THIN FILM DESIGNS FOR 1000V AC RANGE RESISTORS

David Deaver
Fluke Corporation
POB 9090
Everett, WA 98206

Abstract

Alternatives to the traditional coaxial design of precision ac range resistors have resulted in performance breakthroughs, reducing both ac-dc difference and settling times. Application of thin film resistor technology and innovative thermal design has made these advancements possible.

Introduction

In the past decade, national measurement institutes (NMIs) have focused on resolving their differences in the vicinity of 1000V, 100kHz. These differences used to be considerable.

Accredited by NVLAP in 1995, the Fluke Primary Standards Lab sought an additional accreditation by the German DKD in 1997. They accepted most of the claims already approved by NVLAP with standards traceable to either the NIST or the PTB. However, the claims made for 1000V at higher frequencies could only be accepted if standards were calibrated at the accrediting body's associated NMi (NIST or PTB) because of the international differences. Eventually, claims enlarged to include an uncertainty component due to the international differences between NIST and the PTB, were accepted by both NVLAP and the DKD regardless of whether the standards are traceable to NIST or the PTB. By the 1999 joint assessment, the international differences had been reduced enough that the international difference uncertainty was no longer required.

Two examples of high voltage design are considered, the 1000V range resistor in the Fluke 792A and the 1000V divider in the Fluke 5790A.

Coaxial 1000V Range Resistor Designs

Because large values are required for high voltage range resistors, the capacitance to nearby mounting structures greatly affect their frequency response. They have traditionally been mounted in cylindrical enclosures. To the first order, any increase in capacitance caused by a lateral displacement of the resistor toward one side of the enclosure is offset by a reduction in capacitance as the resistor moves away from the opposite side. A driven shield is often used to flatten the ac response of the resistor. The most effective shields provide decreasing field strength longitudinally along the resistor resulting in no current flow in the capacitance to the shield.

These coaxial resistors usually have very high thermal resistance to ambient resulting in very long settling times. When used with a 5mA TVC, the 1000V range resistor would dissipate 5W, easily resulting in 50-100 degC temperature rise.

Thin Film 1000V Range Resistor Designs

For the thin film designs, dimensional stability is much better allowing smaller enclosures. In addition, since the resistors are planar, a rectangular enclosure works nearly as well as the coaxial design making mounting and reducing thermal resistance much easier.

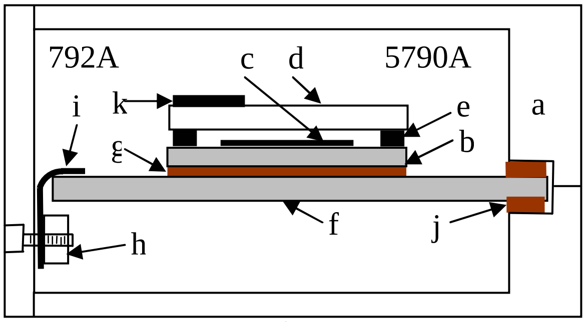

Fig. 1 Construction Details of 792A and 5790A 1000V Resistors

a Aluminum enclosure
b Al_20_3 (alumina) substrate
c Thin film resistor network
d Glass cover
e Glass frit
f BeO (792A) or AlN (5790A) heat substrate
g Flexible adhesive
h Copper mount and heat conductor
i Heat conductor mounting bracket
j Heat conductive elastomeric gasket
k Driven shield (792A only)

Figure 1 shows a simplified diagram of the construction techniques used for the 792A and 5790A 1000V range resistors. Both use a thin film resistor network deposited on an alumina substrate. The thermal resistance of this substrate is much higher than the underlying BeO (beryllium oxide) or AlN (aluminum nitride) heat sink substrate. Alumina is used because of its superior surface smoothness and compatibility with the thin film and glass frit materials. Using a patented process (U.S. Patent number 4,803,457), the temperature coefficient of the thin film resistor can be trimmed to less than a part in 10^6.

The alumina is bonded to the heat conductive substrate with a thin layer of a flexible adhesive. The heat dissipated by the resistor has only to travel through 0.1 mm of alumina before reaching the heat conductive substrate, which has very low thermal resistance. The 792A uses strips of copper soldered to the heat substrate and then clamped to the exterior case to conduct the heat from the resistor. The 5790 clamps the heat substrate between the two halves of the enclosure using thermally conductive gaskets. Both techniques result in thermal resistances from the thin film resistor to the case of less than 1 deg C / Watt.

The low thermal resistance combined with the very low temperature coefficient result in very fast settling times compared to the coaxial designs.

AC Performance

Making the cases smaller increases the capacitance to the resistor resulting in increasing ac-dc difference as the frequency increases. One technique of compensating for this capacitive coupling is through the use of driven shields; that is, a shield connected to the input side of the resistor, which is positioned between the case and the resistor. The 792A uses a driven shield as shown (Figure 2) affixed to the glass lid of the left resistor element. Using the driven shield around one of two series connected resistive elements was analyzed at NIST [1]. In the prototype resistors, the shield was trimmed for best flatness. In the production version, a trim capacitor was added to the low voltage side of the range resistor to allow the flatness to be adjusted. This simple shield technique does not yield the optimum flatness, however. Considerable work was done [2] to design a driven shield for a thin film 1000V range resistor, which would provide an optimum distribution of the electrostatic field to reduce current flowing to the shield or the case.

Fig. 2 792A 1000V Range Resistor

An Alternative to Shields

The 5790A range resistor is a 500 kΩ to 500 Ω , 1000:1 divider followed by an amplifier to provide higher input impedance than a "TVC compatible" range resistor. The higher resistance provided even more of a challenge to flatten the frequency response.

Instead of a driven shield, it was decided to use the dimensional stability of the thin film substrate to design interstitial capacitances into the serpentine pattern of the network. Current flowing out of the network to the case would, to a first order, be supplied by currents from the interstitial capacitances. The 5790A divider is shown in Figure 3. The interstitial spacing is reduced considerably as compared to the 792A resistor.

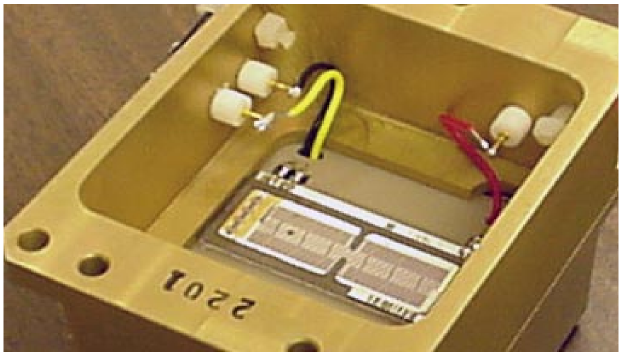

Fig. 3 5790A 1000V Range Divider

Figure 4 shows the large effect of the enclosure capacitance. The output peaks considerably without the enclosure but has a much flatter response when mounted in its aluminum case.

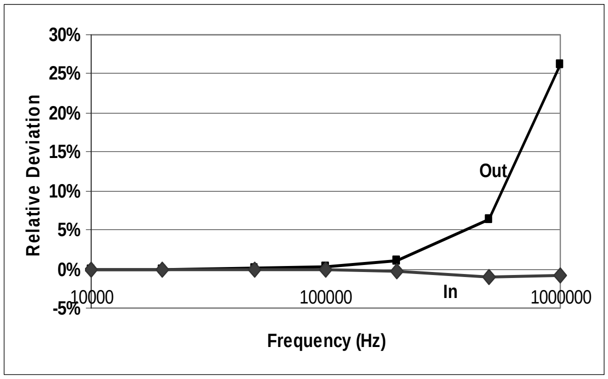

Fig. 4 5790A 1000V Range Resistor In and Out of its Enclosure Relative to a 792A 1000V Range Resistor

AC Stability

For a 1000V range resistor to be useful, its ac-dc difference must also be very repeatable and stable. Two factors make it difficult to use the calibration certificates issued by the Fluke Primary Standards Lab to evaluate the stability of the ac-dc difference of the range resistors. The first is the stability of Fluke's reference standard. Figure 5 shows the 1000V, 100kHz performance based on the NIST assigned values of ac-dc difference The shifts represent not only the actual shifts in its ac-dc difference, but the shifts in the NIST standards and their assigned values. Because considerable work has been done to reduce the differences between national labs at 1000V, 100kHz over the past decade, these shifts in the assigned values by national labs are significant. Secondly, because working standards are used to calibrate the units under test, the drift and changes in assigned values to the working standards will mask the true performance of the units under test.

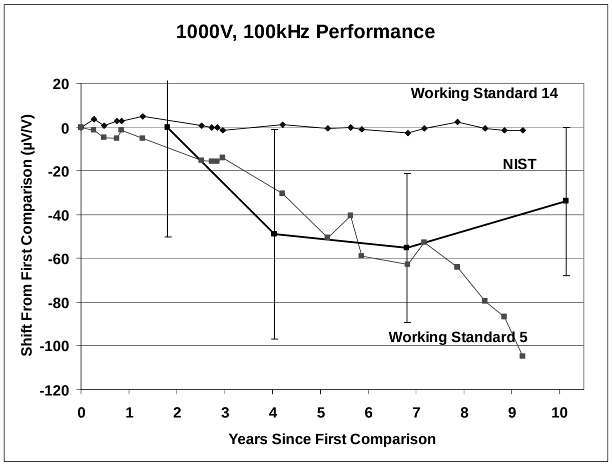

Fig. 5 Reference Standard Relative to NIST and Two Working Standards (no corrections applied)

Working Standards

Figure 5 also shows the change over time in the ac response of the two working standards (designated 5 and 14) relative to the reference standard. The results shown are without ac-dc Therefore, the shifts in NIST assigned ac-dc difference values to the reference standard do not appear in their relative stability plots. Figure 5 shows the ac-dc difference at 1000V, 100kHz of Working Standard 14 has very little drift over time relative to the reference standard. Working Standard 5, however, has considerable drift. Subsequent data presented in this paper will show Working Standard 5 has more drift than was seen in any other studied. It is periodically calibrated against the reference standard to remove this drift. However, this will add considerable scatter to the assigned values to the units under test. As a result of this study, this resistor will soon be replaced. Also, because of the apparent drift of Working Standard 5, the data presented for units under test (UUTs) will be relative only to Working Standard 14.

UUTs Relative to Working Standard 14

Figure 6 shows a plot of the performance of forty units which have been calibrated more than once in the Primary Standards Lab relative to their first calibration. All these data are presented without working standard ac-dc difference corrections applied.

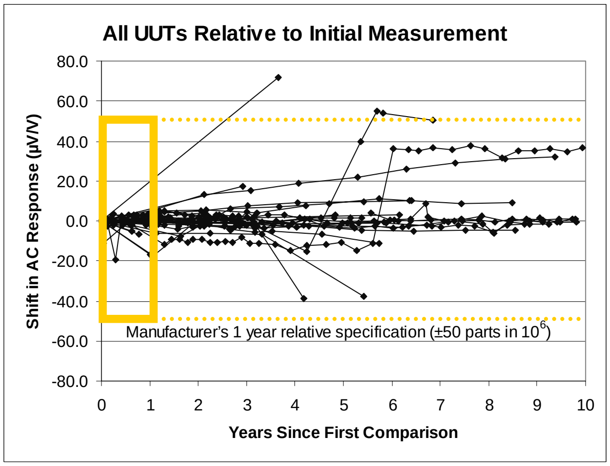

Fig. 6 Shifts of all UUTs at 1000V, 100kHz Relative to Working Standard 14

For reference, the manufacturer's one year drift specification of ±50 uV/V is shown. As can be seen, only two of the UUTs studied and Working Standard 5 show relative shifts greater than ±50 uV/V for the entire duration of the study. Most of the UUTs exhibit little or no drift. Several show significant jumps, however.

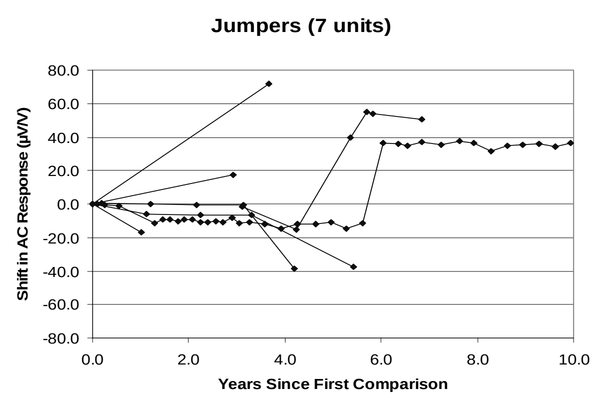

Fig. 7 Seven UUTs exhibiting jumps at 1000V, 100kHz Relative to Working Standard 14

Figure 7 is a plot of seven UUTs which have taken significant jumps. Three of the units have only two data points making it difficult to determine if they drifted or jumped. It is suspected that the jumps in ac response are due to physical trauma; being handled roughly or dropped.

Three of the UUTs in addition to Working Standard 5 exhibit some drift. The UUTs are plotted in Figure 8. The UUTs studied exhibit drifts small drifts small compared the manufacturer's stability specification and are also smaller than that exhibited by Working Standard 14.

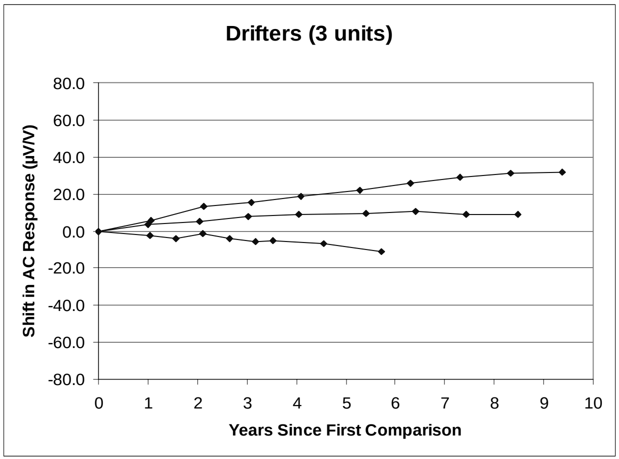

Fig. 8 Three UUTs exhibiting drift at 1000V, 100kHz Relative to Working Standard 14

The remaining UUTs, about 75% of the units show exceptional stability relative to Working Standard 14. This is shown in Figures 9 and 10, the same data but different scaling for the plots.

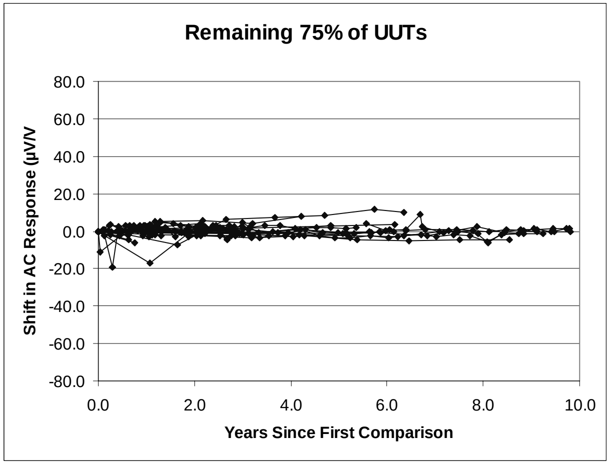

Fig. 8 Drift at 1000V, 100kHz Relative to Working Standard 14 Excluding UUTs that Exhibited Significant Drift or Jumps

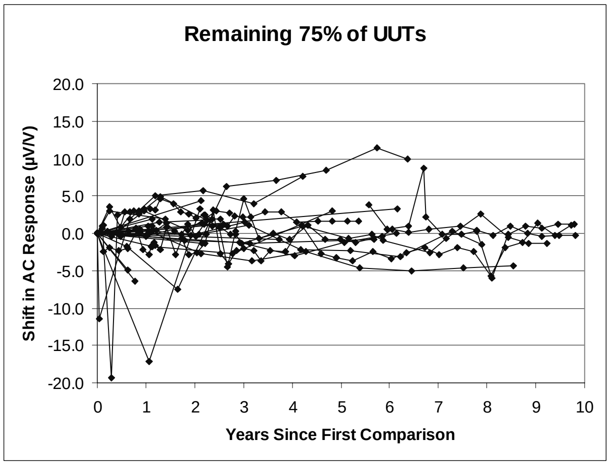

Fig. 8 Drift at 1000V, 100kHz Relative to Working Standard 14 Excluding UUTs that Exhibited Significant Drift or Jumps (expanded vertical scale)

Conclusion

The design of high voltage ac range resistors requires building resistors with very low temperature coefficients, careful control of capacitances, packaging with good dimensional stability, reducing thermal resistances, and controlling the aging characteristics of all these parameters.

The Fluke 792A 1000V range resistor was designed with these constraints in mind. By analyzing the raw data for the intercomparisons between standards and UUTs, an better indication of the resistors ac stability is presented showing the potential using it to reduce uncertainties for high voltage ac measurements even further.

[1] D. Huang, T. Lipe, J. Kinard, C. Childers, "AC-DC Difference Characteristics of High-Voltage Thermal Converters", IEEE Trans. Instrum. Meas., Vol. 44, No. 2, pp. 387-390, April, 1995

[2] M. Klonz, T. Spiegel, H. Laiz, E. Kessler, "1000-V-Resistor for AC-DC Voltage Transfer", IEEE Trans. Instrum. Meas, Vol. 48, No. 2, pp. 404-407, April, 1999