A History of Impedance Measurements

by Henry P. Hall

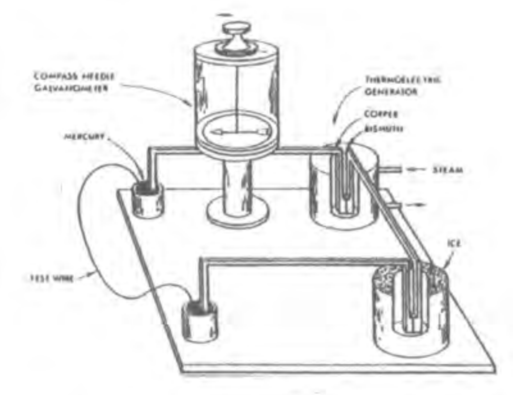
A HISTORY OF IMPEDANCE MEASUREMENTS

PART I. THE EARLY EXPERIMENTERS 1775-1915

1.1 Earliest Measurements, DC Resistance

It would seem appropriate to credit the first impedance measurements to Georg Simon Ohm (1788-1854) even though others may have some claim. These were dc resistance measurements, not complex impedance, and of necessity they were relative measurements because then there was no unit of resistance or impedance, no Ohm.

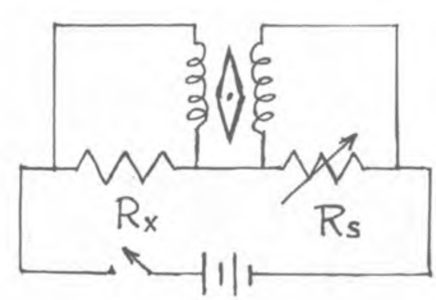
For his initial measurements he used a voltaic cell, probably having copper and zinc plates, whose voltage varied badly under load. As a result he arrived at an erroneous logarithmic relationship between the current measured and the length of wire, which he published in 1825[1]. After reading this paper, his editor, Poggendorff, suggested that Ohm use the recently discovered Seebeck (thermoelectric) effect to get a more constant voltage. Ohm repeated his measurements using a copper-bismuth thermocouple for a source[2]. His detector was a torsion galvanometer (invented by Coulomb), a galvanometer whose deflection was offset by the torque of thin wire whose rotation was calibrated (see figure 1-1). He determined "that the force of the current is as the sum of all the tensions, and inversely as the entire length of the current". Using modern notation this becomes I = E/R or E =I*R. This is now known as Ohm's Law.



1-1 Ohm's Circuit for Measuring Resistance 1826

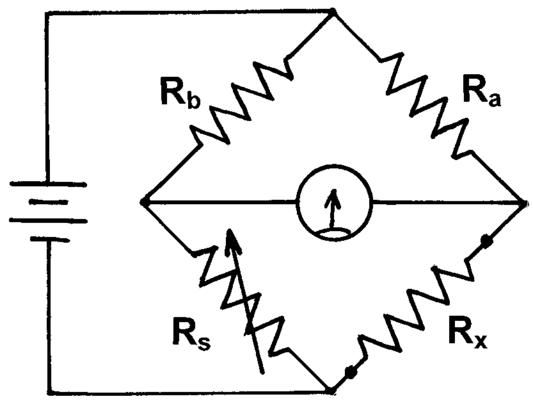
He published this result in 1826 and a book, "The Galvanic Circuit Mathematically Worked Out" in 1827. For over ten years Ohm's work received little attention and, what there was, was unfavorable. Finally it was made popular by Henry in America, Lenz in Russia and Wheatstone in England[3]. Ohm finally got the recognition he deserved in 1841 when he received the coveted Copley Medal of the Royal Society of London[4]. Recognition of his contributions was slower in his home country of Bavaria and he had to wait until 1849 to get the university post he wanted at the University of Munich. After his death, he gained immortality when, in 1881, the International Electrical Congress gave his name to the unit of resistance.

Probably Henry Cavendish (1731-1810) made the first experiments in conductivity in about 1775 but he did not publish and his work went unknown until his notes were published by Maxwell in 1879 who felt that Cavendish had anticipated Ohm's law by some fifty years (some early books refer to Cavendish's Law[5]). Humphrey Davy (1778-1829) and Peter Barlow (1776-1862, known for "Barlow's Tables") in England and Antoine-Cesar Becquerel (1788-1878 (the grandfather of A. H. Becquerel, the discoverer of radioactivity) in France all compared the conductivities of different metals. Becquerel had determined the relationship between conductivity, length and area that Ohm had also found, but published a year after Ohm did. He used a differential galvanometer, which he invented[6], a meter with two opposed windings that gave zero deflection, or a "null", if equal currents were applied. Becquerel probably used the circuit of figure 1-2 in which the two galvanometer



1-2 Becquerel's Differential Galvanometer Method coils shunt the two resistors being compared. (Another possibility is that he connected the two coils in series the two resistors but the circuit shown is more suited for comparing very low resistances which they probably were.) This is the first known use of the null method that has the great advantage that the relationship between the resistances being compared is independent of the source voltage and thus overcomes the problem of unsteady battery voltage that plagued Ohm.

The most famous and important null method, the bridge, was invented by Samuel Hunter Christie when he was a Mathematical Assistant at the Royal Military Academy at Woolwich[7]. Apparently he was familiar with Becquerel's work, but not Ohm's. His circuit was first described in a paper entitled "Experimental Determination of the Laws of Magneto-Electric Induction" in 1833. He called his invention "A Differential Arrangement" and with it he verified Becquerel's relationship between conductance and a wire's dimensions and determined the relative conductances of various metals to greater accuracy. However, his work also was largely unnoticed, probably because his description was awkward and buried in a long and somewhat tedious paper. Finally Charles Wheatstone (1802-1875) referred to Christie's work in a paper in 1843[8]. Wheatstone gave full credit to Christie, but he described the circuit and its advantages much more clearly and it will be forever known as the Wheatstone Bridge (figure 1-3). Wheatstone, originally a musical instrument maker and later Professor of Experimental Physics at King's College, was famous for work in other fields well as electricity inventing the concertina, the stereoscope and the rheostat. He also did important work in telegraphy and with dynamos[9].

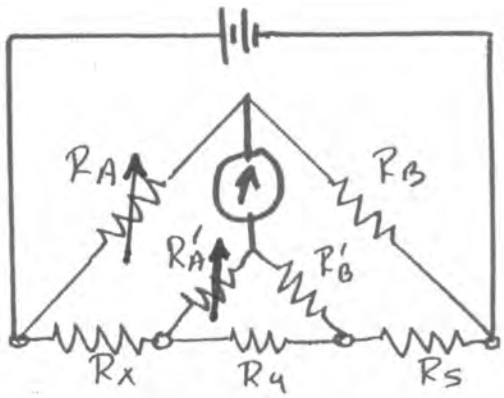


1-3 Wheatstone Bridge
or "Resistance Balance"
Christie 1833
Wheatstone 1843

Wheatstone called Christie's circuit a "resistance balance" and its branches were called "arms", an obvious analogy to a scale balance. The arms were "bridged" by the detecting galvanometer so that the circuit was first called a "bridged network" which later became just "bridge". The two fixed adjacent arms, R_a and R_b in figure 1.3, were called the ratio arms and the other two were the resistances being compared, R_x the "unknown" being measured and R_s the standard. The ratio arms in Christie's and Wheatstone's bridges were equal so that only equal resistances could be compared. Werner von Siemens (1816-1892) introduced unequal ratio arms in 1848 allowing the measurement of widely unequal resistances[10].

A Wheatstone bridge is balanced when no current flows in the detector which occurs when $R_x/R_s = R_a/R_b$ or $R_x = R_sR_a/R_b$. This is the balance equation and it is independent of the input signal level (if all arms are linear) and the detector sensitivity, and it remains unchanged if the source and detector are interchanged. The unknown is measured only by the values of other resistors, one of which is varied to achieve the balance.

William Thomson (1824-1907), later Lord Kelvin of Largs, made a study of bridge errors, particularly those due to the resistances of the connections, which became large when comparing low-valued resistors. He developed his "New Electrodynamic Balance", now called the Kelvin (or Thomson) Bridge or Double Bridge (figure 1-4), that removes the error caused by the resistance, Ry, of the connection between the resistors being compared (called the “yoke") with a second pair of ratio arms, R_A' and R_B', that divide the voltage drop across Ry proportionately so that at balance $R_X/R_S = R_A/R_B = R_A'/R_B'$. He described this bridge in 1862[11]. Note that there are four connections to both R_X and R_S and the resistances of the connecting leads and contacts are placed in the other circuit branches where they have little effect. Low-valued resistance standards usually have four terminals and

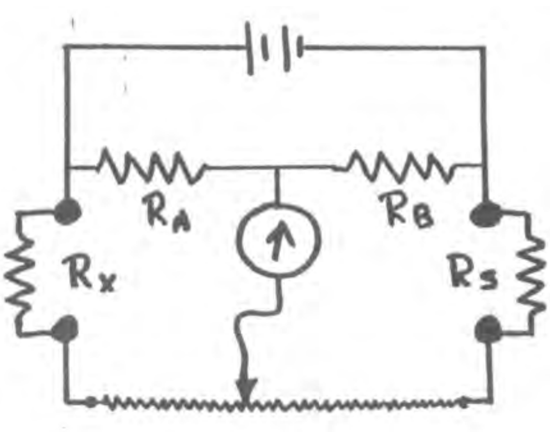


1-4 Kelvin Double Bridge 1862

their resistance is defined as that between the connection junctions at each end. The Kelvin Bridge was the first to make such "four-terminal" connections and as a result they are sometimes referred to as "Kelvin connections". Kelvin, whose name is also given to the absolute temperature scale, was a leading scientist in many fields. He used his bridge to measure the resistivity of copper samples as a quality control tool for the Atlantic cable project. Even though his work in electrical measurements was only one of his minor achievements, he might well be called the father of precision electrical measurements.

Precision was limited by the apparatus available. Many scientists studied bridge sensitivity including Schwendler, Heaviside, Gray and Maxwell concluding that the batteries available were not capable of producing the desired power[12]. Measurement precision was also limited by the detecting galvanometers used. The early galvanometers were the result of work of Ampere, Schweigger, Poggendorff, Cumming and Nobili[13]. Kelvin's reflecting galvanometer (1858), which was invented as a telegraphy receiver, gave much greater sensitivity[14]. It used a small mirror as the moving element and this reflected a focused light beam onto a distant screen. The famous D'Arsonval or moving-coil galvanometer resulted from work of Kelvin and Maxwell and was popularized by Deprez and D'Arsonval in 1882[15]. This design was used by Weston in many pointer-type ammeters and voltmeters, but reflecting galvanometers were used to get the highest sensitivity for dc null detection.

Early bridges and resistance boxes were usually adjusted by means of taper pins that connected blocks of brass arranged in various "patterns" (see Part II). "Dial" bridges used rotary switches and were thus easier to adjust but usually had higher contact resistance. “Slide-wire” or “Meter” bridges, first introduced by Gustav Robert Kirchhoff (1824-1887) use a straight piece of wire, usually German silver, to form the two ratio arms, with a sliding contact making the galvanometer connection[16]. This made the ratio continuously adjustable and measured on a meter scale. Professor Carey Foster's method[17] puts a slide wire between the standard resistance and the resistor being compared with it, see figure 1-5. Two measurements were made with the standard and unknown interchanged thus canceling the effects of extraneous resistance and voltages as long as the resistances of the mercury cup contacts used for the connections remained constant. This provided an alternate method to the Kelvin Bridge for the precision comparison of nearly equal resistances of low value.



1-5 Carey Foster's Method for Comparing Resistors

Yet another way to compare resistors was simply to connect the two resistors being compared in series (and in series with a source voltage) so that they passed the same current and then measuring the voltage across each. Two meters could be used or a single meter could be used for both measurements. Also a differential galvanometer could be used to measure the difference in voltage if the standard resistor could be adjusted to make the voltages equal (see figure 1-2). A modification on this was the

Kohlrausch "Method of Overlapping Shunts" (1904)[18]. It used a differential galvanometer with the two coils shunting the resistors making four-terminal connections. But to avoid errors due to differences in the resistances of the two galvanometer coils, they were ingeniously interchanged in a manner that kept the connection resistances constant. The average of the two measurements could be very precise.

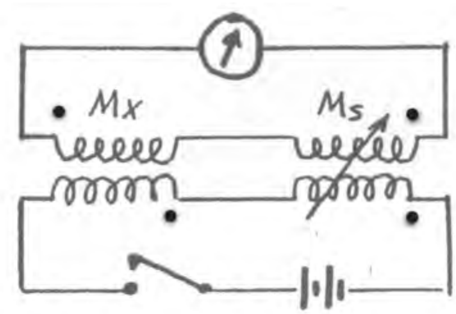
If a potentiometer (or a precision voltage divider) and separate voltage source is used to measure the two voltages, this is called the potentiometer or "potentiometric" method[19]. A galvanometer null would indicate when the potentiometer voltage equaled that across each resistor. This method could give high resolution and compare resistors of widely different values, but both voltage sources had to remain very stable as the two measurements were made. Yet a better method is to connect the divider across both resistors forming a bridge and make four balances, one connecting the galvanometer to each end of each resistor. This allowed four-terminal measurements and had most of the advantages of a bridge but a more complicated calculation was required.

The variety and precision of dc resistance measurements improved greatly through the last of nineteenth century and into the twentieth spurred on by corresponding improvements in the standards of resistance and the founding of the many great national standards laboratories that determined and preserved the values of the electrical units, including the Ohm.

1.2 Dc to Ac, Capacitance and Inductance Measurements

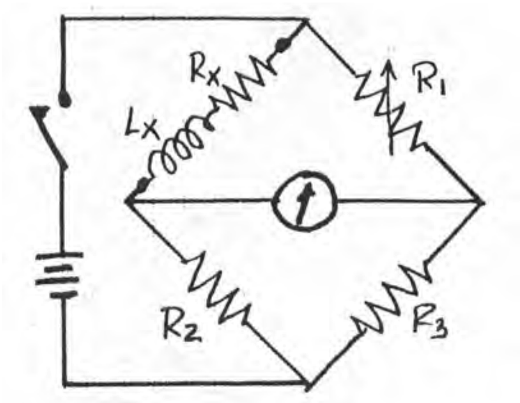
While Ohm's Law originally considered only resistance, there were other quantities that affected current, at least transient current. The first capacitors, Leyden Jars, were invented by von Kleist and von Musschenbroek in the 18th century and improved capacitors were developed by others including Michael Faraday (1791-1867) who measured the "specific inductive capacity" (dielectric constant) of various insulating materials. He measured the relative capacitance of two capacitors using an early electrometer similar to Coulomb's Torsion Balance (Charles Augustin Coulomb 1736-1806) noting the relative decrease in charge of one capacitor when it charged a second capacitor. Relative capacitance was also measured by comparing the relative galvanometer deflections they gave when discharged[20] Like Ohm's resistance measurements, these were "meter" methods whose accuracy depended on the linearity of the detecting charge or current sensing device and the stability of the dc source.

Faraday and Joseph Henry (1797-1878) independently discovered mutual inductance in 1831 and self-inductance in 1832 with Faraday getting most of the credit for the former and Henry for the latter[21]. They measured relative inductance values by meter deflection methods. In 1852 R. Felici demonstrated mutual induction in the simple null circuit of figure 1.6 that compared a fixed inductor against a variable one. Although this was actually not a bridge, it is perhaps the first ballistic (transient) null method and thus an important step[22]. Much later (1882) Heaviside used this simple circuit with a telephone as detector.

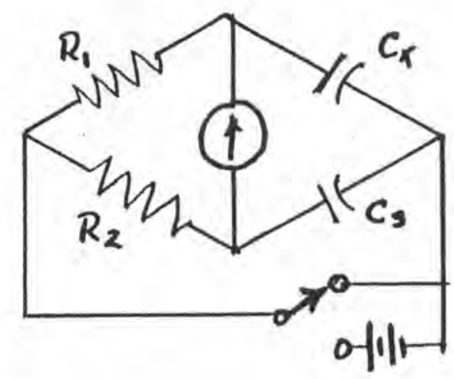


1-6 Felici's Circuit for Comparing Mutual Inductors 1852

James Clerk Maxwell (1831-1879) introduced a ballistic deflection method for measuring inductance and resistance in 1865[23], see figure 1-7. This bridge was first balanced as a Wheatstone bridge with a steady dc applied. Then the battery connection was opened or closed to give an inductive transient. The inductance then could be calculated from the magnitude of the transient galvanometer deflection and the galvanometer's ballistic (impulse) calibration. Thus this was a combined bridge-meter method, a bridge for resistance and a meter for inductance.

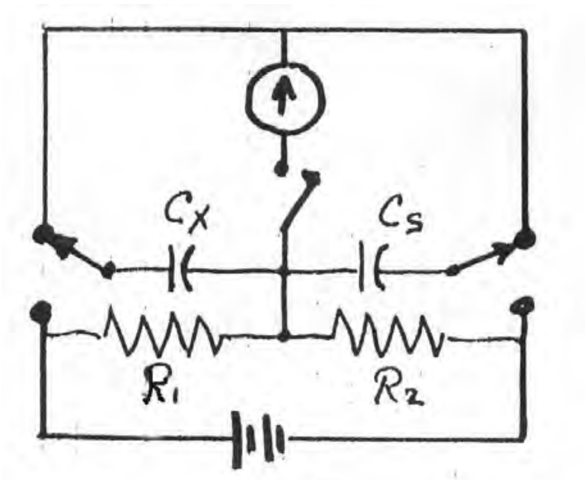


1-7 Maxwell's Ballistic Deflection Method for Comparing Inductors 1865

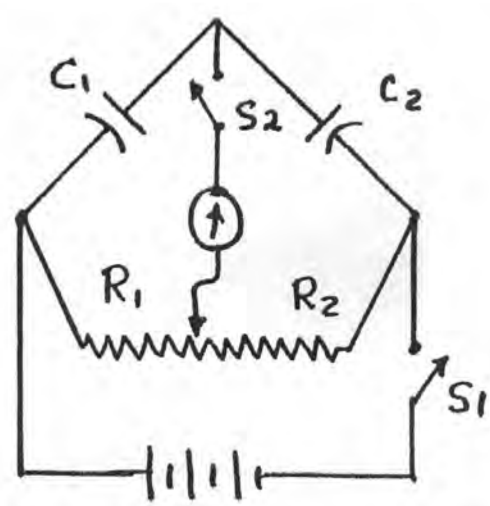


1-8 DeSauty Ballistic Bridge Method for Comparing Capacitors 1871, ac: Wien 1891

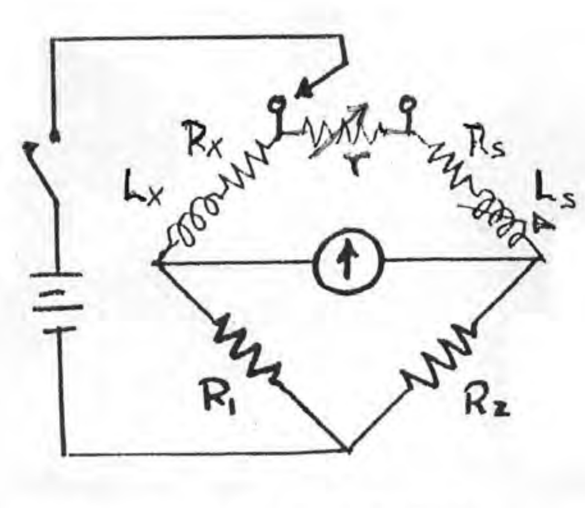
If an adjustment is made to null this transient deflection, the circuit becomes a "ballistic bridge". While Maxwell introduced ballistic bridges for inductance measurements (see below) the first such bridge may have been one by C. V. de Sauty (who worked on the Atlantic cable, as did Kelvin) in (or before) 1871 that he used for capacitance measurements figure 1-8. Here the capacitance ratio is measured in terms of the resistance ratio when the transient is nulled by making the RC time constants equal[24]. Because of this method, bridges that compare the ratio of two capacitors to the ratio of two resistors are often called de Sauty bridges. Several other researchers made null measurements to compare capacitance ratios to resistance ratios, but unlike de Sauty's circuit that switched only the input, they used switches in the circuit itself that were depressed in a certain sequence. In Thomson's (Kelvin's) "method of mixtures", figure 1-9, (1873) switches S_1 and S_2 were closed to charge the two capacitors to voltages, V_1 and V_2, proportional to the resistor ratio. Then these switches were opened and S_3 closed so that the charges on the two capacitors “mix” (positive charge in C_S flows into C_X). If the charges on the two capacitors had been equal, $Q_1 = C_1V_1 = C_2V_2 = Q_2$, the discharge would be complete and there would be no transient on the galvanometer when S4 is closed[15]. The circuit by J. Gott in figure 1-10 (1881) looks even more like a bridge[26]. He charged the



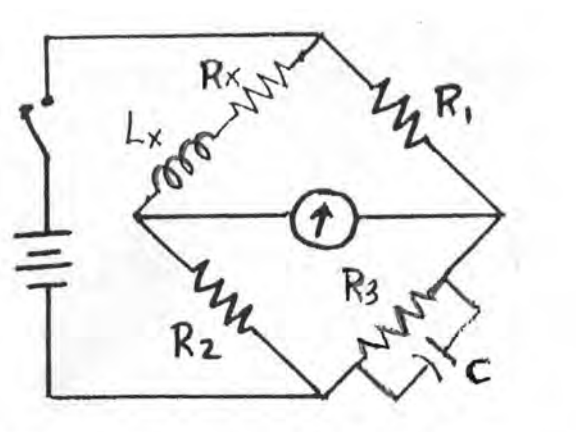
-9 Kelvin's "Method of Mixtures" for Comparing Capacitors 1873



1-10 Gott's Method of Comparing Capacitors 1881



1-11 **Maxwell's Ballistic Bridge for Comparing Inductors 1873**



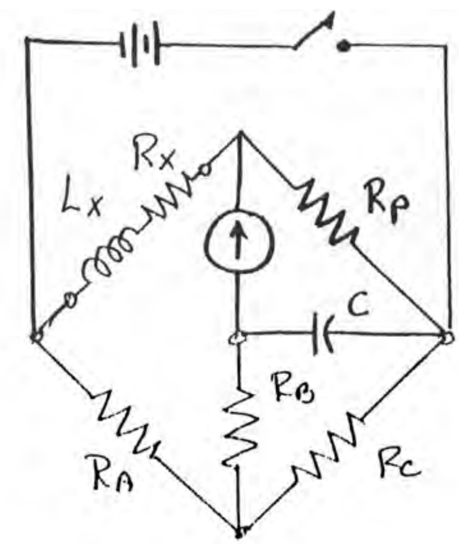
1-12 **Maxwell's Ballistic Bridge for Measuring Inductance in Terms of Resistance and Capacitance 1873 , ac: Wien 1891**

$$L = R_1R_2C$$

capacitors is series with switch S_1 and, with the voltage still applied, closed S_2 to see if a balance was made.

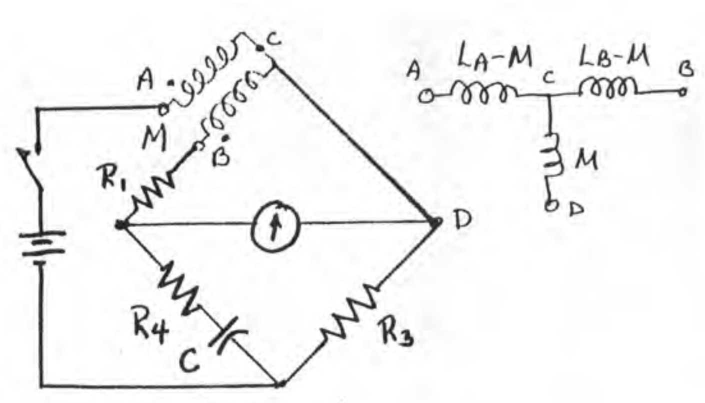
In his famous ***Treatise on Electricity and Magnetism***[27] (1873) Maxwell introduced many ballistic bridge circuits for comparing inductances, both self and mutual that were adjusted for a null. It would be difficult to prove who actually ***used*** the nulled ballistic method first, Maxwell or DeSauty. In Maxwell's circuits, both resistance and inductance were measured. In the circuit of figure 1-11, resistance balance was made first with a constant voltage applied and a resistance, r, added to either arm to get a dc balance. Then an inductance adjustment was made until there was no transient galvanometer deflection. He also showed a bridge circuit for comparing capacitors and one for comparing an inductor with a capacitor. The latter, the most famous Maxwell Bridge, balanced an L/R time constant against an RC time constant so that L was actually measured from the values of a capacitor and two resistors (figure 1-12). This was an important development because today capacitors and resistors generally make much better bridge standards than do inductors. However in Maxwell's time this was not necessarily true and this bridge might was also useful in measuring capacitance in terms of inductance.

There were several modifications of Maxwell's L-C ballistic bridge, perhaps the most famous and interesting is the one by A. Anderson in 1891[28]. Anderson's bridge, figure 1-13, had extra resistive branches that increased its inductance range but which complicated the balance equations (but it can be reduced to Maxwell's bridge by the Y-Δ transformation). This bridge was later used by several prominent researchers. Carey Foster's modification of Maxwell's bridge (1887)[29] compared capacitance to



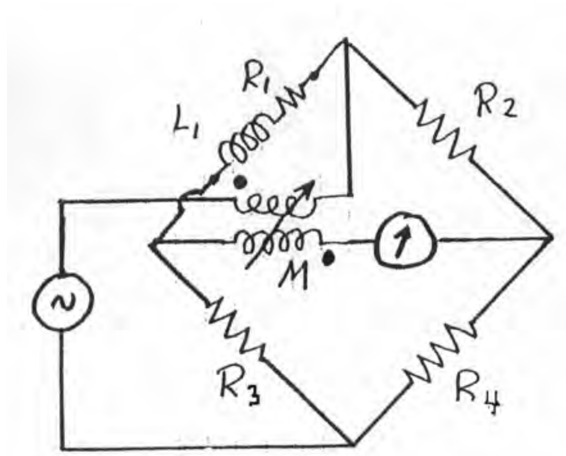
1-13 **Anderson's Bridge 1891**

$$L_X = CR_p(R_A + R_B + R_AR_B/R_C)$$



1-14 **Carey Foster Bridge and Equivalent Circuit for Mutual Inductance 1887 ac: Heydweiller 1894**

$M = R_1R_3C$ $L = M(1 + R_4/R_3)$



1-15 **The Hughes Balance 1880, Heavyside 1892**

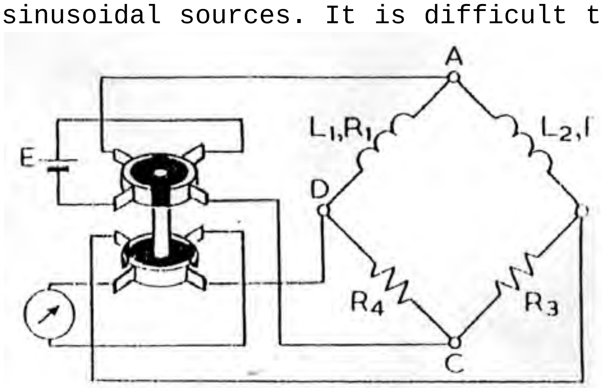
$LR_4 = M(R_1+R_2+R_3+R_4)$
$\omega^2 ML = R_2R_3-R_1R_4$

mutual inductance in a ballistic bridge that looks as if it had one arm shorted, but this arm can be shown to contain the mutual inductance between the coils arm if the "T" (or “Y”) equivalent circuit for inductively-coupled coils is used, figure 1-14 (see Appendix A)

An interesting bridge by Prof. D.E. Hughes, the “Hughes Balance” (1886), added mutual inductance between input and output, figure 1-15. He calculated the balance equations improperly and got astonishing results. Later Heaviside, Weber and Lord Rayleigh (John Strutt) corrected his mistake[30].

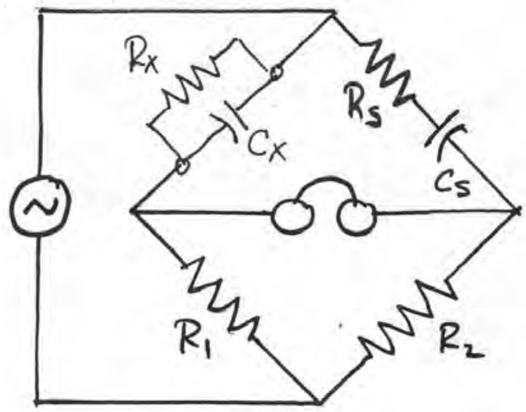
In 1882 M. Brillouin simultaneously reversed the polarity of both dc source and detector at the same time with two commutators on the same shaft. This gave a galvanometer defection in one direction for both on and off transients, and because the direction depended on the sign of the unbalance, this might be considered to be the first use of synchronous or phase-sensitive detection even though ac was not used. This principle also gave much greater sensitivity because the successive transients reinforced rather than canceled each other if the reversal was fast compared to the galvanometer's time constant. W. E. Aryton and J. Perry used this principle in their famous ***Secohmmeter***[31] (1888) which had both hand-driven and motor-driven versions, figure 1-16. (The "secohm" was an early unit of inductance[32].)

True ac bridges required alternating current sources and good ac detectors. A variety of electromagnetic "interrupters", "buzzers" and "hummers" were used in the transition between telegraphic keys and true sinusoidal sources. It is difficult to say when the use of true ac actually started. Detectors for ac were greatly improved with Alexander Graham Bell's 1876 invention of the telephone receiver that was used by Rayleigh, Heavyside, Hughes, Kohlrausch and others to get increased sensitivity in bridge circuits[33].



1-16 **The "Secohmmeter" Commutator Method Aryton & Perry 1888**

"It is to Max Wien that the modern alternating current bridge is due" says Hague in his famous book[34]. Wien (1866-1938) published a classified collection of ac bridge networks in 1891 that included earlier ballistic bridges adapted to true ac as well as introducing new bridges[35]. As a result some people refer to the "Maxwell-Wien"



1-17 The Wien Bridge
1891

$C_X = C_S R_2/[R_1(1 + D_S^2)]$
$D_X = 1/(\omega R_X C_X) = D_S = \omega R_S C_S$
or $\omega^2 R_X R_S C_X C_S = 1$

inductance bridge and the "De Sauty-the Wien Bridge, was a modification of the de Sauty bridge that put an adjustable resistance in series with the standard capacitor rather than in parallel with it (see figure 1-17). This allowed balances on very low-loss capacitors because this bridge could be nulled with a low-valued rheostat whereas one of extremely high value would be required if it were in parallel with the standard capacitor. If the "unknown", C_X, and its loss are represented by an equivalent ***parallel*** capacitance and resistance, the balance equation of Wien's bridge is frequency dependent (see equations in figure 1-17). Many later R-C oscillators, including the first HP oscillator, used this "frequency-bridge" circuit with the "unknown" replaced by a parallel resistor and capacitor. It was also used in a frequency meter, the GR 434-B (1931).

For a source Wien used an induction coil whose primary was switched by a vibrating wire to give a steady frequency. His detector, an "optical telephone", was a telephone receiver with a resonant diaphragm that vibrated a mirror, the first vibration galvanometer and an antecedent of the oscillograph.

Oliver Heaviside (1850-1925) introduced the terms "impedance", "capacitance" and "inductance" in 1892 and an operational notation for complex impedances[36]. Ohm's Law was generalized to E = IZ, where Z = R + jX and $j = \sqrt{-1}$. This allowed ac bridge balance equations to be divided into real and imaginary parts. For a complex impedance the bridge balance equation now became $Z_X/Z_S = Z_A/Z_B$. In most four-arm bridges only one arm, other than the unknown, was intentionally made complex by a series or parallel arrangement of a resistor and either a capacitor or inductor. "Ratio" bridges, such as the series or parallel versions of de Sauty's capacitance bridge, compared similar complex impedances in adjacent arms. "Product" bridges compared a series arm to an opposite, parallel arm using the balance equation rewritten as $Z_X = Z_A Z_B Y_S$ where Y_S is admittance, the reciprocal of impedance: Y = 1/Z. Thus the balance equation for the Maxwell (or Maxwell-Wien) Inductance Bridge was

$$R_X + j\omega L_X = R_a R_b (G_S + j\omega C_S).$$

This could be separated into separate real and imaginary balance conditions $R_X = R_a R_b G_S$ and $j\omega L_X = R_a R_b j\omega C_S$.

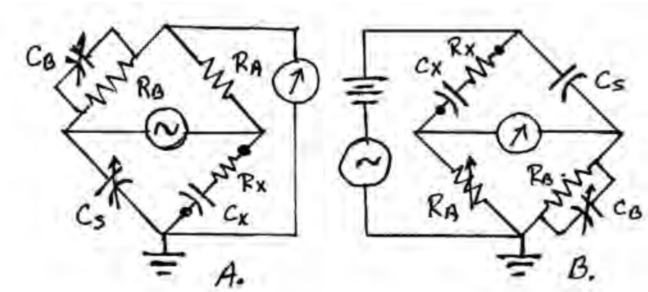
Before Heaviside the balance equations were expressed in cumbersome integro-differential equations. Heaviside also worked out the general balance equations for a four-arm bridge with mutual inductance between all circuit branches, including the input and output as well as the bridge arms.

1.3 An Abundance of Bridges

The work of Wien and Heavyside set the stage for the development of bridges for all purposes, bridges that used almost all possible combinations of resistance, capacitance, inductance and mutual inductance. These bridges are best chronicled by B. Hague in his "bible" of ac bridges, ***"Alternating Current Bridge Methods"*** originally printed in 1923 and revised many times since, the latest version revised by Foord in 1971[37]. There is little point in mentioning all these bridges when Hague's book is easily available. Moreover, many of these bridges are minor variations of other bridges and most were of little lasting importance. With the hindsight of time, we can consider those bridges that have been proven most useful and perhaps a few others of particular historical interest. It is easiest to consider these grouped by the parameter measured.

The capacitance bridge story is relatively simple. Wien added series and parallel resistances to de Sauty's bridge to allow the measurement of series or parallel capacitance, and these are the two capacitance bridges used later in most general-purpose impedance bridges, with the series bridge more important because series capacitance is usually specified for capacitors and because the parallel bridge requires a very high-valued resistor to make low D (dissipation factor, $D = R_X/X_X$) measurements.

At NBS, F.W. Grover in 1907 compared an unknown capacitor against another capacitive arm with no loss adjustment and made both real and imaginary balances with a pair of inductive arms, one or both variable and in series with a variable resistor[38]. The two inductive arms were not coupled as in later transformer-ratio-arm bridges. Fleming and van Dyke's "Four Condenser Bridge" (1912) was a variation of the Wien bridge with capacitive ratio arms[39]. This allowed high-impedance ratio arms for best sensitivity when measuring small capacitances, such as samples of dielectric materials, but avoided the large phase-angle errors of high-valued resistive arms especially at higher frequencies. C.E. Hay made a capacitance version of Anderson's bridge by adding extra branches to the parallel capacitance bridge (1913)[40].

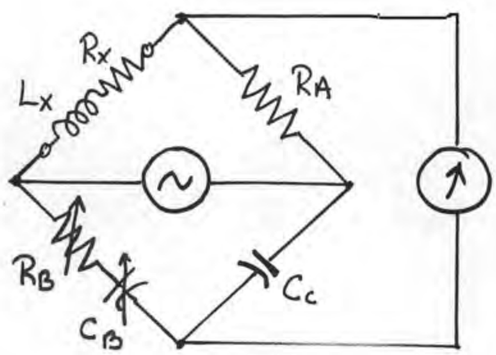


1-18 The Schering Bridge
1920 (Thomas 1915)
A. a Bridge for Low-Loss Measurements
B. a High-Voltage Bridge

$C_x = C_S R_B / R_A \qquad D_X = \omega C_B R_B$

More important than these variations was the Schering Bridge (figure 1-18), named for H. Schering of the PTB, the German national laboratory, who suggested the circuit in 1920[41] even though the same circuit was described in a U.S. Patent filed by Phillips Thomas in 1915[42]. This bridge has several important uses. First it is an excellent bridge for low-loss measurements because the phase adjustment is a variable capacitor that can give high resolution. Second, it has had much use as a high-voltage bridge (both high-voltage ac and ac with high-voltage dc bias) because most of the ac voltage (and all of the dc voltage) is applied only to the unknown and a high-voltage standard capacitor (if the resistor ratio arms are of low value). Finally it makes an excellent high-frequency bridge because both adjustments are variable capacitors that can have excellent high-frequency characteristics (see part 2.4).

The self-inductance bridge story is more complicated because there are so many possible bridges that measure self-inductance in terms of a capacitance, another self-inductance or a mutual inductance. The most important bridges over time have been the Maxwell (or Maxwell-Wien) bridge, of figure 1-12 and its many variations. Anderson's ballistic bridge with its extra arm was modified for ac by Rowland (1898) and used for precision measurements by several including Rosa and Grover of NBS[43]. Stroud and Oates[44] used it backwards (interchanging source and detector) and had that circuit named after them even though it has the same balance equations. C.E. Hay (1910) replaced the parallel R-C arm of the Maxwell Bridge with a series one[45]. This measured parallel inductance, but allowed measurement of higher Q values ($\omega L/R$) without requiring a very high-valued variable resistance. The Hay bridge was also more convenient to use for measurements on inductors when they were biased by dc current because the series R-C arm blocked the flow of dc current. The Hay and Maxwell bridges were both chosen for inductance measurements in later LRC or "Universal" measuring instruments. The Owen bridge (D. Owen, 1915), figure 1-19, removed the parallel resistor of the Maxwell bridge and put instead a series capacitor in an arm adjacent to the unknown[46]. This circuit, and a modification of it with a parallel R-C



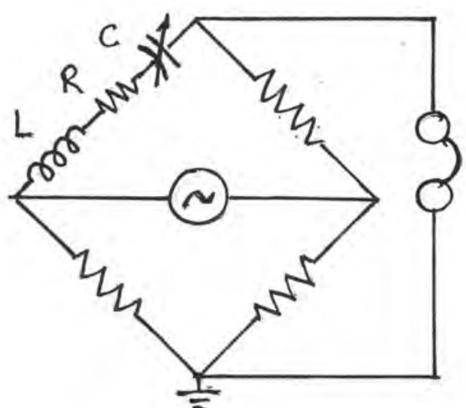
1-19 The Owen Bridge Series Inductance Version 1915

arm that measured parallel inductance, were later used in precision inductance bridges because the inductance adjustment could be a high-resolution decade resistor.

Self-inductors can be measured in terms of capacitance using resonant bridges, series and parallel. The series version, figure 1-20, that balances when $L = 1/\omega^2C$ and the resistance ratios are equal, is credited to Gruneisen and Giebe (1910)[47]. The parallel version was earlier used by Nivan (1887) as a ballistic bridge and by Wien with true ac (1891)[48]. For the parallel resonant version, the simple $L = 1/\omega^2C$ relationship gives the equivalent ***parallel*** inductance. It has a more complicated balance equation if equivalent ***series*** inductance is to be measured. These resonant bridges require a combination of a low-distortion ac source and a frequency-selective detector to get a good null because they are grossly unbalanced for all harmonic frequencies. Resonant bridges were also used to measure frequency, as were many other "frequency bridges" with frequency dependent balance equations, the Wien bridge being the most common example.

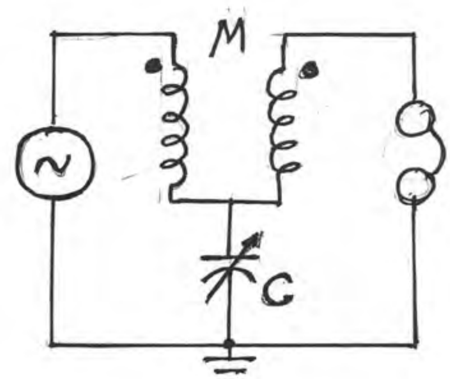
There were several modifications of Maxwell's bridge for comparing two inductors (figure 1-11) including one, the Wien-Dolezalek bridge which used a variable inductance[49]. Wien had a version analogous to his frequency-dependent capacitance bridge that compared fixed inductors by varying resistance and frequency[50].

The number of possible bridge circuits increases enormously if mutual inductance is included. In these early days calibrated, variable, mutual inductors ("inductometers" or "variometers") of various patterns (Ayrton-Perry, Brooks and Weaver, Mansfield etc[51])were among the most precise variable elements so that there were many bridges that measured the other quantities in terms of mutual inductance as well as those for measuring mutual inductance itself. For example the Carey Foster bridge (figure 1-14) and some of its many modifications were used to measure capacitance in terms of mutual inductance instead of as originally used to measure mutual inductance. Albert Campbell's "sifter" method, figure 21, compared capacitance and mutual inductance directly [$M = 1/(\omega^2C)$] with no ratio arms could also be used to measure frequency.



1-20 Series Resonant Bridge

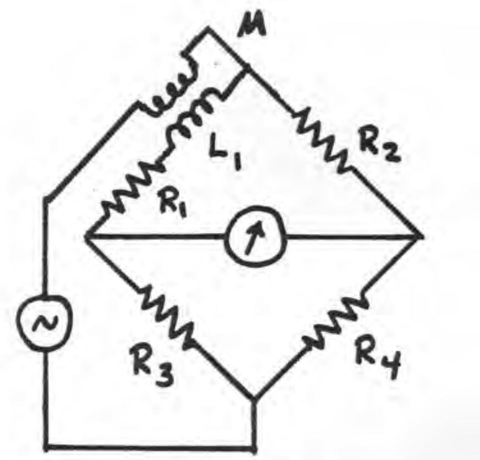
$L = 1/(\omega^2C)$



1-21 Campbell's "Sifter" Method 1908

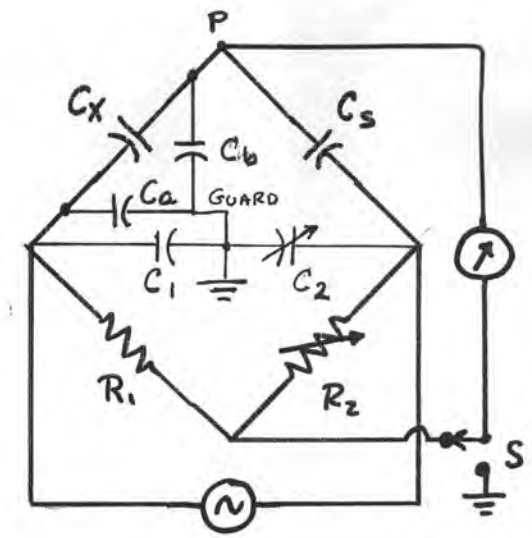
$M = 1/(\omega^2C)$

The Maxwell-Wien bridge of figure 1-22 was used for comparing the mutual inductance of a pair of coils to the self-inductance of one of them. (Its balance equation is easily derived using the equivalent circuit of figure 1-14). It had many modifications (Campbell, Heavyside, and Butterworth) and there were many modifications of these modifications[53]. Most of these had complicated, frequency-dependent balance equations and we might wonder now if all these bridges were really of much practical use.



1-22 The Maxwell L-M Bridge 1873, ac Wien 1891

$M = LR_4/(R_3+R_4)$



1-23 Wagner Ground Guard Circuit 1911

$C_X = C_S R_2/R_1$

if $C_X/C_S = (C_1+C_a)/C_2$

Karl Wagner made an important contribution to bridge measurements when he introduced the "Wagner Ground" (or “Wagner Earth”) in 1911 (figure 1-23). Wagner used these auxiliary bridge arms (C_1 and C_2) to remove the effect of the capacitance between the observer's hand and the detector[54]. More generally it can be used to make guarded, three-terminal measurements such as those on shielded three-terminal capacitors as shown in the figure. Balances are made with the switch in both positions. When the auxiliary arm, C_2, is adjusted so that the point P is at ground potential, C_b has no effect and C_X is measured directly. This auxiliary circuit was later used in commercial capacitance bridges and resistive Wagner balances are used to guard out leakage resistance to ground in dc high-resistance bridges. It is interesting to note that a resistance bridge with a Wagner balance is the topological dual of the Kelvin bridge (figure 1-4) which also has two auxiliary arms and requires two balance adjustments.

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2.1 Comment: Putting the Parts Together

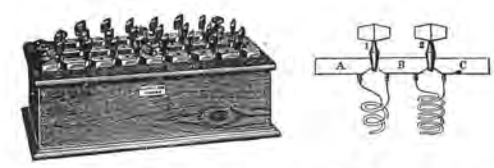
The actual physical embodiment of most of the bridge circuits described so far was usually a bench top combination of fixed, decade and variable passive elements, connected to a voltage source and suitable detector each with its own adjustment circuit elements. These assemblies not only took up a lot of space, they also were not easy to set up or use and were subject to errors. As the use of electricity, and later electronics, rapidly increased, measurements spread out from the scientist's laboratory into industry where the awkward bench-top layouts were intolerable. There was an urgent need for more compact, simplified apparatus that could be used by those who were not expert in the theory and who just wanted to get good results.

2.2 Early Dc Bridges

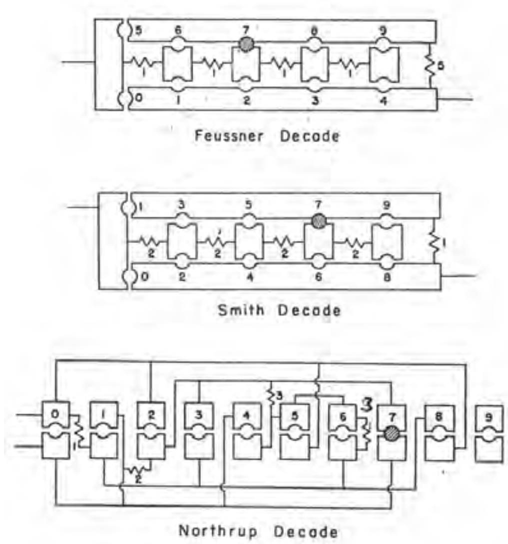
Dc bridge elements; resistance standards, decade boxes (used as adjustable arms), slide-wires and ratio boxes (used for ratio arm pairs) were made by many early companies such as Elliot Bros., Cambridge Instruments, Paul Instruments (which later joined Cambridge) and Tinsley in England, Siemens and Otto-Wolff in Germany, and Leeds and Northrup (L&N) and General Radio (GR) the USA.

L&N, the most famous manufacturer of precision dc electrical measurement equipment, was founded as the Morris E. Leeds Co in 1899 by Leeds (b. 1869) who had previously worked for Queen & Co. in Philadelphia. Edwin Northrup (b. 1866), a physics professor at the University of Texas, joined him in 1903 and the name was changed to Leeds and Northrup. Northrup designed many of their early instruments but left the company in 1910 to join the faculty at Princeton University[1].

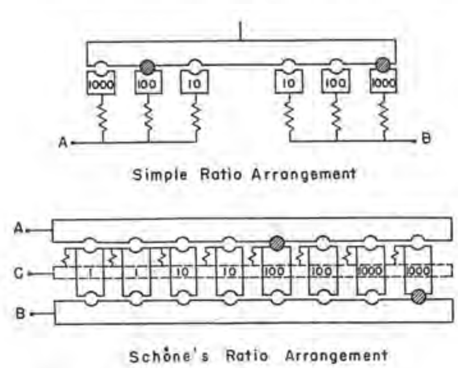
In the earliest decade boxes, such as that made by Elliot Brothers (figure 2-1), the resistance value was switched by taper pins that plugged between blocks of brass making a very low resistance connection. The blocks were arranged in a "pattern" that usually carried the name of its designer. Three types that required only one taper pin per decade to get values from 0- to 9 were those by Feussner (using relative resistor values of 1-1-1-1-5), Smith[2] (using 1-2-2-2-2)and Northrup[3] (using 1-2-3-3), see figure 2-2. Taper pin decades with nine equal resistors per decade were also used and nine resistors are used in most rotary switches decades although sometimes ten were used to get a "10" position. Another rotary decade used only 2-valued resistors and paralleled two of them to get the odd values in such a manner that there were no switching discontinuities[4]. At first these rotary decades used multiple-leaf rotors on brass blocks mounted on top of the panel. It was not until much later that the switches were put under the panel with only the dials visible.



2-1 Taper-Pin Resistance Decade and Pin & Coil Detail
Elliot Bros. Before 1907



2-2 Taper-Pin Decade Patterns



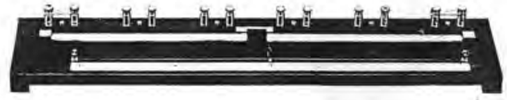
2-3 Ratio-Box Patterns

Separate ratio-arm boxes were also made in several taper-pin "patterns". The simplest used the scheme shown in figure 2-3a, but the most popular was the Schöne pattern[5] (1898) (figure 2-3b] in which any resistor could be put in either arm thereby allowing self-checking of 1:1 ratios.

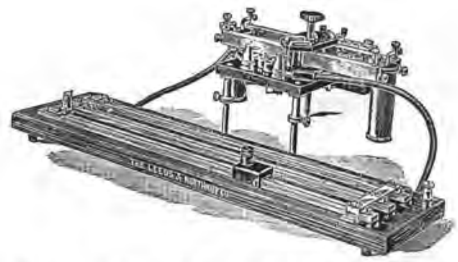
Several companies made separate slide-wires to be used with other elements to form bridge circuits, such as the type 130 by GR [figure 2-4] and many bridges had built-in slide wires as adjustments. The slide wire could be used in several ways. It could be used as single, adjustable, low-valued, two-terminal resistor, but this was not preferable because of the relatively unstable resistance of the sliding contact. It was usually used as a differential resistor (voltage divider) with the slider connected to a high resistance bridge arm or in series with the galvanometer where it would cause little error. The slide wire could form two arms of a bridge for comparing two low-valued resistors or used as a fine balance between the ratio arms. More often the slide wire was put between the unknown and a fixed standard as in the Carey Foster circuit of figure 1-5. L&N made a Carey Foster apparatus, or "coil changer", figure 2-5, that consisted of a test stand with mercury cups to hold the precision fixed resistors being compared, connections for the ratio arms, a mercury cup switch to interchange the resistors and three slide wires of different resistances which could be selected to optimize the circuit[6]. In the Tinsley Wheatstone Bridge of figure 2-6 a double slide-wire is between the unknown and the adjustable arm[7]. H. Tinsley Ltd. was founded in 1904 by Henry Tinsley and is probably the oldest maker of electrical instruments still in business today.

In Kelvin bridges the slide-wire was used alone as a four-terminal standard, as in a bridge made by Nalder Brothers[8], figure 2-7, or with a decade to form the standard as in the L&N Type 4300 bridge[9], figure 2-9. Dual, ganged slide-wires were used in the Hoopes conductivity bridge by L&N[10], figure 2-8. This is a version of the Kelvin Bridge for comparing the relative conductivities of wire samples. The dual slide-wire adjusted both the main ratio arms and the auxiliary Kelvin arms simultaneously.

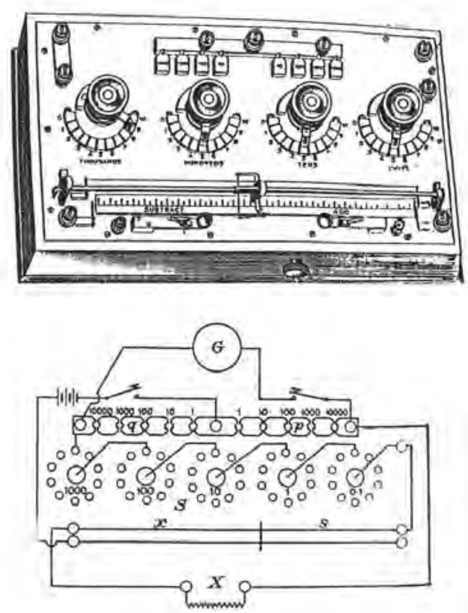
The low-resistance of a slide wire was a drawback except when measuring very low-valued resistances. L&N increased this resistance to 100 ohms by winding fine wire on a mandrel thus increasing the



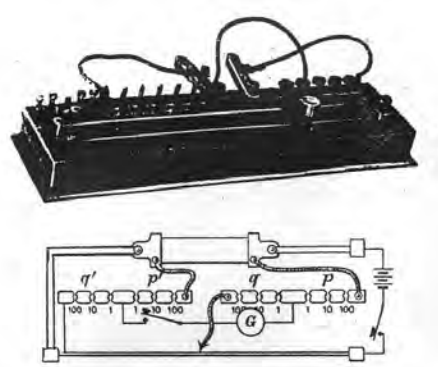
2-4 Slide-Wire Bridge
GR Type 130 1918



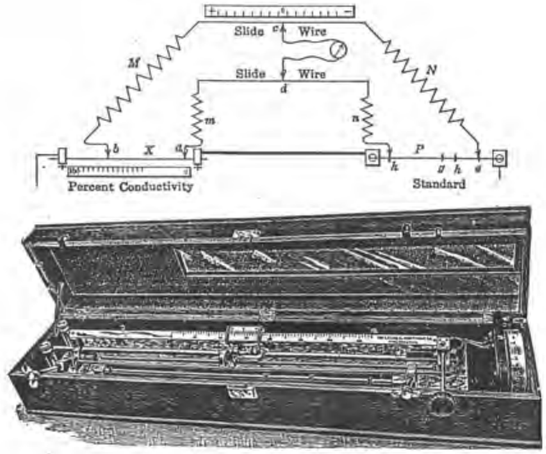
2-5 Carey Foster 'Coil Changer'
Slide Wires and Switch
L&N Before 1917



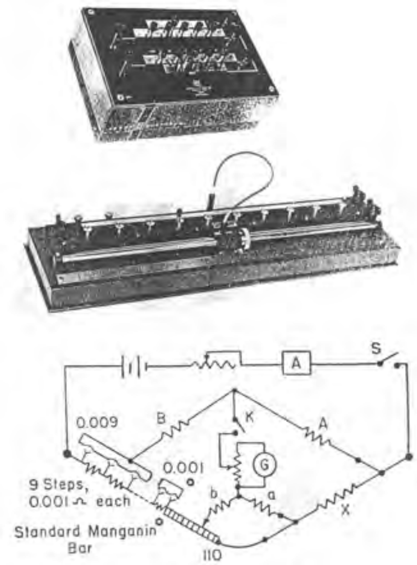
2-6 Wheatstone Bridge with Slide Wire
Tinsley Before 1924



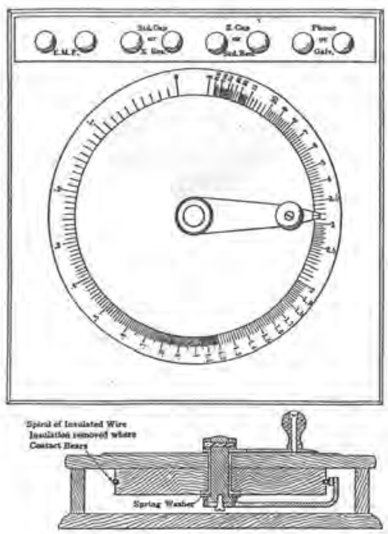
2-7 Kelvin Bridge with Slide Wire
Nalder Bros. & Co. before 1924



2-8 Hoppes Conductivity Bridge
L&N Before 1917



2-9 Slide-Wire Kelvin Bridge
L&N Type 4300

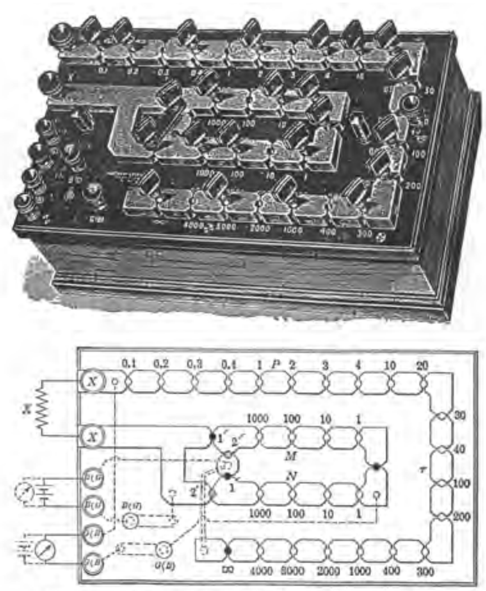


2-10 Rheostat for Wheatstone Bridge
L&N Before 1912

wire's length, an early rheostat[11] (c1910). With it they made a circular "slide wire" that formed the arms of a simple comparison bridge that had a reading from zero to infinity, see figure 2-10. Another way L&N increased the resistance, and the resolution as well, was to increase the wire length by winding the wire in a spiral on a marble drum as shown in figure 2-11. Such a unit was used in a bridge as well as in their famous K2 potentiometer[12].

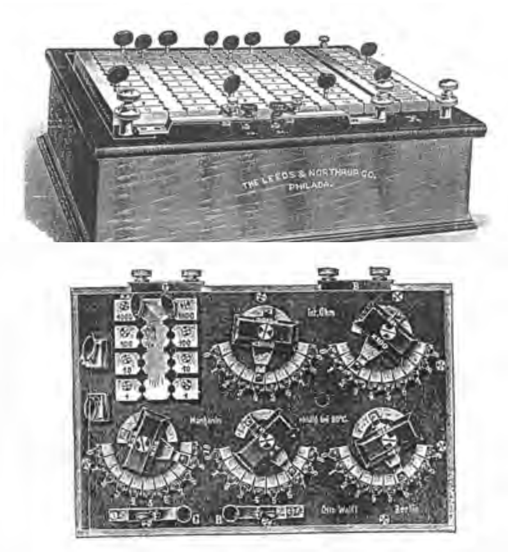
Some early bridges, such as those by Hartmann & Braun[13], figure 2-12 and by

2-11 Multi-Turn Slide Wire
L&N Before 1912

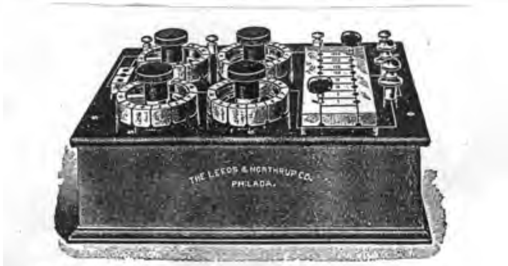


2-12 Taper-Pin Wheatstone Bridge
Hartmann & Braun Before 1924

L&N[14], figure 2-13 used taper pins both for the adjustable arms as well as for the ratio arms. The patterns of the taper pins used in a bridge were sometimes called “bridge tops.” Note the number of taper pins used. It was much easier to adjust rotary switches as used in the Otto Wolff bridge[15] of figure 2-14 and the L&N bridge[16] of figure 2-15. Note that both these bridges used taper pins to adjust the ratio arms because good contact was critical when they were of low value.



2-14 Bridge with Rotary-Switch Decades
Otto Wolff Before 1912



2.15 Rotary-Switch Wheatstone Bridge
L&N Before 1917

An important step in convenience was the introduction of L&N’s famous portable bridge, the Type S “Dial Decade Testing Set” introduced in 1915[17], see figure 2-16. This was preceded by a taper-pin version[18], the “The Leeds Portable Testing Set” of figure 2-17 and a rheostat version[19], “The L&N Fault Finder” shown in figure 2-18 (designed by Northrup himself), both introduced before 1912. The Type S had rotary dials with hidden contacts for both for setting the ratio as well as the main adjustment that ha four decades. It also included a battery and galvanometer and switches for reversing polarity and adjusting sensitivity and it all fitted in a small wooden box. Besides being a general-purpose Wheatstone bridge, these instruments included Murray and Varley "loops", bridge circuits for locating wiring faults, and were standard equipment for maintenance of power and telephone lines. The Type S was manufactured for many years without substantial changes except to its name and type number. It was probably the most popular dc bridge ever built, perhaps the most popular bridge of any kind, ever. It was copied by several other companies.

A class of bridges still used in precision work is the direct-reading ratio set, or DRRS, made by L&N, Biddle and others[20]. This compares two closely equal resistors, and usually two of precise 10:1 ratio also, with a Wheatstone or Kelvin bridge with very narrow range, less than a few percent. These used Waidner-Wolff (or "shunted") decade adjustments[21], see figure 2-19, developed

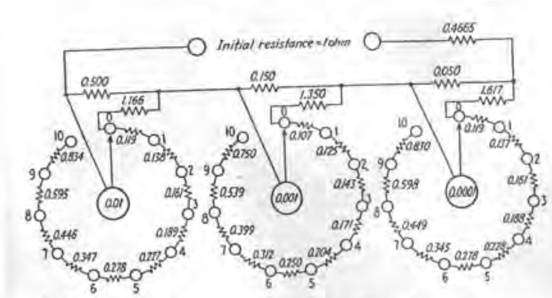
2-16 Dial Decade Testing Set
Wheatstone Bridge & Test Loops
L&N Type S 1915

2-17 Leeds Portable Testing Set
L&N Before 1912

2-18 'Fault-Finder' Bridge
L&N Before 1912

at NBS in 1902 that were highly immune to switch contact resistance because small changes in resistance were obtained by switching resistors of much higher value in parallel with a fixed resistor. By contrast a universal ratio set, URS, could compare resistors of any ratio. It acted like a switched high-resistance slide-wire in that it had resistance decades in two arms that were ganged such that the total resistance was constant. However, the precision Waidner-Wolff adjustments could not be used so that the switch resistance was critical.

Perhaps the ultimate dc bridge is the NBS Precision Bridge, or Wenner Bridge[22], designed in about 1918. This was a collection of standard resistors, Waidner-Wolff decades, taper-pin switches and mercury contact stands all in a large oil bath, see figure 2-20. It was precise as well being impressive. It could be configured in several ways but its main use was as a DRRS with a 1:1 ratio or 10:1 ratio, the latter used to scale the calibration of decade-valued resistor standards over a wide range. A few of these bridges were made by Eppley Labs in about 1960 for use in military laboratories and those of major defense contractors. The original NBS bridge was retired in 1982 after many years of use.

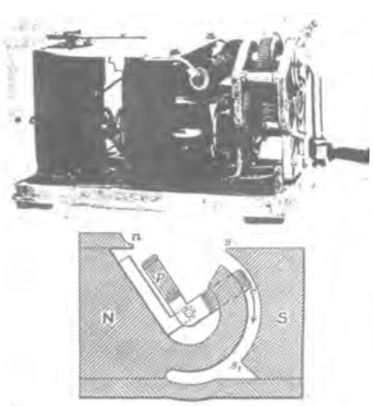


2-19 Waidner-Wolff Shunted Decades
1.000 to 1.111 Ω in steps of .0001 Ω

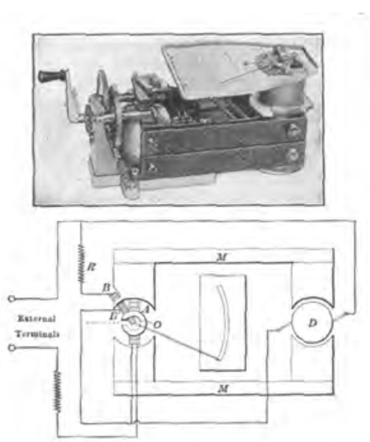
2.20 NBS High-Precision Bridge or 'Wenner Bridge' Removed from Oil Bath 1940

2.3 Other Early Dc Instruments

By far the most common way to measure resistance, albeit not very precisely, was to use an ohmmeter calibrated directly in ohms. It is directly descended from Ohm's circuit but with a battery source and with the additions of a calibrated meter scale, switched ranges and a zeroing adjustment which corrected for variations in the battery’s voltage and resistance. Millions of ohmmeters have been made. The dependence on the source voltage was reduced by the cross-coil ohmmeter principle, ascribed to Ayrton and Perry[23]. It used a meter with two coils at right angles to each other, one carrying the current through the unknown and the other a current proportional to the applied voltage. The freely rotating, soft-iron needle lined up with the resultant field which depended on the ratio of the two currents and thus proportional to resistance. The scale went from zero to infinity. Early, commercial instruments of this type were made by Clark (figure 2-21), Evershed, Paul, Record, Weston and several other companies[24]. Many of these had hand-cranked



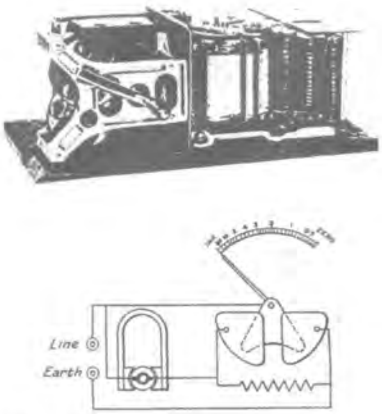
2.21 Clark's Ohmmeter and Two Coil Arrangement Before 1924



2.22 'Megger' High-Resistance Ohmmeter Evershed Before 1917

2.23 'Megger' Biddle 1940

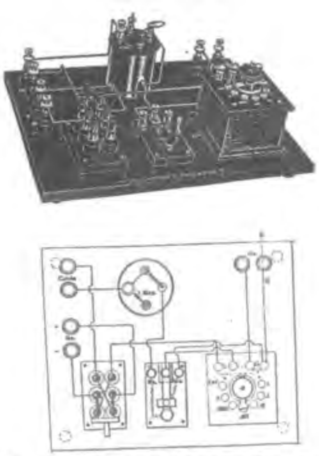
magnetos to generate the test voltage thus avoiding famous instrument to use the two-coil method was the "Megger" that measured very high resistances. It was first made by Evershed in England[25] (figure 2-22) who licensed the James G. Biddle Co. in the US in 1940, see figure 2-23. These had a hand-cranked magneto to develop a high voltage, usually 500v, roughly regulated by a governor. In this instrument the moving coils are between the fixed pole pieces and a coaxially mounted C-shaped iron core that provides a non-uniform field that shapes the meter scale. A somewhat analogous instrument also used for high-resistance measurements was the electrostatic ohmmeter made by Nalder Bros. & Thompson (figure 2-24). It used the electric attraction between capacitor plates to drive the meter pointer. The net attractive force between the two stators and rotor depended on both voltage and current in such a manner that the deflection was largely independent of the magneto-generated voltage applied to the circuit[24].

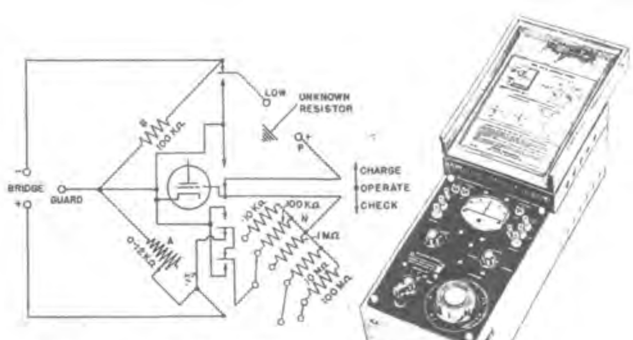


2.24 Electrostatic Ohmmeter
Nalder Bros. Before 1924

Very high resistances were also measured by "Megohmmeters" and "Megohm Bridges". Probably the first megohmmeter was the General Radio 487-A, designed by F. Ireland[27] in 1936. It was an ohmmeter that measured current by measuring voltage across a high-valued standard, in series with the unknown, with a vacuum-tube voltmeter. This class of instrument is made to this day. Their accuracy depends on both the accuracy of the applied voltage and the accuracy of the voltmeter as well as that of the standard resistor.

An early high-resistance bridge was the cable resistance test set by L&N[28], figure 2-25. The first so-called Megohm Bridge, the GR 544-A, see figure 2-26, was designed by R.F. Field in 1933[29]. This was a multi-range Wheatstone bridge using standards as high as 100 MΩ and a vacuum tube (type 32) with low grid current as a detector. Also the variable arm, a rheostat ("pot"), was in the arm adjacent to the unknown so that its resistance was proportional to the conductance of the unknown. However the dial was calibrated in resistance and hence went to infinite resistance when the rheostat was set to zero, a useful way to extend the highest range to extremely high values.

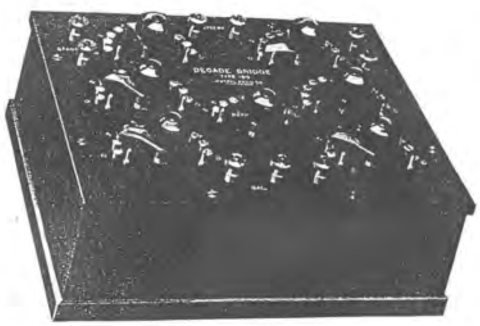

2.25 'Factory Cable Testing Set'
High-Resistance Bridge
L&N Before 1912



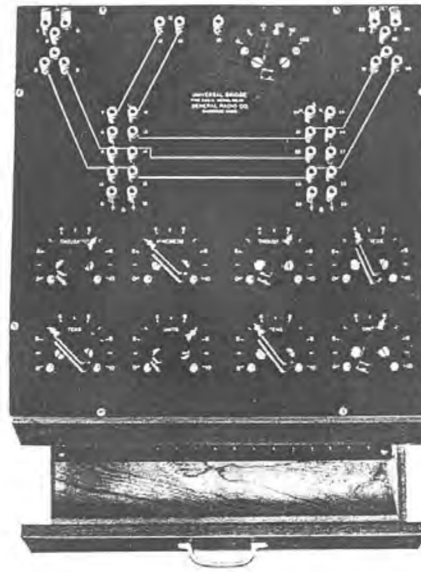
2.26 Megohm Bridge
GR Type 544 1933

2.4 Early Ac Bridges

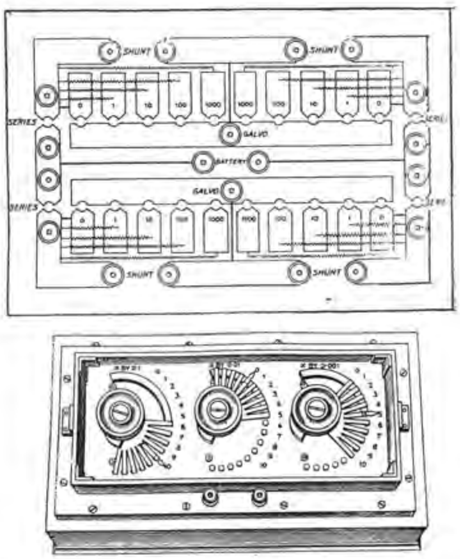
While L&N had the most complete line of dc bridges, GR, the General Radio Co., founded by Melville Eastham in 1915, became the leader in ac bridges. They made several early "decade bridges", the Type 160 (figure 2-27)in 1918[30], the Type 193 in 1919[31] and the Type 293 in 1932[32]. These included switched ratio arms and a resistance decade but required an external standard of resistance, capacitance or inductance. The 293 had a drawer for these external plug-in parts (figure 2-28). An L-C bridge made by Tinsley had resistances of 0, 1, 10, 100, 1000 ohms or an open circuit in each of the four



2-27 Decade Bridge
GR Type 160 1915



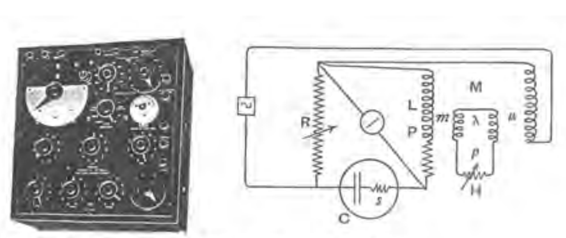
2-28 'Universal' Bridge
GR Type 293 1932



2-29 L-C Bridge and 'Slide Condenser'
H. Tinsley & Co. 1920

arms, but each arm also had terminals where external standards or decade adjustments, such as the "slide condenser", could be connected (figure 2-29). This unique variable capacitance put from zero to ten equal capacitors in parallel using ten contact arms. This avoided the discontinuities of the usual four-capacitor decade box.

Cambridge Instruments, founded in 1881 by Horace Darwin (son of Charles), made two early capacitance bridges using circuits devised by Campbell that used mutual inductances as reactance standards. One of these the Campbell Condenser Bridge[34] (1933) is shown in figure 2-30. It used Campbell's modification of the Carey Foster bridge of figure 1-14 which was direct reading in capacitance and power factor in spite of its complicated balance equation. GR also made two early capacitance bridges, the types 240[35] and 383[36] which used capacitance standards and included buzzer sources and headphones. An option



2-30 Campbell Condenser Bridge
Cambridge Instrument Co.
Before 1935 (Circuit 1917)

for the later bridge was an ac amplifier with an indicating meter (the type 415) so that balances could be made by visual means instead of earphones.

A major step was made by R.F. Field[37] in 1933 when he combined several bridges

2-31 Impedance Bridge
GR Type 650 1933

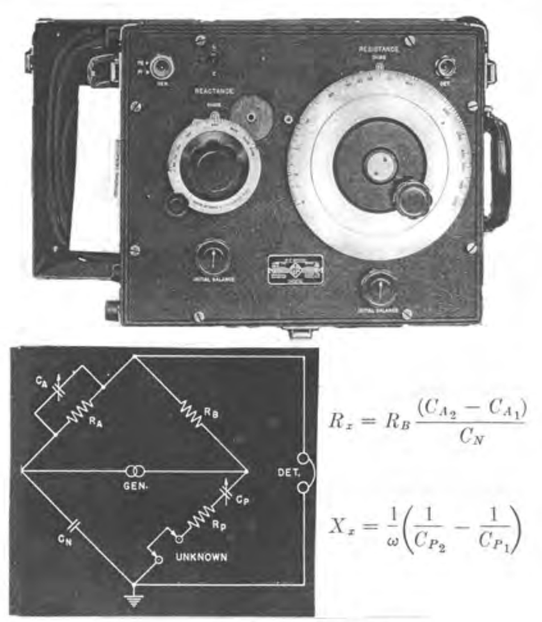
circuits to make the first general-purpose "Impedance Bridge", the GR 650-A of figure 2-31, that measured R, C and L, all "direct reading" (a dial reading with a decade multiplier). Any of four bridge circuits could be selected to measure series capacitance (de Sauty-Wien), series or parallel inductance (Maxwell & Hay) or resistance (Wheatstone with either ac or dc excitation). The switched ratio arm and the main rheostat adjustment were common to all circuits. The accuracy of this rheostat was increased by a "justifying" mechanism that consisted of an adjustable cam plate and a roller cam follower on the rotor arm. This compensated rheostat, along with its logarithmic dial, allowed a bridge accuracy of 1% over each 10:1 range. This instrument included batteries and galvanometer for dc and a hummer for a 1 kHz source, but external headphones were used as the ac detector. Later a line-operated, vacuum-tube RC (Twin-T) oscillator and tuned detector unit (type 650-P1) designed by Lamson[38] was available in 1946. This bridge was extremely popular. It was found in most every college electrical engineering or physics laboratory and this encouraged acceptance in industry. The sloping panel 650-A was also long-lived, finally replaced by GR with the Type 1650 twenty-six years latter. Many other companies, at least thirty, made such "Universal" or “RLC” bridges for R, L and C measurements (see Part 3).

Bridges were being designed for special purposes as well-defined needs appeared, such as testing high-valued electrolytic capacitors. An example of this type was the GR 632-A by Field[39] (1933). This included a 600v dc polarizing supply and a galvanometer for leakage current measurements. This was the archetype for a series of later GR instruments: the type 740 in 1938 by Packard[40], the type 1611 in 1948 by Easton[41] and the type 1617 in 1966 by Hall[42]. These had increasingly high ranges, 250 uF, 1.1 mF, 11 mF and 1.1 F respectively. High-capacitance bridges were made by ESI (model 273), Sprague Electric (1W and 2W series), British Physical Laboratories (CB 154) and others.

Another special-purpose bridge was the "Vacuum-Tube Bridge" used for measuring tube parameters, the Type 361-A in 1928 by Lamson[43], followed by the type 561 by Tuttle[44] in 1932 and the type 1661 by Bosquet[45] in 1959. These were nulled bridges with special circuits that measured plate resistance (r_p), transconductance (g_m) and amplification factor (u). Several other companies made meter-type “tube checkers” that gave indicated only “good” or “bad.”

Yet another need was that for RF measurements. It is claimed by GR that their type 516-A was the first commercial “Radio Frequency Bridge”, introduced in 1932, that operated up to 5 MHz. This was designed by C.T. Burke[46] who also designed the improved 516–C introduced the next year. This

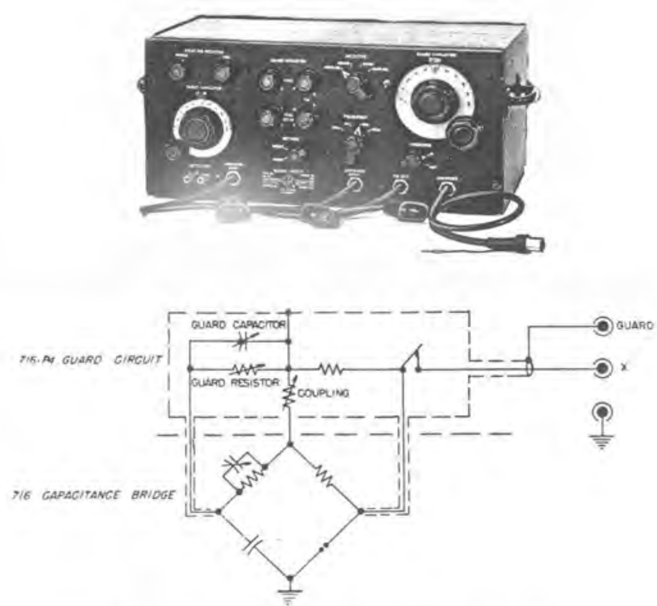
2-32 Radio-Frequency Bridge
GR Type 516 1932



2-33 Radio-Frequency Bridge
GR 916-A 1939

was a 1:1 ratio Schering bridge but with an added resistance adjustment in series with the main capacitor so that it measured resistance as well as capacitance and dissipation factor. Also, it had provision for both for both series and parallel substitution methods, see figure 2-32. This instrument was the forerunner of many later high-frequency Schering bridges made by GR, the type 916-A by D.B. Sinclair[47] in 1940, figure 2-33, followed by the 1601 in 1950[48] and the 1606[49] in 1955, the latter two designed by R.A. Soderman. These used series substitution, the DUT was connected in series with a variable capacitor in one arm and measured by the differences in the two adjustments between their settings with the DUT connected and those made with a short circuit   The most precise capacitance bridges of this era also used the Schering circuit. The GR 716-A designed by Field[50] in 1936 used a worm-gear driven precision capacitor and made both direct-reading measurements and parallel substitution measurements (with the DUT placed in parallel with the main capacitor), figure 2-34. The dissipation factor, D, balancing component was also a variable air capacitor and its high resolution allowed precise D adjustments for dielectric measurements. This bridge was modified to -B and -C versions the latter being the workhorse precision capacitance bridge up until the 1960s when it was replaced by transformer-ratio-arm bridges. A 1 MHz version by Easton[51], the 716-CS1, was the premier 1MHz capacitance bridge for many years.

2-34 Capacitance Bridge (Schering)
GR Type 716-C 1947
(Type 716-A 1936)



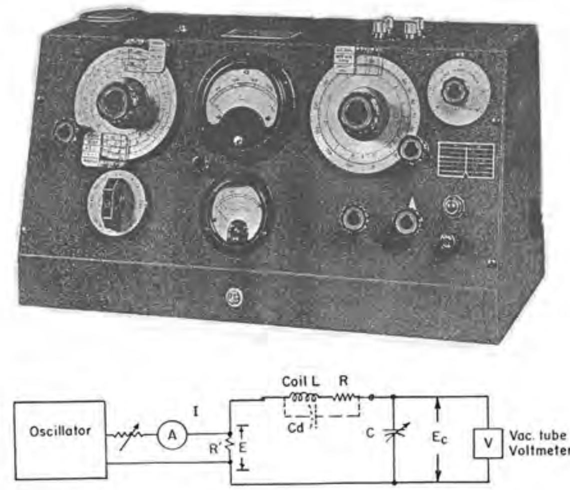
2-35 Guard Circuit for Capacitance Br.
GR Type 716-P4 1952

Guarding was necessary for both dielectric measurements and measurements on low-valued, three-terminal capacitance standards, see (figure 1-21). I.G. Easton designed one for the 716-C, the 716-P4[52]. This had not only a "guard" adjustment, but also a "coupling" adjustment (see figure_2.35) that made the guard adjustment less critical. The inherent guarding of transformer-ratio-arm bridges eventually made such guard balances unnecessary.

The GR type 667-A (again by Field[53]) was the most popular precision, laboratory inductance bridge from 1934 until it was replaced by the 1632 in 1959. The 667-A was ratio bridge, that is it compared the unknown inductor to an internal standard inductor, a 1 mH, toroidal unit, but it also had a variable inductor in series with the DUT to allow a final balance without a "sliding null" (interaction between the two balances) that made the adjustments slow, sometimes impossible. The later Type 1632 is an Owen Bridge designed by Lamson and Hersh[54]. This also had non-interactive adjustments because both variable components were in the same arm (see figure 1-19.

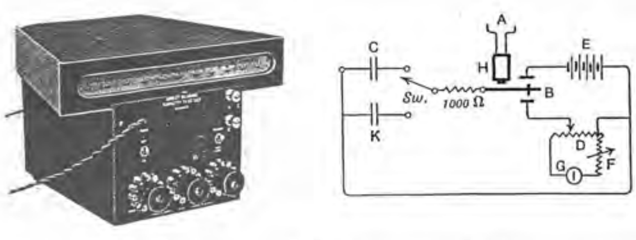
2.5 Other Early Ac Instruments

Perhaps the most famous RF measuring instrument was the Boonton Radio Company's Type 100A "Q Meter" designed by C.J. Franks and W.D. Loughlin and introduced in 1934[55]. This popular instrument went through many revisions over the years with the BRC types 160-A appearing in 1939 (see figure 2-36) and 260-A in 1953 being the best known. Hewlett-Packard, who bought BRC, listed the type 4342A Q meter in its catalogs through 1993. In this circuit the unknown inductor is resonated against a variable capacitor whose dial reads inductance directly at certain frequencies and the inductor's Q value is proportional to the resonant peak voltage and is read on the scale of a vacuum-tube voltmeter.



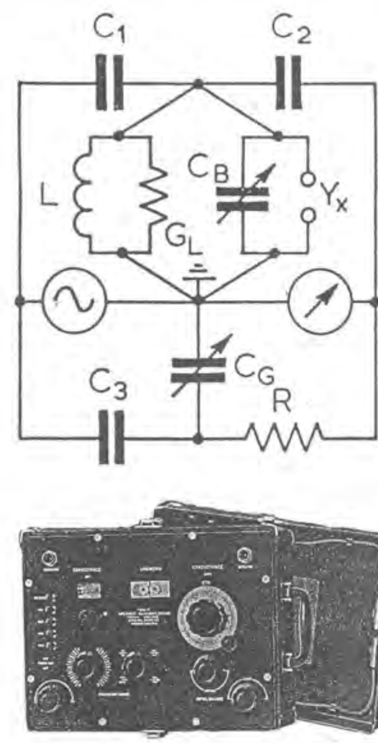
2-36 Q Meter
BRC Type 160-A 1939
(Type 100-A 1934)

Capacitance and inductance meters trace back to Maxwell's early ballistic circuit where inductance was determined from a galvanometer deflection and to periodically switched methods using a vibrator or rotating commutator such as one by Fleming and Clinton[56] (1903). A commercial instrument sold by Tinsley was the Gall capacitance meter[57] (1933) of figure 2-37 used a similar principle. Its accuracy was improved by calibration against an internal capacitance standard ("K" in the figure) and it provided several capacitance ranges by adjustment of the resistors in series and in shunt with the meter.



2-37 Gall Capacitance Meter
Tinsley & Co. 1933

Also of interest were a bridged-T circuit by Tuttle[58], the GR 721 Coil Comparator of 1937, and a Twin-T by Sinclair[59], the GR 821 Twin-T Measuring Circuit, 1940, see figure 2-38. These were null-type instruments like bridges but had the advantage that the input and output were both grounded so that no isolation transformer was necessary. The latter instrument used variable air capacitors for both balances and used the parallel substitution method. It was direct-reading in capacitance over its frequency range (.46 to 40 MHz) and in G at 1, 3, 10 and 30 MHz and was probably the most accurate instrument for conductance measurements at these frequencies.



2-38 Twin-T Impedance Measuring Circuit
GR Type 821 1940

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PART III. ELECTRONICS COMES OF AGE 1946-1965

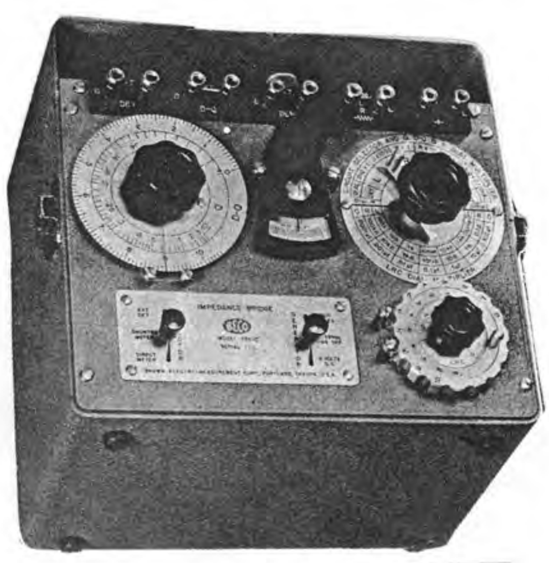
3.1 Comment

World War II changed a relatively small "radio" industry into a broad "electronics" industry that included television, "hifi", microwaves, radar, calculators, computers, automatic controls, expanded telecommunications and many other new applications for electronics. The needs of the "cold war" and "space age" accelerated the process with heavy funding in the U.S. from the Department of Defense and NASA. The requirement for calibration "traceability" to the National Bureau of Standards (NBS),(now the National Institute of Standards and Technology, NIST) for all suppliers to the US military was introduced by in 1959 and amplified in later documents[1]. This requirement gave a strong impetus to measurements of all sorts. Moreover industry demanded instruments that were easier to use and that gave direct-reading results. They needed instruments to measure wider ranges of impedance values and at higher frequencies. They demanded speed to test the millions of components being made and better accuracy to test them to tighter tolerances.

3.2 General Purpose Impedance (“RCL" or "Universal") Bridges

General Radio couldn't keep up with the demand for their general-purpose Type 650-A bridges during WWII, and moreover, the US government wanted to have a second source that was located away from the East coast in case of an enemy attack. Therefore GR farmed assembly out to Brown Engineering Co. (BECO, later Brown Instruments), in Portland, Oregon who made 400 of them[2]. They then rearranged the 650 parts to form a neater package with only two dials by ganging the three D-Q rheostats and this came to be called the “Brown Bridge” both for its color and its designer Frank Brown who was aided by Doug Strain. Strain joined Brown to form Brown Electro-Measurement Corp, BECO, and he developed a brand new RLC bridge, the popular Model 250, Figure 3-1. After two more name changes BECO became ESI, Electro-Scientific Industries, a company headed by Strain, which became a major supplier of both ac and dc bridges and standards and GR’s main competitor.

ESI’s compact 250 series used a high-resolution, coaxial arrangement of two decades and a pot, called a “Dekapot”, as the a main adjustment which allowed much better accuracy specifications (0.1% for R and ¼% for C). GR replaced their old type 650 with a "transistorized" Type 1650 (1959)[3] and, while this still had the same single-dial readout limiting the accuracy to



3-1 Impedance Bridge
BECO (ESI) Type 250 1949

3-2 Impedance Bridge
GR Type 1650-A 1959

1% (figure 3-2), it was nevertheless very popular. ESI achieved 0.1% C and L accuracy (.05% for R) in their Type 291-A Impedance Measuring System designed by Merle Morgan in 1960 (figure 3-3). In 1962 GR countered with their high-resolution GR 1608 that had a concentric 100-position, switched resistance (a "centade") and a pot (rheostat) that drove an odometer-type mechanical counter. Initially this instrument had a specified accuracy of 0.1% in R, L and C, but later this was improved to .05%, the best for this class of instrument[4], see figure 3-4.

3-3 Impedance Measuring System ESI Type 291-A 1961

3-4 Impedance Bridge GR Type 1608-A 1962

Many other companies joined in the competition for the general purpose RLC bridge market and their bridges used a variety of readout methods from large dials (RCA LB-50/52, Winslow 385-B), fixed dials and pointers (Marconi 868A, figure 3-5), knob-driven decades (AVO B-150, figure 3-6), lever-driven decades (GR 1656), coaxial decades (Fluke 710A, figure 3-7), coaxial dials and decades (Marconi 1313 & 2700) and RINCO 502-A) and linear "slide-rule" adjustments (Wayne-Kerr B500, AVO Type 1, and Simpson 2785, figure 3-8). Some other companies that made low-frequency "RLC" or "Universal" bridges were British Physical Laboratories, Cambridge Instruments, Muirhead, Nash & Thompson, Tinsley, Rhode & Schwarz, Philips, Siemens and even Heathkit who had one you could build yourself (see appendix B).

3-5 Universal Bridge Marconi Model 868 c1958

3-6 Universal Bridge AVO Type B 150 c1968

3-7 Impedance Bridge
Fluke Type 710A 1962

3-8 Impedance Bridge
Simpson Model 2785 1968

3.3 DC Bridges

Portable, self-contained (with source and detector) dc bridge systems also had a competitive market. While L&N continued to make new versions of and Wheatstone Bridges, types 4287 (figure 3-9) and 4289 which were more

3-9 Precision Portable Kelvin Bridge
L&N 4287 c1970

3-10 Portable/Laboratory Wheatstone Bridge
Biddle Type 72-434 c1975

3-11 Potentiometric Voltmeter Bridge
ESI Model 300 1964

modern looking and more accurate. Other companies, such as Industrial Instruments and Shallcross, made resistance bridges in wooden boxes that looked much like the others made portable bridges (such as the Cambridge type 41157) with similar specifications. Biddle-Gray made an attractive series of portable dc bridges (figure 3-10) and ESI came out with a convenient-to-use "Potentiometric" bridge designed by N. Morrison that also had voltage-measuring capability (type 3000, figure 3-11). Later even GR got in the dc market with a 6-lever Kelvin/guarded-Wheatstone bridge (type 1666). There was also a class of small, less-accurate "single knob" bridges, perhaps the most unique being the Croydon ("Cropico") Type PW4 that saved panel space by putting the null-detecting galvanometer inside the dial.

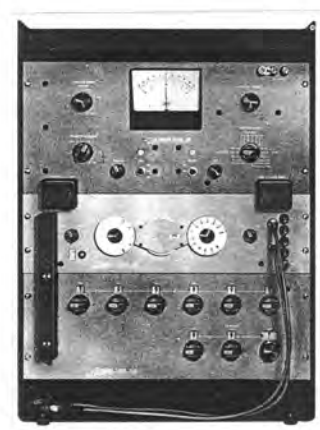
The precision dc bridge arena was just as active. L&N, the long-time leader, made many new precision Wheatstone and Kelvin bridges, such as their Type 4232 that still had taper-pin ratio arm adjustments (figure 3-12), and later the handsome 4737 Guarded Wheatstone Bridge shown in figure 3-13, and the elegant 4398 Double Ratio Set, figure 3-14, a direct-reading ratio set (DRRS) that had a "lead" balance as well as the Kelvin "yoke" balance[5]. (The lead balance compensates for connection resistance put in the R_A arm of the Kelvin Bridge shown in figure 1-4.) ESI captured a large portion of the precision dc market with several precision dc bridge systems, particularly the model 242 Kelvin bridge also by Morgan (figure 3-15), which won important military contracts. This was a complete measurement system with a very sensitive detector that allowed part-per-million sensitivity over a wide resistance range. Much of their success was due to excellent application notes such as that by Jack Riley[6] that detailed calibration procedures for the "traceability" measurements now required of all suppliers to the military.

3-12 Guarded Wheatstone Bridge
L&N 4232A c1955

3-13 Guarded Wheatstone Bridge
L&N 4737A c1960

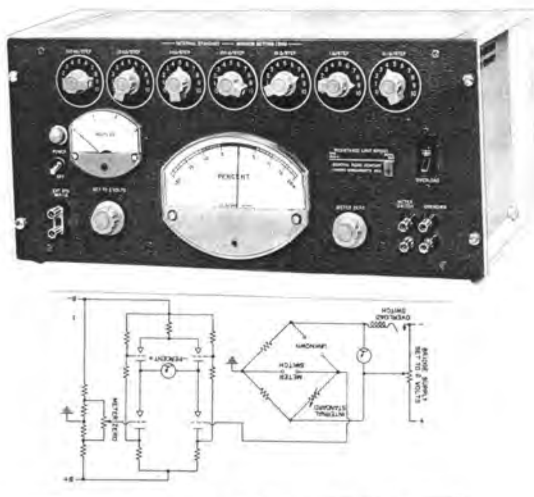
3-14 Double Ratio Set
L&N 4398 1965

Loeb Julie, of Julie Research, designed a "Ratiometric®" dc bridge[7] that used an easily-calibrated, voltage divider as the balancing adjustment. This gave good accuracy and made traceability easier. However, the divider, which had a high resistance, was placed in series with the unknown and balanced against a pair of ratio arms and, as a result, the system had reduced sensitivity when measuring low-valued resistors and it was not direct reading in resistance. Other suppliers of more conventional precision bridges were Biddle, Otto-Wolff, Rubicon, Sullivan, Tinsley and Yokagawa Electric (YEW). One of the most important developments in dc bridges, the Guildline Current-Comparator



3-15 Resistance Measuring System
ESI Model 242 1960

Bridge, uses transformer ratio arms and is discussed below.



3-16 Resistance Limit Bridge
GR 1652 1952

A new class of dc instruments, the Resistance Limit or Deviation Bridge, became popular for the fast sorting of resistors. Perhaps the first was the GR 1652 in 1952[8], (figure 3-16) but there were many similar instruments made with multi-decade resistance standards, but later ones had switched ratio arms to extend the measurement range thus making them excellent precision bridges when balanced. However for sorting, these bridges are not balanced as were earlier deviation bridges. Instead the standard is set to the nominal resistance value and the bridge unbalance voltage is indicated on a meter calibrated in percent deviation. Thus the test speed is limited only by dexterity of the operator in connecting the parts and the speed of the meter movement. Some, such as the Biddle 71-131 (figure 3-17) added "High-Go-Low" lights for increased testing speed. Other later units had limit-actuated relays to permit automatic sorting with external equipment. Also later units, such as the ESI type 263 (figure 3-18) and the GR type 1662, used feedback to linearize the deviation meter scale that, unaided, is quite non-linear as shown in figure 3-16.

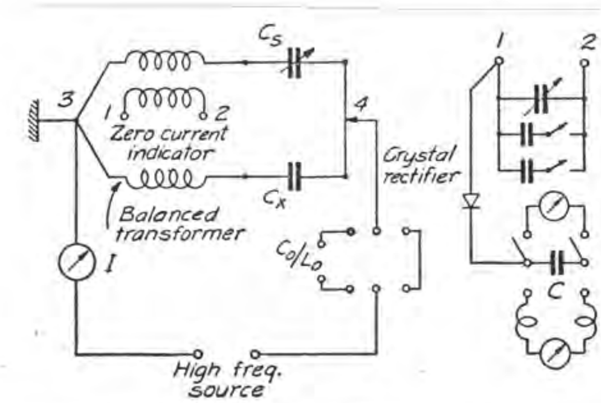
3-17 Guarded Resistance
Deviation/Limit Bridge
Biddle 71-131 1970

3-18 Deviation Bridge
ESI Model 263 1971

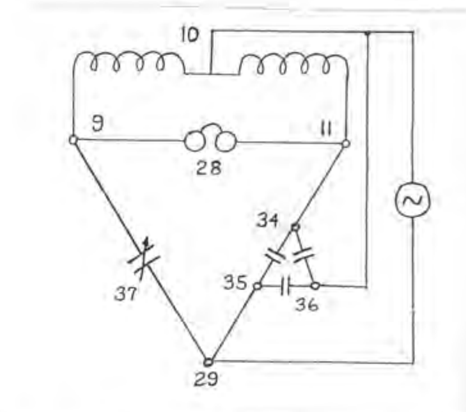
3.4 Precision AC Bridges: The Transformer-Ratio Arm Bridge

An important development in precision ac bridges was the use of a pair of inductively-coupled bridge arms, or "transformer ratio arms", which have the advantages of a precise and constant ratio and of high tolerance to shunt loading (refer to Appendix A).This technique has early roots in the use of a two-coil differential telephone invented by Chrystal[9] (1880) only four years after Bell's invention of the telephone. The revised Hague book[10] says “this instrument was used to compare an unknown impedance against a standard of the same kind” and “its principle is the foundation of modern measurements with high precision using ratio transformers”. Elais[11] (1891) and Trowbridge[12] (1905) showed that a three-winding transformer could be connected to a single-winding telephone to get the same result. Diagrams of their circuits would look much like later three-winding “transformer” bridges, but the pair of balanced coils was probably thought of more as a differential detector, analogous to Becquerel’s differential galvanometer (figure 1-2), than as the ratio arms of a bridge.

In his book of 1933 August Hund[13] describes an audio frequency “differential system” that uses a three-winding transformer with a core made of iron wire wound on a toroiod.
o. He notes that the turns ratio may be other than 1:1 to similar impedances of unequal value. He also shows differential circuits for radio frequencies that use wooden core and have an output winding that is resonated for high sensitivity (figure 3-19). His circuits have been referred to as “Hund’s Differential Method”[14], but one reference[15] calls one of these circuits “Hund’s bridge”.

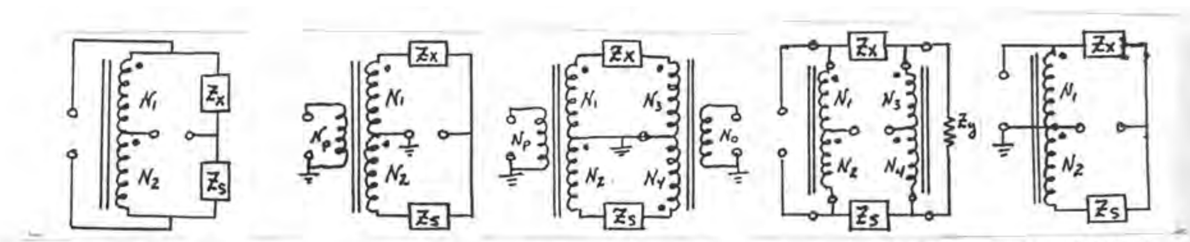


3-19 Differential System for Measuring High Frequency Capacitance
A. Hund 1924



3-20 Diagram from UK Patent 323037
A. Blumlein Filed in 1928

The modern TRA bridge also has roots in early self and mutual inductance comparison bridges particularly those of Heaviside and Campbell. The latter[15] noted the guarding capability of tightly coupled windings in 1922, but it was the versatile genius Alan Blumlein[17] who first clearly stated the advantages of using coupled ratio arms in a four-arm bridge. A figure from one of his patents[18] shows a guarded measurement of a three-terminal capacitor (see figure 3-20). In this and later patents he showed a variety of "transformer bridge" circuits including some using transformers in both input and output circuits. His circuits were discussed in papers by Walsh[19] (1930) and Starr[20] (1932) which describe the use of three-winding transformers in bridge circuits.



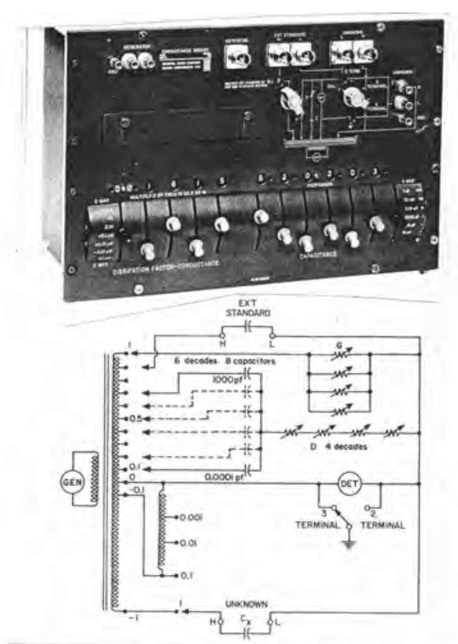
a. Coupled-Ratio-Arm Br. b. 3-Winding Br. c. Double-Ratio Br. d. Ac Kelvin Br. e. Lynch Bridge

3-21 Transformer-Ratio-Arm Bridge Circuits

Five basic transformer-bridge connections are shown in figure 3-21. The first uses the pair of inductively coupled windings as ratio arms. Ideally $N_1/N_2 = Z_X/Z_S$ but the winding impedances, resistance and leakage inductance, do affect the balance somewhat but the effect can be very small if high-permeability toroidal cores are used (μ values greater than 10^5 are possible) and if the windings are carefully made. The second circuit uses a third windings that allows a common ground for the source and detector. Here the winding impedances don't affect the ratio, but instead they are put in series with Z_X and Z_S and thus this circuit is not good for comparing very low impedances. The third circuit, referred to as a double-ratio bridge, is capable of an extremely wide impedance range because the balance equation depends on two winding ratios: $Z_x/Z_s = (N_1/N_2)(N_3/N_4)$. The next is an ac version of a Kelvin bridge that uses a second transformer to balance the "yoke" impedance, Z_y. This is sometimes referred to as the Hill Bridge because Hill made good use of it[21]. Here the ratio N_3/N_4 should be set equal to N_1/N_2. Note that 4-terminal connections are made to both Z_x and Z_s. The last circuit is unbalanced and thus has somewhat poorer ratio accuracy. The transformer is used as an inverter to get a signal of opposite phase. A.C. Lynch[22] used this circuit in a substitution capacitance bridge in which the unknown capacitance was added in parallel with a variable capacitance and a difference measurement made. Hence the ratio was not critical. It has the advantage of tolerating extreme loading to ground on either side of the DUT because these admittances are placed directly across either the source or the detector where they don't affect the balance conditions. (One should note that like all true (passive) bridges the source and detector of these bridges can be interchanged, at least in theory. However there are practical considerations, particularly pickup in the transformer from external sources that causes more trouble if the transformer is in the output. Note that if the detector is connected to the transformer in the 3-winding bridge (Figure 3-15b) the circuit diagram is the same as that of the early “differential method”.

One of the earliest applications of the method for precision measurements was a bridge by Garton[23] (1940) that could detect 2 micro-radians of loss angle. Clarke and Vanderlyn[24] (1949) developed a commercial general-purpose mutual admittance bridge using the circuits of Blumlein. Oatley and Yates[25] (1954) discussed the use of this type of bridge for the precise comparison of impedance standards which proved to be the most important application of "transformer" bridges". Siemens and Halske made an early commercial TRA bridge. An interesting application was the capacitive aircraft altimeter designed by Watton and Pemberton[26] (1949) that measured capacitances down to 1 aF (then referred to as μμμF) to detect the effect of the earth on the capacitance between two wing-mounted electrodes. In spite of this high sensitivity to capacitance changes it had a very limited range as an altimeter.

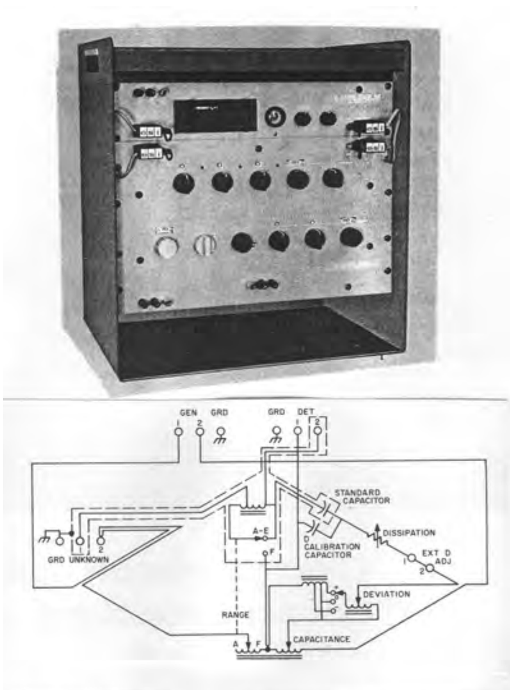
The particular advantages of transformer-ratio-arm bridges were critical in the application of "A New Theorem in Electrostatics" by Thompson and Lampard[27] (1956) that showed it was possible to have a calculable standard of capacitance whose value depended only on a single length measurement. The practically realizable value of capacitance was very low, less than 1 pF, so that accurate measurements required good guarding and precise ratios were needed to extend the calibrations to higher, more useful values. A team of scientists was assembled at NBS to work on the design of a bridge with extreme accuracy for these absolute measurements[28]. Their work was the basis for the precision NBS bridge still in use. It uses the three-winding transformer connection (see Figure 3-21b) with eight precision capacitors of decade values, 10 aF to 100 pF, switched, by lever switches, between fixed transform taps of decimal steps. Thus each capacitor represented one digit of the readout. A modified version of this design, the GR 1615 designed by John Hersh[29] (1962), uses six low-temperature-coefficient air capacitors and second transformer with decade ratios to extend the range, see figure 3-22. This bridge and an even more precise version, the GR 1616, also designed by Hersh[30], are used in most every standards lab in the world and the 1615 is still being made (by IET Labs).



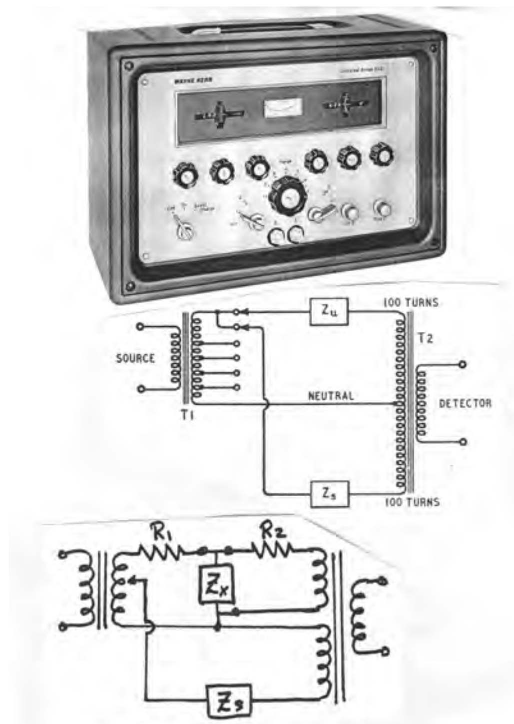
3-22 Capacitance Bridge
GR 1615-A 1962

The competing ESI models 700 and 701 used a single temperature-compensated capacitance standard and an adjustable multi-decade transformer (or IVD, inductive voltage divider) as the main adjustment as shown in figure 3-23. This made calibration easier but resulted in higher transformer output impedance that limited the frequency range[31].

The company that made the most use of transformer-ratio-arm bridges was Wayne-Kerr in England, founded in 1946 by Richard Foxwell and Raymond Calvert and named for movie stars Naughton Wayne (a British comedy star) and Deborah Kerr who were then working for a film company owned by a relative of Foxwell's. (Thus Kerr is pronounced "car".) They used transformer ratio arms in almost all of their bridges including their low-frequency B-221 Universal Bridge designed by Calvert[32]. While this bridge measured admittance over a wide range, an external adaptor (Model Q221) was used to measure extremely low impedances by connecting them in the leg of a Tee network as shown in figure 3-24. The transfer impedance of this Tee network is $R_1 + R_2 + R_1R_2/Z_X$. The first two terms can be balanced by a fixed resistor in series with the standard Z_S making $Z_X \sim R_1R_2Y_S$ but for very low values of Z_X the resistors R_1 and $_2$ are negligible and can be ignored.

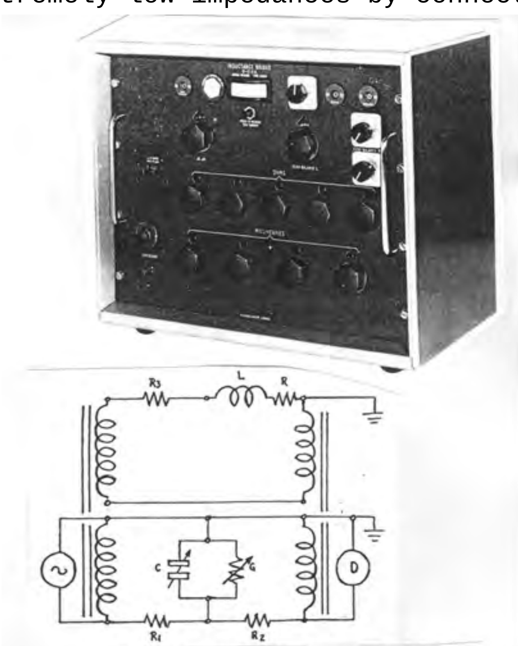


3-23 Capacitance Measuring System
ESI Model 700 1960



3-24 Universal Bridge
Wayne-Kerr Model B221 c1955
Lower diagram shows bridge with Low-Impedance Adaptor

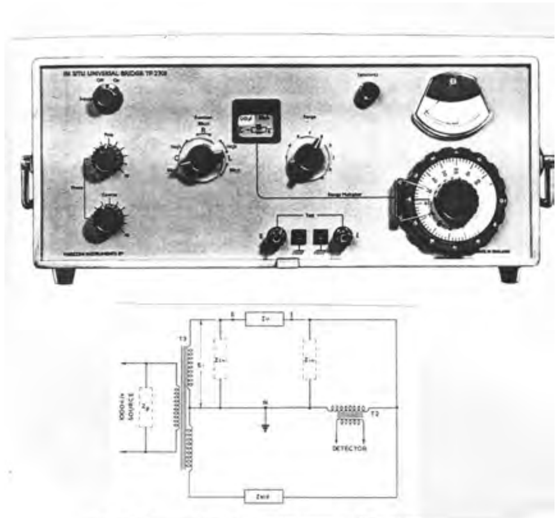
H.W. Sullivan Ltd. also used transformers with a Tee network as the standard in their model R4000 "Decade Inductance Bridge"[33]. In this case the network was an R-C network whose transfer impedance is $R_1 + R_2 + R_1R_2(G + C)$ which at balance equaled $R_3 + R_X + j\omega L_X$. Note that the “spoiler” resistor R_3



3-25 Decade Inductance Bridge
Sullivan Type R4000 c1967

was added to balance the resistance $R_1 + R_2$. This bridge used the transformer asymmetrically (as does the circuit of figure 21e) and it also used the isolating property of a transformer to permit the grounding of both the unknown inductor and the variable standards C and G (see figure 3-25).

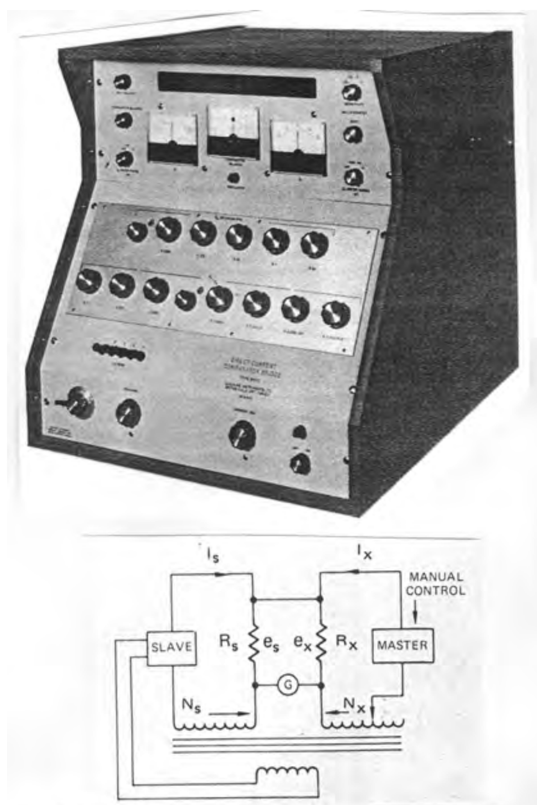
The inherent guarding capability of a transformer-ratio-arm bridge allowed them to make "in-situ" or "in-circuit" measurements as long as all circuit paths shunting the DUT were guarded. The Marconi model TF 2701 In-Situ Bridge was made especially for this purpose (see figure 3-26).



3-26 In Situ Universal Bridge
Marconi TF 2701 1964

The advantages of using inductively-coupled ratio arms for precision low-frequency ac measurements on resistance standards were discussed by D.L. Gibbings[34] of NSL (National Standards Laboratory, Australia) and by J.J. Hill[21] of the NPL (National Physical Laboratory, England) both of whom designed Kelvin-type transformer bridges with a transformer dividers as the auxiliary, yoke-balancing arms (see figure 3-15d). Gibbings' version used a two-stage transformer for the main ratio which improves the ratio accuracy. Foord, Langlands and Binnie[35] [3.35] of the University of Glasgow made a four-terminal bridge by using transformers to inject the yoke-lead voltage drops into the main transformer-ratio ratio arms thus canceling the errors they caused to a high degree.

Transformer ratio arms were adapted for dc resistance measurements in the Guildline Current Comparator Bridge, Type 9920 (figure 3-27), a design based on the work of MacMartin and Kusters[36] at the Canadian NRC (National Research Council). In this circuit a dc ampere-turn unbalance in the ratio transformer is detected by its distorting effect on a square-wave modulating signal. This unbalance controls the slave supply that keeps $I_S N_S = I_X N_X$. The bridge is manually balanced until the detector is nulled and $R_X I_X = R_S I_S = R_S I_X N_X / N_S$ or $R_X = R_S N_X / N_S$. This bridge allows precise scaling of dc resistance over a wide range of resistance with the extreme accuracy and stability of a precision ratio transformer.



3-27 Direct Current Comparator Br.
Guildline Model 9920 1966

Yet another application of transformer-ratio-arm bridges was in the measurement of high-voltage capacitors. A paper by Kusters & Petersons[37] of the NRC was a classic on this subject.

A clever application of transformers is their use in bridges that make electrodeless measurements on high-conductivity, electrolytic fluids. In one method[38] the fluid is in a tube that forms one turn on both an input and on an output toroidal transformer. In another method, patented by Relis[39], was used in the Beckman RS5-3 In-Situ Salinometer and RS7-B Induction

Salinometer. In both instruments two toroidal transformers are placed side by side and immersed in the fluid which forms a one-turn “winding”. The conductivity of the sample is balanced by adjustable components connected between opposed windings on the two transformers.

3.5 RF Bridges

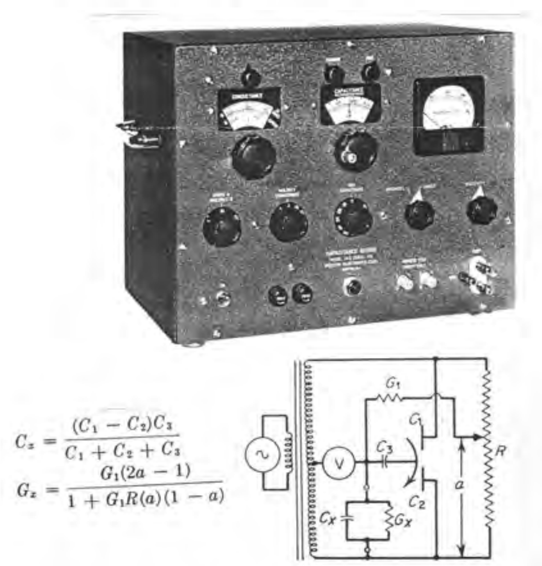
Transformer ratio arms were also used in RF bridges. Kirke[40] (1945) described bridges designed at the BBC (many by Mayo) including one designed 1935 and a ultra-short-wave bridge that went up to 200 MHz. Calvert of Wayne-Kerr designed a series of HF transformer-ratio-arm bridges, the types B201, B601, B602, B-701, B801 and B901, the last (figure 3-28) operating up to 250 MHz[41]. Note that there are very few turns on the ratio transformer of this VHF bridge.

Direct capacitance bridges designed by John Mennie[42], the Boonton Electronics Models 74 (100kHz) and 75 (1 MHz), used a circuit patented by C. H. Young[43] of Bell Labs in 1945 which combined a three-winding transformer with a differential capacitor see figure 3-29. Mennie also used transformers in his Model 63 Inductance Bridge (to 500 kHz) and his Model 33 Admittance Bridge (to 100 MHz).

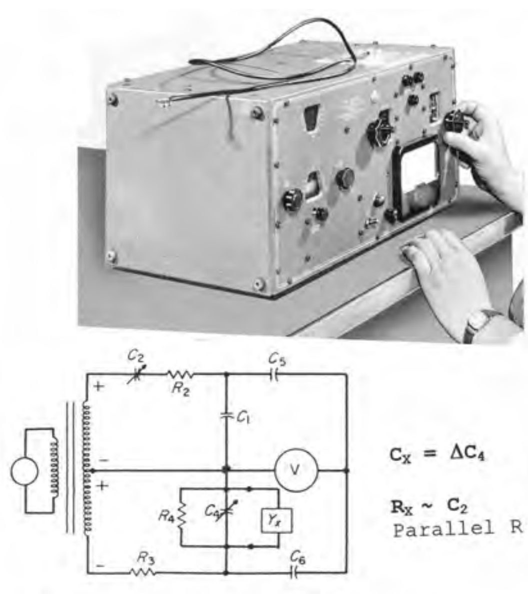
The latter was a parallel substitution circuit in which the change in admittance between the unknown and an open-circuit was measured. This was similar to his earlier (1952) Model 250 RX Meter[44], figure 3-30, which he designed for the Boonton Radio Corp, (later acquired by HP). This was not a meter but a bridge, a transformer bridge with two Tee networks (a so-called "Opposed T") but was referred to as a modified Schering Bridge. It measured equivalent parallel resistance and capacitance and, at certain frequencies, parallel inductance, and it operated from 0.5 to 250 MHz.

Donald Woods[45] of the British Ministry of Aviation modified the Twin-T of Sinclair (see figure 2-38) to have two pairs of measurement terminals, making it a so-called "dual" bridge (1952) (figure 3-31). His bridge was an assembly of

3-28 V.H.F Admittance Bridge
Wayne Kerr Model B901 1962



3- 29 Capacitance Bridge
Boonton Electronics Model 74 1955



3-30 R-X Meter
Boonton Radio Model 250 1952

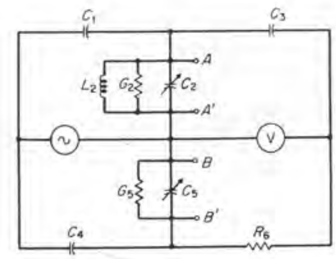
coaxial components with precision connectors and used variable capacitors for both capacitance and conductance balances. The unknown was measured first at one terminal pair and then the other giving added information that removed bridge errors. Les Huntley[46] (1965) at NBS (NIST) modified and improved this circuit and his instrument is still used to make high frequency calibrations of standards with coaxial connectors.

3.6 Special Purpose Bridges

Besides the special bridges designed for measuring electrolytic capacitors, high-voltage capacitors and vacuum-tube parameters (see part II), another type of special purpose bridge was the “incremental inductance bridge” designed to measure iron-cored coils and transformers while dc bias current was applied[47]. If the signal was small compared to the bias, the measured inductance was called the incremental value at that bias. Most of these bridges could also apply large ac signals to simulate line-voltage. Many of these, such as the Freed 1110-A, figure 3-32, applied the dc between opposite corners of the bridge and used the Hay or the series Owen circuits which had arms containing series capacitors which blocked the applied dc current from the adjustable arms putting it all through the DUT. Bridges such as Maxwell's bridge that used parallel R-C arms required an added blocking capacitor. Other instruments used novel circuits to measure biased inductors such as the GR 1633, which used a bridge circuit containing active elements, see section 3.9 below.

Another large class of special bridges heretofore unmentioned is so-called "temperature" bridges; bridges used to measure resistance thermometers, particularly platinum resistance thermometers (see review of these bridges in reference 3.48). Classic dc bridges for this purpose were designed by Callender (1891), Northrup (1906), Smith (1912) and Mueller (1917). Because the resistance of the temperature sensors was relatively low (usually 25 ohms) and of narrow range, many of these bridges used Waidner-Wolff adjustments that greatly reduced the effect of switch contact resistance (see part II). As shown by Hunter[49] and Hill & Miller[50], low-frequency transformer bridges could be used in this application and they had the advantages of being immune to thermoelectric emfs as well as having precise and constant ratios.

While most bridges were designed to test components or standards and therefore had displays that read R, L or C, there were bridges (and meters, see below) that read other quantities such as complex impedance and admittance or their magnitudes and phase angle. A good example was Easton's GR1603[51], figure 3-33, which was an audio-frequency Schering

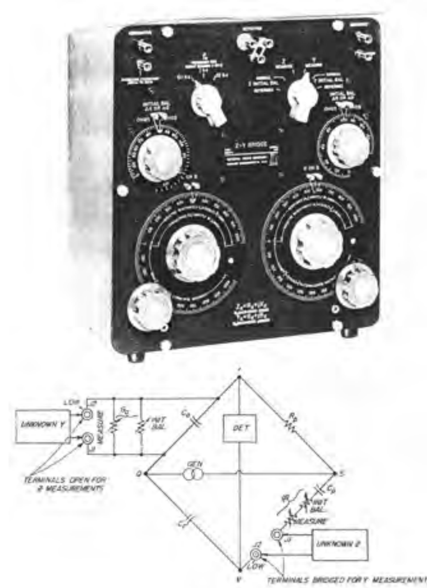


$$C_1 + C_2 + C_3 + \frac{C_1 C_3}{C_4}(1 + R_6 G_5) = \frac{1}{\omega^2 L}$$

$$\omega^2 R_6 C_1 C_3 \left(1 + \frac{C_5}{C_4}\right) = G_2$$

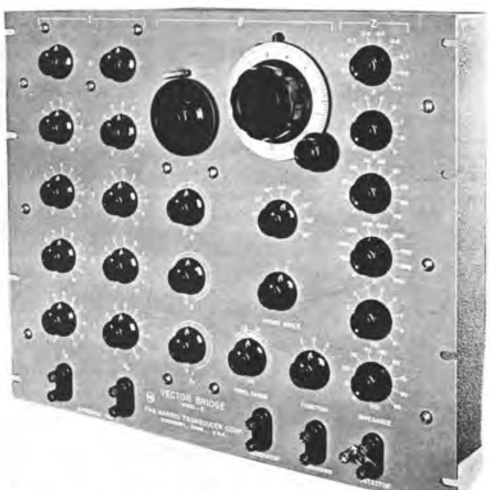
3-31 Dual Admittance Bridge
D. K. Woods 1952

3-32 Incremental Inductance Bridge
Freed Type 1110-A c 1954



3-33 Z-Y Bridge
GR Type 1603-A 1955

bridge that used variable resistors ("pots") rather than the variable capacitors used in RF bridges and made both series and parallel substitution measurements to measure either R and X or G and B. This was a useful instrument for measuring electrical devices and networks that had large phase angles. The Harris Transducer Corp. Type B "Vector Bridge" that read impedance or admittance and phase angle had 26 knobs on the panel. Another unusual bridge was the Gertsch/Singer CRB series Complex Ratio Bridges that measured complex voltage ratios of networks, transformers, resolvers etc. These used precision inductive dividers for the main balance and active circuits to get the quadrature signal for the phase-angle balance[52].



3-34 Vector Bridge
Harris Transformer Co. Model B

3-35 Complex Ratio Bridge
Gertsch/Singer Model CRB 1 1958

3.7 Impedance Meters

Though usually not as accurate as bridges, impedance meters were much easier to use because no manual balancing was necessary. Several companies made C and L meters that were the ac equivalent of dc ohmmeters and either measured the current through the DUT with a constant voltage applied or the voltage across it with a current applied. A good example was the BEC (Boonton Electronics Corp.) model 71A designed by R. E. Lafferty[53], figure 3-36, which measured both C and L at 1 MHz. BEC later sold an improved model 72A, figure 3-37. The sloping-panel Radiometer Type MM2, figure 3-38, read R, L and C over a wide frequency range.

Boonton Radio's popular Q meter was revised and its frequency range extended in new models. Other manufacturers such as Freed, Marconi and Yokagawa

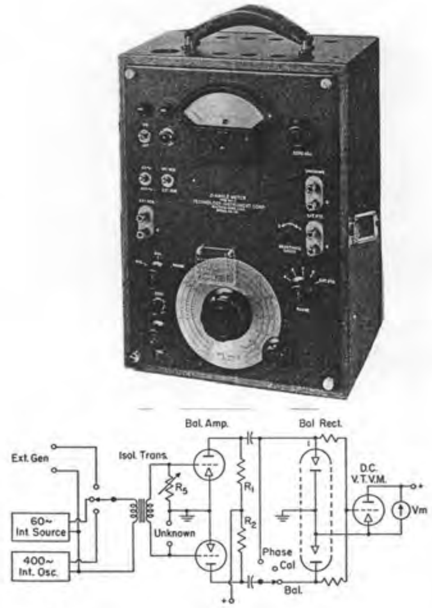
3-36 Capacitance Meter
BEC Model 71 1965

3-37 Capacitance Meter
BEC Model 72A 1971

3-38 RLC Meter
Radiometer Type MM2 c1970

Electric (YEW) also made Q meters. Note both BRC and YEW were later bought by HP who included a more modern version, the Type 4342A, in their 1993 catalog.

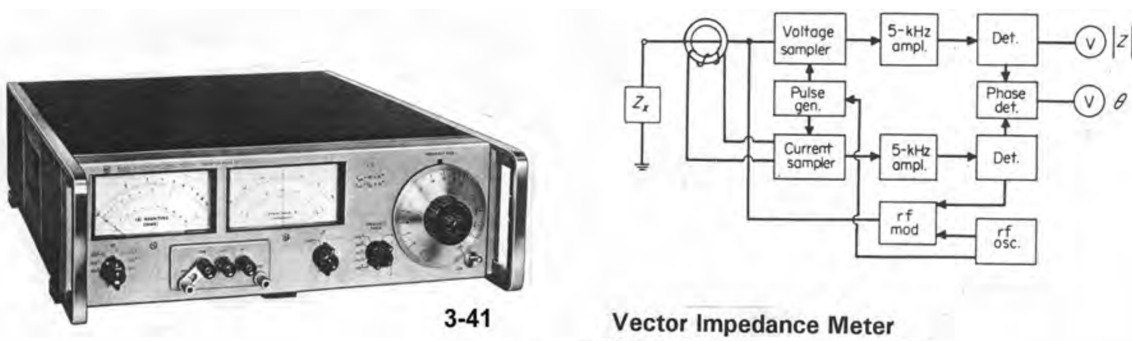
3-40 Vector Impedance Meter
Radiometer Type GB11 c1950



3-39 Z-Angle Meter
Technology Inst. Co. c1947

Series resonance was also used in capacitance meters such as the Rhode & Schwarz (Federal) Type FT-KARA which used an inductor as the standard to resonate with the unknown capacitance, the opposite of the Q meter.

A disadvantage of most impedance meters is that they measure only one quantity, not C and D or L and Q. The Z-Angle Meter of Technology Instruments Corporation), figure 3-39, was designed by Luke Packard (who left GR to co-found TIC, which was called Acton Labs for some years.) This is a hybrid instrument that uses bridge-like balance for impedance magnitude but, when balanced, reads phase angle on a meter. Another somewhat similar instrument is the Radiometer GB-11 Vector Impedance Meter[54] (figure 3-40) that uses the "Grützmacker" Bridge[55]. This also requires a magnitude balance and reads phase angle on a meter. The later Boonton Radio (later HP) model 4800 Vector Impedance Meter, figure 3-41, reads both magnitude and phase with no balancing required over a wide frequency range, to 500 kHz, using a toroidal transformer to sample the current in the unknown.

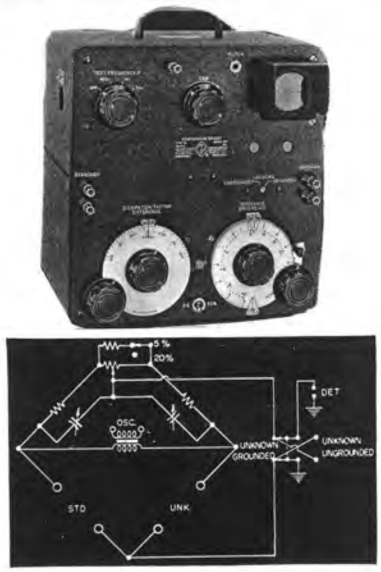


3-41 Vector Impedance Meter
BRC/HP Type 1965

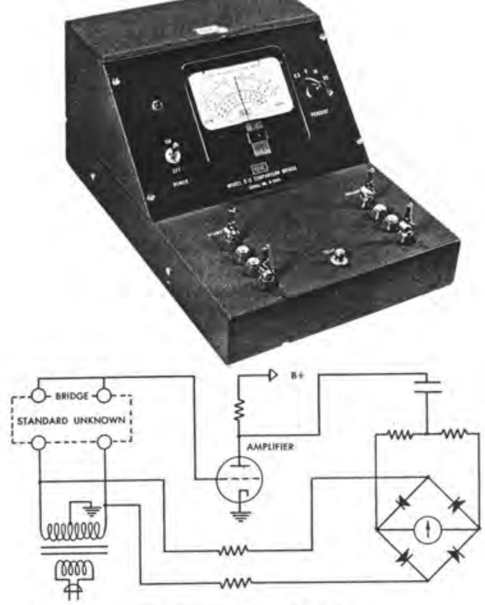
48

3.8 Impedance Comparators

The "limit bridge" principle discussed above as used for sorting resistors at dc was also used to sort components, C, L and R, at ac. These instruments provided only the ratio arms, thus requiring an external standard as well as DUT, and hence some were called "impedance comparators". They required phase-sensitive detectors not only to get the sign of the deviation, but also to separate out the real and imaginary parts. The first was the GR 1604-A Comparison Bridge designed by Holtje[56] that used 1:1 resistive arms that could be adjusted over a 20% range and for null on the



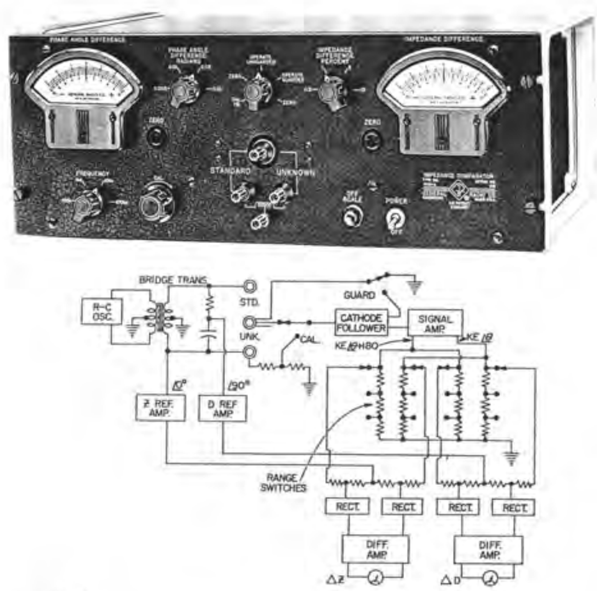
3-42 Comparison Bridge
GR Type 1604-A 1954



3-43 Comparison Bridge
S.I.E. Model E2 1954

CRT detector. It also had a phase or D-Q balance. The unbalance indicated by the CRT could be used for fast sorting. Later instruments used meters to indicate the percent unbalance. The Southwestern E2 Comparison Bridge, figure 3-43, designed by Erath[57] used balanced windings on the power transformer to drive the standard and unknown and thus was a transformer bridge. By contrast other instruments, such as the Industrial Instruments Type 1110 Impedance Comparator, figure 3-44, used resistive ratio arms and a 1 kHz test signal. These instruments, and several other similar ones, read only magnitude difference. The GR 1605-A Impedance Comparator[58], figure 3-45, also read phase angle difference. It had several ranges with resolution down to .01%. If the components were reasonably pure, the magnitude difference reading was closely equal to percentage differences in R, L or C and the phase difference was closely equal to D differences for capacitors or inductors or Q differences for resistors. This was one of the first instruments to use a high-permeability toroidal transformer with twisted-pair windings for its precise 1:1 ratio arms. Comparators became very popular for incoming inspection and production testing and were made by many companies including ESI, Rohde & Schwarz, Bruel & Kjaer and many others.

Ac Comparators and dc limit bridges were built into many early

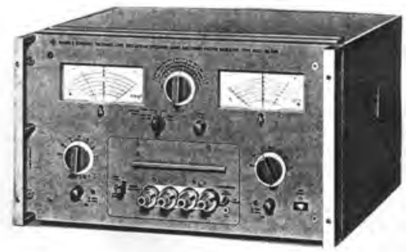


3-45 Impedance Comparator
GR Type 1605-A 1955

3-44 Impedance Comparator
Industrial Inst. Type 1110 c1955

automatic test systems that included mechanical component handlers. One of the earliest in the USA was the Industrial Instruments AB series (1958) and in Germany such systems were made by Klemt. The GR 1605 was used in one of the first in-circuit test systems. It compared the impedances between terminals on a terminal strip or printed-circuit card to those of a "known good" similar assembly[59].

3.9 Electronics in Instruments



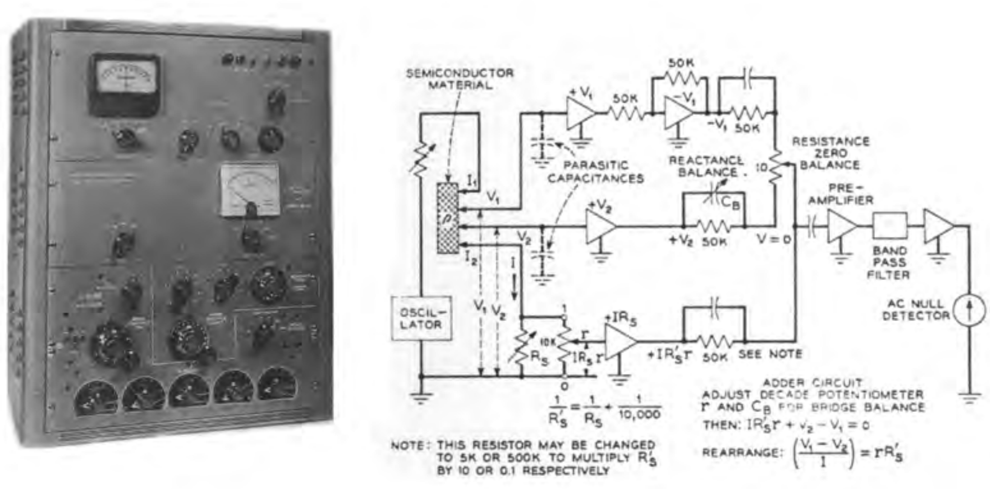
3-46 Limit & Dissipation Factor Indicator
Rhode & Schwarz KVZT c1965

As soon as vacuum tubes were available they were used in making better signal sources. Perhaps the earliest was Vreeland's mercury-cathode triode oscillator in 1908[60] and many famous vacuum-tube oscillator circuits many followed Eccles-Jorden, Colpitts, Hartley etc. An early use of tubes in ac detectors was that by Adams & Hall[61] (1919). Probably the first oscillator-detector system built in a commercial bridge system was Lamson's[62] 650-P1 module for the famous GR 650 bridge. It used R-C Twin-T Circuits both in the oscillator and the selective amplifier. The 650's successor, the 1650-A, was one of the first bridges to use transistors in its internal source and detector.

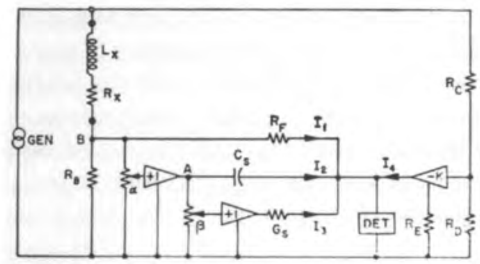
Active null detectors were also used in dc bridges where the main problem was getting low drift in the input circuits. Many detectors used "choppers" to modulate the dc and these were mechanical vibrators, transistor switches or non-linear magnetic devices. High resistance ("megohm") bridges such as the GR 1644, used sub-miniature "electrometer" vacuum tubes that have extremely low grid current.

Impedance meters used active circuits in the measuring circuit such that the accuracy of the instrument depended directly on the precision of the active elements which usually were feedback amplifiers. In the case of comparators, it was the measured impedance ***difference*** that depended on the accuracy of the amplifiers. Gertsch Complex Ratio Bridges used voltage followers in the secondary balance (see above).

M. A. Logan[63] of Bell Labs was probably the first (1961) to use amplifiers in the main balance of a bridge circuit. He used vacuum tubes in three-stage, unity-gain amplifiers and inverters to get good 4-terminal (four-point probe) ac measurements on semiconductor samples even though there was high resistance in each connection (figure 3-47). Probably the first commercial “active” bridge was the GR 1633, (see figure 3-48)



3-47 Four-Point-Probe Bridge
Logan, Bell Labs 1961



If

$$R_F = \frac{R_E(R_C + R_D)}{R_D}$$

then

$$L_X = \frac{\alpha C_S R_B' R_E (R_C + R_D)}{R_D}$$

$$Q_X = \frac{\omega L_X}{R_X} = \frac{\omega C_S}{\beta G_S}$$

3-48 **Incremental Inductance Bridge**
GR Type 1633 1962

introduced in 1962 that used high-feedback transistor amplifiers to allow a bridge circuit that could display Q directly at several frequencies well as series inductance and resistance[64]. W. P. Harris[65] of NBS (1967) made a ULF bridge operating down to .001 Hz for low-frequency measurements on dielectric materials that used Philbrick dc operational amplifiers. It used a Lissajous pattern on a long-persistence oscilloscope as a detector down to 0.1 Hz and on a Z-Y recorder below that. Needless to say, making a balance at .001 Hz took considerable time.

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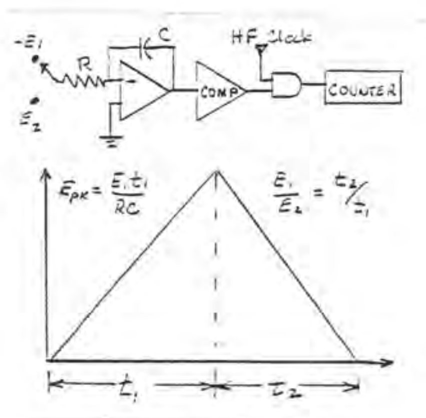
Part IV THE DIGITAL ERA 1966-Present

4.1 Comment

Measuring instruments with digital readouts have the advantages of high resolution and of not requiring visual interpolation of an analog scale. Perhaps even more important today is their ability to pass data to a computer thus avoiding the possibility of human error in the reading and recording of measurement data and eliminating the time it takes for a human to perform these functions. Moreover, once the data is passed on to a computer, it can be used to perform the overall task for which the measurement was made: sorting components, controlling processes, characterizing networks, studying materials, calibrating impedance standards etc. The human operator now gets the final output, what he really wants, and need not be concerned with the result of any single measurement. Measuring instruments have become the interface between the physical world and the computer world, a critical part of the "information age".

4.2 Digital DC Meters

The first instruments with digital readouts were counters, timers and frequency meters that were completely digital in nature and needed no analog-to-digital conversion. Early digital voltmeters compared the unknown voltage to the output of a precision D/A converter or used integrating methods such as voltage-to-frequency converters or pulse-width modulators. Many other A/D techniques quickly became available, but the most important for precision meters of all sorts was the dual-slope or up-down integrator which was described in a 1966 paper by H. Schmidt[1] and is related to a modification of the integrating pulse-width modulator patented by R. W. Gilbert[2] in 1963. This circuit not only converts an analog voltage to a digital number, it also makes a division, the ratio of two voltages, the one that drives the integrator voltage up and the other, of the opposite sign, that drives it down, see figure 4-1. The up slope occurs for a fixed time interval, a fixed number of pulses, N_1, of a HF clock. The time of down slope depends on the down voltage and is measured as a count N_2 that stops when the output voltage returns to zero. Thus the ratio of the two voltages is the reciprocal of the ratio of the two time intervals or the two counts. In a dc voltmeter this ratio is that of the unknown voltage to a voltage standard.



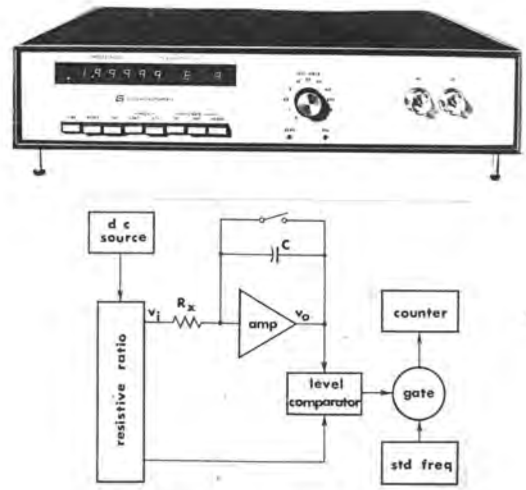
4-1 Dual-Slope Integrator

Digital meters of all types quickly became very popular and could be very precise because the accuracy was not limited to the resolution of an analog meter scale. Many digital multimeters (DMMs, digital voltmeters that also measure current and resistance) measure resistance by connecting the DUT to a precision current source and measuring the voltage across it. On the other hand most of them take the ratio of the voltage across the DUT to the current through it, the current being measured as the voltage across a standard resistor in series with the DUT. This has the advantage that their accuracy is not dependent on the stability of a current source. Digital milli-ohmmeters and micro-ohmmeters apply more current to very low-valued resistors than do DMMs and thus get better accuracy at these values. For example the ESI Model 1700 (figure 4-2) which, ith the SP 3779 plug-in unit, applies 1 ampere and can resolve 0.1 μΩ.

4-2 Digital Ohmmeter
ESI Type 1700 1977

Digital resistance limit bridges can be used with preset, internal or external, digital limit comparators for automatic sorting to percent tolerances. DMMs that read resistance, not percent deviation, require limits expressed in resistance values rather than percent. Later, "smart" meters calculated the percent deviation from the resistance reading and a nominal resistance value that had been entered into memory.


4-3 Digital Megomhmeter
Beckman Type L-9 c1982



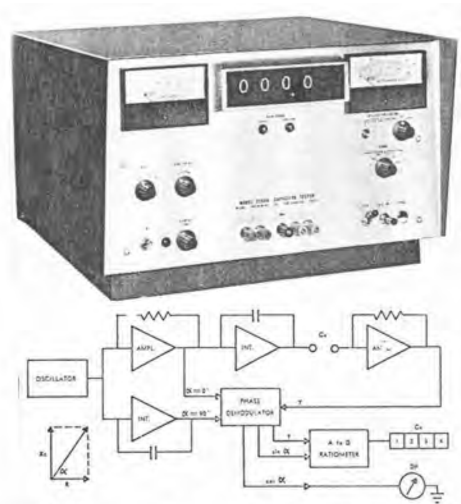
4-4 Digital Teraohmmeter
Guildline Model 9520 c1970

Analog-to-digital methods were applied to megohmmeters such as the Beckman Model L-9 (figure 4-3), but most a applications of megohmmeters, such as leakage resistance measurements, require only low ac curacy and thus high-resolution digital readouts are of little advantage except for logging data or setting limits. However, measuring precision, high-valued resistors requires the best possible accuracy and the Guildline Teraohmmeter, type 9520 (figure 4-4) that was based on a design by H. Tsao[3] of NRC was by far the most accurate, more accurate than most megohm bridges. It measured 100 MΩ to .035%, 1 TΩ to .2% and 1 EΩ (10^{15} ohm) to 1%. It too uses an integrator but the integrator resistance is the resistance being measured and the capacitance is an air capacitor to keep the leakage current negligible. A revised version of this instrument is still one of the most accurate of this type.

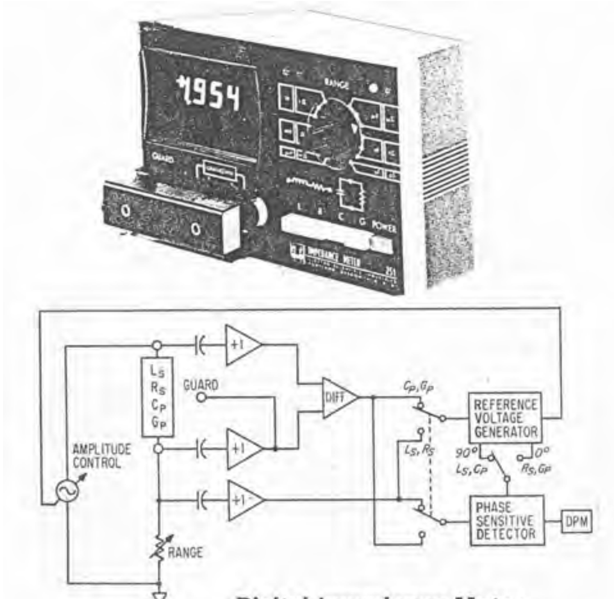
4.3 Ac Digital Meters

Digital ac impedance meters also use the dual-slope integrator to make the voltage/current division but they required phase-sensitive detectors to supply the correct dc voltages. Examples of meters that measured capacitance were the early (1960) Electro-Instruments series CD Digital Capacitance Meter (figure 4-5) and the Micro Instruments 5300 series Capacitance Tester (c1965)

4-5 Digital Capacity Meter
Electro-Instr. Model CD 1960

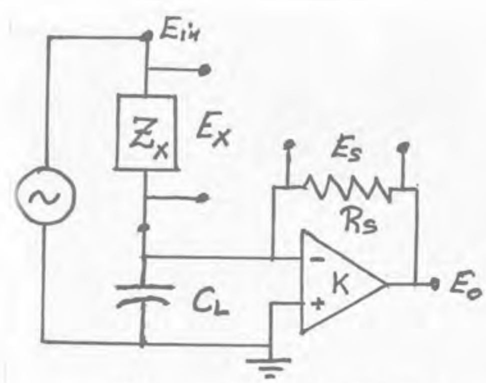

4-6 Capacitance Tester
Micro Instr. 5300A c1965

(figure 4-6). Digital impedance meters that measured R, L and C were the ESI Model 251, figure 4-7 and the GR 1685, figure 4-8. These instruments had accuracies of 0.25% or so, some to 0.1%, and they competed well with general-purpose bridges. They had two disadvantages. Having no memory, they could only make one division at a time and thus they could measure and display the main component (R, L or C) or the phase component (D or Q), but not both simultaneously. Also their phase accuracy, particularly accuracy of low D measurements, was limited by the ability of getting a precise 90° phase shift for the necessary phase reference signal.



4-7 Digital Impedance Meter ESI Model 251 1973

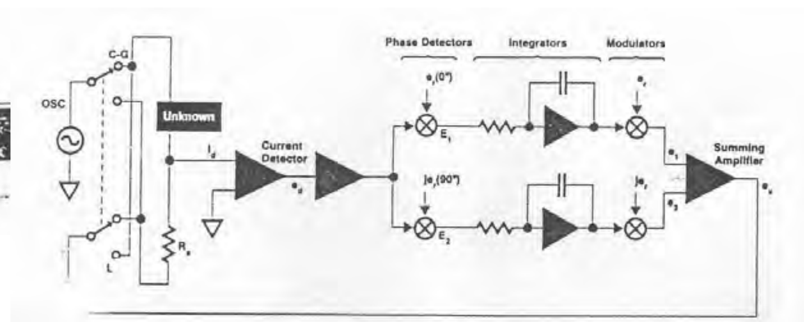
4-8 Digital Impedance Meter GR Type 1685-A 1973



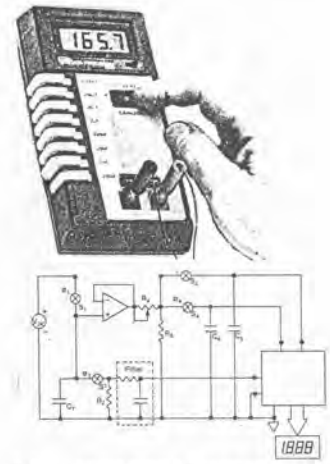
4-9 Front - End Circuit

The GR 1685 and most other meters used an inverter amplifier and standard resistor as the current detector, as shown in figure 4-9. The amplifier brought the junction of Z_X and R_S near ground potential so that there was little current through a loading capacitance, C_L, thus keeping the error small. The error due to C_L is $\omega C_L R_S/K$ where K is the open-loop at the test frequency. While this scheme is usually adequate at lower frequencies for reasonable loading capacitances, it becomes

4-10 1 MHz LCR Meter HP Model 4271 1974



poorer at higher frequencies where K is greatly decreased and the loading admittance of stray capacitance increased. HP (Yokagawa-Hewlett Packard or YHP) developed a integrating-modulating scheme for their type 4271 1 MHz meter[4] in which this junction point was brought to ground by an automatic “bridge” balance that had very high effective loop gain (figure 4-10). The voltages across the unknown and the standard were still measured by a dual-slope converter as in other meters, the "bridge" only improved the guarding capability. HP used this microprocessor-based Z meters. This instrument had two dual-slope detectors so that it could indicate C and D, C and G or L and R simultaneously.



4-11 Hand-held Capacitance Meter
Data Precision Model 938 1979

Another class of digital meters was that of small, hand-held capacitance meters. While these were very useful and inexpensive, many of them, such as type 938 by Data Precision (1979) (figure 4-11), used RC charge-discharge methods rather than sinusoidal signals so that their measurements of frequency-dependent capacitors, such as those with electrolytic or high-K ceramic dielectrics, did not agree with those made at the industry-specified test frequencies. Later other hand-held meters, such as the AVO/Biddle B183, did use standard test frequencies and measured inductance and resistance as well as capacitance.

4.4 Automatic AC Bridges

Several attempts were made to mechanically automate the balancing process so that the accuracy of bridges could be combined with the speed and ease of use of a meter. In 1951 Graham[5] described a complex inductance bridge using phase-sensitive detectors and servo motors that drove a variable resistor and an inductor. Frischman[6] automated a GR 716-C Schering bridge for dielectric measurements in 1960 by driving its variable capacitors in a similar manner. Barnes also mechanically automated a GR 1611 for high capacitance measurements, their type 61, see figure 4-12. Rohde & Schwarz also had a motor-driven bridge “for heavy current capacitors”, their type KVZA (figure 4-13). Simmonds Aerocessories, Inc. made a mechanically automated bridge of their own design (model 387011) for testing capacitive fuel gages.

An interesting development was the "semi-automatic" HP 4260A Universal Bridge, developed by a team at YHP under Yoshimoto[7], see figure 4-14. The main bridge adjustment, the R, L or C balance, was manually made but the secondary (D or Q) balance was an electrically variable component, the


4-12 Automatic High Capacitance
Test Set Type 61
Barnes Dev. Co. 1961


4-13 Automatic Test Bridge
R&S Type KVZA 1960

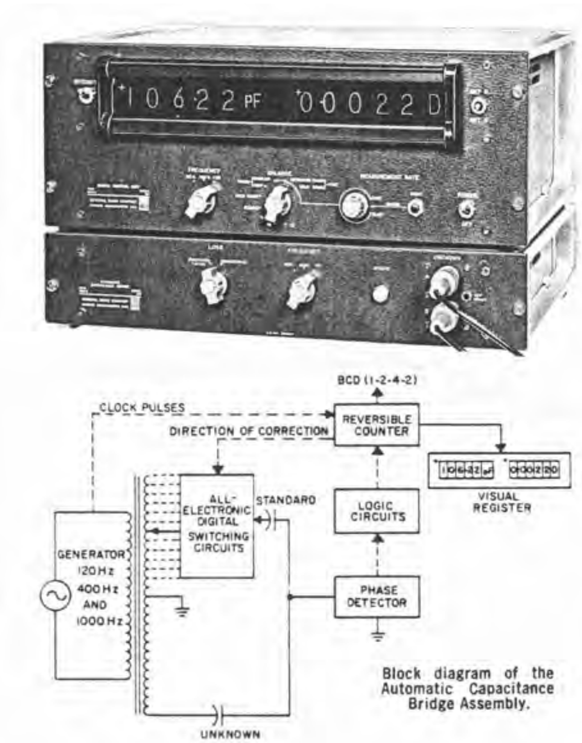
4-14 Universal Bridge
HP Model 4260A 1966


4-15 Automatic Precision Bridge
R&S Type RLCB 1969

ac resistance of diodes driven by the phase-detected bridge output. This made the main balance easier, particularly when there is interaction between the balances, the so-called “sliding null” of most RLC bridges had when measuring low-Q inductors. The D or Q value was not determined automatically, but if these values were desired, a manually-balanced rheostat could be substituted for the diodes and that balance could then be made quickly. Rohde & Schwarz had a somewhat similar unit, the "RLCB" bridge, designed by Schmidt and Kolbe[8], that also used diodes as the electrically variable bridge component, see figure 4-15. A patent by Whatley[9] filed in 1965 had proposed using photo diodes. Wayne-Kerr made a "Push-Button" bridge, the B641, whose digital adjustment as made sequentially by manual buttons guided by a meter indication, see figure 4-16, using a method described by Calvert and Mildwater[10] in 1963.

4-16 Universal Impedance Bridge
“Push-Button Bridge”
W-K Model B641 1966

A milestone was reached in 1965 with the introduction of the first digitally-balanced automatic capacitance bridge, the GR 1680, developed by R.G. Fulks[11]. This used transistor-switched, weighted-conductance, digital-to-analog converters to adjust the balance of an active transformer-ratio-arm bridge circuit, see figure 4-17. The bridge unbalance voltage was sampled and phase detected and the result drove reversible counters that drove the D/A converters until a null was reached. Alternately, each digit could be balanced separately, starting with the first, a technique that allowed a faster balance. The digital inputs to the converters at balance were the digital outputs. External signals could control the test conditions and the “start” pulse and the digital output was available on a rear connector. As a result the 1680 was used in many automatic test systems, usually with a DEC PDP-8 computer. One might note that this instrument was designed before analog or digital integrated circuits were available and thus used only transistors, more than 250 of them.



4-17 Automatic Capacitance Bridge
GR Type 1680-A 1965

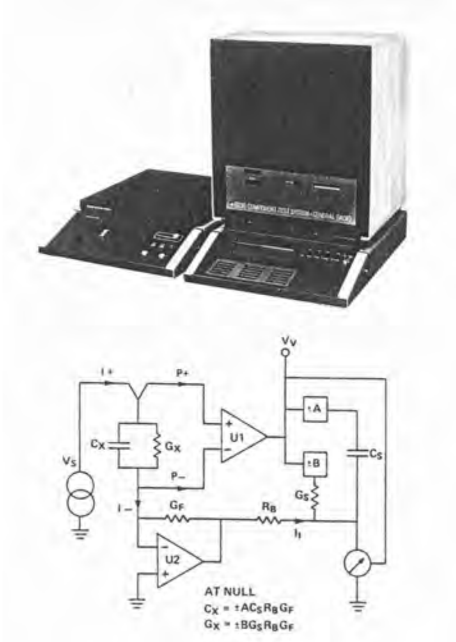
The GR 1680 measured equivalent parallel C and G and also D. It could also measure negative capacitance so that it could balance an inductance but a calculation was necessary to get the value ($L = -1/\omega^2 C$). The later GR type 1683 by Coughlin[12] measured series R, L, and C using several different active bridge configurations which were active modifications of the basic bridges in the old manual "universal" bridges. Again, the variable elements were switched-conductance D/A converters. Micro Instruments Co. made a 1 MHz Automatic Bridge, the Model 6201, as did GR. Their type 1682 by Sette[13] was a transformer-ratio-arm bridge that switched capacitors of weighted value to get the balance. Other Automatic bridges were made by Hewlett-Packard in the US, and Marconi, Culton and Wayne-Kerr in the UK and Kohan in Japan.

4.5 Computer-Bridge Systems.

Many early component-sorting systems had no computer but used instead digital limit comparators[14]. The component handler initiated the measurement and, when the measurement was complete, the digital bridge output was compared to preset limits and the handler was indexed starting the next cycle. However, if the system included a computer, components could be sorted in many categories ("bins") and thus it often paid to use a computer rather than several separated limit comparators. Moreover, the computer gave many other advantages: control, memory, printer interface etc.

But the bridge-computer combination allowed more than just sorting. Many special purpose systems were designed to do what couldn't have been done before. A good example was testing multiple-pair telephone cables. A system by Fulks and Lamont[15] used the 1680 automatic bridge to test telephone cables with 100 twisted pairs for crosstalk between them.. Using only guarded capacitance measurements, it calculated mutual capacitance and unbalance to ground and then measured all 4950 pair-to-pair combinations for unbalance between pairs. Previously only manual, sampling measurements had been made and they took much more time than the automatic system.

An automated, precision, resistance-measuring system was developed by Geraci et al[16] in 1969. An automatic calibration system designed for the US Army was described by Seeley & Barron[17] that calculated many impedance quantities, ac as well as dc, from automatic measurements on basic voltage and resistance standards. A 50 Hz to 250 MHz, transmission measuring system by Geldart, Haymie and Schleich[18] of Bell Labs calculated a variety of parameters from automatic measurements and stored calibration constants. Also microwave test systems were automated such as that by Adam[19].



4-18 Passive Test System
GR Type 2230 1975

4.6 Computers in Bridges and Meters

When computers came on single circuit boards, such as the DEC LSI-11, the computer could be incorporated with instruments in the same box as was done in the GR 2230 Passive Test System that measured dc quantities as well as ac impedance. Unlike earlier automatic bridges, the ac bridge in this system designed by Kabele[20] (1975) (see figure 4-18) ***depended*** on the computer; it could not operate without it. Besides controlling the bridge balance, the computer calculated the desired parameters. The bridge itself measured only parallel C and G, but the computer calculated not only series and parallel C and R, and D and Q, it also calculated inductance from negative capacitance. Thus, because of the computer, the bridge did not have to be "direct reading" in the desired measurement parameter and only one bridge circuit was needed to measure all impedance parameters.

4-19 1MHz Automatic Capacitance Br.
BEC Model 76 A 1976

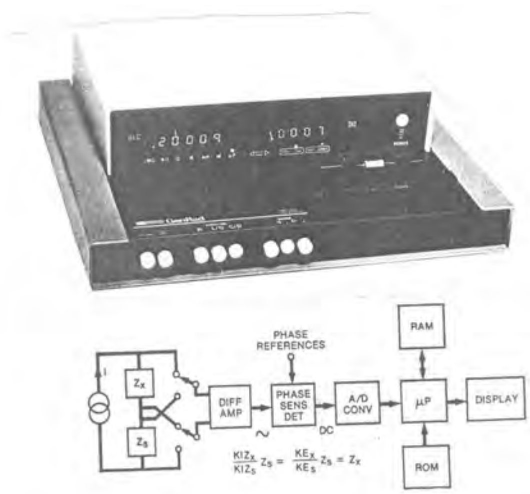
When small, inexpensive microprocessors were available they could be put ***in*** an instrument. The first microprocessor-controlled bridge was the BEC 76A, Automatic Capacitance Bridge figure 4-19, designed by R. C. Lee[21] (1976). Besides controlling the bridge, the microprocessor calculated series C and R, as well as D and Q, from the parallel C and G balance values. It also calculated the percent deviation of the measured value from an entered value and it applied stored zero corrections. These are important features that are now included in all current impedance measuring instruments. The ESI 296 Auto LCR Meter (1976) was a microprocessor-controlled impedance meter that converted the results into many parameter combinations as well as percent deviation from an entered L, R or C value (figure 4-20).

4-20 Auto LCR Meter
ESI Model 296 1976

4.7 Computing Impedance Meters

The microprocessor could do more than control a bridge and operate on the results; it could change the basic measurement method, combining the speed of digital meters with the accuracy of automatic bridges and at a lower cost than either. The microprocessor could make a complex division and thus calculate complex impedance using the ac version of Ohm's Law, Z = E/I. The current was measured by placing a standard resistor in series with the DUT and measuring the voltage across each sequentially, with the same amplifier and A/D converter (see the simplified diagram in figure 4-21). Because the same detector was used for both measurements, its gain and phase shift had no effect, they canceled in the division. Moreover, the two phase references, which were used to get the quadrature components of each voltage, needed only to be at 90° with each other, their phase relationship to the voltage or current of the DUT had no effect. This allowed the 90° phase relationship to be made easily by digital means and, as a result, the method gave very good phase accuracy as well as magnitude accuracy if an A/D with high resolution and linearity was used. The microprocessor calculated any impedance quantity from the measured complex voltage ratio and the known value of the current-measuring standard resistor.

This method was first used on the GR 1657 "Digibridge™" in 1976, figure 4-21, designed by Gipe, Hall and Sullivan[22]. Its name was a misnomer for it was a really a meter, not a balanced bridge, although "bridge" was (and still is) often loosely used to refer to any impedance measuring device. This was only a 0.2% instrument (.001 in D), but was much less expensive than automatic bridges of comparable accuracy. GR was very hesitant to described the operation of their new instruments in any detail in a paper even though the instruction manual for the 1657 gave the full circuit diagram. As a result, the best description of the new method was in the HP Journal[23] in



4-21 RLC Digibridge™
GR Type 1657 1976

4-22 Multi-Frequency LCR Meter
HP Model 4274 1978

their description of the HP models 4274A (figure 4-22) and 4575A that use the same basic method (but with the front-end circuit of figure 4-10). These instruments were designed by Maeda and Narimatsu of YHP.

4-23 Precision RLC Digibridge™
GR Type 1693 1988

GR followed the 1657 with instruments with tighter and tighter specifications, wider ranges and a keyboard that allowed numeric entry as well as selection of parameters and test conditions. The last of the line, the GR 1693 (figure 4-23) had an accuracy of .02% at 1 kHz and went from 12 Hz to 200 kHz. (This instrument and other Digibridges™ are now sold by IET Labs). The GR 1693, like other precise instruments of this type, is calibrated by external standards rather than relying on the accuracy of the range resistors. Thus they can be recalibrated regularly and the actual value of their internal standards was not critical. As wider frequency ranges were used, calibrations were made at several frequencies with calculated corrections at the intermediate frequencies. Note that the frequency used has to be precisely known in order to calculate capacitance and inductance accurately. Inexpensive crystal oscillators are accurate enough for many of these instruments but the most accurate have their frequency calibrated against an external standard and a correction entered.

4-24 Video Bridge®
ESI Model 2100 1981

Most of these instruments had two displays, primary (RLCZ) and secondary (DQ etc) that used light - emitting diodes (LEDs) and some method of displaying units and test conditions. The ESI Type 2100/2110 "VideoBridge" (figure 4-24), designed by N. Morrison, has a CRT readout that gave a high resolution readout and also displayed the units, the test frequency and voltage and other information. Later, liquid-crystal displays (LCDs) were used which could display a lot of information without the disadvantages of CRTs (high voltage, noise, power consumption and cost).

4-25 LCR Meter
Stanford Res. SR 715 1991

Microprocessor-based digital impedance meters were or are still made by at least twenty companies including Agilent (formerly HP), Quadtech, Stanford Research (see figure 4-25), Wayne Kerr (figure 4-26) and Tinsley (UK), Keithley, Fluke/Philips, Danbridge (Denmark), Chen Hwa and Chroma (Taiwan), Hioki (Japan), Goodwill (Korea, figure 2-27), Combinova (Sweden) and HuGuang and MPC (PRC), see appendix C. Tegam sells many of the instruments of the ESI line and IET Labs acquired the GR Digibridge™ line of instruments.

4-26 Automatic LCR Meter
W-K Model 4225 1984

These instruments are all quite similar in principle, if not in appearance, and most all have extremely wide range of R, C and L, good 3-terminal (guarding) and 4-terminal ("Kelvin") capability. They also have the advantages of speed, some up to 50 or more measurements per second, the current record being 5.6 ms measurements set by the Agilent (formerly HP) E4980A. Many have only low-frequency capability but many others several can go up to 1 MHz such as HP's 4284, figure 4-28 and the QuadTech 7600, figure 4-29. Agilent's extensive line of RLC meters also extends up to much higher frequencies with the older 4275 (1978) that goes to 10 MHz and the 4285 that goes to 30 MHz. They also have replaced their old analog-display Vector digital display of magnitude and phase and operates up to 110 MHz. This makes two-terminal measurements as does their type 4191A RF Impedance Analyzer that goes to 1000 MHz and which measures R, L, C, D and Q as well as |Z|,|Y|,|Γ| and θ (figure 4-30).

4-28 Precision LCR Meter
HP Model 4284 1988

4-27 LCR Meter
Goodwill Model 815B c1995

4-29 Precision LCR Meter
QT Type 7600 1995

4-30 Vector Impedance Meter
HP Model 4193A c1990

A noteworthy meter with special capability is the Wayne-Kerr Inductance Analyzer, model 3245 (figure 4-31). Besides measuring the usual ac impedance parameters over a wide frequency range it also measures dc resistance and turns ratio. It supplies an ac signal level up to 5 volts and the dc bias needed to test iron-cored transformers and chokes, up to 1 ampere internally and 100 amperes with external bias units.

4-31 Precision Inductance Analyzer
W-K Type 3245 1982

4.8 Instruments in Use Today

These microprocessor-based impedance meters have replaced all of the manual RLC bridges, automatic bridges and the older, non-computing, digital, and analog meters. Some of the companies that made these earlier instruments are still around, but many of them have disappeared, either they have gone out of business or were bought by other companies.

Many of these µP based meters have excellent repeatability making them ideal for the comparisons of standards of similar value. Some, such as the GR/IET Labs 1689 and 1693, have ppm resolution for comparison measurements and have a standard deviation at 1 kHz of about 2 ppm for a 1 second measurement. These can make 3σ comparisons to 1 ppm by averaging fifty measurements, often with a total measurement time less than the time it would take to balance a precision bridge. As a result these meters are used in many standards labs for comparing standards of all types. These meters are better than any commercial bridge for comparison of standard inductors and high-valued capacitors. NIST recognized this and has used a GR 1689M µP-based meter for comparing inductance standards[24].

These meters do have eventual limitations in both accuracy and precision. Their accuracy depends on the linearity of their amplifiers and A/D converters, but is mainly limited by their calibration and the stability of their internal standards. These factors limit ratio accuracy as well and ratio accuracy is needed for scaling impedance values. (Ratio accuracy is not limited by calibration accuracy if both measurements are made on the same range.) Their precision is limited by A/D resolution and eventually by noise. Manual transformer-ratio-arm (TRA) bridges apply higher signal levels and thus are less affected by noise and they have very good ratio accuracy. Thus older manual precision capacitance bridges, such as the GR 1615 and 1616, are still used for precision capacitance calibrations. However they don't have the many advantages of computer control.

4-32 1 kHz Automatic Capacitance Br.
A-H Type 2500A 1992
(Type 2500 1985)

A high-resolution, automatically balanced bridge would be slow and expensive to make because of many switches that would be required. Andeen-Hagerling[25] has solved this problem by making a hybrid combination of a bridge and meter, their Capacitance Bridge model 2500A, figure 4-32, which has 3 ppm accuracy and .07 ppm resolution at 1 kHz. This instrument has an 8½ digit readout, the first three digits are automatically-switched, high- precision capacitors and the last digits come from a high-resolution A/D converter. This instrument is also used by NIST[26] and by many standards labs as well.

Although low-frequency ac meters can be used to test most resistors, resistance measurements are usually made today using digital dc multimeters, both in the shop, on the production floor and in the lab. These, except for the cheapest, are capable of computer control and the advantages that go with it. Hand-held, digital volt-ohmmeters have replaced delicate, less accurate analog meters for casual use. Computer-controlled digital multimeters, DMMs, are fast and accurate enough to replace limit bridges for sorting resistors. Some standardization labs still use traditional high-resolution bridges and ratio sets for comparing

4-33 Digital Multimeter
Agilent Type 3458A

4-34 Digital Multimeter Fluke Type 8508A

resistance standards, but many use precision DMMs such as the 8½ digit Agilent 3458A (figure 4-33) or the Fluke 8508A (figure 4-34) that have accuracies of a few ppm and resolution better than 0.1 ppm. The Guildline Current-Comparator Bridge is still one of the best instruments for scaling resistance calibrations to different values. An alternative is to use series-parallel ratio boxes for scaling, making only 1:1 measurements with a high-resolution DMMs or a conventional DRRS. The main limitation of DMMs is at extremely low and extremely high values of resistance. Specialized micro-ohmmeters apply higher currents and thus get better resolution at very low values. At very high values, analog and digital megohmmeters apply much higher voltages for better sensitivity. For precision high-resistance work, the updated Guildline Teraohmmeter, model 6520, is probably the best.

4.9 A Long Way From Ohm

The history of impedance measurements illustrates the changes in the science of electricity and the development of electronics from the age of the early experimenters to the computer age of today. The designers of impedance measuring instruments took advantage of the latest ideas and devices to make their products more useful and more competitive. These instruments had to measure the widening range of component values with accuracies consistent with the increasing accuracies of new components at measurement rates sufficient to handle the exploding number of components used. Thus their development was driven by needs of technical change and realized by results technological advances.

It's somewhat ironic that the present day calculating impedance meters use Ohm's Law in a more obvious way than do classic bridges and older impedance meters. GR was once accused of patenting Ohm's Law in their "Digibridge™" patent[27] that gives the complex formula for the division of two complex numbers as the means of calculating impedance from measurements of voltage and current. It is also ironic, and perhaps sad, that your author, who has been fascinated by the history of classic bridges and has designed several commercial bridges, should have been instrumental in the end of the long bridge era. To my knowledge no new, commercial, true (nulled) bridge, manual or automatic, has been introduced for many years.

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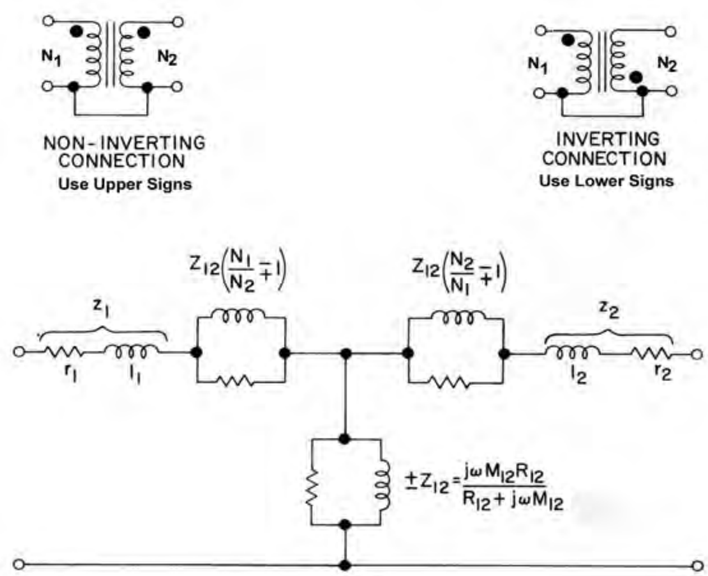
4.27 Hall, H.P., "Method of and apparatus for the measurement of impedance and other parameters with microprocessor calculating techniques", US Patent 4,196,475, Filed Sept 2, 1976, Issued 1980

Appendix A

An equivalent circuit for a two-winding transformer with a common connection



In this equivalent circuit r_1 and r_2 are the resistances of the two windings and l_1 and l_2 are the leakage inductances of the two windings, the inductance of each due to magnetic flux that does not couple to the other winding.

Z_{12} is the mutual or transfer impedance between the windings that consists of the mutual inductance M_{12} in parallel with a resistance, R_{12}. The latter represents core loss, both eddy current loss and hysteresis loss. No capacitances are included in this low-frequency equivalent circuit.

Note that for a transformer with an iron core, M_{12} and R_{12} are nonlinear and not constant with frequency, signal level or temperature. However, if z_1 and z_2 are very small compared to Z_{12}, the transformer can provide extremely accurate ratios. This can be accomplished by twisting the windings together and using a high-permeability core. Usually a toroidal core is used that is made from metal tape, thin tape to keep eddy current losses small

To get an equivalent circuit for a transformer with isolated windings, add an ideal 1:1 transformer to either end of the above circuit.

If we let Z_0 be the (average) mutual impedance between one turn on each winding, then $Z_{12} = N_1N_2Z_0$. This makes the open-circuit input impedance $Z_{11} = z_1 + N_1^2Z_0$, roughly proportional to the square of the number of turns as we would expect.

Appendix B

RLC or Universal Bridges **List Not Complete**

Company/Type No./Name/Comment	Bas Acc	Main Readout	Power	Date
Advance Electronics BR1	1%			
AVO B150 3 knobs		3 knobs		
AVO Type 1 Universal Measuring Bridge	1%	Slide-rule	ac	
AVO Type 2 Universal Measuring Br.	1%			
Beckman, Shasta DIV #602 < 1955		2 Concent Dials		1968
British Physical Labs UB202	1.5%			
Brown Eng. Model 200A US:TM 11-2634	1%	Modified 650		1945
Cambridge Inst 43347 Universal Br				
Cambridge Instrument Co. Ltd	0.2%			
Clough Brengle Model 230		Elec eye/photo	ac	
Clough-Brengle Model 712	low	small, portable		
Cresent ZM 11A/U RLC Br USArmy?				
Danbridge Universal Br. UB1	1%			
ESI 250-DA				
ESI 291 Universal Meas System				
ESI 815AF ? BECO?		3d+pot, portable		
ESI/BECO 250-B Universal Impedance Br				
Fluke 710A Universal Impedance Bridge	0.2%			1960
Fluke 710B Universal Impedance Bridge	0.1%	Coaxial		1964
Freed 1150-A Universal Bridge	0.5%			
G.& E. Bradley Ltd 131 Impedance Br	1%			1964-
GR 1608 “	.05%	counter, con adj	Line	1962
GR 1650 A&B Impedance Br	1%	Dial	Batt	1959
GR 1656 “	0.1%	4 levers	Batt	1970
GR 650 Impedance Br. Batt, 650-P1 ac	1%	Dial	Bat/P1	1933
Heathkit IB 2A Impedance Bridge				
HP 4260 Semi-auto phase bal		counter		1966
HuGuang (Shanghai) QS18A 20,000 sold				<1983
Industrial ZB series	1%			
Leader LCR-740 LCR Bridge	0.5%	multi-turn pot		
Marconi TF 1313 Universal Br.	0.25%	pointer		<1963
Marconi TF 2700	1%			
Marconi TF 373 Universal Imp Br				c1940
Marconi TF 868 fixed dial with pointer	1%	pointer		<1963
Muirhead D-897-A 0.5%	0.5%			
Nash & Thompson				
Philips GM 4144 Universal Measuring Br.	1.5%			
Philips PM 6300	1%	Dial		
Philips PM 6301 RCL Bridge	1.2%			
RCA LB-50/52 Precision Impedance Bridge	1%			
Rhode & Schwarz				
RINCO 502A see Fluke				1959
Siemens & Halske Rel 3 R217 Imped Br				
Siemens M565-A1 Universal Br	1.5%	Dial		<1969
Simpson 2785 Precision R-L-C Bridge	1%	slide-rule	batt	1968
Tesla BM-401 C, L and ac R (Czech)				<1963
Thomas Industrial Automation Ltd LCR20	1%	dial		<1969
Tinsley 4551 General Utility Br.	1%			<1969
Tinsley 4725 LCRF Bridge System	.1%	Dec R & C boxes		b1969
Wayne-Kerr B500 Logarithmic LCR Bridge		4 ter Slide rule		1969
Winslow Co. 385 Impedance Bridge	1%	2 dials	batt	1960
YHP 4255A LCR Bridge	0.5%	decades		
YHP 4265B LCR Bridge	0.2%	3 dig + dial		b1976

Appendix C

Microproscessor-based RLC_Meters up to 1 MHz (Not Complete)

Agilent 4263B*	0.1%	100-100k		
Agilent 4285A*	0.1%	75k-30M		
Agilent 4287A*	1%	1M-3G		
Agilent E4980A*	.05%	20-2M		
AIM Type 401 LCR “Databridge”, see Tinsley				1983
Boonton 5110				
Chen Hwa 100	0.2%			
Chen Hwa Model 100/102	0.1%	120,1k	5/4	
Chen Hwa L.C.R.Z Meter 1012/1013		120,1k,10kHz		
Chen Hwa 1061/1062 High Freq LCR Meter	0.1%	40-200k		
Chen Hwa 1063	0.1%	40-200k	5/4	
Chen Hwa 1069				
Combinova 11021*				
Combinova 11022*				
Combinova 11025*				
Chroma 1061A*				
Chroma 1062A*				
Chroma 1075*				
Chroma 11021*				
Chroma 11022*				
Chroma 11025*				
Danbridge CT10	.07%	111 or 1kHz		1983
Danbridge CT30 0.05% .0002	.05%	1,10,100k		
Danbridge DB210*	.05%	5: 100-100k		
ESI 2100/2110 VideoBridges				<1979
ESI 2150/2160 VideoBridges				
ESI 296,				
ESI 2400 LRC Bridge Flat panel, .25%,	.25%			
ESI 410 1 MHz				1980
Fluke 6303*	.25%	1 kHz		
Fluke 6304*	0.1%	204: to 100kHz		
Fluke 6306*	.05%	DC to 1 MHz		
Goodwill LCR-815B Taiwan (dist Instek)	0.2%	120(100)/1kHz		
GR/QT 1657 Digibridge™	0.2%	120/100 & 1kHz	5/4	**1976**
GR/QT/IET 1659* See IET Labs				
GR/QT/IET 1689* & 1689-M* “				
GR/QT/IET 1692* “				
GR/QT/IET 1693* “				
GR 1658				
GR 1688 L-C				
GR 1687 1 MHz				
HIOKI 3520	0.3%	40Hz-100kHz		
HIOKI 3530				
HIOKI 3511-50*		120, 1k		
HIOKI 3522-50*		DC-100kHz		
HIOKI 3532-50*		42-5M		
HIOKI 3535*		100k-120M		
HP 4263A LCR Meter See Agilent	0.1%	Sel 100-100kHz		
HP 4284A Precision LCR Meters		20-1MHz		
HP 4192A LF Impedance Analyzer		5 Hz-13 MHz		
HP 4285A See Agilent				
HP 4274 Multi-Frequency LCR Meter		100H-100kHz		1979
HP 4275 Multi-Frequency LCR Meter		100k-10 MHz		1979
HP 4275 Multi-Frequency LCR Meter		100k-10 MHz		1979
HP 4276A LCZ Meter		100Hz-20kHz		

HP 4277A LCZ Meter		10kHz-1MHz		
HuGuang Inst ZL2 LCR Meter		1kHz	1/3.5	
HuGuang Inst ZL3 Automatoic LCR Meter		100Hz&1kHz	2/4.5	
IET Labs, see GR				
Instek 815*		12Hz-2kHz		
Instek 817*		12Hz-10kHz		
Instek 819*		12Hz-100kHz		
Instek 820*		12Hz-200kHz		
Keithley/NF 3321/2321	0.1%	120,1,10&100k	4.5/4.5	
Keithley 3322	0.1	11 freq to 100k	4.5/4.5	
Keithley 3330	0.1%	201 frq to 100k	4.5/4.5	
Kokuyo KC535		120,1kHz		
Kokuyo KC536		120,1kHz,10k		
Kokuyo KC537		120,1k,10,100k		
Kokuyo KC538	0.3%	1MHz		
Kokuyo KC530		1kHz		
Kokuyo KC540 Series with comparator				
MCP Corp (Shanghai) BR2820*	0.3%	100,120&1kHz		
MPC Corp BR2823*	0.1%	100,120,1k,10k		
MPC Corp BR2827*	.05%	16: 50Hz-100k		
Philips/Fluke 6303A				
Philips/Fluke 6304				
Philips/Fluke 6306				
QuadTech 7400				
QuadTech 7600				
QuadTech 1710 Digibridge LCR Meter				
Quadtech 1750 LCR Meter				
QuadTech 1920*	0.1%	10Hz-1MHz		
QuadTech 7000*	.05%	10Hz-2MHz		
QuadTech 1730T*	0.1%	DC-100kHz		
QuadTech 1715	0.2%	4: 100Hz-1k		
Racal-Dana #9341 have IB 1982	.25%			1982
Stanford Research SR 715*	0.2			
Stanford Research SR 720*	.05%			
Sullivan AC5555 Automatic Component Analyser	0.1%	1kHz	4/4	
Stanford Research SR 715*	.05%	to 100kHz		
Stanford Research SR 720	.2%	To 100kHz		
Tegam 3525 *	.08%	120, 1k	4.5/4.5	
Tegam 3550 *	0.1%	42-5M	5/4	
Tinsley/Prism 6401* “LCR Databridge”	.25%	100/120, 1k	4/0	
Tinsley/Prism 6451* “LCR Databridge” D&Q	.1%	100/120, 1,10k	5/0	
Tinsley/Prism 6471* “LCR Databridge”	.1%	100, 1,10,100k	5/0	
Tinsley/Prism 6458* “LCR Databridge” rack	.1%	100/120. 1,10k	4/0	
Thurbly Thandar LRC400*	0.1%	3	5/4	Lim
Venable Inst. RLC 260-011*		1Hz-15 MHz		
Venable Inst. RLC 300-011*		1Hz-2.w 2MHz		
W-K 4220/4225 LCR Meters 0.25% 4-dig	.25		4/0	
W-K 4210-4210S LCR Meters 5 digit 0.1%,	0.1%	120,1k,10k	5/0	
W-K 4250	0.1%	120,1,10,100k	5/0	
W-K 6225 two 5-dig readouts	.02%	20-300kHz		
W-K B905/905A LCR Meter .05%				
W-K B605 4 digits, one meter,	0.1%	120,1k,10k		<1983
W-K 4230 *	0.1%	To 200kHz		
W-K 4234 *	0.2%	To 100kHz		
W-K 4235 *	0.2%	To 200kHz		
W-K 4236 *	0.2%	To 500 kHz		
W-K 4237 *	0.2%	To 1 MHz		
W-K 4238 *				

W-K 4239 *		
W-K 4255 *	0.1%	To 1 Mhz
W-K 4265 *	0.1%	Dc-100kHz
W-K 4275 *	0.1%	DC-500 kHz

* Available in 2007

ESI meters sold by Tegam, HP instruments by Agilent, GR by IET Labs.