Thermal Converters

AC-DC DIFFERENCES OF HIGH VOLTAGE THERMAL CONVERTERS

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ABSTRACT

For some high voltage thermal converters (HVTC's), ac-dc differences vary with age, test timing sequence, and voltage level, especially for 1000-V ranges at frequencies above the audio range. A major contributor to these variations is dielectric loss and its changes with temperature, voltage, and frequency. The results of intercomparisons of HVTC's and certain methods to reduce ac-dc differences and their voltage coefficients are described.

INTRODUCTION

HVTC's are used as working and calibration standards of ac-dc difference up to 1000 V and 100 kHz. Their ac-dc differences can be compensated to yield small values by using internal, adjustable shields or by using software corrections in a transfer instrument. Although inherently quite stable, the ac-dc differences of HVTC's do vary as a function of warm-up time, frequency, applied voltage, and, somewhat, with age. Voltage coefficients between 500 V and 1000 V can be several hundred ppm or more for some worst case resistors, see Fig. 1. This investigation into some of these changes and ways to reduce them has revealed certain useful relationships and contributing factors which permit reduction of ac-dc difference variations.

AC-DC DIFFERENCES OF HVTC's

General Construction Characteristics

The high voltage ranges, e.g., 100 V to 1000 V, of thermal voltage

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converters commonly contain multiplying range resistors of 40 kΩ, 120 kΩ, 200 kΩ, or 400 kΩ and two thermoelements (TE's) rated at 2.5 mA and 5 mA [1]. Automatic transfer instruments may also contain input dividers using resistors in these ranges. A typical construction used in our experiments is shown in Fig. 2.

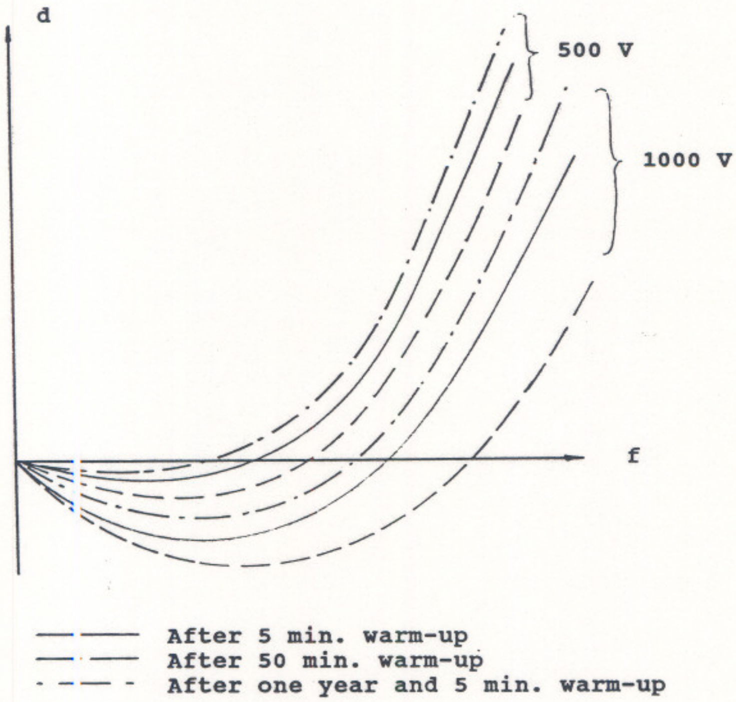

Fig. 1 Examples of ac-dc difference, d, for high voltage ranges versus frequency, f.

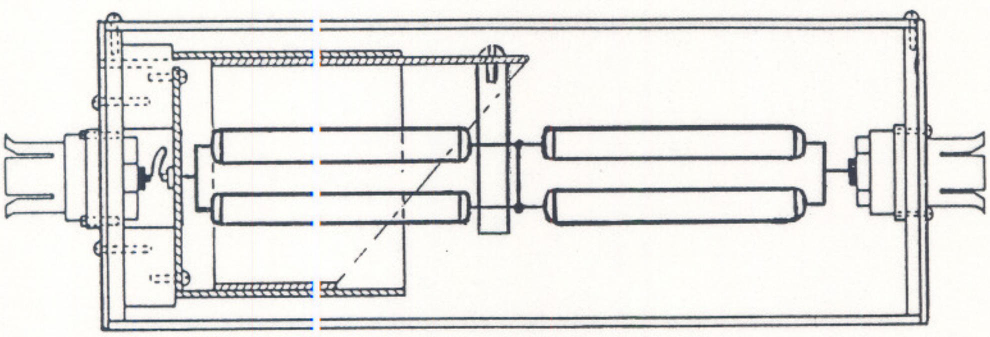

Fig. 2 Typical construction of a HVTC.

HVTC's Without Internal Shields

For HVTC's without internal shields, generally $R_r >> R_{TE}$, ωL_r, or ωL_{TE} where L_r, C_r, and R_r are the distributed inductance, distributed capacitance to the shield, and resistance of the multiplying range resistors; and L_{TE}, C_{TE}, and R_{TE} are the similar parameters for the thermoelement. Therefore, the ac-dc difference contribution from the transmission line effect, d_T, can be expressed as [2]:

$$d_T \approx \frac{\omega^2}{2}\left[\frac{-L_rC_r}{3} - \frac{L_{TE}C_{TE}}{3} - 2\frac{L_{TE}C_r}{3} + \frac{R_r^2C_r^2}{90}\right] \qquad (1)$$

If lower order small quantities are neglected, then

$$d_T \approx \frac{(\omega R_r C_r)^2}{180} \qquad (2)$$

Eq. 2 indicates that ac current is bypassed through the distributed capacitance from the resistor to the shield, so less ac current flows through the thermoelement producing a positive ac-dc difference. The ac-dc differences calculated using this relationship are in general agreement with experimental results for such simple structures containing no internal shields. The calculated results indicate that the transmission line effect of input connectors, current standing-wave contribution in the TE, skin effect in the cylinder or magnetic leads of the TE, all important for lower voltage ranges and/or at higher frequencies, can generally be neglected compared to the contribution to ac-dc difference shown in eq. 2. The distributed capacitance between unshielded range resistors and the outer cylinder which permits ac current to bypass the TE to ground is, therefore, a main source of error and it can be significantly reduced by the use of an internal shield structure.

HVTC's With Internal Shields

Usually an internal, adjustable shield [3] is used to compensate, or reduce, the ac-dc difference of HVTC's at frequencies above 10 kHz, see Fig. 2 & 3. The distributed capacitance between the range resistor and the internal shield permits more ac current to flow into the range resistor if the shield is on the high-voltage end or more ac current to flow directly into the TE connection if the shield is on the low-voltage end. In either case, more ac current flows into the TE than without the shield.

Using a similar analysis as eq. 1, the ac-dc difference contribution due to the transmission line effect, d_T, for the internal shield structure is

$$d_T \approx -\frac{(\omega R_1 C_1)^2}{180}$$

where R_1 and C_1 refer to the shielded R_1 indicated in Fig. 3. Therefore the total ac-dc difference caused by the transmission line effect from both the unshielded region, indicated as R_2 and C_2, and the shielded regions can be expressed approximately as

$$d_T \approx \frac{(\omega R_2 C_2)^2}{180} - \frac{(\omega R_1 C_1)^2}{180} \tag{3}$$

Note that if $R_1 \approx R_2$ and $C_1 \approx C_2$, then $d \approx 0$. If there is no additional internal shield surrounding R_2, but just the outside cylinder is present, and if the resistors are equal, then C_2 will be less than C_1. To make $d \approx 0$, the length of S_1 must be less than that of the resistor, and to compensate for the effect of the dielectric loss, the length of S_1 may need to be adjusted.

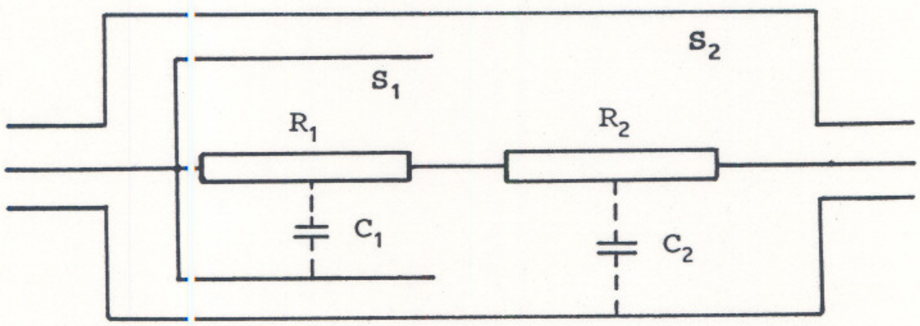

Fig. 3 Simplified diagram of shields in a HVTC

Dielectric Loss

There are distributed capacitances between all current carrying parts of the structure inside the external cylinder. In general, these distributed capacitances contain dielectric materials. The dielectric loss of the ceramic substrate for the resistors is generally very small and stable. The dielectric loss of any protective coating, insulating material, or the resistor film may be much larger and may change with age. The dielectric loss and dielectric constant are not merely fixed properties of the material, but depend on the manufacturing processes and working temperature.

The equivalent parallel resistance of a capacitor is inversely proportional to the capacitance, frequency, and dissipation factor. Therefore, the ac-dc difference contribution arising from the dielectric loss is approximately proportional to the frequency. Evidence of this relationship is given in the empirical section below.

Empirical Results

From the above analysis, coefficients of both the first and the second power of the frequency would be expected to contribute to the ac-dc difference. An empirical equation may be written as

$$d = d_0 + Af + Bf^2 \qquad (4)$$

where d_0 is roughly the ac-dc difference of the TE as a current converter at audio frequency, Af is the term caused by the dielectric loss, Bf^2 is the ac-dc difference caused by the distributed capacitance associated with the resistor and shield structures, and f is the frequency.

A non-linear, least squares fit was performed to determine the coefficients from experimental data. Table 1 shows experimental data and values calculated from the fitted curve for a 500-V converter. The fitted equation for this TVC was:

$$d = -0.88 - 0.113f - 9.4\times10^{-4}f^2$$

with d in ppm and f in kHz. The residual standard deviation was 0.9 ppm.

Table 1. Comparison Between Fitted Equation and Measured Data

Ac-Dc Difference (ppm)

f(kHz)	1	20	50	100
Experimental results	-1	-2	-9	-21
Non-linear fit	-1	-3	-8	-21

VOLTAGE COEFFICIENTS

The existence of voltage coefficients for the ac-dc difference of high-voltage ranges is well known [1,4]. The power applied to HVTC's at 1000 V is four times that at 500 V, so the working temperature of the resistors is usually much higher. The dielectric loss of the structure may be considerably different at 1000 V than at 500 V, and this is a major cause for voltage coefficients of ac-dc difference in compensated HVTC's.

The difference in the temperature of the range resistor may cause a change in the resistance value from one voltage to another. For HVTC's with no internal shield, the change in ac-dc difference can be seen from eq. 2, i.e. $\Delta d/d = 2\Delta R/R$. But, if an internal shield is used to compensate the ac-dc difference to nearly zero, then the voltage coefficient will also be compensated to nearly zero as shown from eq. 3. Thermal expansion is another source for voltage coefficients. Calculations show this to be a small factor for HVTC's in very rigid structures, and after internal shield compensation, this effect is reduced even further.

In order to produce HVTC's with small voltage coefficients, different types of resistor and structures were tested and various treatment and conditioning methods for the resistors were tried. Experiments showed that, before conditioning, some resistors exhibited voltage coefficients as large as several thousand ppm between 500 V and 1000 V. Other resistors were relatively good with coefficients of only a few hundred ppm. Using resistor conditioning and proper structure, the voltage coefficients can be reduced to the 10 or 20 ppm range. Some specific results are given below.

Surface Cleaning

Resistors without coatings are generally regarded as possible good candidate components for HVTC's. Four 400-kΩ resistors without coatings were mounted in a cylinder without an internal shield. The voltage coefficients between 500 V and 1000 V were measured before and after cleaning the surface of the resistor film, and the results are given in Table 2.

Table 2. Experiments on Resistors Without Coating

Voltage Coefficient (ppm)

f(kHz)	20	50	100
Without C,T & S	-17	-79	-2456
C	+2	-72	-884
C+T	+25	+33	+81
C+T+S	+12	+13	+7

C = after surface cleaning
T = after treatment
S = internal shield added

Conditioning of Resistors

Various forms of conditioning were used to treat resistors in order to reduce the voltage coefficients. The results are shown in Tables 2, 3, & 4. After treatment, the voltage coefficients were reduced even further by scraping away some varnish and reducing some of the dielectric material used to fix the resistor.

Table 3. Experiments on the Better Quality Resistors

Voltage Coefficient (ppm)

f(kHz)	20	50	100
Without T & S	+38	+45	-5438
T	+67	+291	+1088
T+S	+24	-1	+25

T = after treatment
S = internal shield added

Table 4. Experiments on Lower Quality Resistors

Voltage Coefficient (ppm)

f(kHz)	20	50	100
Shield is at input, or high voltage end	-402	-1222	-2886
Shield is at TE, or low voltage end	-439	-1421	-3561
Shield is at input, or high voltage end after treatment	-396	-958	-1984

Internal Shield

As mentioned above, the internal shield can not only compensate, or improve, the frequency flatness of HVTC's, but can also reduce the voltage coefficients because the ac voltage across some of the distributed capacitance is smaller. Some results of this effect are shown in Tables 2 & 3. Interchanging ends of the resistor module, and thereby changing the internal shield from the high-voltage to the low-voltage end, also effects the voltage coefficients. The coefficients are larger with the shield at the low voltage end and shown in Table 4.

TEST-SEQUENCE TIMING

Since ac-dc difference and its voltage coefficient are functions of the working temperature of the multiplying range resistor, the timing of the measurement test sequence and warm-up time will in general affect the ac-dc difference determination or ac voltage measurement. For some well constructed and/or conditioned modules this effect may be small; but not so small for others. Warm-up times as long as 20 - 45 minutes have been required for stable results on some resistors.

Observations have been made on the effect of a momentary break in the supply voltage when switching between ac and dc supplies. For switching times of a few tens of milliseconds or less, little or no changes in the results have been observed. However, in some cases, if slow-acting switches are used or if power supplies have built-in high-voltage delays for safety reasons, then quite significant systematic differences can be produced. Variations of a few tens of ppms have been observed from this source. These errors, or changes in observed ac-dc difference, are nearly frequency independent.

CONCLUSION

Voltage coefficients for HVTC's and ac voltage measurement instruments are problems for both users and manufacturers, but can be reduced by the use of appropriate or conditioned resistors and careful design and construction. Voltage coefficients are also reduced by adjustment of the internal compensation shield for nearly zero ac-dc difference. Due to the same factors which contribute to voltage coefficients, performance of HVTC's is affected by test-sequence timing.

REFERENCES

[1] E.S. Williams, "Thermal Voltage Converters and Comparator for Very Accurate AC Voltage Measurements," J. Res. Natl. Bur. Stand.-C. Eng. and Instrum., vol. 75C, nos. 3 & 4, July-Dec. 1971.

[2] De-Xiang Huang, Ming-Lu Chen, and Shui-Zhi He, "RF-dc Differences of Coaxial Thermal Standards," IEEE Trans. Instrum. Meas., vol. IM-39, no. 2, p313-317, Apr. 1990.

[3] F.L. Hermach and E.S. Williams, "Thermal Voltage Converters for Accurate Voltage Measurements to 30 Megacycles per Second," AIEE Trans., pt. I, vol. 79, p200-206, July 1960.

[4] Philip Martin and R.B.D. Knight, "Components and Systems for AC/DC Transfer at the PPM Level," IEEE Trans. Instrum Meas., vol. IM-32, no. 1, Mar. 1983.