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High Voltage Divider Calibration with the Reference Step Method

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High voltage DC measurements, from 10 kV up to several hundred kV, are usually traceable through resistive dividers which have a divider ratio on the order of 10 000 to 100 000. The reference step method [M.D. Early et al., *IEEE Trans. Intsrum. Meas.* **62**, 1600 (2013)] provides a highly accurate ratiometric method of calibrating 1000 V calibrators across a wide range of voltages. We adapt this method for measuring the ratio of high voltage dividers at low (≤ 1000 V) voltages as a first step to establishing traceability at high voltages.

1. Introduction

High voltage DC measurements rely on accurate resistive dividers. Voltage traceability is typically disseminated at the 10 V level and most modern long scale voltmeters are most accurate in the 1 V to 10 V range. Higher voltages are measured by using a resistive divider, with a known ratio, to reduce the voltage to a value that can be measured on the 10 V or 1 V range of a calibrated DC voltmeter. A divider that will be used at 100 kV must then have a divider ratio (of input over output voltage) of 10 000 or more. For this type of divider the high voltage arm will typically have a resistance between several hundred MΩ to several GΩ and the low voltage arm will have a resistance in the 10 kΩ to 100 kΩ range.

Accurate self-calibrating Hamon dividers exist for ratios up to 100:1, but this method becomes cumbersome for higher ratios. Several techniques exist [1,2] to make accurate resistance measurements of each arm of the divider separately. However divider resistance values tend to drift over time, particularly when the divider is used at high voltages. And it is not always convenient to repeatedly break down the system so that the resistors can be measured. Fortunately, the reference step method of Early et al. [3,4] provides a very accurate way of directly measuring the ratio of dividers with a large divider ratio without the need to take apart the system. The reference step method was conceived as a way to calibrate 1000 V DC calibrator, and it can be used to measure the error in the ratio of voltage outputs of a calibrator across many different ranges. This calibrator can then be used as a standard against which to measure a voltage divider. For example, for a divider with a 10 000 nominal divider ratio, we input 1000 V and get 0.1 V out. The ratio of these two voltages can be compared to the same ratio as realized by the calibrator that has been standardized with the reference step method. We must take into account the possible shift in the ratio when the divider is used at higher voltages, but with careful design these effects can be reduced below 10 μV/V [5].

2. The Reference Step Method

We present an outline of the reference step method here; for full details on implementing this method see the paper by Early et al. [3]. The reference step method calibrates a DC voltage source which we will call the device under test source (DUT source). The DUT source is calibrated using a reference voltage source (reference source) and a digital voltmeter (DVM). The reference source must have good stability on a time scale of a few hours and the DVM must have a good stability on the time scale of 10 minutes. But the longer term drift and the linearity of both the reference source and DVM are not critical. If for, example, we wish to calibrate the 2 V to 1 V ratio of the DUT source, the procedure is as follows:

1. Set both the DUT source and the reference source to 0 V and measure the difference in the outputs with the DVM.
2. Set both the DUT source and the reference source to 1 V and again measure the difference in the outputs with the DVM.
3. Subtract the results of step 2 from step 1 to get the difference d_1 which is the 0 V to 1 V interval as realized by the DUT source minus that same interval as realized the reference source.

Notice that the offsets in the DVM and the reference source drop out, and since the DVM reads near zero for both measurements, the gain error in the DVM is not critical.

4. Set the DUT source to 1 V and the reference source to 0 V and measure the difference in the outputs with the DVM.
5. Set the DUT source to 2 V and the reference source to 1 V and measure the difference in the outputs with the DVM.
6. Subtract the results of step 5 from step 4 to get the difference d_2 which is the difference in the 1 V to 2 V interval as realized by the DUT source minus the original 0 V to 1 V interval of the reference source.

Notice again that the offsets in the DVM and the reference source drop out and, since the DVM reads near 1 V for both measurements, the gain error in the DVM is not critical.

Now the error in the ratio of the 2 V DUT setting to 1 V DUT setting is to a good approximation $(d_2 - d_1)/s$ where s is the nominal step size (1 V in this case). We can step up again to find the error in the 3 V to 1 V ratio of the DUT source:

7. Set the DUT source to 2 V and the reference source to 0 V and measure the difference in the outputs with the DVM.
8. Set the DUT source to 3 V and the reference source to 1 V and measure the difference in the outputs with the DVM.
9. Subtract the results of step 8 from step 7 to get the difference d_3.

Now the error in the 3 V to 1 V ratio of the DUT source is $(d_3 + d_2 - d_1)/s$. In this way we continue until we have the 10 V to 1 V ratio of the DUT source calibrated. At this point we can calibrate the reference source at 10 V against the now calibrated 10 V setting of the DUT source and step up in $s = 10$ V steps to 100 V. The process is continued across all the ranges of the

DUT source. At some point we may wish to calibrate the reference source against a short and a 10 V reference standard if we wish to calculate the absolute errors in the DUT source and not just ratio values. The entire process requires in a large number of measurements, but the process can be automated and run overnight.

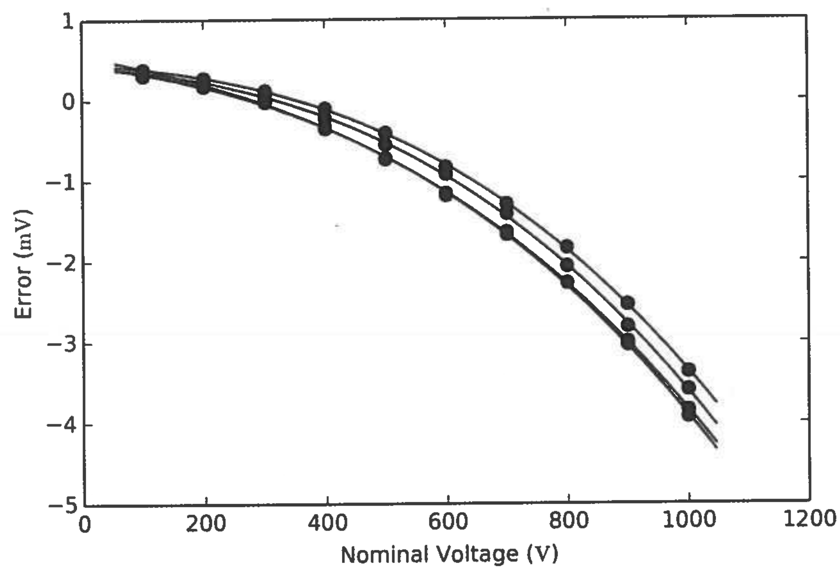

Fig. 1. The errors in the 1000 V range of our source are plotted here as found from four different calibration runs conducted over 12 days. To get absolute errors, the source was compared to a 10 V Zener standard at the start of each run. Dots represent the measured errors and each run is fit to a second order polynomial.

3. Reference Step Calibration Results

We have implemented the reference step method using a Datron 4708 calibrator as the DUT source, a Datron 4808 as the reference source, and an HP3458A multimeter as the DVM[1]. Fig. 1 shows the measured errors on the 1000 V range of the DUT source for four calibration runs taken over 12 days. The source is calibrated against a 10 V standard at the beginning of each run so absolute errors could be calculated from the ratio error measurements. There is some non-linearity in the source on this voltage range, but the results are repeatable to within 1 μV/V of the source setting.

[1] Certain commercial equipment, instruments, or materials are identified in this report to facilitate understanding. Such identification does not imply recommendation or endorsement, nor does it imply that the materials or equipment that are identified are necessarily the best available for the purpose.

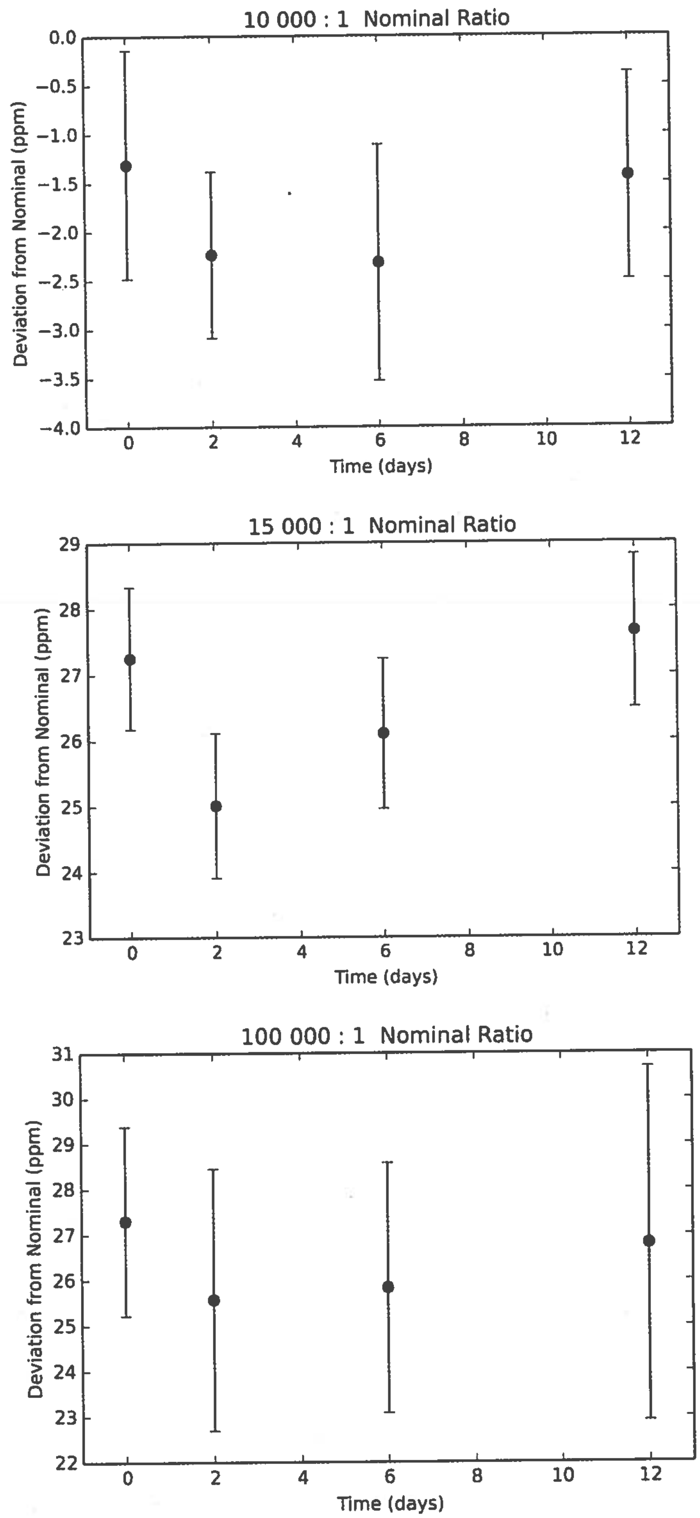

Fig. 2. Shown here, from top to bottom, are the errors in the 1000 V : 0.1 V ratio, 1000 V : 0.0667 V ratio, and 1000 V : 0.01 V ratio of our source found from the four different calibration runs shown, in part, in Fig. 1. In the top panel, the 0.1 V output was produced with the source on the 1 V range as this range is slightly more stable than the 100 mV range for our particular source.

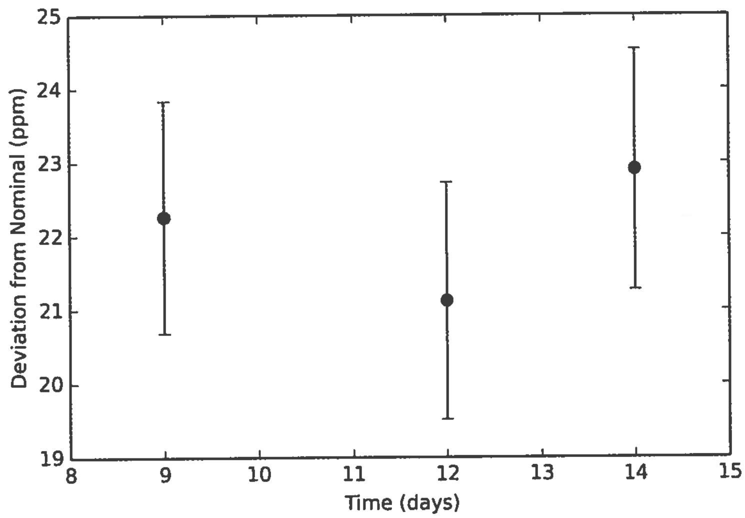

Fig. 3. The deviation from nominal for the measured ratio of a 15 000:1 high voltage divider with a 1000 V input voltage. The divider was measured with the source corresponding to the data shown in Figs. 1 and 2 and the day number in this figure corresponds to the day number in Fig. 2.

Fig. 2 show the stability of the ratio of the DUT source 1000 V setting to the 0.1 V, 0.0667 V, and 0.01 V settings. These settings give ratios of 10 000:1, 15 000:1, and 100 000:1 respectively. The variability of 10 000:1 ratio is on the order of 1 ppm (relative changes are seen in the measured ratio on the order of 1×10^{-6}). The variability in the higher ratios is slightly larger, on the order of 2 ppm, as the stability of our source is not quite as good on the lower settings.

This source was then used to calibrate a 15 000:1 high voltage divider. We again took advantage of the short term stability of the DVM and calibrated it against DUT supply at 0 V and 0.06667 V. Then the DUT supply was connected to the divider input and the supply was switched between 0 V and 1000 V (1000 V $\approx$ 15 000 $\times$ 0.06667 V) while the DVM measured the divider output. The result for measurements conducted on three different days is shown in Fig. 3. An accuracy on the order of 2 ppm or better is achievable with this method.

4. Conclusion

We have shown that the reference step method provides a convenient method for calibrating high voltage dividers at low voltage with accuracies at the ppm level. The method requires only two voltage supplies and a DVM with good short term stability. Traceable high voltage measurements also require a careful characterization of the divider over its entire voltage range. Effects such as resistor heating and corona discharge can cause the divider ratio at high voltages to deviate from the low voltage value. For a good divider these effects are not large [5], though they usually will dominate the uncertainty budget at high voltages. Still, the reference step method is a beautiful tool with which to find the initial low voltage ratios, providing a high accuracy while requiring little specialized equipment.

5. References

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