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Application Note

Application for Precision Impedance Meters in a Standards Laboratory

The GenRad 1689 Precision RLC Digibridge™, which measures resistance, capacitance and inductance, has found wide acceptance in production and incoming inspection applications because of its high measurement speed and accuracy. Its impedance and frequency ranges have also made it an important tool for component engineering and quality control measurements. The 1689 model has also been found to be a valuable instrument in many Standards Laboratories, where it has assumed tasks that used to require manually balanced bridges and special test setups. In addition, it provides some new measurement capability not previously available. This application note discusses some of these applications and techniques.

Required Capabilities for Precision Measurements

The measurements of highest precision in a standards lab are the 1:1 comparisons of similar impedance standards, particularly the comparison between the standards calibrated at the National Institute of Standards and Technology (NIST) and similar reference standards that remain in a lab. This application requires measurement resolution and repeatability to detect parts-per-million (ppm) differences but does not require extreme, direct-reading accuracy. Two standards of very nearly equal value are compared using "direct substitution"; they are measured sequentially and only the difference between them is determined. When reading directly in value, the resolution of the GenRad 1689 is between 10 and 100ppm.

The 1689 unit does however have a Δ% mode where the difference between an entered nominal value and the measured value is displayed in percent with resolution of .0001% (or 1ppm). Single measurements made in this Δ% mode at a rate of one/second have a standard deviation of about 2ppm at 1kHz. The use of the instruments AVERAGE mode reduces this by $1/\sqrt{N}$ where N is the number of measurements averaged. Thus, an average of 5 measurements or more reduces this deviation to below 1ppm. Using averaging, it is possible to get the difference between two impedances to 2ppm or better. It should be noted that although averaging many measurements takes time, an automatic bridge like the 1689 can take a lot of measurements in the time it takes to balance a high-resolution, manual bridge.

Digibridge Model 1689 Advantages

A favorite (and fairly easy) measurement technique is to record 5 averaged measurements and then take the median of these. This gives a record of the spread as well as increasing the precision, and is independent of a large error caused by a line spike, lightning or other non-Gaussian noise sources. It should be noted that the 1689 unit has a MEDIAN mode that takes the middle value of three measurements, these median values can be averaged automatically to give one final result. The 1ppm resolution of the 1689's Δ% mode is not limited to values near full scale as it is on six-digit, manual bridge readouts. For these, the resolution of a six-digit reading of 111111 is 9ppm. The 1689 unit does not discriminate against such values; it has the same 1ppm resolution at all values. It also has 1ppm resolution in D and Q (tangent of phase angle), a useful capability but more important for dielectric measurements than for RLC calibrations.

Scaling

Scaling a calibration of one impedance value to another value is another precision measurement required in the standards lab. There are many techniques used for this process that differ for different types of impedance standards: resistance, capacitance or inductance. One method common to all is to simply measure each value with a bridge, assume the bridge ratio is perfect and apply the ppm correction of the known standard to the unit being measured. This method gives high accuracy when using a transformer-ratio-arm bridge such as the IET 1615 or 1616 Capacitance Bridges (formerly manufactured by QuadTech), but such bridges aren't available for inductance or high capacitance. The .02% accuracy of the 1689 unit compares favorably with available manual bridges that make these measurements. Its Δ% mode can be used to give ppm resolution for both measurements by entering a different NOMINAL VALUE for each measurement. This improves the instrument accuracy as well because it is not limited by resolution of the display. Moreover, ratio measurements on the same range are independent of a calibration error or drift in the internal standard. Measurements on different ranges can be improved by a re-calibration using special standards, such as the calibration kit available for use with the 1689 instrument.

Multi-Terminal Connection

Another important feature not usually available in precision lab bridges is the multi-connection capability that allows both 4-terminal, Kelvin connections and 3-terminal, guarded measurements. This adds up to a 5-terminal capability (not 7) which is rarely found in lab bridges and which is particularly important if measurements must be made on both very high-value and very low-value impedances. The automatic open- and short-circuit zero correction capability of the 1689 unit augments the multi-terminal capability by subtracting out the effects of unguarded stray capacitance and mutual inductance between connecting wires.

More Advantages & Applications

Speed

Obviously, automatic instruments such as the GenRad1689 have the advantage of speed because a balancing procedure is not required, but this is not a particularly important advantage when only a few calibrations need to be made. However, there are situations where balancing an AC bridge can be tiresome, especially when low-Q components are being measured as they require an annoying series of alternate balances of the two adjustments needed to null an AC bridge. Speed itself can be important when checking multi-dial decade boxes. For this task, a suggested trick is to use the MEDIAN mode that will reject the erroneous measurements made while the dial settings are being changed.

Automation

A final advantage of an automatic instrument with IEEE-488 bus interface capability is the opportunity of having the result printed out, thus avoiding the opportunity of making a mistake in recording the result, as well as making the record more legible. Moreover, with a computer in the system, any required correction calculations can be made without the chance of more errors, especially the all-to-common problems with + and - signs. Of course a computer, suitably programmed, also can lead the measurement technician through a complicated calibration process with prompts and procedures that ensure proper measurement techniques and precise data manipulation.

Specific Applications

The applications given below fall into two categories. In some of them, the GenRad 1689 fills a definite need and can make better measurements than any available manual bridge. In others, the 1689 can make the required measurements, but not as well as specialized, expensive lab instruments. This latter category extends to all AC impedance measurements at or below 100kHz, so for many standards labs that don't require the highest accuracy, the 1689 unit becomes a "standards lab in a box."

Comparison of Inductance Standards

A made-to-order application that uses most of the features mentioned above is the inter-comparison and scaling of inductance standards. This application is particularly important because there has been no inductance bridge available with ppm resolution except, maybe the GenRad 1632 that was discontinued several years ago. The 1632 was a six-digit, two-terminal bridge (one grounded) with only 0.1% direct-reading accuracy. It was very good for comparing two, similar decade-valued (1, 10, 100 etc.) inductors. It wasn't particularly good by today's standards because of the 0.1% direct reading accuracy. Balancing a 1632 to high precision was a slow procedure especially when measuring standards like the IET 1482 Inductance Standards (formerly manufactured by QuadTech) that have low Q values, especially at 100Hz, where many measurements must be made.

Applications

Inductance Standards

Moreover, the effective AC resistance of these standards is primarily the resistance of copper wire that has a temperature coefficient of almost 4000ppm/°C. Even a 1/100th of a degree change in the temperature of the wire due to ambient changes or applied power causes an annoying bridge unbalance that makes the inductance measurement difficult. An automatic bridge like the GenRad1689 has no such problem; the resistance can change at any (reasonable) rate without affecting the inductance reading (if you measure equivalent series inductance). Because of this, and the 1689 ease of use, the instrument is ideal for making 1:1 comparison measurements on inductance standards.

A five-terminal (guarded and Kelvin) capability would have been an advantage in calibrating these inductance standards, but because they were being calibrated long before either 3-terminal or 4-terminal capability was available on an inductance bridge, NIST uses a grounded, 2-terminal connection. With early precision meters, ground was guard, not one of the main connections, but this did not cause a problem. The only thing to remember, when measuring something like the IET 1482 Standard Inductor is to tie the case to its LOW terminal (with the link provided) and to insulate the case from ground. This keeps the internal stray capacitances that effect high-inductance measurements the same as the 2-terminal calibration by NIST.

Ratio Measurements

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, their low Q values and the stray capacitances involved when two are connected together. Transformer-ratio-arm bridges, capable of precise scaling, are not available for inductance measurements. They can be made from commercially available parts, but are difficult to construct and use. Fortunately, extreme accuracy is not required because the best NIST 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 a 1689, on the same range and using the Δ% readout, typically have errors totaling less than 20ppm. 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 is less accurate because a range change is often required, or if on the same range, there is apt to be increased non-linearity error. They should be good to 50ppm at 1kHz over the basic overall range of the instrument.

Application: Inductor Setup and Comparison

1689 Setup and Zeroing

Figure 1: 1482 Inductance Standard

Set-up:

Connect appropriate cables and adapters for 1482.
Select Slow Measurement Speed
Turn Median Mode "ON"
Set Averaging to 5 or 13
Select Ls and Q
Select Test Frequency

Table 1: Inductance Value and Test Frequency

"L" Value	Test Frequency
100 µH to 10 mH	1 kHz
100 mH to 10 H	100 Hz

Perform open and short compensation

Inductors are calibrated by the substitution method in which two measurements are made: one with the inductor connected to the bridge and the other with the same connecting wires but with the inductor replaced by a shorting bar or link. For an inductor with three terminal panel, the first measurement is made with the bridge connected to the pair of insulated terminals, and a short is then either applied to these terminals or the connecting wires are moved to the left pair of terminals which are connected by the link. For an inductor with the new, six terminal panel, the bridge is still connected to the upper right pair of terminals (connection terminals). The measurement of the inductor is made with the link on the lower terminals in the left or L position to connect the coil. The short is then applied by moving the link to the right or Lo position on the lower terminals (reference terminals).

The advantages of the new panel and connections are that the mutual inductances between the internal leads, coil and shorting link are independent of connections and environment because they are an invariant part of the inductor and that the connecting wires are not subject to disturbance when the short is applied at terminals separated from the connections.

In many calibrations outside of NIST, a direct comparison method is used. The unknown is simply compared to an inductor of almost equal value that has an NIST calibration and the measured difference is used to obtain the value of the unknown. This technique was described above. The measurement with the short circuit is implicit in this new calibration, however, because the NIST used a short in the original calibration and the new calibration is valid only with the short applied at the position used in the original calibration.

Inductor Comparison

When a calibrated six terminal inductor is available, the calibration of other inductors can still be influenced by the inductance of the internal leads. If the two inductors are compared in the usual manner by a difference measurement using the same external leads, the measured difference includes not only the difference between the two inductance changes at the reference terminals but also the difference between the two internal lead inductances. Calibration by this method is subject to error unless the differences in internal lead inductance are negligible or are measured. Generally the error by direct comparison due to differences in internal lead inductance is less than 0.02%.

When lead inductance is not sufficiently constant, its effect can be eliminated by another method of comparison. The two six terminal indictors can be connected in series to the bridge. A first measurement is made with the short of one inductor in the L position while that of the other is in the Lo position on the reference terminals. A second measurement is then made with both links moved to the opposite terminals. The measured difference is the difference between the two inductance changes at the reference terminals and is independent of the internal lead inductances because they appear in both measurements and cancel in the difference.

The 1689 Digibridge is connected to the 1482-A Inductance Standard as illustrated in Figure 2. A 14-guage piece of bus wire is used to connect between the high terminals of both known and unknown standards. PH and IH are connected to the low side of the known and PL and IL are connected to the low side of the unknown. Shorting bars should short between low and guard terminals for each standard.

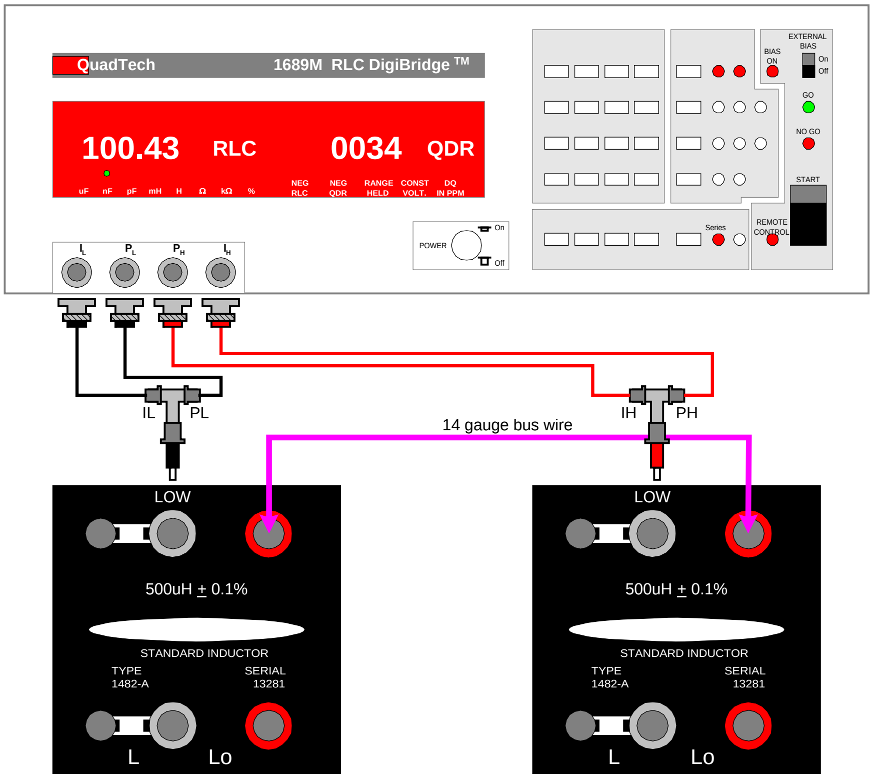

Figure 2: Connection of 1689 Digibridge to 1482-A Inductor

Inductor Standards

Table 2 contains the inductance, accuracy, DC resistance (DCR) and quality factor (Q) values for the 1482 line of Inductance Standards. Formerly manufactured by General Radio Company and QuadTech, the 1482 Inductor is now manufactured and sold by IET Laboratories of Westbury, New York.

Table 2: Inductance Standard Accuracy, DCR and Q Values

Catalog Number	Description Standard Inductor	Nominal Inductance	Adjustment Accuracy (Percentage)	Resonant Frequency (kHz)	* DC Resistance (Ohms)	* Q At 100Hz
1482-9701	1482-A	50 µH	±0.5	3100	0.039	0.81
1482-9702	1482-B	100µH	±0.025	2250	0.083	0.76
1482-9703	1482-C	200 µH	± 0.025	1400	0.15	0.84
1482-9704	1482-D	500µH	± 0.1	960	0.38	0.83
1482-9705	1482-E	1 mH	± 0.1	800/400	0.84	0.75
1482-9706	1482-F	2mH	± 0.1	580	1.52	0.83
1482-9707	1482-G	5mH	± 0.1	320	3.8	0.83
1482-9708	1482-H	10mH	± 0.1	220	8.2	0.77
1482-9710	1482-J	20mH	± 0.1	145	14.5	0.87
1482-9711	1482-K	50mH	±0.1	84	36.8	0.85
1482-9712	1482-L	100mH	± 0.1	71	81	0.78
1482-9713	1482-M	200mH	± 0.1	39.0	109	1.15
1482-9714	1482-N	500mH	± 0.1	24.5	280	1.12
1482-9716	1482-P	1H	± 0.1	14.6	616	1.02
1482-9717	1482-Q	2H	± 0.1	10.6	1125	1.12
1482-9718	1482-R	5H	± 0.1	6.8	2920	1.08
1482-9720	1482-T	10H	± 0.1	4.9	6400	0.98

*** Limits:** After making the measurements, verify the readings did not change more than 0.01% per year.

High-Capacitance Measurements

Precision capacitance bridges such as the IET 1615 and 1616 have ranges up to 1uF 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 3-Terminal bridges (with a guard) make single connections to each end of the capacitor being measured. For good accuracy at higher values, four-terminal (Kelvin) connections are needed to remove the effects of self-inductance. Automatic short-circuit zero corrections are a good way to remove the remaining effects of mutual inductance between leads.

High-Capacitance Measurements

The 1689 unit has these capabilities of four-terminal connection and auto zeroing as well as extreme range and good accuracy. The normal range of the 1689 extends to .099999F, but using its RATIO mode the display range can be extended (nominally) to 10,000 Farads! However, don't look for a capacitor of that value to measure, for even if one could be found, the 1689 would not be able to measure it. However it can measure 1F with fairly good accuracy at 100Hz even though its specifications might not indicate so. This is because the 1689 specifications assume that the zeroing calibrations, open and short, are made at 1kHz 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 100Hz the accuracy specification at 1F is 120%, but with a short circuit calibration at 10Hz, 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 IET 1417 Capacitance Standard (formerly manufactured by QuadTech). There are special fixture considerations that improve the measurement accuracy of the 1689 by 5 to 1 at such values. More important are measurements on standards of lower values, between 1uF and 1F, again such as the 1417. The 1689 can measure these with good accuracy, usually better than required since these standards are less stable than lower valued ones, such as the IET 1404 or 1409 Standard Capacitors.

Mid-value and Low-value Capacitance Measurements

There are bridges, such as the IET 1615 mentioned earlier that measure capacitance from 1uF or less with better precision and accuracy than the 1689. The 1689 is not necessarily recommended for inter comparisons of reference standards in high-level labs, it is however, very adequate for calibrating the reference standards of lower-level labs and all working standards and decade boxes.

Generally, the 1689 instrument is more sensitive than the 1615 for capacitance of 1uF or higher at low frequencies. The 1689 applies more voltage and has much better repeatability if many measurements are averaged in the same time it would take to balance the 1615 bridge. Furthermore, the 1689 unit is 4-terminal whereas the 1615 model is not, so there are connection errors, particularly those due to series inductance at higher frequencies. The repeatability of measuring a 1000pF capacitor with the 1689 at 1kHz is good. The standard deviation should be approximately $2\text{ppm}/\sqrt{\text{N}}$, where N is the number of measurements averaged, so comparisons can be very good. The accuracy is less at lower values, so lower values should be compared at a higher frequency. At 10kHz one can compare a 100pF standard to better than 1ppm or a 10pF standard to better than 10ppm.

It is interesting to note that the repeatability of the 1689 as comparable to that of the precision 1615 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.

Application: Capacitor Setup and Comparison

1689 Setup and Zeroing

Set-up

- Connect appropriate cables and adapters for standard such as 1409 or 1404.
- Select Slow Measurement Speed
- Turn Median Mode “ON”
- Set Averaging to 5 or 13
- Select Cs and D
- Select Test Frequency at 1kHz
- Perform open and short compensation

Measurement of capacitor standards is similar to measurements of inductors using a direct comparison method. The unknown is simply compared to a standard capacitor of almost equal value that has a NIST calibration and the measured difference is used to obtain the value of the unknown. This technique is straight forward when dealing with three or four terminal standards as cable geometry and stray capacitance issues are negligible. When measuring two terminal capacitance standards, such as type 1409, that are calibrated in a two terminal configuration care must be taken to keep exact cable geometries so as not to introduce error due to stray capacitance. This is extremely importance on low value of capacitance.

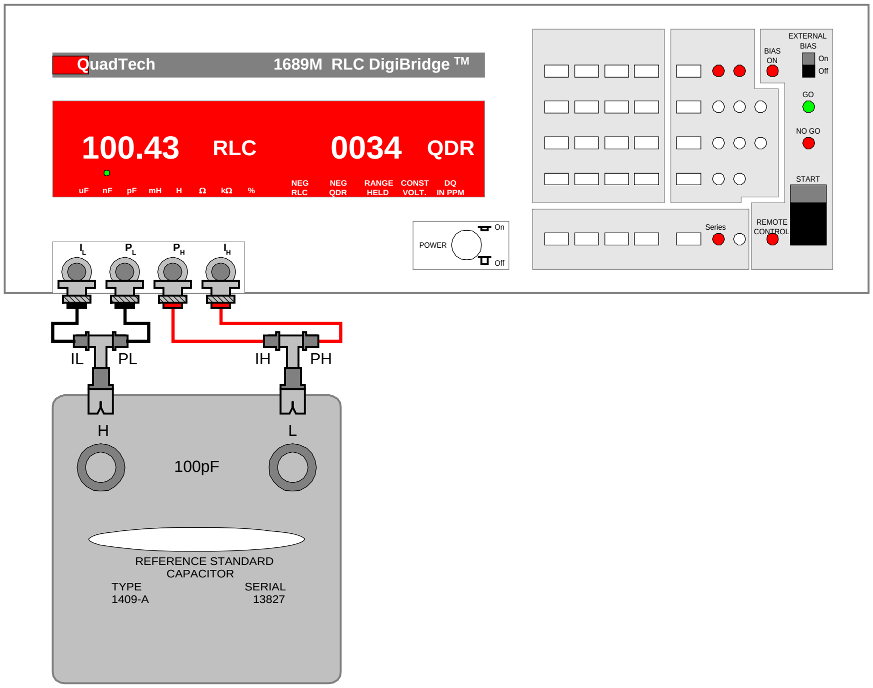

Figure 3: Connection of 1689 Digibridge to 1409 Capacitance Standard

AC Resistance Measurements

The GenRad1689 is probably unequaled for AC resistance measurements over its frequency range (12Hz to 100kHz). Unfortunately many 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, the size of the 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, but the DC habit has been hard to break.

For most resistors, the AC-DC difference is negligible at 100Hz or even 1kHz. For flat-card wire-wound resistors, the difference can be less than 1ppm up to 1MΩ if equivalent parallel resistance is used at high values to avoid errors due to lumped parallel capacitance and series resistance is used at low values to avoid errors due to series inductance. Lower measurement frequencies should also be used for very low values to avoid skin effect errors. There are significant differences for high-value, coil-wound resistors, because of capacitance not inductance, and for high-value, multi-resistor networks such as decade boxes and build-up standards. The AC-DC difference of resistance standards are generally very small and often can be easily determined by measuring it, and a small metal film resistor of similar value at both AC and DC. Here the assumption is made 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 one doesn't heat it up by applying too much power or touching it). Once such differences are determined, AC could be used for precision calibrations.

Summary

The GenRadModel 1689 Digibridge should definitely be considered for use in a standards laboratory. It can make some calibrations more accurately than possible with traditional instruments and will make many other required measurements easier and faster. The 1689 model can be used for even more measurements in lower-level labs and for almost all RLC measurements when AC resistance measurements are acceptable.

For complete product specifications on the Digibridge Line of LCR meters or any of IET's products, visit us at http://www.ietlabs.com/digibridges.html Do you have an application specific testing need? Call us at 1800-899-8436 or email engineering at sales@ietlabs.com and we'll work with you on a custom solution. Put IET to the test because we're committed to solving your testing requirements.

References:

Hill, J.J.: "Calibration of DC Resistance Standards and Voltage Ratio Boxes by an AC Method", Proc. IEEE Vol. 112 No.1, January 1965