AC-DC Difference Characteristics of High-Voltage Thermal Converters

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Abstract—**This paper describes a study of high-voltage thermal converters (HVTC's) at voltages above 100 V at frequencies up to 100 kHz. Techniques for the construction of HVTC's are described, and the effects of aging and dielectric loss on the resistor, changes in the timing sequence of ac-dc difference tests, relay dead-times, warmup times, and voltage level dependence are given.**

I. Introduction

HIGH-VOLTAGE thermal converters (HVTC's) are used as working standards of ac-dc difference up to 1000 V and 100 kHz. Their multiplying resistors can be compensated to yield small ac-dc differences by using adjustable internal shields or by using software corrections in a transfer instrument. Although inherently quite stable, the ac-dc differences of HVTC's may vary as functions of warm-up time, applied frequency, applied voltage, and, somewhat, with age. Voltage coefficients between 500 V and 1000 V can be several hundred parts-per-million (ppm) or more for some worst-case resistors. The latest international intercomparison of HVTC's at high voltage and high frequency reported differences among the participating laboratories of as much as 122 ppm in ac-dc difference at 1000 V and 50 kHz [1]. The present work was undertaken to study the various contributions to the ac-dc difference of HVTC's at different voltage and frequency levels and to identify methods which might reduce the variation between the participating laboratories.

II. AC-DC Differences of HVTC's

HVTC's (for example 100 V to 1000 V) generally consist of a thermoelement (TE) whose heater is in series with an external multiplier resistor module to form the desired voltage range. These resistors commonly have values of 40 kΩ, 120 kΩ, 200 kΩ, or 400 kΩ, and the TE is commonly rated at either 2.5 mA or 5 mA [2]. Automatic transfer instruments may also contain input dividers using resistors in these ranges.

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In general, for HVTC's without internal shields, the ac-dc difference contribution from the transmission line effect, δ_T, can be expressed as [3]

$$\delta_T \approx \frac{\omega^2}{6}\left[\frac{R_r^2C_r^2}{30} - L_rC_r - L_{\mathrm{TE}}C_{\mathrm{TE}} - 2L_{\mathrm{TE}}C_r\right] \quad (1)$$

where ω is the angular frequency of the applied ac voltage, 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} and C_{TE} are similar parameters for the TE. Normally, the leading term will dominate this expression. If lower-order small quantities are neglected, then

$$\delta_T \approx \frac{(\omega R_rC_r)^2}{180}. \quad (2)$$

Equation (2) indicates that the 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, and skin effect in the cylinder or magnetic leads of the TE, all important for lower voltage ranges at relatively higher frequencies, can generally be neglected compared to the contribution to ac-dc difference shown in (2). The distributed capacitance between the unshielded range resistor and the outer cylinder, which permits ac current to bypass the TE to ground, is therefore a main source of error. This error can be significantly reduced by the use of a driven internal shield structure. In general, the distributed capacitances between all current-carrying parts of the structure inside the external cylinder contain dielectric materials. The dielectric loss of the substrate for the resistors, if it is ceramic, may be very small and stable; however, the dielectric loss of any protective coating or insulating material may be much larger and may change with age. Any dielectric loss in the resistor module will affect the ac-dc difference of the HVTC.

Usually an internal, adjustable shield [2], shown diagrammatically as S_1 in Fig. 1, is used to compensate, or reduce, the ac-dc difference of HVTC's at frequencies above 20 kHz. 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

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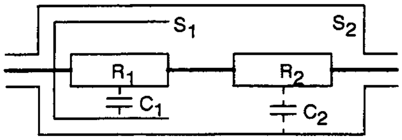

Fig. 1. Electrical schematic of an HVTC module showing internal shield (S_1) at high-voltage end. S_2 refers to the grounded surrounded enclosure.

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 in (1), the ac-dc difference contribution due to the transmission line effect, δ_T, for the internal shield structure is

$$\delta_T \approx -\frac{(\omega R_1 C_1)^2}{180} \quad (3)$$

where R_1 and C_1 refer to the resistance and capacitance of the shielded resistor R_1 indicated in Fig. 1. 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

$$\delta_T \approx -\frac{(\omega R_2 C_2)^2}{180} - \frac{(\omega R_1 C_1)^2}{180}. \quad (4)$$

If there is no additional internal shield surrounding R_2, and if $R_1 \approx R_2$, then C_2 will be less than C_1. To make $\delta_T \approx 0$, the length of S_1 must be less than that of the resistor, and adjustment of the length may be required to compensate for the dielectric loss. By adjusting the shield to make $C_1 \approx C_2$ in (4), the ac-dc differences of the HVTC at high frequencies may be greatly reduced.

III. Voltage Coefficients

The existence of voltage coefficients for the ac-dc difference of high-voltage ranges is well known [2], [5]. If the resistors in the module are supported by a dielectric material, any dielectric loss in the structure will add to the overall dielectric loss of the HVTC. Furthermore, the dielectric loss and dielectric constant are not merely fixed properties of the material, but depend on the manufacturing processes and working temperature of a specific resistor. Since the power applied to an HVTC at 1000 V is four times that applied at 500 V, the working temperature of the resistor may be much greater for the higher voltage. The dielectric-loss contribution to the ac-dc difference may be considerably different at 1000 V than at 500 V. This is a primary cause of voltage coefficients of ac-dc difference in compensated HVTC's and of variations in ac-dc difference with respect to warmup time and aging. Voltage coefficients of ac-dc difference may also appear on lower voltage ranges at higher frequencies. In one extreme case, it has been reported that the RF-dc difference at 100 MHz of one thermal voltage converter changed 2000 ppm between 0.5 and 1 V [6].

TABLE I
Summary of Tests on Better-Quality, Uncoated Resistors, Showing the Effect of Various Treatments on the Voltage Coefficients of the HVTC's. Measurements Were Made at 500 V and 1000 V

	Ac-dc Difference (ppm)		
Frequency (kHz)	20	50	100
Initial values	-17	-79	-2456
After surface cleaning	+2	-72	-884
After surface cleaning and thermal treatment	+25	+33	+81
After addition of internal shield	+12	+13	+7

Another possible source of a voltage coefficient is the variation of the value of the resistor with temperature for different applied voltages. For HVTC's with no internal shield, the change in ac-dc difference can be seen from (2) to be $\Delta\delta/\delta = 2\Delta R/R$. If an internal shield is used to compensate the ac-dc difference to nearly zero, however, the voltage coefficient will also be compensated to nearly zero as shown in (4). The effect on ac-dc difference from thermal expansion of the resistor and surrounding structure will generally be negligible, providing that all of the elements comprising the structure are rigid.

In order to study the voltage coefficients of HVTC's, different types of resistors and structures were tested and various methods of conditioning 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 initially relatively good with coefficients of only a few hundred ppm. After thermally conditioning the resistors and adding an internal shield, the voltage coefficients were reduced to 20 ppm or less.

Resistors without surface coatings were regarded as 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 of the surface of the resistor film, and the results are given in Table I. It was determined that cleaning the gaps between two film or wire tracks was an extremely important factor in reducing the ac-dc difference.

Various forms of conditioning, including thermal treatment, were employed on selected resistors in an attempt to reduce their voltage coefficients by evaporation of any moisture and curing of the dielectrics. In addition, varnish on the resistor and some of the dielectric material used to fix the resistor were removed, further reducing the voltage coefficients. The results of treating the resistors are shown in Table II.

An internal shield in the resistor module can not only improve the frequency dependence of an HVTC, but can also reduce the voltage coefficients of the HVTC because the ac voltage across some of the distributed capacitance is smaller. These results are presented in Tables I and II for good-quality

TABLE II
SUMMARY OF TEST ON COATED RESISTORS, SHOWING THE EFFECTS OF THERMAL TREATMENT AND THE ADDITION OF INTERNAL SHIELDS ON THE VOLTAGE COEFFICIENTS OF HVTC'S

	Ac-dc Difference (ppm)		
Frequency (kHz)	20	50	100
Initial values	+38	+45	-5438
After thermal treatment	+67	+291	+1088
After addition of internal shield	+24	-1	+25

TABLE III
SUMMARY OF TESTS ON A LOWER-QUALITY RESISTOR, SHOWING THE EFFECTS OF DIFFERENT SHIELD PLACEMENT AND TREATMENT

	Ac-dc Difference (ppm)		
Frequency (kHz)	20	50	100
Shield at high-voltage end	-402	-1222	-2886
Shield at low-voltage end	-439	-1421	-3561
After thermal treatment, sheild at low-voltage end	-396	-958	-1984

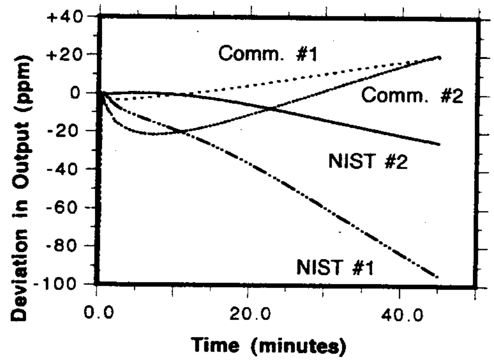

Fig. 2. Long-term drift rates of four1000-V resistors. The voltage was applied at $t = 0$ minutes and the results have been normalized to zero at the TE time constant.

TABLE IV
EFFECT OF VARIOUS RELAY DEAD-TIMES FOR AN HVTC USING A COMMERCIAL RESISTOR. APPLIED VOLTAGE IS 600 V ON A 600-V HVTC

	Ac-dc Difference (ppm)			
Frequency	1 kHz	20 kHz	50 kHz	100 kHz
8 ms delay	-4	+1	+26	+145
95 ms delay	-4	-1	+25	+145

resistors. The effect of an internal shield on a lower-quality resistor, as well as the effect for various placements of the shield, are summarized in Table III. In general, placing the shield at the high-voltage end of the resistor module produces the greatest compensating effect in the resistor.

IV. EFFECT OF THE MEASUREMENT PROCESS

Because of the thermal sensitivity of the contributions to the ac-dc difference of HVTC's, it might be expected that the measurement process itself introduces systematic errors through timing variations. Several variables in the measurement process were altered to quantify the effect of the measurement process on the ac-dc difference of HVTC's. Among the variables tested were the effect of resistor drift, changes in relay dead-time, the delay between relay switching and collection of data, and changes in warmup time.

The thermal time constants of thermoelements are on the order of a few seconds. Resistor modules, on the other hand, may have time constants of several minutes, and the value of the resistance may drift with time for very long periods. Given a sufficiently long dead-time between application of ac and dc voltage or an asymmetry in the dead-time between the application of ac and dc voltage, the contribution of the resistor drift can be significant. Four resistors, all of good quality with internal shielding and low dielectric loss, were measured to determine their drifts. Two commercially made resistors and two made by NIST (of different construction) were measured using the same TE. The results are shown in Fig. 2. Several of these resistors exhibited a substantial drift in the value of the resistance.[1] Although this does not necessarily imply a drift in the ac-dc difference of an HVTC using these resistors, it does have implications for long relay dead-times or short warmup times.

To check the effect of relay dead-time on the ac-dc difference, tests were made with relay dead-times of 8 ms and 95 ms using the same measurement system with 600 V applied to a 600-V HVTC. The dead-times were symmetric for switching from ac to dc or vice-versa. The results are summarized in Table IV for one of the commercial resistors. Essentially no change in the ac-dc difference was observed with delay times up to about 100 ms, but large changes in the ac-dc difference have been observed for delay times of several seconds. Variations in ac-dc difference of HVTC's of a few tens of ppm have been observed when there was asymmetry in the time required to switch from ac to dc or from dc to ac.

After relay switching, various HVTC's require different times to reach equilibrium, as reflected in Fig. 2. To ascertain the effects of different delay times, HVTC's were tested at 1000 V and 100 kHz with various delays. These HVTC's included the two NIST resistors measured against each other as well as a commercial resistor (Comm. #2) measured against NIST #1, the NIST resistor which showed the greatest drift in Fig. 2. The results, summarized in Table V, show a very small trend, which may be due to heating effects over the course of the measurement, rather than the variation in the delay time. This result is true even for resistors which show large drifts of opposite slopes, as illustrated by the test using the commercial resistor and the NIST resistor.

[1] It should be noted that, because of its drift, resistor NIST #1 is not used for routine calibrations.

TABLE V
EFFECTS OF VARIOUS DELAY TIMES ON THE AC-DC DIFFERENCE OF SEVERAL RESISTORS. THE MEASUREMENTS WERE MADE AT 1000 V APPLIED TO A 1000-V HVTC AT 100 kHz.

	Ac-dc Difference (ppm)				
Delay (sec)	30	45	60	75	90
NIST #1 vs. NIST #2	+255	+254	+252	+252	+251
Comm. #2 vs. NIST #1	+628	+628	+628	+626	+624

Several tests were conducted to determine the change in ac-dc difference of an HVTC as the resistor was warming. In these tests, voltage was applied to a NIST standard HVTC for approximately one hour, after which the test HVTC was connected to the measurement system and compared to the standard HVTC during its warm-up from room temperature. Two test resistors were used. One was untreated and unshielded, and the other had an internal shield but was not previously thermally conditioned. In addition, various delay times were used for the shielded resistor to check the combined effects of delay times and warmup drift. The results of this test are shown in Fig. 3 for both resistors, and also for the untreated, unshielded resistor after thermal conditioning and installation of an internal shield. As Fig. 3 shows, the addition of an internal shield has a greater effect on the ac-dc difference than do variations in the delay time, or in the warmup time of the HVTC.

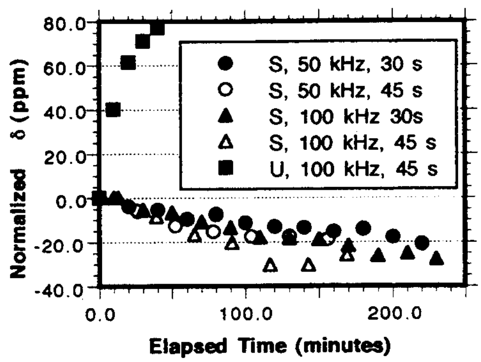

Fig. 3. Ac-dc differences as a function of warmup time for various resistors at different frequencies and delay times. Voltage (600 V on a 600-V range) was applied to the NIST standard HVTC at $t = 0$ in the plot. After a one-hour warmup, the test HVTC was connected and measurements made as it warmed from room temperature. In the legend, S indicates an internal shield was present, and U indicates the absence of an internal shield. The resistors were untreated in all cases.

V. CONCLUSION

The ac-dc difference of an HVTC is a function of both the resistor module used for the HVTC and the measurement process. Resistors which normally have large voltage coefficients and large ac-dc differences at high frequencies may be greatly improved by thermally conditioning the resistors and removing any protective coating on the resistor to reduce the dielectric loss. In addition, a driven shield at the high-voltage end of the resistor module reduces the effect of capacitive coupling and decreases both the ac-dc difference and voltage coefficient of the HVTC at higher frequencies.

The measurement process may contribute to the ac-dc difference of an HVTC. Measurements indicate that taking reasonable care in selecting relays with fast switching times, choosing appropriate timing between relay switching and initiation of data collection, and ensuring symmetry between application of alternating and direct voltage will ensure that the system makes a very small contribution to the ac-dc differences of the HVTC.

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