divider, samplers (two 3458 digital sampling voltmeters, two PXI5922 digitizers), sampling trigger (signal generator) and computer system. The two channel voltage signals output from the calibrated broadband phase source are converted to be signals that can be received by samplers through broadband resistor voltage divider. The samplers adopt equal interval sampling by controlling sampling trigger to output sampling pulse by computer. The samples are stored into computers and then analyzed by DFT and interpolation compensation algorithm. Finally the phase difference between the two channel voltage signals output from calibrated phase source is obtained.

2.1 Broadband Resistor Voltage Divider

The broadband resistor voltage divider converts the high voltage into proper value received by samplers. The number of dividers is 7. Each one has a fixed output proportion. The rated input voltagesare7.5V, 15V, 30V, 60V, 120V and 240V, and all of the rated output voltagesare 0.8V. The input impedance of voltage divider is among 75kΩ～300kΩ. In order to improve the performance of divider, reduce the resistance load effect and temperature effect, reduce the influence of parasitic resistance caused by leakage current, improve the anti-interference ability, reduce the voltage

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divider contrast and angle difference, and improve the stability of the voltage divider, each resistor voltage divider takesmanyeffective measures, such as using insulation bracket and equipotential shielding protection, output impedance transformation,capacitive compensation onphase angle error and electromagnetic shielding protection technology [5].

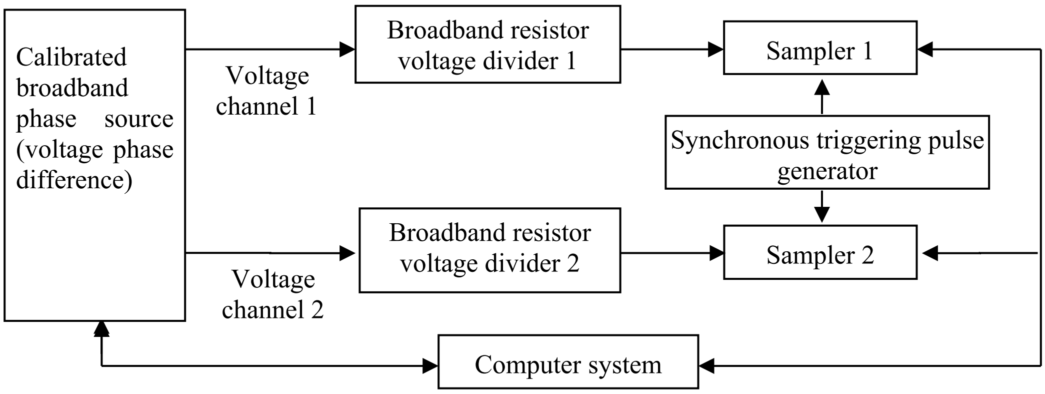

Fig.1 Principle diagram on broadband phase calibration device

2.2 Sampler

Because the measured AC signal has wide frequency bandandone sampler cannotcover the entire frequency range, the frequency of measured AC voltageis divided into two sections, 10Hz～1kHz sampled by 3458A from Agilent company, and 1kHz～100kHz sampled by PXI5922 digitizerfrom NI company. The experiment results show the angle difference between two channels is less than 0.0001^{o} from 1kHz to 100kHz.

2.3 Sampling Trigger

3458A is a digital samplingmultimeter. Two multimeters should be used.In order to improve the common mode interference suppression ability, using two PXI5922 digitizers composed of dual channel differential sampling system.In order to reduce the influence of internal sampling clock jitter,sampler need to work in the external trigger mode.To realize synchronous sampling between them, the external trigger functions should be used and the trigger signals are produced by 33522 signal generator from Agilent company.

2.4 Sampling Strategy and Compensation Algorithm

The calibration device adopts equal interval sampling under the control of the sampling trigger and the quasi synchronous sampling is satisfied by choosing proper sampling frequency. The signal processing is based on DFT and compensation correction algorithm by double peak spectrum lines [4]. The details about the algorithm is that the samples are analyzed by DFT firstly and then two spectrum lines with large magnitude are chosen to construct interpolation scheme to correct the measurement errors caused by the longrange spectrum leakage, short range spectrum leakage and negative frequency leakage. The accuracy of the adopted algorithm is less 1μrad which has been verified by experiments. It has no limit on the non-integer period sampling bias, has low requirements onthe sampling hardware system, and has a high measurement speed.

3. Phase Traceability of the Sampling System

The phase traceability of the sampling system adopts the method of modeling, namely the phase of each part of sampling system is calibrated respectively and then the uncertainty is evaluated by mathematical model. The sampling device is divided into two parts. One is the sampling system on 0.8V basic voltage and broadband AC resistor voltage divider. In 10Hz ~ 100 kHz, the phase differences under a series of fixed frequency points are chosen to be calibrated. The polynomial curve fitting is used in different frequency sections to obtain the consistency deviation of phase shift between two channels of 0.8V basic voltage sampling system and the frequency curves on δ_{D1} and δ_{D2} and then correct the final phase measurement results.

4. Evaluationon Measurement Uncertainty of Calibration Device

4.1 Model of Phase Measurement

The mathematical model of phase measurement is as follows

$$\varphi = (\varphi_S - \delta_{S0} + \delta_{D1} - \delta_{D2}) \tag{1}$$

where φ is the phase angle between two channel voltages of calibrated phase source; φ_S is the phase angle achieved by sampling measurement system; δ_{S0} is the consistency deviation between two channels of sampling measurement system; δ_{D1} is the phase difference of broadband resistor voltage divider 1; δ_{D2} is the phase difference of broadband resistor voltage divider 2.

Because each input variable is measured by the same sampling measurement system, all the input variables are related. The measurement uncertaintiesofphase difference of the sampling system can be divided into systematicerrorswhich are related completely and random errors which are not relevant. The systematic errors can be corrected. Therefore, the uncertainty of phase difference is mainly from the random errors. the combined standard uncertainty of phase difference is

$$u(\varphi) = \sqrt{u(\varphi_S)^2 + u(\delta_{S0})^2 + u(\delta_{D1})^2 + u(\delta_{D2})^2} \tag{2}$$

where $u(\varphi)$ is the standard uncertainty of phase difference of phase calibration device; $u(\varphi_S)$ is the standard measurement uncertainty caused by 0.8V basic voltage phase angle measuring system; $u(\varphi_{S0})$ is the standard measurement uncertainty caused by the random errors measuring one basic voltage signal by two samplers; $u(\delta_{D1})$ is the standard uncertainty of phase angle calibration results when the broadband resistor voltage divider 1 is calibrated by two samplers; $u(\delta_{D2})$ is the standard uncertainty of phase angle calibration results when the broadband resistor voltage divider 2is calibrated by two samplers.

4.2 Standard Measurement Uncertainty Caused by 0.8V Basic Voltage Phase Angle Measuring System

Using two samplerstomeasure directly the phase difference between two voltage signals, the main uncertainty components are from two parts. One is systematic errors caused by the inconsistency of hardware circuits and trigger time of two channels. The other is random errors caused by the effective bits of sampler, the traceable dispersion of sampler, leakage, noise and the jitter of sampling trigger signals [7].

4.3 Standard Uncertainty of Phase Angle Difference Calibration Results of Broadband Resistor Voltage Divider

The calibration on the phase angle of voltage divider adopts half range recursive method [8, 9]. The uncertainty of phase difference can be obtained by recursion and accumulation.The uncertainty of this level divider is the combination of the uncertainty of last level divider and the dispersion of the measurement results of this level.

4.4 Measurement Uncertainty of Broadband Phase Difference Calibration Device

For 10Hz, 100Hz, 1kHz, 10kHz and 100kHz, keepingtwoinput channels with same amplitude voltage, respectively 7.5V, 15V, 30V, 60V, 120V and 240V, the best measurement uncertainties of this calibration device are shown in table 1. Within the range of 10Hz~100kHz, the uncertainties are lower than 0.005^o .

Table 1 Measurement uncertainty of phase calibration device（*k*=2）

	7.5V	15V	30V	60V	120V	240V
10Hz	0.0007^o	0.0007^o	0.0008^o	0.0008^o	0.0009^o	0.0009^o
100Hz	0.0006^o	0.0006^o	0.0007^o	0.0007^o	0.0008^o	0.0008^o
1kHz	0.0009^o	0.0009^o	0.0010^o	0.0010^o	0.0010^o	0.0010^o
10kHz	0.0017^o	0.0017^o	0.0017^o	0.0017^o	0.0018^o	0.0019^o
100kHz	0.0036^o	0.0038^o	0.0039^o	0.0040^o	0.0041^o	0.0042^o

4.5 Experiment Verification

The developed device is used to calibrate low frequency phase source 5500-2 of Clarke-Hess Company. Under the condition of outputtingtwo same amplitude voltages, the calibrationresults are shown in table 2.

Table 2 Phase calibration results of low-frequency phase source 5500-2

reference channel	signal channel	output of phase difference value	frequency	calibration results	error value	permissible error
5V	5V	0º	10Hz	0.0032º	-0.0032º	±0.005º
			100Hz	0.0018º	-0.0018º	±0.005º
			1kHz	0.0028º	-0.0028º	±0.005º
			10kHz	0.0089º	-0.0089º	±0.010º
			100kHz	0.0312º	-0.00312º	±0.040º
120V	120V	90º	10Hz	89.9993º	0.0007º	±0.010º
			100Hz	89.9998º	0.0002º	±0.010º
			1kHz	90.0001º	-0.0001º	±0.010º
			10kHz	90.0047º	-0.0047º	±0.030º
			100kHz	90.0353º	-0.0353º	±0.080º

5. Conclusion

The new broadband phase calibration device based on sampling technology was introduced in this paper. The sampler adopted commercial sampling instruments. The interpolation compensation algorithm based on DFT under non-integer period sampling was used. The developed device had the advantages of wide-frequency band, good stability and small uncertainty. Now this device has been applied to calibrate the low frequency phase source.

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