Experimental Studies of the RF–DC Differences of Voltage Standards

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Abstract—**The RF–dc differences (d) of primary voltage standards have been determined by experimental and theoretical processes. Comparisons of five different types of voltage standards have been made.**

I. INTRODUCTION

IN THE People's Republic of China, the primary voltage standards, which are of different types in different frequency ranges, are checked against other standards in adjacent frequency regions. Audio-frequency multijunction thermal converters (MJTC's) are used as primary low frequency references for coaxial thermal voltage converters (CTVC's). CTVC's may be used to measure the frequency response of MJTC's and used as primary references for the thin film bolometric bridges in the frequency range of 30 MHz and below. The thin film bolometric bridge is used to measure the frequency response of CTVC's above 10 or 30 MHz. The voltage standards, based on different principles and constructions, have been compared with CTVC's at frequencies from 1 to 100 MHz. In this way some error sources might be discovered and eliminated which were neglected by theoretical analysis, and the voltage standards are, therefore, based on more reliable experiments.

The structure, theoretical analysis, and calculations related to RF–dc differences of CTVC's have been described in detail elsewhere [1]–[6]. The d's of the actual converters are close, or very close to, the theoretical values, but they inevitably differ due to differences in materials and workmanship. Therefore, the determination of d of the primary standard converters must be decided only by a combination of experimental data and theoretical considerations.

II. THE DETERMINATION AND VERIFICATION OF d VALUES FOR CTVC'S

A. The Frequency Response of CTVC

The bolometric method has been widely used to measure voltages from 1 MHz to 3 GHz in China since 1970. A bolometer element—either a barreter made of platinum, a semiconductor bead thermistor, a self-heating thermocouple, or a thin film thermistor designed in different shapes and made by different organizations—is placed into a RF holder and subjected to the heating effect of incoming voltage. Holders of different dimensions were used for different frequency ranges. The accuracies of thin film bolometric bridges are from 0.25 to 1 percent. The d of the CTVC's increase with increasing frequency and at frequencies from 100 to 300 MHz generally can reach several percent. The RF response of CTVC's can be measured by the thin film bolometric bridge. Examples of the frequency response of CTVC's ranging from 0.2 to 5 V are shown in Fig. 1.

B. How to Obtain the Empirical Formula

When the frequency is higher than 50 kHz for magnetic leads, and 5 kHz for platinum leads, the d of a CTVC can be expressed as

$$d = Af^{1/2} + Bf^2 + d_0 \tag{1}$$

where d_0 is the ac–dc difference at audio frequency, A and B are coefficients, and f is the frequency in megahertz [4], [6].

In experiments on a CTVC which is not compensated, d_0 can be determined by audio-frequency voltage standards, and two d values at two frequencies between 100 and 300 MHz can be tested by a bolometer, then we can get A and B from (1). In fact, because the error in the determination of d tested by a bolometer may reach ±0.25 percent, A and B will also have a large uncertainty. So, by taking the d values at several frequencies and using the least squares method to get A and B, the errors of A and B are reduced. Even so, when A and B are determined from data at higher frequencies, the errors of d are still too large around 1 MHz.

In order to reduce the errors around 1 MHz, we can measure two or several CTVC's. For two CTVC's, we can derive the following equations:

$$d_{1i} = A_1 f_i^{1/2} + B_1 f_i^2 + d_{01} \tag{2}$$

$$d_{2i} = A_2 f_i^{1/2} + B_2 f_i^2 + d_{02} \tag{3}$$

$$\Delta_j = d_{2j} - d_{1j} = (A_2 - A_1) f_j^{1/2} + (B_2 - B_1) f_j^2 + d_{02} - d_{01} \tag{4}$$

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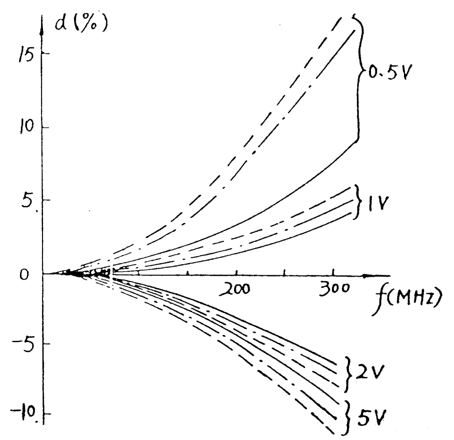

Fig. 1. The RF–dc differences of CTVC's computed theoretically and measured against the bolometer bridge: —— theoretical value; · – · – · – our CTVC: – – – – Singer Co. CTVC.

TABLE I
DATA TESTED BY BOLOMETER AND THE RESULTANT d OF CTVC

d (%) range f(MHz)	0.5v		2v		5v	
	Tested Data	$d=.0134f^{1/2}+2.34\times10^{-4}f^2$	Tested Data	$d=-.00075f^{1/2}-7.7\times10^{-5}f^2$	Tested Data	$d=-.0020f^{1/2}-8.36\times10^{-5}f^2$
0.4				-0.00049		-0.00128
1		0.0136		-0.00082		-0.00209
10		0.0658	-.008	-0.010		-0.0147
30	0.293	0.2842	-.073	-0.0731	-.086	-0.0862
50	0.660	0.6802	-.164	-0.197	-.188	-0.223
100	2.33		-.756	-0.774	-.802	-0.856
150	4.79		-1.65		-1.76	
200	7.69		-3.07		-3.16	
250	11.35		-4.84		-5.02	
300	15.12		-6.75		-6.9	

where the subscript 1 stands for one converter, 2 stands for another converter; f_i in (2), (3) ranges from 30 (or 50 MHz) to 300 MHz, and $i = 1, 2, \cdots, n$; and f_j in (4) is less than 300 MHz. d_{1i} and d_{2i} can be obtained using a bolometer as reference, Δ_j can be obtained precisely by direct comparisons of two CTVC's, $j = 1, 2, \cdots, m$. Then we can use the least squares method to calculate accurately A and B of each CTVC from (2)–(4), and we can obtain the d values at any frequency.

Above 200 MHz, some higher order error terms which are neglected in theoretical analysis will probably affect the d values slightly, so it is difficult to use one empirical formula to accurately express the d values over a wide frequency range from 50 kHz to 300 MHz. Therefore, the frequency range is divided into two bands, 50 kHz to 50 MHz (or 100 MHz), and from 30 to 300 MHz, and uses slightly different A and B values, respectively, to express d values for one converter. Thus the RF–dc differences can be obtained with high accuracy over a wide frequency range. The experimental results of primary standards made in recent years are shown in Tables I and II. A similar method can be used for other primary or reference standards.

TABLE II
COMPARISON RESULTS OF 2- AND 5-V CTVC'S

f (MHz)	$d_{2v}-d_{5v}$ (%)	Δ d (%)	e (%)
1	0.00127	0.00118	-0.0001
10	0.0046	0.0052	0.0006
30	0.0131	0.0124	-0.0007
50	0.0262	0.055	0.0288
100	0.0817	0.058	-0.0237

III. CONSTRUCTION DETAILS AND COMPARISONS OF SEVERAL VOLTAGE STANDARDS

A. *Wide Frequency Range Thin Film MJTC*

An MJTC on a plastic film substrate is put in the plane perpendicular to the coaxial line as shown in Fig. 2. On one side of the film, there are two radial resistors in opposite directions, which are in parallel electrically. The heater material is a NiCr alloy, the length of resistor is approximately 2.5 mm, and the parallel resistances are from 50 to 600 Ω. On other side of the film, there are three thermocouples which are almost perpendicular to each heater, with the hot junctions over the heaters. The lengths of thermocouples are from 3 to 5 mm, the total number of thermocouples is 6, and the total resistance is several kilohms. The signals are applied to one terminal of the coaxial line and the output at the opposite terminal of the line. The heater, thermocouples, and their gold leads are made by vacuum evaporation. This device is also called a "thermovac" as mentioned by Selby [7]. Because the heater and ac or dc source are connected directly without a coupling capacitor, the diameter of the holder is about 2 in and is much smaller than for the bolometer. Another advantage is the elimination of the need for matching the two resistor-halves. Such matching is an absolute requirement for accurate measurements in the bolometer. This UHF MJTC and its mounting cover the frequency range from 10 Hz to 1 GHz.

The thin film bolometric bridge of the Chinese National Institute of Metrology (NIM) is used to calibrate a CTVC whose RF–dc differences are less than 5 percent at 1 GHz and below. Then a UHF thin film MJTC is compared to a calibrated CTVC. The d of UHF thin film MJTC's are less than ±0.5 percent up to 1 GHz and are very small at 1 kHz. Generally, the variation with frequency of the response of UHF thin film MJTC's is expected to be extremely small. However, when it is measured using the CTVC as a primary standard, the variation exceeds the predicted values as shown in Table III. Its d values are mainly caused by losses from around 1 to 500 MHz and caused by the inductance of the heater at about 1 GHz. Due to the presence of thermocouples, the distributed inductance of the heater is reduced, and the distributed capacitance of the heater is increased. An additional temperature rise is caused by the dielectric loss of plastic film and the induced RF current in the thermocouple circuit because of some asymmetry in the thermocouple geometry.

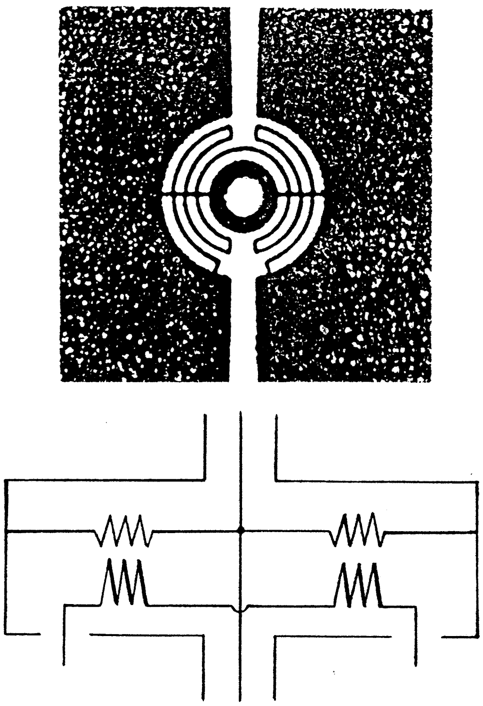

Fig. 2. MJTC thermovac device.

TABLE III
TESTED *d* OF THE THIN FILM MJTC

Standards \ d(%) \ f(MHz)	1	10	30	50	100	300	500	700	900	1000
Bolometer			-.03		-.10	-.30	-.23	-.09	-.03	.18
C.T.V.C	-.0099	-.0343	-.052	-.064	-.082	-.266				

B. The Frequency Response of Micropotentiometer (MPT)

In the micropotentiometers (MPT's), a UHF vacuum thermoelement or UHF thin film MJTC is used to measure current. The output resistor is a thin resistive film deposited on a disk substrate. In the millivolt range, the inductance and skin effect of disk resistors are very small and can be neglected [8]; so the RF–dc differences of MPT's are caused mainly by RF current measurement error and transmission line effects in the output connector.

In China, the bolometric bridge is used as the primary standard to calibrate an RF millivoltmeter which is used to measure the output RF voltage of an MPT. The frequency responses of small MPT's for which the distances from the resistor film to the center of thermoelement are small, are much flatter than those of both CTVC's and large MPT's at several hundred megahertz.

The 0.5-V CTVC serves as a primary standard to measure the MPT's at 0.2 V, and they are connected through a precision short Tee connector. In order to reduce the loading error on the MPT, namely the transmission line effect of the output connector of the MPT, a resistance load can be connected to the Tee in parallel with the 0.5-V CTVC to make the load on the MPT approximately equal to 50 Ω. Alternatively, the transmission line effect can be calculated and corrected for when the load of the MPT is not equal to 50 Ω. The MPT consists of a 40-mA thermoelement and a 5.3-Ω disk resistor, and the results are shown in Table IV. Up to 30 MHz, the accuracy of the MPT is ±0.2 percent and the standard deviation of the measurement is about 50 ppm. We believe that the uncertainties of MPT calibrations from 1 to 30 MHz can be reduced by using a CTVC as a primary standard and by improvements such as the resolution of MPT's.

TABLE IV
TESTED *d* OF MICROPOTENTIOMETER AGAINST A 0.5-V CTVC

d(%) \ f(MHz)	1	10	30
7808#40mA 5.3Ω	-0.013%	-0.028%	-0.043%

C. Comparison of CTVC and Thin Film Bolometer at Several Tens of Megahertz

The bolometric bridges used in China are similar to Selby's device [7] as shown in Fig. 3. With the thickness of thin resistor film of about 0.015 mm, according to Selby's formula, the skin effect of the resistor can be neglected up to 3 GHz. The inductance of the thin film resistor can be calculated and tested; its value is about 0.8 nH. The inductance causes an error [9] given by

$$\delta_L = \frac{\omega^2 L^2}{2R_{\mathrm{RF}}^2} = 0.005 \text{ percent},$$

$$\text{when } f = 1 \text{ GHz}, \; R_{\mathrm{RF}} = 50 \; \Omega.$$

The input capacitance of the holder structure in series with the resistor in the RF circuit can also be easily tested and its influence at lower frequency can be expressed as

$$\delta_c = \frac{1}{2}\left(\frac{1}{\omega c R_{\mathrm{RF}}}\right)^2$$

δ_c is about 0.015 percent for larger structures with 50-Ω resistors at 10 MHz. The influence of transmission line of input connector is reduced as much as possible and can be calculated according to the conventional formula. When the distance is about 3 μm, this error is less than 0.03 percent at 1 GHz, but the random error of the thin film bolometric bridge is greater, and can reach hundreds of parts per million.

Experimental comparisons of CTVC's with the thin film bolometric bridge, the primary standard of NIM, at frequencies from 10 to 100 MHz are shown in Tables V and VI.

D. The Frequency Response of the Compensated Voltmeter Model DO-1

The voltmeter's detector consists of a vacuum diode tube, as shown in Fig. 4, and is similar to Model B3-9 made in U.S.S.R. It has been popular in China and U.S.S.R. After rectification, the RF voltage is compared

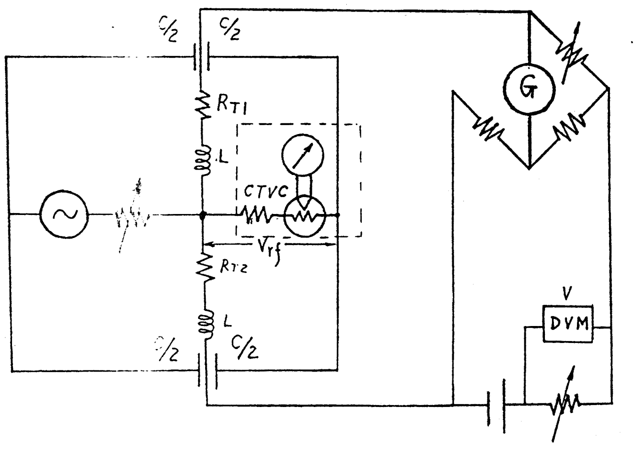

Fig. 3. The comparison of CTVC and bolometer.

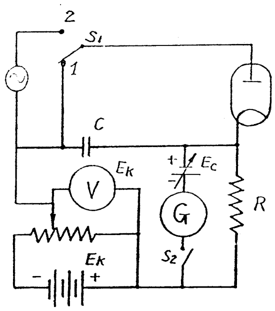

Fig. 4. The simplified circuit of compensated voltmeters, Model DO-1.

TABLE V

TESTED d OF BOLOMETER AT 10 MHz

Voltage	1 V	2 V
d	−0.01%	−0.02%
σ	0.006%	0.006%

TABLE VI

COMPARISON OF FREQUENCY RESPONSE OF BOLOMETER AND CTVC

	Bolometer	CTVC	difference
$d_{50MHz} - d_{30MHz}$	−0.083%	−0.124%	0.041%
$d_{100MHz} - d_{30MHz}$	−0.672%	−0.701%	0.029%

with a dc compensating voltage which can be easily measured. When the frequency is high, the inductance of leads, and the capacitance of the diode and leads cause resonance error. The electrons require time to travel over the distance to the anode and this also contributes to the error. Finally the input connector of the voltmeter causes transmission line errors. Its d values are generally less than ±1 percent in the frequency range from 400 Hz to 500 MHz as shown in Fig. 5. The accuracy of Model DO-1 is ±0.5 percent up to 50 MHz and ±3 percent up to 500 MHz [10]. When the Model DO-1 at NIM was measured using a CTVC as primary standard, the d value of Model DO-1 was +0.09 percent at 30 MHz.

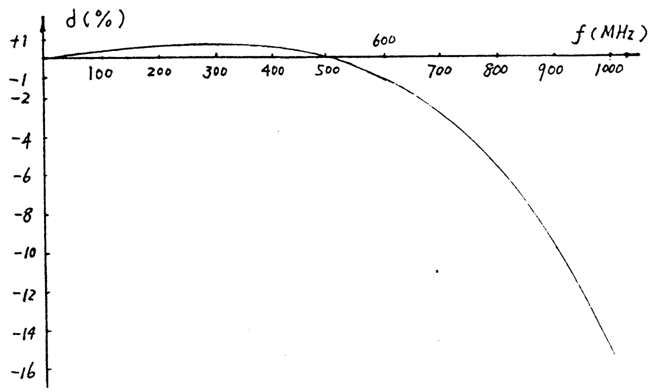

Fig. 5. The frequency response of compensated voltmeter, Model DO-1.

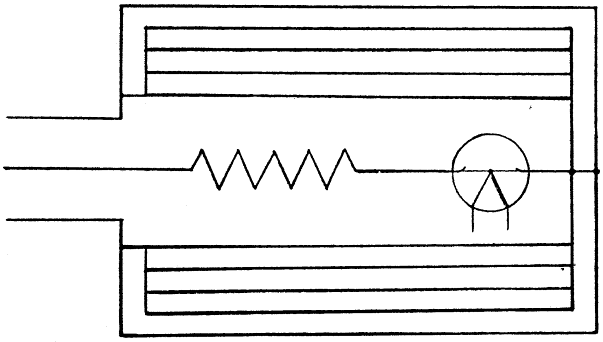

Fig. 6. CTVC with bifiliar ground leads.

E. CTVC with Bifilar Ground Leads Configuration

The bifilar ground leads which are split into sixteen lines are designed and mounted inside a cylinder as shown in Fig. 6. The transmission mode is a combined bifilar and coaxial line. Several such 1-V converters have been made with good workmanship in order to reduce skin effect, reduce the inductances of the resistor and thermocouple, and increase the distributed capacitances of the resistor and thermocouple to the ground. The RF–dc differences have been reduced as estimated, but the RF–dc differences still depart from zero due to different thermoelements.

One of them, 101#1V, was found to have an extremely flat frequency response. When it was measured using the bolometric bridge as a primary standard, the tested d values were less than ±0.1 percent up to 300 MHz and seemed to be almost zero below 100 MHz. When it was measured using the CTVC as primary standard, errors still existed below 100 MHz as shown in Table VII, and analysis showed that the errors were caused mainly by the skin effect of 101#1V.

In addition, a 5-V converter was made with a thermoelement having platinum leads, and was also measured using a CTVC as primary standard. The variation between the two was about −10 ppm at 1 MHz.

F. Summary

The RF–dc differences of five voltage standards mentioned above are very small, and the experimental results

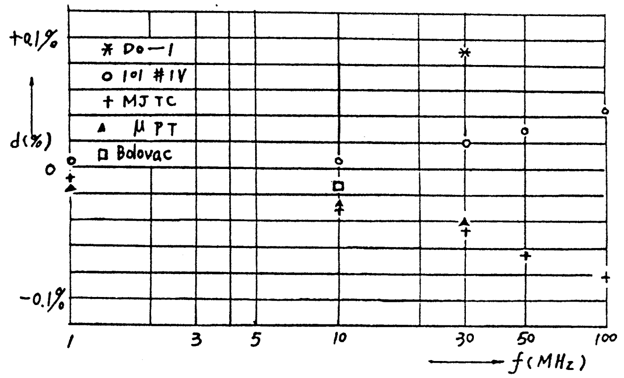

Fig. 7. The RF–dc differences of five RF voltage standards.

TABLE VII
TESTED *d* OF CONFIGURATION COMPENSATION CTVC

Standards \ d(%) f(MHz)	1	10	30	50	100	150	200	250	300	350	400
Bolometer			0	-.04	.01	.03	.06	.10	.03	-.08	-0.33
C.T.V.C	.0029	.0047	.020	.028	.045						

measured using a CTVC as primary standards are shown in Fig. 7. At the same time, these experiments verify the accuracy of the CTVC as primary standards.

IV. CONCLUSION

The RF–dc differences of some standards at frequencies from 10 Hz to 300 MHz, or even up to 1 GHz, are quite small, but the *d* values at frequencies from 0.1 to 50 MHz are not as small as may be possible. The recommended method to determine the *d* values is to derive an empirical formula, and then to correct it from measured data. The uncertainties of primary voltage standards established by this method are ±0.007 percent at 1 MHz, ±0.01 percent at 3 MHz, ±0.02 percent at 10 MHz, ±0.07 percent at 30 MHz, ±0.15 percent at 50 MHz, and ±0.3 percent at 100 MHz. These uncertainties are established on the firm basis of the theory and the experiments, and have been established while leaving sufficient margin for error.

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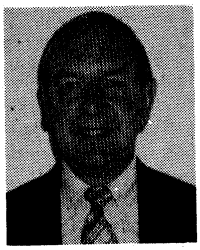

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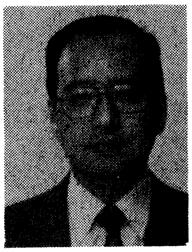

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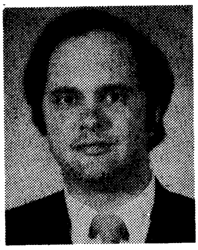

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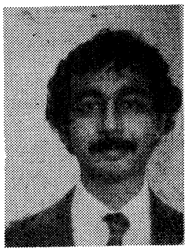

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