A bridge to accurate measurements

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Introduction

In *"The Story of Electrical and Magnetic Measurements"* [1] Joseph Keithley (1915-1999) described how the knowledge of the magnetic and electric phenomena was discovered throughout the centuries.
What the reader might notice is that *"natural philosophy"* always played an important part in the education of the early scientists. Smart observations and creative experimenting gradually led to the understanding of all the issues that have changed our world so much. In the 17-th century magnetic and electric fields were as illusive as `dark energy` and `dark matter` in our times. By now the average highschool-student used to have a better understanding of electricity than the smartest professors in the former ages, although the natural origin of these phenomena is not yet fully understood.

Our `studieverzameling` has a rich collection of artifacts that might generate an historic reflection on key milestones in the development of our profession. Each of the many thousand components in our basement [2] has its own story, a huge task to bring all this to the surface. In the field of measurement-equipment the historic `bridges` are well represented. The most interesting items are being restored with preference, some of them we love to describe here. For this occasion we selected two instruments that marked the transition from thermionic valves to semiconductor devices at the end of the fifties.

AC-bridges:

The general purpose of a bridge-circuit (Fig.1) is to compare the electrical properties of a component with a well defined reference. In principle bridges are accurate voltage dividers where the output will be null if the conditions for an equilibrium are met. **The supplied voltage then has no influence on the result.**
They come in many varieties but in essence a lot of them can be reduced to the following circuit:

$$\frac{Z_1}{Z_2} = \frac{Z_3}{Z_4}$$

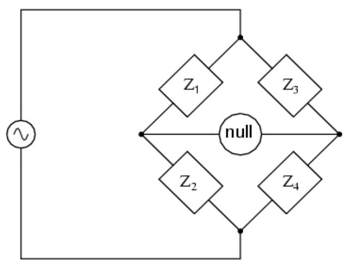


Figure 1

Generalized AC impedance bridge: Z = nonspecific complex impedance.

The availability of a reproducable AC voltage brought Max Wien (1866-1938) to the publication of a classified collection of ac-bridge-networks in 1898. The terms `impedance`, `capacitance` and `inductance` were introduced a little earlier in 1892 by Oliver Heaviside (1850-1925).

The generalisation of Ohms law to $\underline{U} = \underline{I} * \underline{Z}$ in 1826 allowed the bridge balance equations to be divided into a real and an imaginary part where $\underline{Z} = R + jX$ and $j^2 = -1$.
$\underline{Z1}$ can be the unit under test, $\underline{Z2}$ is the reference. $\underline{Z3}$ and $\underline{Z4}$ (in the ratio-arm) are well defined components, sometimes either a calibrated potentiometer or a transformer with discrete branches. (such as a `ratiotran`)
The bridge is usable as a *universal impedance meter* to determine resistance, capacitance and inductance in all its complex combinations. **In principle the accuracy is only limited by the reference-elements.**

The ESI model 291-A Impedance measuring system

Electro Scientific Industries Inc. (ESI) originated in 1953 out of the Brown Electro-Measurement Corporation (BECO) that was funded in 1944 in Portland (Oregon). [3] BECO started production as a second source for the legendary General Radio (GR) model 650 capacitance bridge [4], required by the US government in considerable numbers. Having a second source from the other side of the continent was good practice as by then the German U-boats were swerling along east coast of the USA. [5]

After the war BECO developed its own version so the rather big GR instrument was modified to a more neathly package, called the`Brown bridge` [6] with a basic accuracy of 1%.
Several namechanges followed and in 1953 the business continued as ESI. They gradually improved the line of impedance bridges to ± 0.1% using a set of three coaxial decade-switches on top of a variable control called the `decapot` (Fig.2).

The ESI 291A in our collection (Fig.3) was designed by Merle Morgan in 1960.
It consists of three 19″ rack-units; the passive bridge-circuit 290A (Fig.4), on top the DC generator/ detector 840 with a nice and sensitive spotlight galvanometer and in the middle the AC generator/ detector 860A with the `Magic Eye` tuning indicator. Together with the null galvanometer a swift and safe measurement can be made to the required precision.
A special plug-in circuit was available for different frequencies.

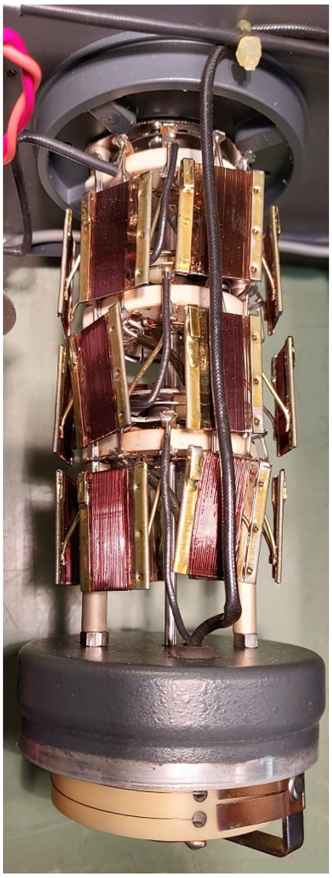


Figure 3: Rack mounted setup

Figure 2: Decapot

Figure 4: Passive bridge with the reference capacitor on the left.

The DC-accuracy for resistance and conductance is ± 0.05%.
Inductance and capacitance can be determined within ± 0.1%.
In order to compare two (equal) components there are five significant figures available on the ESO-decadial dials. (120,005 divisions)
With the onset of the transistor-age this instrument can be regarded as the `last of the mohicans`.
The ESI 290-A remained nevertheless a popular disposition for a long time after.
Nowadays you will see them on Ebay for between $ 200.- (290A) and $ 750.- (complete rack).

Around 1966 ESI moved into a new factory and diversified the product line.
Several new systems were launched such as an analog computer, an electrostatic electron microscope and a defilibrator. Not all of them were a commercial succes.

Some systems were remarkable ingenious such as the **algebraïc computer ESIAC-10** that was bought by our university in 1965. You will find a comprehensive description in the ETV-Maxwell 25-3 from the hands of Kees Pronk and Piet Trimp. [7]
The main application was the analysis of high order control-systems, its response and stability.

In 1969 the first ESI laser trimming system saw the light for use in the semiconductor and component industry. This was the start of a succesful range of instruments that became more or less their core business.
Increasing need for investments led to floatation of the stock in 1983.

In 2019 **MKS Instruments Inc.** acquired full ownership of ESI. It found its place as a subsidiary of a company with wide roots in the process-industry.

Figure 5: The ESI complex function analyser

The General Radio 1650-A, a portable Impedance Bridge. (Fig.6)

The introduction of the `*transconductance-resistor*` (transistor) gave the young GR-engineer Henry Hall the opportunity to design a really portable impedance bridge with some unique features (1959).

Most of our practical measurements can perfectly do with an accuracy of 1% for R, L and C.
Although there are other principles to measure these electrical components, the classical bridge circuits give the most reliable and repeatable results due to the control of frequency, AC-amplitude and DC-bias (detailed specs see[8]). The bridges are configured with 2 rheostats and a standard reference capacitor.

Figure 6: GR1650 in a swivelcase

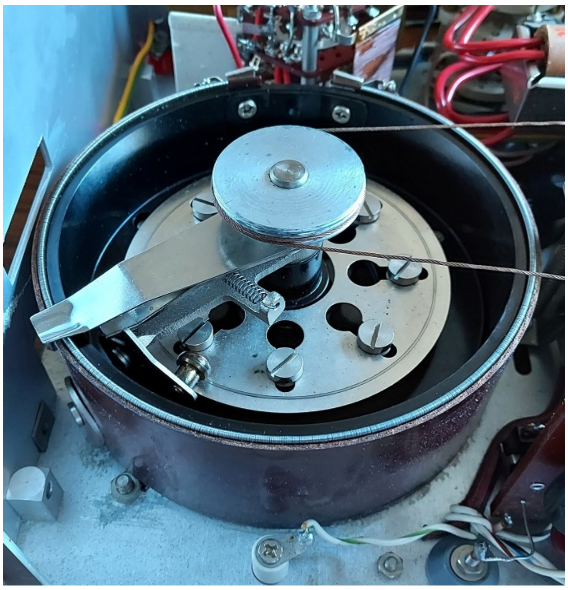


Figure 7: RN with 8 calibration screws

Bridge- circuitry GR 1650A: (Fig. 8)

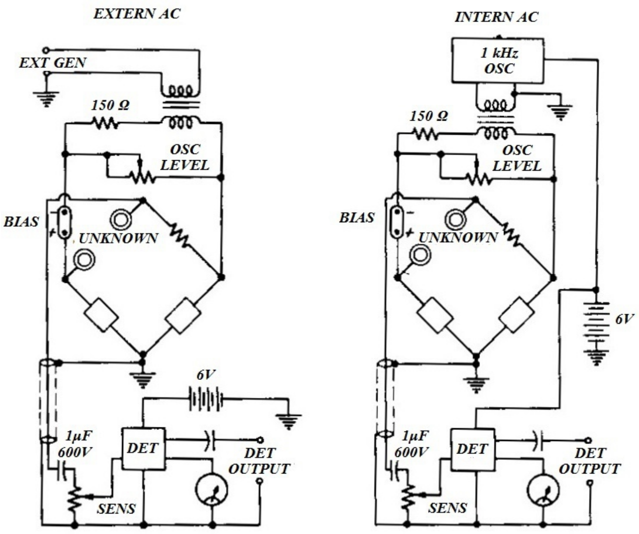


Figure 8: Functional diagram

The bridge is fully selfpowered with 4 D-type batteries. (6 Volt @ 10-60mA)
It has an internal oscillator (1 kHz) and a very sensitive detector. (DC and AC)
For AC the detector has a switchable selective filter at 1 kHz to reduce hum and noise.

An external generator can be used at frequencies between 20 Hz and 20 kHz without reducing the accuracy.
High resistance ranges can be more accurate with extern AC or DC. ($U_{max} <$ 500 V)
External DC bias (<600 V) will enable to setup the working-point of the unit under test.

Bridge-configurations GR 1650A: ***Resistance*** (Fig.9)

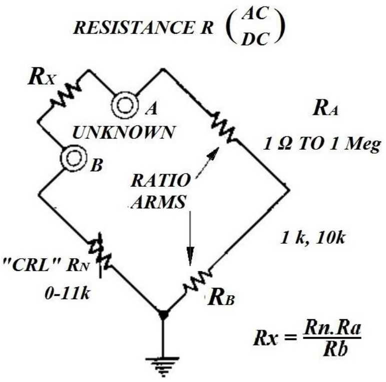


Figure 9

The ***variable ratio-arm:*** *(R_N)* consists of a calibrated potentiometer, *("CRL")* at on one end connected to the ground. (Fig.9 and 10 a/b)
R_N is wound around a partial exponential wide strip that enables the scale of the CRL-dial to be logarithmic between 1 and 11 (linear between 0 and 1).
The scale-value from 1 - 11 can change then with a constant percentage of the range per degree of rotation. This will facilitate the unique and patented *"orthonull-function"* (see below).
The moving slider is calibrated on eight positions of the CRL-dial (Fig.7 and 12), thus assuring an accuracy of ±1 procent over the whole decadial range. Measurement range: 1 mΩ – 10 MΩ.

Bridge-configurations GR 1650A: ***Capacitance*** (Fig.10 a/b)

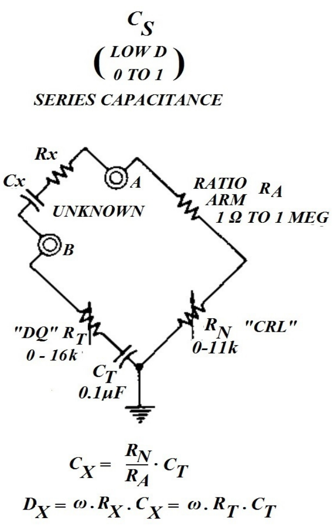


Figure 10a

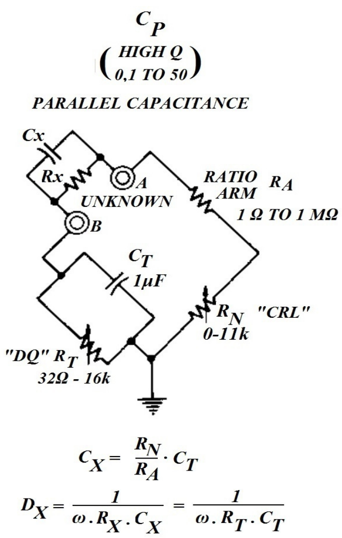


Figure 10b

The ***constant ratio-arm:***
R_A determines the CRL measurement-range (1 pF to 1100 µF in 7 ranges).
This arm is implemented with 6 switched resistors from 1Ω to 100kΩ. (±¼ %)
Bifilar winding [9] keeps the selfinduction of these resistors low.
The high range R_A reference resistor is a precision metal-film type of 1MΩ.

The D-Q rheostat R_T is an all exponential wound potentiometer with a coverage of 54 dB for a wide measurement range.
The D-Q inaccuracy is < 1%.

Serial Capacitance Cs: Low D (0-1)   Figure 10a.
The mica reference-capacitor C_T (0.1µF ±0.2%) is placed in series with R_T.
Parallel Capacitance Cp: High D (0.1-50) Figure 10b.
Here the rheostat R_T is placed in parallel with the reference capacitor C_T. (1µF ±0.2%)

Bridge-configurations GR 1650A: ***Inductance*** (Fig.11 a/b)

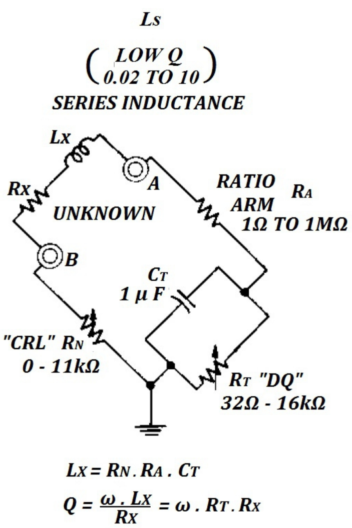


Figure11a: Maxwell bridge

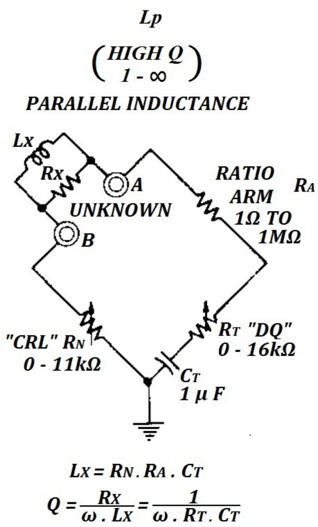


Figure 11b: Hayes bridge

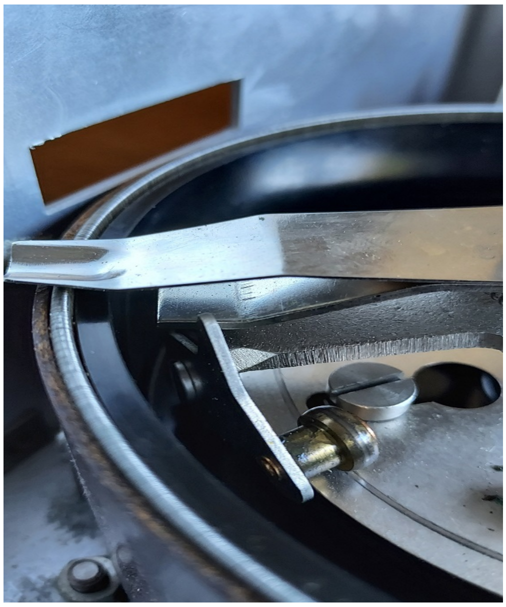


Figure 12: R_N (adjustable slider)

Serial inductance Ls: Low Q (0.02-10) Figure 11a.
R_N is placed in series with the unknown L_X-R_X. C_T and R_T are in parallel.
Parallel inductance Lp: High Q (1-∞) Figure 11b.
R_N is placed in series with the unknown L_X-R_X. C_T and R_T are in series.

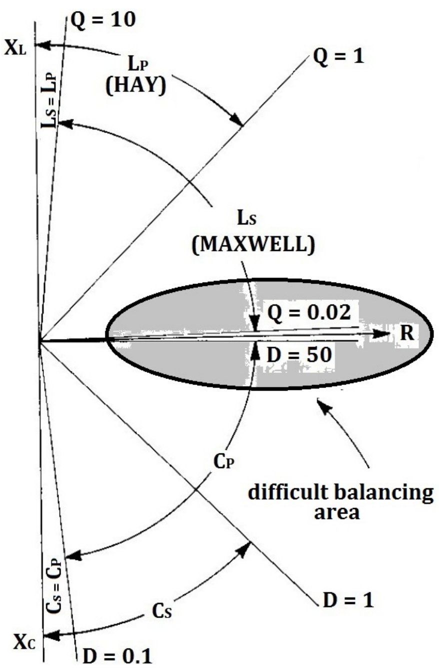


Figure 13: D-Q card

The Orthonull feature:

The D-Q coverage card (Fig.13) shows the available ranges of the dissipationfactor D and the quality-factor Q @ 1kHz.
Both D and Q can be established by R_T with ±1% accuracy if D<7 or Q>1/7.
When dealing with reactive components that have **high losses** (high D or low Q) it is **profoundly difficult** to balance a Maxwell/Hay bridge. The real part of the impedance then is a lot larger than the imaginary component. This generates a "sliding null" due to the **interdependence** of the two balancing controls.

Around null the output of a Maxwell-bridge can be expressed as:

$$\frac{E\,out}{E\,in} = \frac{Rx + j\omega.Lx - \left(\frac{Rn.Ra}{Rt} + j\omega.Rn.Ct.Ra\right)}{complex\ denominator} \qquad \text{(Form. 1)}$$

The denominator is more or less constant around the null.
Changing R_T only controls the real component R. (see Fig. 14)
Rotation of R_N affects both the real and the imaginary factors.

Looking at Formula 1 the magic solution would be to **keep the ratio *R_N/Rt* constant**: R_N now only affects the imaginary part. This will avoid a sliding null and makes balancing more easy.

Mechanical Implementation:

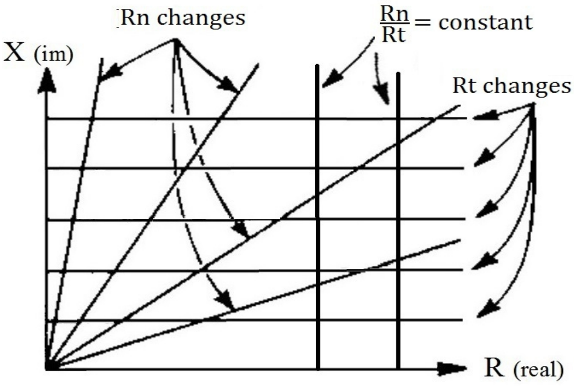


Figure 14: Loci of Rn and Rt adjustments in Z.

When the orthonull handle is activated, both logarithmic potentiometers are driven by "CRL" Rn. The traction-ratio is such that Rn/Rt will be constant. Both relative changes per degree of rotation are the same within the Rn-range of 1 to 11. The mechanical friction is light so that changing the "D-Q" Rt control will not rotate Rn. As a result the combined adjustments generate **a vertical movement** in the complex plane. (Fig.14) Without this a lot of separate corrections near the real axis R are needed to achieve the same vertical fit. Fig.16 and 17 will illustrate the effect of this function.

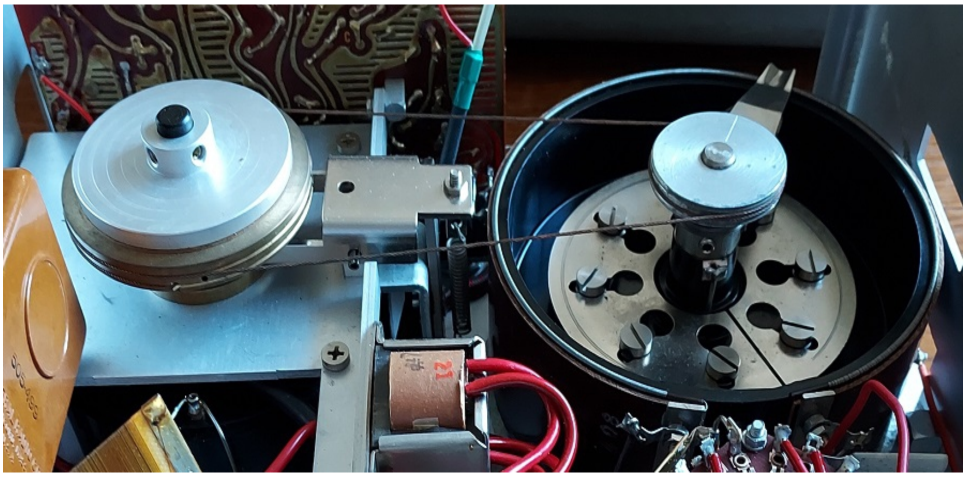


Figure15: Friction-clutch coupling of the CRL and the D-Q rheostats.

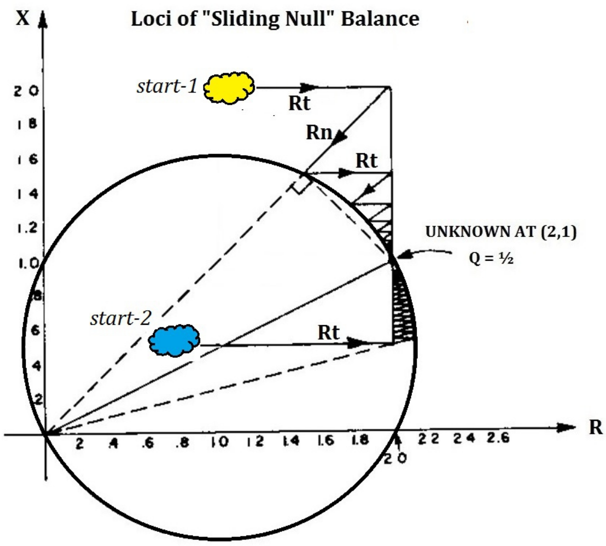


Figure 16: Iterations without Orthonull

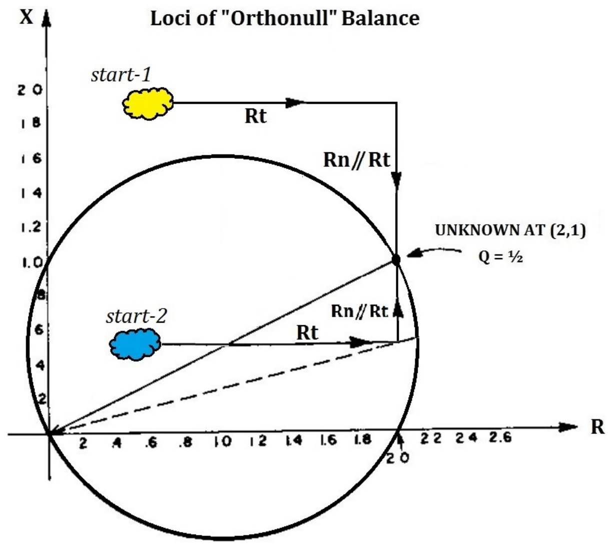


Figure 17: Iterations with Orthonull

In General Radio catalog-P (1959) the GR1650A is offered for $ 440.- but the bridges are widely available on Ebay today. You can often choose from more than ten instruments with prices between $ 100.- and $ 250.-

Conclusion:

Trough the ages **impedance measurement** has developed from a crude laboratory excercise to fully programmable digital instruments. [10] The precision of the early experiments was actually quite good with respect to the available tools. From a couple of percent to much less than 1 part per million within a few decades is remarkable. The **electrical bridge** played an important part in this evolution. [11]

The Orthonull feature was Henry Hall's first patent.[12] At the age of 94 he is still an active consultant. Thanks to creative and competent engineers like him, we benefit from reliable and efficiënt electronics, the `right stuff` that might win a war.
Reconstructing the history of a bright idea is an inalienable privilege in managing a historical collection. On mondays you are very welcome in our souterrain where you can see a lot of equipment in operation.

Sources and recommended reading:

[1] - https://tudelft.on.worldcat.org/oclc/557402393

[2] - https://studieverzameling.ewi.tudelft.nl/

[3] - https://www.ietlabs.com/esi

[4] - https://digital.sciencehistory.org/works/jm214p20f

[5] - https://uboat.net/maps/us_east_coast.htm

[6] - https://www.youtube.com/watch?v=MwxKNIfNqJg

[7] - https://studieverzameling.ewi.tudelft.nl/images/pdf/esiac-20B2.pdf

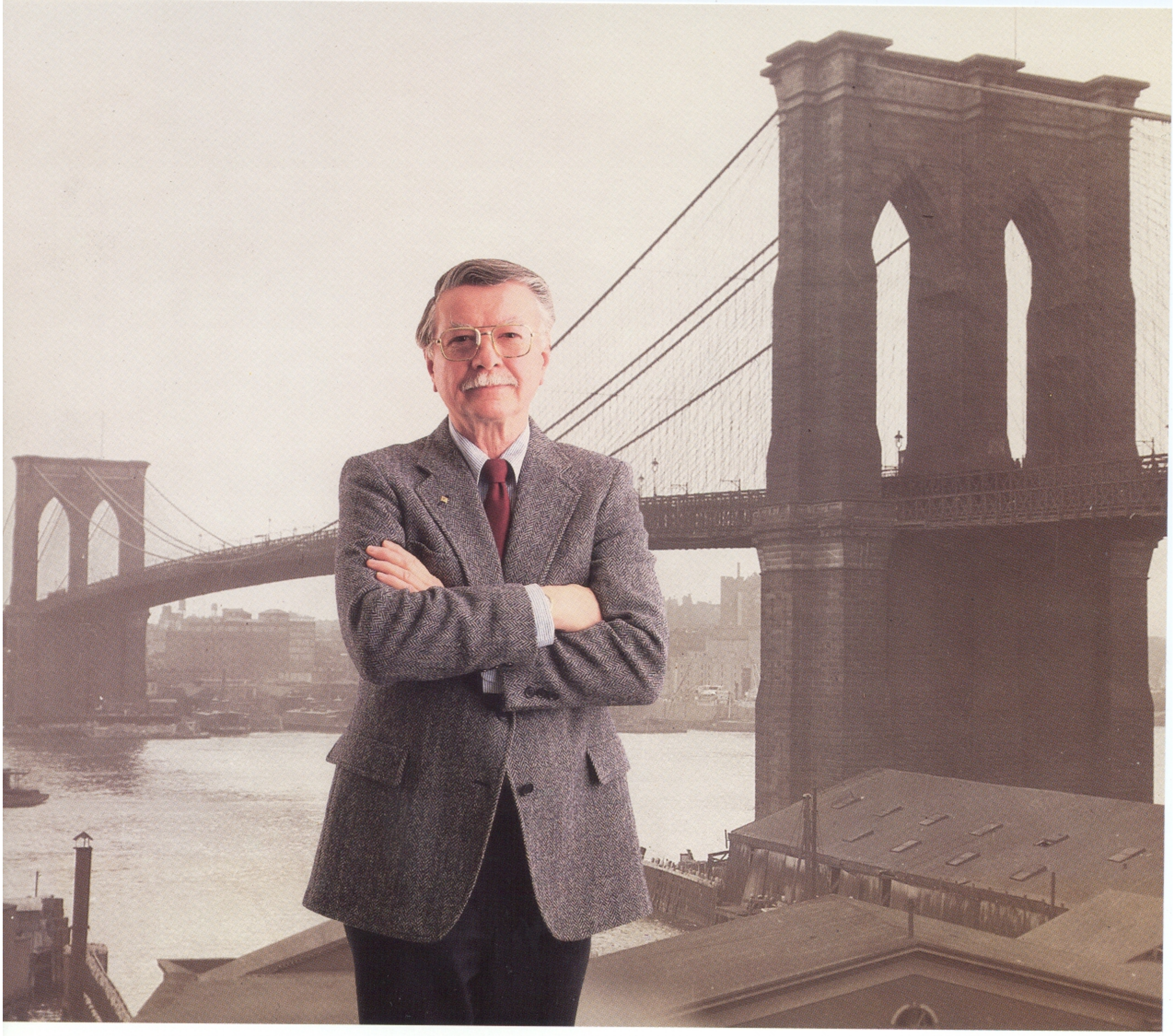
[8] - https://www.ietlabs.com/pdf/GR_Experimenters/1959/GenRad_Experimenter_March_1959.pdf

[9] - https://e-magnetica.pl/bifilar_winding#non-inductive_bifilar_winding

[10] - https://www.ietlabs.com/pdf/application_notes/12-Henry%20Hall%20Digibridge%20Patent-Digibridge.pdf

[11] - https://www.ietlabs.com/pdf/GR_Appnote/How%20Electronics%20Changed%20Z%20Meas.%20IMTC%202004.pdf

[12] - https://patentimages.storage.googleapis.com/a4/8b/d4/183e31c7666775/US2872639.pdf



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Many of the automatic impedance bridges sold worldwide today use at least one of Henry's patented techniques.

*Patent Nos. 4 196 475, 4 342 089 & 4 242 631

Henry, a senior scientist, has been at GenRad for more than 38 years. He's the father of modern impedance measurement. Henry's the person responsible for creating the basic technology that made GenRad Digibridge® RLC testers No. 1 in passive component testing.

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