GenRad

ENHANCING PRECISION AND CAPABILITY FOR MANY CRITICAL MEASUREMENTS USING A DIGITAL IMPEDANCE METER

James J. Pecora
GenRad Incorporated
300 Baker Avenue
Concord, Massachusetts 01742
(508) 369-4400

ABSTRACT

Precision digital impedance meters are increasingly being used as valuable tools, in the standards laboratory environment, and replace older manual bridges in some applications and solve other measurement problems that are beyond the capability of traditional instruments. Some microprocessor-based RLC meters have accuracy and precision that surpasses manual test systems. This paper reviews the advantages of the latest generation of these instruments which includes improved direct reading accuracy, parts-per-million precision, multi-terminal capability (both guarded and Kelvin connections), speed, computer control, and data logging. It will also address specific applications such as direct 1:1 comparisons, and N:1 ratio scaling of inductance, capacitance and ac resistance calibrations.

INTRODUCTION

Bridges have been used for the intercomparison of standards since 1843 when Sir Charles Wheatstone adapted and popularized S. H. Cristie's[1] invention. Early variations and adaptations of the bridge principle were made by many of the great names of electrical science; Siemens, Maxwell, Heavyside, Kelvin, Wien and many more. The accuracy of the bridge was developed to meet changing requirements enabling us to realize the specialized sub-ppm systems of the great national laboratories, most of which are based on the inherent ratio accuracy of precision transformers. Automatically balanced bridges appeared over 20 years ago, but they traditionally have not been used for precision calibrations because of the lack of resolution and repeatability. In this same time period, the first digital meters were popular but these had even lower accuracy. Over time newer microprocessor-based digital meters appeared with remarkable precision, a consequence of the use of highly linear analog-to-digital converters, good signal processing techniques, and high-resolution digital complex multiplication. Accuracy was also improved by using stable standards and applying stored calibration corrections. While manual bridges required separate circuits for the different impedance parameters, R, L and C, these meters can measure any quantity because the result is calculated from a set of voltage measurements; only the calculations change for different parameters. GenRad has found that the accuracy and precision of these new instruments, as well as their other features, qualify them for several tasks in our highest level lab as well as many more measurements in labs of lower level.

CAPABILITIES REQUIRED FOR PRECISION MEASUREMENTS

The highest precision measurements in a standards lab are the 1:1 direct comparisons of standards of approximately equal value such as the comparison of traveling standards calibrated at NBS with similar standards kept in your own lab. This intercomparison does not require good direct-reading accuracy, but it does require parts-per-million resolution and repeatability. The difference between the values of two units must be determined by the comparing instrument, and this is done by making sequential measurements on the two standards using the same conditions. The direct readout of a RLC meter may be limited to 10 to 100ppm, but some of these instruments have a Δ% mode[2] which gives resolution of .0001%, or 1 ppm; the difference between the measured value and an entered nominal value. We have measured the standard deviation of such measurements at

1kHz at a1-per-second rate to be about 2 ppm which compares to the 4 ppm deviation typical of today's precision calibration instruments[3]. By using the automatic averaging adaptability of these instruments, this deviation can be reduced by 1/SQR(N) where N is the number of measurements averaged. By averaging 25 measurements on each of the two standards being compared, one can get comparisons to 2ppm with confidence. This may sound time consuming, but consider the time it takes to balance a manual bridge with ppm resolution. A technique of GenRad's is to record the results of five averages of five measurements and take the median of these. This gives an indication of the precision and allows the operator to make additional measurements if the spread of these averaged measurements is excessive.

Note that this ppm resolution in the Δ% mode is not limited to values near full scale as it is on a six digit, manual bridge readout where the resolution of a six digit reading of 111111 is only 9ppm. A precision digital meter with Δ% mode does not make this distinction.

A more difficult measurement in the standards lab is the scaling of a calibration of one standard to another of a different value, often different by a 10:1 ratio. Usually this must be repeated several times, up and down, to cover a wide range of values. Different techniques are used for R, L and C and by different labs as shown in Figure 1.

When an instrument has a precise ratio, the easiest method available is to measure each standard being compared and combine the difference in the deviations of each from its nominal value with the calibrated value of the "known" device to get the calibrated value of the "unknown" device. High resolution deviation measurements are required as well as a good ratio accuracy, but good absolute accuracy is not. Many of the inherent errors of an impedance meter are removed in such a procedure. The Δ% mode can be used for both measurements with different entered nominal values to get the high ppm resolution of the Δ% mode. Again, averaging many measurements reduces the measurement spread due to noise. Making both measurements on the same range cancel calibration errors and any drift of the instrument's internal standards so that the largest remaining error is the nonlinearity of the electronic amplifiers and the analog-to-digital converter used. These techniques reduce a catalog .02% direct reading accuracy specification to typical accuracies of 20ppm for scaling measurements over small impedance ratios. Because all ranges of these instruments can be precisely calibrated, measurements can be almost as good over greater ratios that require different internal ranges of the instrument.

FIGURE 1: Common Calibration Scaling Method

DC Resistance:
- Series/parallel resistor networks (such as ESI SR1010)
- Current Comparator Resistance Bridges (Guildline 9975)
- Precise Fixed Ratio Bridges (such as L&N 4394)

Capacitance:
- Transformer-Ratio-Arm Bridges to 1uF (such as GR1615)
- Transformer-Ratio Standards 10uF to 1F (GR1417)
- Custom series/parallel boxes

Inductance:
- Send whole set to NBS, 1:1 comparisons only.
- Custom built transformer-ratio-arm bridges

AC Resistance:
- Custom transformer-ratio-arm bridges
- DC scaling methods with ac-dc corrections on each standard.

An important feature not usually available in manual instruments is the ability to make both 3-(guarded) and 4-terminal (Kelvin) measurements at the same time[4]. This adds up to 5 terminals, not 7. While both techniques may not be needed for any single measurement, they are both required if a wide range of values are measured. The automatic open-circuit and short-circuit zeroing corrections available on today's precision micro-processor based meters can remove remaining, unguarded capacitance and mutual inductance between connections. The multi-terminal capability also allows the use of networks as standards, for example an resistance-capacitance T network to simulate a high-valued inductor such as 1000H[5].

An automatic instrument has the advantages of speed and ease of use. No balancing procedure is required. While speed itself is not especially important for measurement of the highest precision, it does allow the accumulation of data that can be operated on statistically. There are situations where balancing a manual bridge can be tedious; when measuring low Q standard inductors. Also, raw speed is important for checking multi-dial decade boxes.

An advantage of an automatic instrument with IEEE bus capability is the opportunity of having the results printed out and avoiding the chance of making a mistake and ensuring legibility. Moreover, with a small computer in the system, any required correcting calculations can be made without the chance of making those common little mistakes that cause so much trouble, such as those made when subtracting negative numbers. Of course, a computer properly programmed, can lead a technician through a complicated calibration process with procedures, prompts and automatic data entry so that all he needs to do is make proper connections and push a button when ready.

GENERAL APPLICATIONS

In addition to these capabilities the precision digital meter is compact, light weight, and transportable. With features mentioned above, one can appreciate the value of a micro-processor based precision digital meter. For example the precision digital meter can be used as a transfer standard, "...for calibrations at remote sites or for equipment that cannot be easily returned to the central lab."[6] Mil-Std-45662 defines a Transfer Measurement Standard as "Designated measuring equipment used in a calibration system as a medium for transferring the basic value of reference standards to lower echelon transfer standards or measuring and test equipment." Also, the same instrument may be used in an application as a conductivity standard[7]. At a specific lab level the micro-processor meter may be implemented with procedures that use it as a secondary or field standard, and at yet another lab level with a different procedure that uses it as a primary standard, thus enhancing the precision digital meter as a valuable, economic alternative to many independent, single function instruments.

SPECIFIC APPLICATIONS

The applications below fall into two categories. In some of them the precision impedance meter actually makes better measurements than any older equipment can. In others, it can make the measurements easier and faster, but not as accurately as specialized systems in top-level labs. However, it does have the accuracy required for lower-level labs and for them can become a "standards lab in a box" because it can make so many types of measurements.

Comparison of Standard Inductors

This application uses most of the features mentioned above for the intercomparison and scaling of inductance standards. This application is particularly important because there has been no inductance bridge available with ppm resolution since the GR1632 was discontinued many years ago (many of these are still being used). The GR1632 was a six-digit, two-terminal bridge (one grounded) with only 0.1% direct-reading accuracy. Once ideal for comparing two, similar decade-valued (1, 10, 100, etc.) inductors, it could not be considered particularly useful by today's standards. At GenRad we have several of these beautiful old bridges, but we have gone to our precision meter for these 1:1 comparisonsbecause it is easier to use. Balancing a GR1632 to high precision was a slow procedure especially when measuring GR1482 Inductance Standards which have low Q values at 100 Hz. Moreover, the effective ac resistance of these standards is primarily the resistance of copper wire which has a 4000 ppm/degree C temperature coefficient. Even a 1/100th of a degree change in the temperature of the wire, due to ambient changes or applied power, causes a bridge unbalance which makes the inductance measurement difficult. The automatic GR1689 has no such problem; the resistance can change at a reasonable rate without affecting the inductance reading so long as you measure equivalent series inductance.

A five-terminal, guarded-Kelvin, capability would have been an advantage in calibrating these inductance standards, but because the older GR1632 has been used for so long, NBS calibrations use a similar grounded 2-terminal connection. Today's impedance meters are multi-terminal, and guard is grounded, not one of the other terminals. This does not present a problem provided one remembers to tie the case of a GR1482 standard to its LOW terminal with the link provided, and to insulate the case from ground. This maintains the internal stray capacitances that effect high-inductance measurements as they were when they were calibrated at NBS.

Standard inductances are particularly hard to scale in value by combining two or more units in series or parallel (as is done with resistors) because of their size, the stray capacitances involved, and their low Q values. Transformer type bridges for inductance comparisons are not available, although they can be made, they are complicated to construct and use. Fortunately extreme accuracy is not required because NBS calibrations have an estimated uncertainty of only .02%. However, ratio measurements used to scale these calibrations should be much tighter to avoid adding errors. Ratio measurements of 2:1 made on the same range and using a percent readout, should have errors totaling less than 20 ppm. This allows comparisons of inductors of intermediate value (those values starting with a 2 or 5) to be compared against the even decade values with negligible added error. Scaling calibrations over a 10:1 range are less accurate because a range change is often required and because the greater spread on the same range increases possible non-linearity errors. However they should be good to 50ppm at 1 kHz over the basic overall range of the instrument.

Historically we have been sending our whole reference set of standard inductors, 17 different values, to NBS on a periodic schedule, several each year. We would prefer to send only one. This would be adequate for many labs if careful scaling was done with a precision digital meter. However because we sell these standards and calibrate them for other labs, we want to be as close to NBS calibrations as possible. We now use 2:1 scaling for the 2 and 5 values, which we no longer make but do calibrate, and therefore we send only the 6 decade values (100uH to 10H) to NBS.

High-Capacitance Measurements

Precision capacitance bridges such as the GR1615 and GR1616 have ranges up to 1 uF at high accuracy. This range can be extended somewhat by using external standards, but the accuracy deteriorates rapidly as the capacitance is increased because of the inductance of the wiring and the leakage inductance of the ratio transformer used in the bridge. These bridges are three-terminal, and guarded, but single connections are made to each end of the capacitor being measured. For accuracy at higher values, four-terminal (Kelvin) connections are needed to remove the effects of self-inductance. Automatic short-circuit zero corrections are acceptable to remove the remaining effects of mutual inductance between leads.

The precision digital meter has these capabilities as well as extreme range and accuracy. A typical meter range of a meter extends to 0.1F, but using a RATIO mode[8] the display range can be extended to 10,000F! However, do not look for a capacitor of that value to measure, the micro-processor based meter would not be able to measure it accurately. However a precision digital meter can measure 1F with fairly good accuracy at 100 Hz, even though its specifications may not be stated as so. This is because the specifications assume that the zeroing calibrations, open and short, are made at 1 kHz only. If these are made at the frequency of measurement, the accuracy of extreme values depends mainly on the repeatability which can be improved by averaging. For example at 100 Hz a typical spec for 1F is 120%, but with a short-circuit calibration at 100 Hz, accuracy is about 5% for one measurement and 2% if 10 measurements are averaged. And yes, there are standards of capacitance at such values, for example the GR1417. We have made special adaptors that improve the measurement accuracy of the precision digital impedance meter by 5 to 1 at such values. More important are measurements on standards of lower values, between 1uF and 1F, such as the GR1417 and others, that the micro-processor meter can measure with improved accuracy, because these standards are less stable than lower valued ones, such as the GR1404 or GR1409.

Mid-valued and Low-valued Capacitance Measurements

There is no doubt that some bridges, such as the GR1615, measure capacitance from 1uF on down with substantially better precision and accuracy than any automatic bridge, and we do not recommend them for intercomparisons of the reference standards in high-level labs. However, it is adequate for calibrating the reference standards of lower-leveled labs and all working standards and decade boxes. See Figure 2.

It is interesting to note that the repeatability of a precision digital meter is comparable to that of the precision GR1615 if measurements are made at the same level (1V rms) and if averaging is used to make the overall measurement time the same. An automatic instrument is not necessarily less precise than a manual one. They both use the same laws of physics and the automatic instrument has the advantage of statistical data manipulation.

AC Resistance Measurements

The micro-processor impedance meter is capable of precision ac resistance measurements over a frequency range of about 10 or 20 Hz to 100 or 200 kHz. Unfortunately most precision resistance measurements call for dc instead of ac even though ac measurements avoid thermal voltage errors, have lower noise and can use precise transformer-ratio scaling techniques. Moreover, unit of resistance, the ohm, is determined from ac measurements and has to jump from ac to dc. Attempts have been made to use ac for the most precise resistance measurements[9], but the dc habit is hard to break.

For most resistors, the ac/dc difference is negligible at 100 Hz or even 1 kHz. For flat-card, wire-wound resistors, the difference can be less than 1 ppm up to 100 kohm if equivalent series resistance is used for low values and parallel for high values. There are significant differences for high-valued, coil-wound resistors, because of capacitance not inductance, and for high-valued, multi-resistor networks such as decade boxes and build-up standards. The ac/dc difference of a standard resistor often can be easily determined by measuring it and a small metal film resistor of similar value at both ac and dc and assuming that the film unit has negligible ac/dc difference (which it probably does) and that it was stable for the time required (which it usually will be if you don't heat it up by applying too much power or touching it). Once such differences are determined, ac could be used for precision calibrations. The ac/dc differences of many fixed, lab-type resistance standards have been determined and they are generally very small[10].

There are occasions where ac resistance values are specified. We use the precision digital impedance meter to intercompare the standards of a resistance calibration kit[11] which is used at ac.

FIGURE 2: OUTLINE OF GENRAD'S STANDARDS LAB INSTRUMENTATION FOR RLC MEASUREMENTS

	CAPACITANCE			DC RESISTANCE		
	< 1uF	> 1uF	INDUCTANCE	< 10 Meg	> 10 Meg	AC RESISTANCE
Devices Sent to NBS	1404 10-1000 pF	N/A	1482 10uH-10H	1444* 10 Kohm	N/A	N/A
1:1 Comparison Devices	1615 or 1616	1689	1689	1666	1644 Δ%dial	N/A
Reference Standards	1404 or 1408*	1417	1482	1444*	Precision "T" Networks	From DC Resistance
Scaling Devices	1615 or 1616	1417 or 1689	1689	Transfer Boxes	1644 & "T" Networks	From DC Resistance
Secondary Standards	1404 1409	1417	1482	Transfer Boxes	Special Standards	1689 Cal Kit
Odd Value Measuring Devices	1615	1689	1689	1666	1644	1689
Decade Devices	1413 1412 1423	1424* 1425*	1491	1433	N/A	N/A

*No longer available

SUMMARY

A precision digital meter should be considered for use in the standards lab. It can be integrated at many different lab levels and in varied functions. The micro-processor based meter can make some calibrations more accurately than traditional instruments, and will make many other required measurements easier and faster. It can be used even more in measurements in lower-leveled labs and almost all RLC measurements if ac resistance measurements are acceptable.

REFERENCES

[1]B. Hague and T. R. Foord (1957), *Alternating Current Bridge Methods*, Sir Isaac Pitman & Sons, Ltd., London, pp 2 - 7.

[2] GenRad (1985), "Operation," *GR1689/1689M Precision RLC Digibridge Instruction Manual* 1689-0120-05, June 1985, GenRad Inc., Bolton, MA, pp 3-17 to 3-18.

[3] David L. Agy (1987), "Interpreting Specifications of Calibration Instruments," John Fluke Mfg. Co., Inc., Everett, WA, *National Conference of Standards Laboratories 1987 Symposium,* Denver, CO, p 1.

[4] H. P. Hall (1979), "Why So Many Terminals? Understanding Impedance Measurement Techniques," *Electronic Test,* Feb. 1979, pp 50 - 59.

[5]B.Hague and T. R.Foord, op. cit., pp 58 - 61.

[6] David L.Duff (1987), "The Calibration Lab as a Profit Control Center," *National Conference of Standards Laboratories 1987 Symposium* , Denver, CO, p 35-2.

[7]Ibid., p 35-4.

[8]GenRad Inc., op. cit., pp 3-21 through 3-23.

[9] J. J. Hill (1965), "Calibration of D.C. Resistance Standards and Voltage-Ratio Boxes by an A.C. Method," *Proc. IEE* , London, Pt. 1, Vol. 112, #1, Jan, pp 211 - 217.

[10]Ibid., pp 211 - 217.

[11]GenRad (1985), "Calibration Kit (1689-9604),"*GR1689/1689M Precision RLC Digibridge Instruction Manual -1689-0120-05*, GenRad Inc., Bolton, MA, June 1985, pp 5-49.