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Establishment of AC power standard at frequencies up to 100 kHz

Xianlin Pan[a], Jiangtao Zhang[a,*], Zhaomin Shi[b], Qing He[a], Jun Lin[b]

[a] *National Institute of Metrology, Beijing, China*
[b] *College of Instrumentation and Electrical Engineering, Jilin University, Changchun, China*

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ABSTRACT

This paper describes the establishment of wideband power standard for traceable measurements of electrical power of sinusoidal signals. The standard is mainly comprised of a set of resistive voltage dividers, a range of current shunts and dual-channel sampling system. The amplitude and phase angle errors of each of the components have been evaluated accurately at frequencies up to 100 kHz. The design of this power standard system has been proposed to cover the voltage ranges up to 600 V, current ranges up to 100 A and frequencies up to 100 kHz. The measurement results of each component have been given in the paper. The total uncertainties of this power standard at current ranges from 1 A to 100 A and at 600 V have also been presented at different measuring frequencies and power factors.

1. Introduction

At present, commercial power measurement instruments have been widely applied and generate a growing traceability need at frequencies even up to hundreds of kilohertz. The establishment of the power standard requires not only the determination of the amplitude errors but also phase angle errors of voltage dividers (VDs) and current shunts, especially at low power factors and high frequencies. In the application of the harmonic power standard establishment, the solution has been proposed to calibrate the Voltage Dividers (VDs) and shunts at frequencies up to 3 kHz at NIM, China [1]. For the higher frequencies power measurement, other national metrology institutes have also proposed different solutions. At the National Measurement Institute, Australia (NMIA), the electrical power standard has been established, using the Thermal Power Comparator [2] to relate the alternating power to that of known dc signals at frequencies up to 200 kHz [3]. For this power standard, the phase angle errors of the voltage dividers have been determined with the use of a special zero-power factor Ref. [4] and the phase angle errors of the current shunts have been calibrated against a set of radial micropotentiometer resistors in a step-up procedure [5]. At RISE Research Institutes of Sweden, the power standard based on the sampling digitizers and a phase-controlled phantom power source has also been reported to cover the frequencies up to 1 MHz [6]. For this power standard, a phase comparator has been developed to determine the phase angle errors of the shunts [7] and the phase angle errors of the VDs have been calibrated with the use of the sampling digitizer in a step-up procedure [8].

At the National Institute of Metrology (NIM), China, the national power standard has been established at voltages up to 600 V, currents up to 100 A, frequencies up 100 kHz and power factors from 0 to 1. A set of resistive voltage dividers (RVDs) with serial-parallel connection has been designed to scale down the input voltage with ratios of 100:1, 199:1 and 301:1. A set of cage-like designcurrent shunts has also been built to transfer the input current into voltage and cover the current ranges from 1 A to 100 A. A dual-channel digitizer is applied to measure the relationship between the output voltages of RVD and shunt. The amplitude errors of the RVDs and shunts can be calibrated against the national voltage standard and current standard by means of ac-dc transfer technology in a step-up procedure. So how to solve the traceability in phase angle errors of the RVDs and shunts is critical for the establishment of the ac power standard.

2. System of the power standard

The power measurement system is shown in Fig. 1. It is comprised of power signal generator, a set of RVDs and current shunts, a dual-channel power digitizer and device under test (DUT). The power signal generator includes a dual-channel voltage source, a power amplifier and a transconductance amplifier (TCA). The dual-channel voltage source is used to generate two voltage signals with adjustable phase angle and amplitude and to drive the voltage amplifier and TCA respectively. The voltage signal U and the current signal I are applied into the RVD with a buffer amplifier and current shunt R_{CS} directly. The output voltage U_{RA} and U_{CS} are connected into the input terminal of the dual-channel digitizer from National Instrument PXI-5922, and also applied to two voltmeters, Fluke 5790A. The power analyzer is DUT.

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[*] Corresponding author.
E-mail address: zhangjt@nim.ac.cn (J. Zhang).

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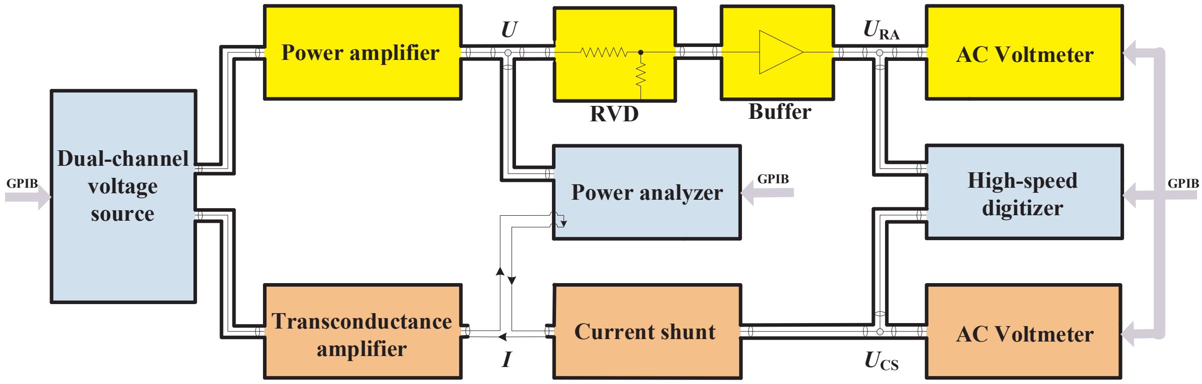

Fig. 1. Diagram of national power standard system.

The automatic measurement system connects with a computer by IEEE-488 bus.

2.1. Resistive voltage dividers

A set of RVDs with serial-parallel coaxial connection has been designed to scale down the voltage ranges at NIM, China [9]. The structure of the RVD is shown in Fig. 2. The upper part of the RVD contains *m* sets of resistive elements in serial connection and the lower part contains *n* sets of resistive elements in parallel connection. The resistive elements of both parts are selected with identical thin-film resistors from Vishay Company. The phase angle influences of RVD are mainly from the time constant of each resistive element and capacitive leakage, especially at high frequencies and high resistive values. For this serial-parallel designed RVD, the influence from the time constant difference of the resistive elements can be ignored. The capacitive leakage influences include the leakage capacitance from resistive elements to the housing, and the capacitance across each resistor. The capacitive leakage influence in phase angle error of the RVD has been derived and described as follow, and is impossible to be determined directly.

$$\theta = -\left\{\left(\sum_{i=1}^{m}\frac{(i\times n\times(m-i)+i)}{mn+1}\times C_i+\frac{m}{mn+1}\times C_p\right)-\left(\sum_{x=0}^{m-1}\sum_{i=x+1}^{m}\frac{(i-x)^2\times n}{mn+1}\times C_{xi}\right)\right\}\times\omega R=-f(C)\times\omega R \tag{1}$$

where θ is the phase angle error of the RVD, C_i is the equivalent capacitance between each resistor in series part and the housing, C_p is the equivalent capacitance between the resistors in parallel part and the housing, C_{xi} is the capacitance across each resistor, m is the number of resistors in serial connection, n is the number of resistors in parallel, ω is the angle frequency, and R is the resistance of each resistive element. Based on the special relationship between the capacitive distribution and resistive elements, as seen from Eq. (1), a basic self-calibration principle has been proposed and described in details as follow. Two RVDs, marked $\text{RVD}_{1\#}$ and $\text{RVD}_{2\#}$, have been built with identical structure parameters to keep the same capacitive distribution. The $\text{RVD}_{1\#}$ and $\text{RVD}_{2\#}$ are designed with resistive element R_1 and R_2 respectively. The resistance value of R_2 is K times of R_1. Assuming that the phase angle errors of the $\text{RVD}_{1\#}$ is θ_1, the phase error of $\text{RVD}_{2\#}$ is $\text{K}\theta_1$, so the difference between two RVDs is $(\text{K}-1)\theta_1$. By measuring the difference, the phase angle errors of two RVDs can be determined respectively.

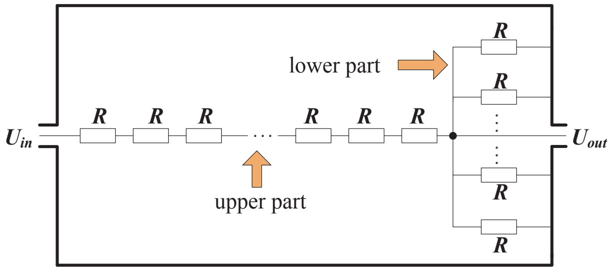

Fig. 2. Basic structure of RVD with serial-parallel connection.

Based on this series-parallel design, three groups of RVDs have been built with ratios of 100:1, 199:1 and 301:1 to cover the voltage ranges up to 600 V. Each group includes two RVDs with identical structure parameters and different resistive elements, and shown in Table 1 in details.

The Fig. 3 shows the inner physical structure of the RVDs with ratio of 100:1 as marked RVD_1 and RVD_2 in Table 1.

The phase angle errors of the three groups of RVDs have been self-calibrated respectively at frequencies from 400 Hz to 100 kHz. The measurement results of RVDs, as marked RVD_1, RVD_3 and RVD_5 in Table 1, have been given and shown in Fig. 4. As seen from this figure, the phase angle errors of each RVD show well the linearity relationship with frequencies. By the self-calibration measurement, the RVD_1, RVD_3 and RVD_5 can be used as the reference standard for determining the phase angle errors of other VDs.

In the application of power measurement, the RVD is usually combined with a buffer amplifier to reduce the output impedance and the loading influence. In this paper, the RVD_2, RVD_4 and RVD_6, mentioned in Table 1, are applied to combine independently with a buffer and capacitive compensated at 100 kHz. The phase angle errors of each the combinations can be calibrated against the reference standard respectively. The measurement in phase angle errors of the combinations with ratios of 100:1, 199:1 and 301:1 has been done at frequencies up to 100 kHz and the results are shown in Table 2. The level dependence in phase angle errors of the RVDs has also been measured to be less than 20 μrad at the voltage ranges from 100 V to 600 V and the frequency ranges up to 100 kHz.

The amplitude errors of each of the combinations can also be calibrated independently against the dc voltage standard and thermal voltage converters (TVCs) with known ac-dc difference. The measurements have been done at frequencies up to 100 kHz and at voltage

Table 1
Design parameters of the RVDs.

Groups	RVDs	Ratios	m	n	*R* (kΩ)
Group1	RVD_1	100:1	11	9	0.5
	RVD_2		11	9	1.0
Group2	RVD_3	199:1	22	9	0.2
	RVD_4		22	9	1.0
Group3	RVD_5	301:1	20	15	1.0
	RVD_6		20	15	2.5

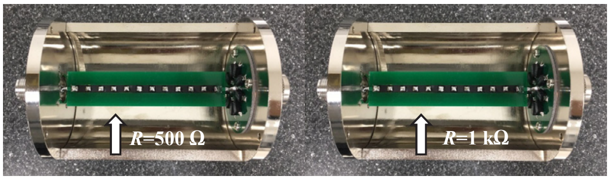

Fig. 3. RVDs with ratio of 100:1.

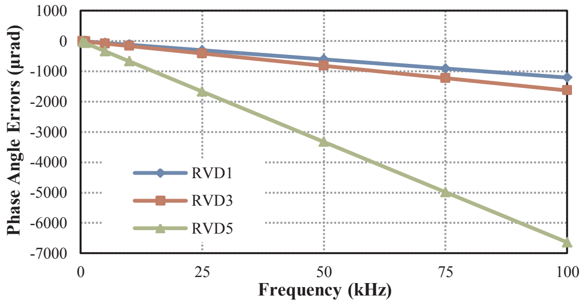

Fig. 4. Phase angle errors of RVDs with different ratios.

Table 2
Phase angle errors of three combinations.

Measurement results in μrad, at the frequencies *f* in kHz						
Combinations	0.4	10	25	50	75	100
RVD_2 + Buffer	2	23	34	43	60	98
RVD_4 + Buffer	1	14	23	34	57	84
RVD_6 + Buffer	1	5	8	11	24	56

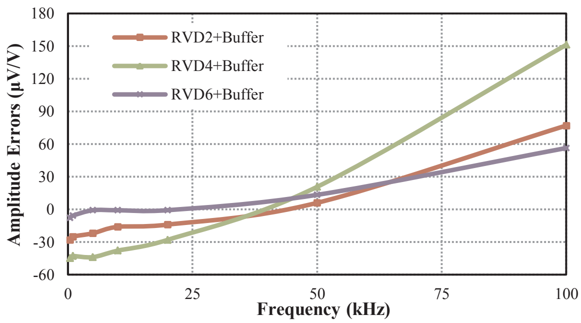

Fig. 5. Amplitude errors of three combinations.

ranges up to 600 V. As seen from the measurement results, shown in Fig. 5, the amplitude errors are less than 180 μV/V at frequencies up to 100 kHz with the stability within 10 μV/V after 30 min' preheating process.

2.2. Current shunts

A set of current shunts with cage-like design has been built to cover the current ranges from 1 A to 100 A. In the application of the ac power measurement, particularly at high frequencies and low power factors, the determination of both the ac-dc difference and the phase angle errors of the shunts is required. A 1-Ω coaxial time constant standard has been developed as the phase angle reference of the shunts at NIM [10] and the basic structure is shown in Fig. 6.

This time constant standard contains eighteen constantan wires with a diameter of 0.6 mm and length of 105 mm in parallel connection. These constantan wires evenly distribute along a circular surface between two printed circuit boards with copper layer. The current input terminal is connected to the core of the copper board and current is fed through the constantan wires to the copper housing of shunt as current loop. The phase angle errors of the time constant standard have been determined by measuring the equivalent inductance against a mutual inductance, and the standard uncertainties range from less than 1 μrad at 400 Hz to 20 μrad at 100 kHz.

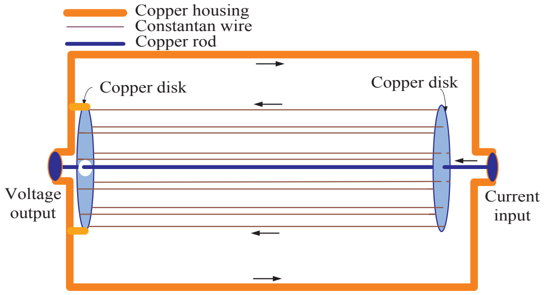

Fig. 6. Basic structure of the time constant standard.

A method has been proposed to measure the phase angle errors of high current shunts at frequencies up to 100 kHz and described in [11]. This method is based on the three-branch binary inductive current divider (BICD) [12] to calibrate the shunts against the reference standard in parallel with inductive voltage divider (IVD). A set of IVDs with ratios of 2:1–100:1 has been designed and the phase angle errors have been calibrated against the reference VDs. Using this method, the phase angle errors of the 100 A current shunt can be directly calibrated against the 1 A current shunt paralleled with 100:1 IVD in only one step. Meanwhile, other shunts can also be calibrated against the reference standard with different IVDs. The level dependence in phase angle errors of the current shunts has also been evaluated to be less than 20 μrad at 100 kHz. A set of current shunts with ranges from 1 A to 100 A has been measured at frequencies up to 100 kHz and the results in phase angle errors have been given and shown in Fig. 7. As seen from the Fig. 7, the phase angle errors of each shunt show good linearity relationship with frequencies.

The dc resistances of the shunts ranging from 0.01 Ω to 1 Ω have been calibrated against the resistance standard with the standard uncertainties less than 5 μΩ/Ω. The ac-dc difference of the shunts has been determined through traceable measurements in terms of the fundamental current standard during a step-up procedure. A set of shunts with ranges from 1 A to 100 A has been measured in ac-dc difference at frequencies up to 100 kHz and the results have been given and shown in Fig. 8. The level dependence in ac-dc of the shunts has been measured to be less than 2 μA/A at 1 A [13] and also been evaluated for high current shunts up to 100 A within 20 μA/A under the frequency ranges from 1 kHz to 100 kHz.

2.3. Dual-Channel digitizer

The amplitude errors of the two voltage signals from the outputs of

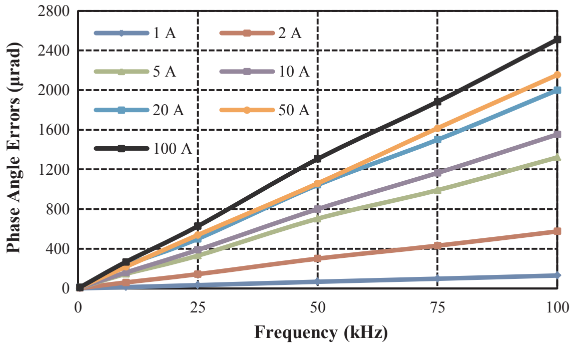

Fig. 7. Phase angle errors of current shunts.

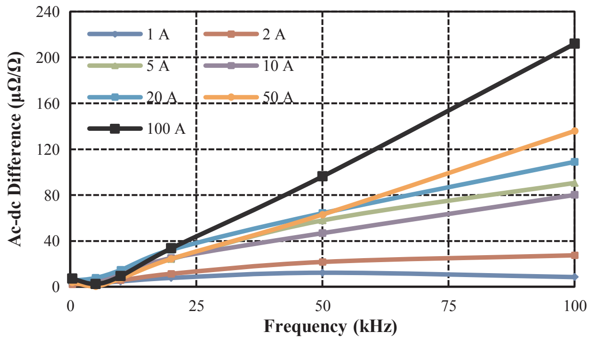

Fig. 8. Ac-dc difference of current shunts.

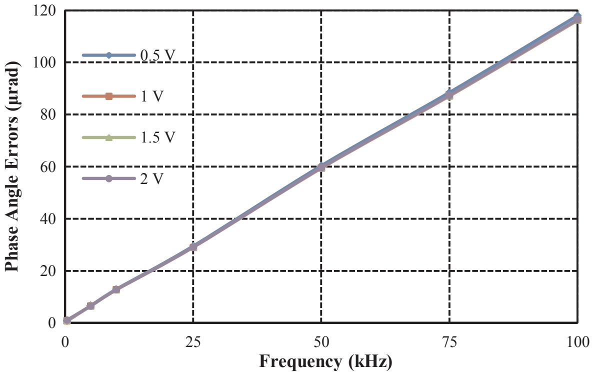

Fig. 9. Phase angle errors between two channels of the digitizer.

the RVD and current shunt can be directly calibrated against the accurate voltmeter at frequencies up to 100 kHz. The dual-channel digitizer NI-PXI-5922 has been applied to measure the phase angle errors between the two voltage signals. The digitizer has been set to be operated at sampling rates from 100 kS/s at 1 kHz to 10 MS/s at 100 kHz. The phase angle relationship between two channels of the digitizer has also been measured at frequency ranges from 400 Hz to 100 kHz and the voltage ranges from 0.5 V to 2 V. The measurement results have been given and shown in the Fig. 9. As seen from the Fig. 9, the phase angle errors for this digitizer show good linearity relationship with frequencies up to 100 kHz and non-linearity influences at voltages from 0.5 V to 2 V are within 5 μrad. The phase angle errors have also been evaluated and appeared not to depend on the phase angles between two channels at frequencies up to 100 kHz [14].

3. Uncertainty budget

Table 3 shows a typical uncertainty budget of the ac power standard at frequencies from 400 Hz to 100 kHz at 600 V, 100 A and power factors of 0, 0.5 and 1. As seen from this Table, the budget is mainly comprised of the influence from RVDs, shunts and difference between two channels of the sampling digitizer. Each component of the power standard has been evaluated both in amplitude and phase angle errors, including the level dependence influence and the stability effect during the measurement procedure. The correction coefficient has been applied at different power factors. The coefficient $|\cos\theta|$ is used to correct the influence from amplitude errors of each component, and the coefficient $|\sin\theta|$ is for the influence from phase angle errors. The standard uncertainty of the power standard, covering the voltage ranges up to 600 V and current ranges up to 100 A, is within 70 μW/VA at frequencies from 400 Hz to 100 kHz when the power factor is 1, and less than 90 μW/VA when the power factor is 0.

Table 3
Uncertainty budget of ac power standard at current ranges from 1 A to 100 A and frequency ranges from 400 Hz to 100 kHz at 600 V.

The uncertainties components		Unit	Frequency in kHz					
			0.4	1	10	20	50	100
Amplitude and phase angle errors from RVDs								
Amplitude errors of RVDs	u_{am}	μV/V	12	14	14	18	27	38
Phase angle errors of RVDs	u_{ph}	μrad	2	3	10	19	35	61
Amplitude and phase angle errors from Sampling digitizer								
Amplitude errors of channel 0	u_0	μV/V	4	4	4	5	5	5
Amplitude errors of channel 1	u_1	μV/V	4	4	4	5	5	5
Phase angle errors of two channels	u_{phs}	μrad	1	1	1	2	5	10
Linearity errors	u_{li}	μrad	1	1	1	1	1	1
Amplitude errors from current shunts								
1-A shunt	u_{1AF}	μΩ/Ω	5	6	7	7	8	10
2-A shunt	u_{2AF}	μΩ/Ω	7	8	9	9	10	14
5-A shunt	u_{5AF}	μΩ/Ω	8	9	11	12	13	17
10-A shunt	u_{10AF}	μΩ/Ω	10	11	13	14	15	22
20-A shunt	u_{20AF}	μΩ/Ω	12	13	15	17	18	26
50-A shunt	u_{50AF}	μΩ/Ω	15	18	20	24	25	34
100-A shunt	u_{100AF}	μΩ/Ω	20	22	26	32	36	54
Phase angle errors from current shunts								
1-A shunt	u_{1AP}	μrad	1	2	3	5	10	20
2-A shunt	u_{2AP}	μrad	5	7	8	12	18	30
5-A shunt	u_{5AP}	μrad	7	11	15	19	25	40
10-A shunt	u_{10AP}	μrad	5	9	14	17	23	36
20-A shunt	u_{20AP}	μrad	7	11	16	20	26	41
50-A shunt	u_{50AP}	μrad	8	13	18	23	29	46
100-A shunt	u_{100AP}	μrad	12	16	19	25	37	51
Standard uncertainties of ac power standard in μW/VA								
Current ranges		Power factors	0.4	1	10	20	50	100
1 A		1	14	16	17	20	29	40
		0.5	10	12	15	23	40	67
		0	2	3	10	20	37	65
2 A		1	15	17	17	21	29	41
		0.5	12	14	17	26	43	71
		0	6	7	13	23	40	69
5 A		1	16	18	19	22	30	42
		0.5	13	16	21	30	46	75
		0	7	11	18	27	44	74
10 A		1	16	18	20	24	32	44
		0.5	13	15	21	29	45	74
		0	6	9	17	25	42	72
20 A		1	18	20	22	25	33	46
		0.5	14	18	23	31	47	77
		0	7	12	19	27	44	74
50 A		1	20	24	25	31	37	52
		0.5	16	21	26	35	50	81
		0	8	13	21	30	46	77
100 A		1	23	27	30	37	46	66
		0.5	20	24	29	40	58	89
		0	12	16	22	32	51	81

4. Conclusion

The national ac power standard has been established at NIM, China to cover the voltage ranges up to 600 V and current ranges up to 100 A at the frequencies from 400 Hz to 100 kHz and power factors from 0 to 1. The standard is mainly focused on solving the calibration of the phase angle errors of the voltage dividers and current shunts, especially at high frequencies. The measurement uncertainties of the standard have been evaluated and given in this paper at different power factors and working frequencies. The power standard system will be applied to provide the traceability for the commercial power measurement instruments.

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