Extension of Voltage Range for Power and Energy Calibrations

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***Abstract*— A special purpose ac voltage divider system with ratios of 600, 480, 360, 277, and 240 V to 120 V has been developed to extend the range of primary electric power calibrations from 120–600 V at 50 and 60 Hz. The developmental goal has been to realize ac voltage scaling within 5 μV/V overall relative uncertainty. By employing a technique consisting of a special two-stage resistive divider compensated with an active circuit, the overall uncertainty achieved after calibration is 4 μV/V.**

Index Terms—**Active voltage divider, calibration, power measurement, precision.**

I. Introduction

At the National Institute of Standards and Technology (NIST), the primary realization of the quantity of ac electric power, the watt, is accomplished by means of a "power bridge" [1]. The bridge is optimized for operation at 120 V and 5 A. Calibrations at other voltages and currents are possible using scaling transformers within the power bridge. To further extend the voltage range to 600 V, it was decided to investigate an amplifier-compensated resistive divider technique, similar to that successfully applied to high-voltage capacitive dividers [2]. The goal was to develop a multi-ratio divider for voltage ratios to 600 V/120 V having a relative uncertainty within 5 μV/V.

II. Operating Principle

The basic circuit is an active, two-stage voltage divider with each stage configured as an operational amplifier. As originally implemented in a related development of a high-voltage capacitive divider [2], the analogous resistive divider is shown in Fig. 1(a). The first-stage divider designated as the coarse divider is formed by amplifier, A_1, and the resistors, R_{S3} and R_{S4}. It provides an approximate output voltage, V_{21}, given by the following equation:

$$\begin{aligned} V_{21} &= -V_1(R_{S4}/R_{S3})(1-\epsilon_1) \\ &= -V_1(R_{S2}/R_{S1})(1-\epsilon_1-\epsilon_2) \end{aligned} \quad (1)$$

where the error term, ϵ_1, is caused by the finite loop gain of A and the connected passive circuit; the second error term, ϵ_2, results from the small difference between the two nominally-equal resistance ratios, (R_{S4}/R_{S3}) and (R_{S2}/R_{S1}).

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Since most of the signal contributing to the output voltage, V_2, is supplied by A_1, the second stage amplifier, A_2, has to provide only a small error voltage, V_{22}, given by the error terms in (1). In practice A_2 supplies such an error voltage, but with a small error of its own, ϵ_3, due to the finite loop gain of A_2 and the passive network connected to it. Thus

$$V_{22} = V_1(R_{S2}/R_{S1})(\epsilon_1+\epsilon_2)(1-\epsilon_3). \quad (2)$$

Amplifier A_3, with its network of four equal resistances subtracts V_{22} from V_{21}. By subtracting (2) from (1) the following expression relating input and output voltages is obtained:

$$V_2 = V_{21} - V_{22} = -V_1(R_{S2}/R_{S1})[1-(\epsilon_1+\epsilon_2)\epsilon_3]. \quad (3)$$

While in the preceding analysis the subtracting amplifier circuit is treated as ideal, in practice it has its own errors caused by the finite loop gain and small differences in the resistance values. The result is that the error terms in (3) are modified but the overall error is similar, consisting of a product of two small quantities, each $<10^{-3}$.

The circuit of Fig. 1(a) is useful also for the analysis of the dynamic stability of the entire instrument. Both feedback loops, the first consisting of A_1, R_{S4}, and R_{S3}, and the second involving A_2, A_3, R_{S2}, and R_{S1} must be stable. It should be noted that the two loops do not interact with each other with respect to feedback performance. The output of A_1 is added in the second loop as an equivalent controlled source. The second loop is more difficult to stabilize as it contains two amplifiers, doubling the phase shift in the critical high-frequency region. Careful compensation is required to produce a stable circuit.

The circuit of Fig. 1(a) can be simplified by combining in A_1 the original function with the signal adding function of A_3 as shown in Fig. 1(b). The output of A_2 is connected to the summing point of A_1 through a resistor R'_{S4} having the same nominal value as R_{S4}. This adds the output of A_2 directly to the output of A_1 without any amplification or attenuation. A different value for R'_{S4} will increase or decrease the gain of the loop containing A_2. The previously derived equations are equally applicable to the circuit of Fig. 1(b). With respect to stability considerations, A_2 by itself must be stable, and the loop containing A_1 and A_2 must be stable. The circuit of Fig. 1(b) is superior for the intended application to that of the equivalent implementation of Fig. 1(a) because an amplifier is eliminated, the number of circuit components is reduced, and the stability and interference problems are slightly mitigated.

TABLE I
MEASUREMENT OF RESISTOR AND DIVIDER RATIOS

Nominal Ratio (resistance or voltage)	DC Resistance Ratio Correction (x 10^{-6})	AC Resistance Ratio at 24 V		Divider Ratio at 24 V Output		Divider Ratio at 120 V Output (data set 1)		Divider Ratio at 120 V Output (data set 2)	
		Ratio Correction (x 10^{-6})	Phase Angle (μrad)	Ratio Correction (x 10^{-6})	Phase Angle (μrad)	Ratio Correction (x 10^{-6})	Phase Angle (μrad)	Ratio Correction (x 10^{-6})	Phase Angle (μrad)
240/120	+ 2.3	+ 6.5	- 11.5	+ 7.0	- 12.5	+ 11.7	- 11.8	+ 13.1	- 11.8
360/120	- 7.2	- 7.7	- 26.4	- 8.0	- 26.5	- 1.4	- 26.2	- 1.2	- 26.8
480/120	- 2.1	- 3.6	- 45.6	- 3.6	- 46.5	- 6.3	- 45.2	- 5.6	- 45.7
600/120	- 4.1	- 6.0	- 76.1	- 6.0	- 77.5	- 6.7	- 76.9	- 6.1	- 76.8
Estimated Uncertainties		± 3	± 3	± 3	± 3	± 2	± 2	± 2	± 2

The Ratio Correction (RC) is defined by the equation True Ratio = Nominal Ratio x (1 + RC).

Positive phase angle of the divider ratio means that the output voltage phasor leads the input voltage phasor.

The data set 2 for the divider ratio at 120 V was obtained 30 days after data set 1.

TABLE II
MEASUREMENT UNCERTAINTIES

Source of Uncertainty	Ratio Error (x10^{-6})	Phase Angle (μrad)
Initial calibration	± 1.2	± 1.2
Electronic circuit	± 0.6	± 0.6
Ambient temperature	± 0.7	0
Power coefficient variation	± 1.2	0
Lead impedances	± 0.6	± 0.6
RSS	± 2.0	± 1.5
2(RSS)	± 4.0	± 3.0

performance of the divider in the NIST power calibration equipment.

On the basis of these results, the strategy for future use of this divider is to perform its calibration at the time of each critical use when the lowest uncertainty of $\pm 5 \times 10^{-6}$ in ratio is required. For most of the other work higher uncertainty is acceptable, and calibration at regular intervals may suffice. Testing is continuing to assess long-term performance and to seek more stable resistors.

V. MEASUREMENT UNCERTAINTIES

The estimated uncertainties of the divider, excluding variations in the resistance ratio due to the power coefficient, which effectively are applied as corrections, are given in Table II. The bottom line in the table represents 0.95 probability of the uncertainties being within the stated limits.

VI. CONCLUSIONS

A voltage divider for extending the calibration range of wattmeters and watthour meters has been developed and constructed. It easily meets the accuracy requirements for calibration of industrial standards for which an uncertainty of $\pm 50 \times 10^{-6}$ is offered. For the highest accuracy standards such as those involved in international comparisons among national standards laboratories for which voltage scaling uncertainty within $\pm 5 \times 10^{-6}$ is required, calibration of the instrument at the operating voltage is needed. An amplifier circuit enables operating moderately high-resistance-value resistors as precision three-terminal impedance elements and also provides low-impedance output without contributing any additional errors. At the present time the accuracy limitation is imposed by the power coefficient of the precision resistors, the reduction of which is being explored.

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REFERENCES

[1] N. Oldham and O. Petersons, "Calibration of standard wattmeters using a capacitance bridge and a digital generator," *IEEE Trans. Instrum. Meas.*, vol. IM-34, pp. 521–524, Dec. 1985.

[2] O. Petersons and S. P. Mehta, "An active voltage divider and phase shifter," *IEEE Trans. Instrum. Meas.*, vol. IM-36, pp. 362–368, June 1987.

[3] O. Petersons and W. E. Anderson, "A wide range high voltage capacitance bridge with 1 ppm accuracy," *IEEE Trans. Instrum. Meas.*, vol. IM-24, pp. 336–344, Dec. 1975.

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