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Establishment of AC power standard at frequencies up to 100 kHz

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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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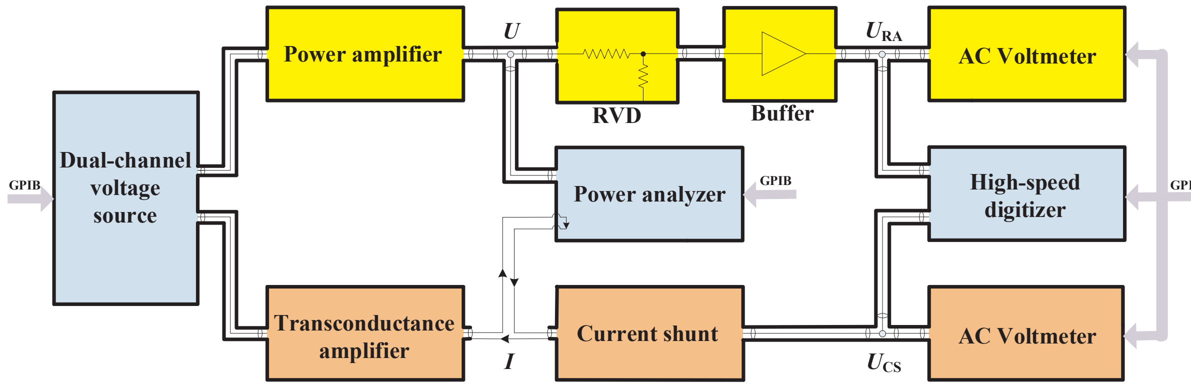

Fig. 1. Diagram of national power standard system.

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.

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

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 $RVD_{1\#}$ and $RVD_{2\#}$, have been built with identical structure parameters to keep the same capacitive distribution. The $RVD_{1\#}$ and $RVD_{2\#}$ 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 $RVD_{1\#}$ is θ_1, the phase error of $RVD_{2\#}$ is $K\theta_1$, so the difference between two RVDs is $(K-1)\theta_1$. By measuring the difference, the phase angle errors of two RVDs can be determined respectively.

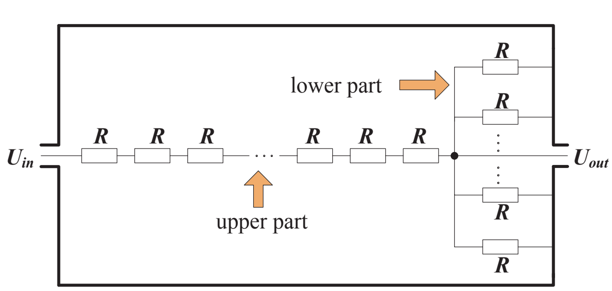

Fig. 2. Basic structure of RVD with serial-parallel connection.

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