An Accurate, Automated 10-V Measuring System

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Abstract—**A microcomputer-based system to measure dc voltages accurately to 10 V is described. It consists of a self-checking voltage divider with a terminal linearity of ±0.015 ppm (1σ), a 26-channel scanner, a stable 10-V source and at least one known voltage reference. It has proven to be particularly useful in the automatic calibration of solid-state voltage standards and voltage dividers.**

I. Introduction

MOST NATIONAL standards laboratories use the Josephson effect to define their unit of voltage. Although the use of standard cells to maintain a 1.018-V reference is still prevalent among standards laboratories, the use of solid-state voltage references of good quality and stability is increasing. Compared with the Weston chemical cells, the solid-state references are more rugged, easier to maintain, more convenient to use (especially in Josephson array work), and commercially available in several output voltages, e.g., 10, 6.5, 1.018, and 1 V.

The microcomputer-based measuring system to be described has been assembled at the National Research Council of Canada for the automatic and accurate calibration of voltage references of all values up to 10 V. It can also be used for voltage divider calibrations.

II. General Description

The heart of the automated 10-V measuring system (Fig. 1) is a microprocessor-based reference binary voltage divider (REF BVD, or BVD) [1]. The divider, when powered by a solid-state 10-V reference (power switch ON, Fig. 1), can be programmed by a desktop microcomputer to perform: 1) autocalibration or 2) autobalance, when the system null voltmeter is used to compare the BVD's output V_{out} with an internal voltage V_{test} or a test voltage V_x, respectively. A 26-channel scanner allows many sources of test voltage to be measured automatically. This system differs from the others reported in the literature [2]–[4] in the way it generates the requisite voltage ratios and compensates for the extraneous voltage offsets in the measuring circuit.

A single test divider is shown in Fig. 1, where two current leads to its input terminals *A* and *C* are required. Otherwise, all the cables (dashed lines) connected with the scanner are potential leads of solid copper, guarded by a coaxial shield. The single-pole, 26-channel scanner uses

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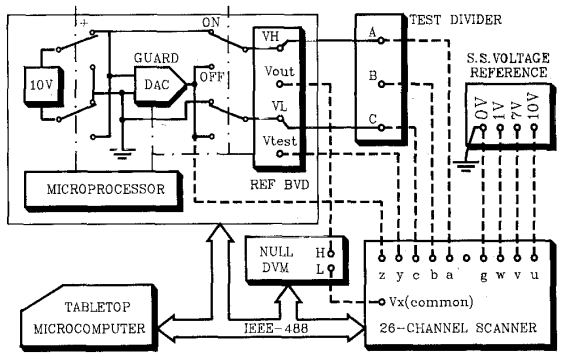

Fig. 1. Block diagram of the automated 10-V measuring system, featuring a binary voltage divider (BVD), a null digital voltmeter (DVM), and a scanner. Solid lines are current leads; dashed lines are potential leads.

sealed, pulse-operated latching relays mounted on a single circuit board inside a heavy metal housing. It is designed to let no more than one channel be selected at any one time. As shown, channel-*y* is used for autocalibration, channel-*z* for offset measurements, and channel-*g* for system ground.

A digital voltmeter (DVM) having a 0.1-μV basic resolution is used as the system null voltmeter. Its input guard circuit is driven at the common-mode voltage supplied by a digital-to-analog converter (DAC). Normally, each independently balanced measurement returns the average of 10 DVM readings, each taken over 100-ac power-cycles. In the more tolerant autocalibration environment, however, each DVM reading is taken over only 10-ac power-cycles.

In a typical calibration run, the 10-V measuring system is paced through an autocalibration routine in about three minutes, then it is standardized against at least one *known* voltage reference V_{ref}, accessible via the scanner. A *ratio-to-voltage* conversion factor M (≈ 10 V) is calculated, making the divider effectively a 10-V potentiometer. Independent voltage measurements can then be made every two minutes, also via the scanner.

All the above system components communicate with the desktop microcomputer via the IEEE-488 interface.

III. Measurement Procedures and Results

The self-checking BVD had been extensively studied when it was driven at ±10 V and reversed dc measurements were made. Under these conditions, the voltage divider is highly accurate and well-behaved because thermal EMF's and voltage offsets tend to be averaged out.

With the original 25-bit BVD, arbitrary voltage *ratios* between zero and unity could be measured with an uncertainty (1σ) of $\pm 0.017 \times 10^{-6}$ of input.

An apparently more difficult situation for any 10-V measuring system to handle accurately is the calibration of ground-referenced voltage sources when reversed dc measurements are inappropriate.

To begin with, the scanner was evaluated *in-situ* by the system with all input cables terminated on a heavy grounded copper bus. As the channels were cyclically scanned, the residual EMF's were measured with the help of a nanovolt preamplifier. Provided that the readings were taken at least 5 s after a channel selection, their distribution had a standard deviation of 0.016 μV. When making a sequential comparison of like voltages, the uncertainty is largely due to the scanner which contributes $\sqrt{2} \times 0.016$ or 0.023 μV.

The following practices have been adopted in order to make unipolar measurements as accurately as possible with the existing equipment. First, all stages of the divider are to be self-checked before use, and under the actual (unipolar) measuring condition. The lower-order 12-bit potentiometer of the original 25-bit divider was not subject to regular calibrations, and it exhibited a small voltage offset error in unipolar operations. Its removal from the circuit has meant that only the self-checking 13-bit divider is retained, and that the DVM may be measuring up to 1.2 mV during a final "balance." Neither situation causes any practical problems.

The relatively high output resistance (up to 120 kΩ) of the BVD can be troublesome. In the past, the DVM's loading effect was compensated for by 1) computing the BVD's output resistance R_{out} [5] at the balanced setting, and 2) measuring the guarded DVM's input resistance to ground (RLG or RHG in Fig. 2(a)). The effects due to offset voltage V_{os} and offset currents were minimized by reversed dc averaging. More recently, the following procedure has been adopted to compensate for all the above influences.

In addition to the normal, "power-ON" balance measurement (top, Fig. 2(b)), a "power-OFF" measurement (bottom) is also made. In the latter case, the BVD's setting is left unchanged; its input terminals as well as the DVM's input on the V_x side are connected to the guard voltage V_g, which is likewise not changed from its value (mean of V_{out} and V_x) at balance. This "power-OFF" reading captures *in-situ* the sum of all loading and offset errors at balance, and it is always subtracted from the "power-ON" reading to give a compensated result. Note that neither R_{out} nor the DVM's input parameters need to be known explicitly. Provided that the resistance change as seen by the V_x input of the DVM is less than a few kilohms from one balance measurement to the other, the compensation is virtually error free.

It is recognized that problems may arise from ac noise pickup and rectification by circuit components (e.g., Zeners). A number of incremental measurements were made

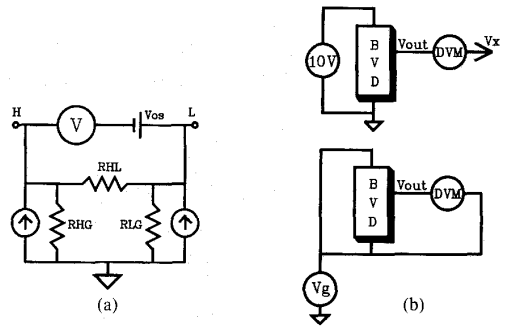

Fig. 2. (a) Equivalent circuit of a guarded digital voltmeter (DVM). An ideal voltmeter (V) in series with the offset V_{os} is shunted by RHL (≈ 10 GΩ). Leakage resistances RHG and RLG, plus bias current sources are ground-referenced. (b) Simplified circuits showing the "power-ON" → "power-OFF" sequence (top → bottom) of measurements. The guard voltage $V_g \approx V_{out} \approx V_x$ at "balance."

TABLE I
1-σ UNCERTAINTY ASSIGNMENT FOR THE 10-V MEASURING SYSTEM

A. Conversion Factor M ($\approx$ 10 V)		
(Reference $V_{ref} \approx 1.018$ V)		
10-V supply	(short term)	±0.010 ppm
BVD ratio		0.015
Offset corr.	(17 nV/V_{ref})	0.017
Scanner	(23 nV/V_{ref})	0.023
V_{ref}	(not included)	-----
RSS Subtotal (σ_1)		±0.033 ppm
B. Measurement of Ratio $G_t = V_x / V_{in}$		
(Uncertainty in ppm of $V_{in} \approx$ 10 V)		
BVD ratio (G_t)		±0.015 ppm
BVD ratio drift		0.008
Offset corr. & scanner		0.003
RSS Subtotal (σ_2)		±0.017 ppm
C. Measurement of $V_x = M \times G_t$		
Variance of V_x : $\sigma_3^2 = \sigma_1^2 + \sigma_2^2 / G_t^2$		
Example:		
For $V_x \approx 7$ V, $G_t \approx 0.7$		
σ_3 = ±0.041 ppm (of V_x)		

by introducing an additional length of input cable in a noisy environment on two types of Zener references at hand, but no problems were encountered. However, more exhaustive tests involving other references have not been attempted.

In assessing the uncertainties (Table I) for the 10-V system, it is assumed that the average of four independently balanced measurements (in one given polarity) will always be used. The ratio uncertainty of the 13-bit BVD has been marginally improved to ± 0.015 ppm. The nominal value of the standardizing V_{ref} will affect the overall

uncertainty in determining the conversion factor M. For the present purpose, standardization at 1.018 V is assumed, and the uncertainty of the reference standard(s) is not included in the uncertainty budget.

To check the above measuring procedure for accuracy, a 6-element self-checking resistive ratio device [6] was employed. It was connected into the system as a "test divider" (Fig. 1). There exists two dual configurations yielding the same nominal ratio of $N/10$ ($N = 1, 2, \cdots$). (The process is described in [1], Section IV.) When the input voltage between A and C has been normalized to ± 10 V, the geometric mean of the voltages at B obtained from the dual configurations should be equal to N V precisely. No discrepancies exceeding 0.3 μV were observed.

IV. Conclusion

The increasing popularity of solid-state voltage references has prompted the assembly of this automated 10-V measuring system. It is expected to handle the automatic calibration of voltage standards up to 10 V, in either polarity. The same system can be used for voltage divider as well as DVM linearity calibrations to eight significant digits.

It should be pointed out that the differential measurement procedures adopted for the system were mainly responsible for realizing the best performances of the scanner and the null voltmeter.

At present, the standardization is carried out at the 1-V level. The advent of 10-V Josephson arrays will likely change this practice.

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