Impedance Bridges for the Megacycle Range

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This paper reviews ac bridges developed for use in the Bell System for the measurement of impedance parameters, particularly at frequencies in the megacycle range. Three recent bridges designed for measuring networks and components for coaxial systems are described.

INTRODUCTION

The need during recent years for increased accuracy of impedance measurement in the megacycle range has led to advances in the art of bridge measurement. A particular stimulus has been the development of a new coaxial system, designated L-3, for transmitting over distances up to several thousand miles a continuous frequency band extending roughly from 0.3 to 8 megacycles per second. Such a system will be capable of providing on a single coaxial unit the combination of a single television channel and as many as 600 one-way telephone channels. The large loss inherent in transmitting this wide frequency band over the cable makes it necessary to provide an amplifier about every four miles, and these amplifiers and associated networks have created difficult measurement problems.

MEASUREMENT PROBLEMS

The measurement problems arise partly from the wide frequency band, approximately thirty times the minimum frequency. This makes equalization of the system for satisfactory transmission very difficult, particularly in transmitting a television signal which covers a frequency band equivalent to about a thousand telephone channels and which must be equalized for phase as well as loss.

Even more important, however, are the problems arising from the close spacing of the amplifiers, with the result that a transcontinental circuit requires up to a thousand amplifiers in its path. Departures in individual transmission characteristics will produce cumulative errors, making it necessary to maintain close control over the manufacture and adjustment of all of these amplifiers and associated networks. This calls for networks of highly refined design and requires ancillary measurement facilities of greater precision than heretofore available at these higher frequencies.

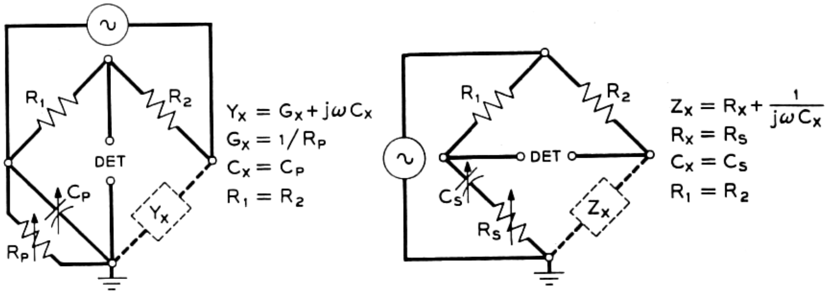
The design of transmission networks to meet exacting requirements is a subtle art, embracing on the one hand the use of complex mathematical manipulation to produce theoretical networks having the desired loss and phase characteristics, and requiring, on the other hand, a down-to-earth knowledge of the properties of the actual components used including parasitic effects and interaction of the various elements when assembled into a network. To furnish this knowledge, to measure the component resistors, capacitors, inductors and transformers which are the building blocks of the networks, to evaluate the ever-present parasitic effects, to determine simplified circuit equivalents of the more complex components such as transformers, and to answer other questions too numerous to mention, measurements of impedance parameters – precise measurements – are required.

EXISTING BRIDGE TECHNIQUE

For measuring impedance and admittance parameters, that is R, L, C and G, suitable ac bridges, ordinarily simply designated as impedance bridges, have long held a high place in the Bell System because of their inherent reliability and precision, and their ability to cover a wide range of values. The development of many of the original bridges[1, 2, 3, 4] for frequencies above the audio range stemmed from the needs of the earlier carrier systems. With this development came also analysis of shielding technique,[5] standardization of capacitance,[6, 7] and a systematic classification of bridge methods[8] by J. G. Ferguson in 1933, in which bridges were grouped into two major types designated as ratio-arm and product-arm, respectively. Following this classification, combined impedance and admittance bridges were developed,[9, 10] utilizing a single set of bridge standards for both kinds of parameters by changing the configuration of the bridge network. There have also been special purpose bridges[11, 12, 13, 14] for use at audio and the lower carrier frequencies. More recently, coaxial impedance standards[19] having values calculable from physical dimensions have been developed.

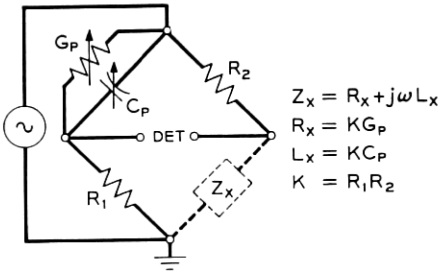
Bridges for frequencies above one-half megacycle were used in the Bell System as early as 1919,[15] but relatively few bridges were built until the mid 1930's when new carrier systems required bridges in the megacycle range. A ratio-arm bridge[16] using external standards was developed for precise measurements up to three megacycles. Interconnection of bridge and standards using coaxial cords provided flexibility of configuration resulting in an admittance bridge for high impedances and a series-reactance bridge for medium impedances. These two bridge circuits are shown schematically in (a) and (b) of Fig. 1. A separate, self-contained Maxwell product-arm inductance bridge, shown schematically in Fig. 1c and illustrated in Fig. 2, was designed primarily for measuring low-impedance parameters up to one megacycle/sec. Inductance was measured using calibrated air capacitors, and resistance was measured by means of conductance decades employing wire-wound resistors. The bridge included a double-shielded coupling transformer and complete shielding not shown in the simplified schematic.

To show clearly the scope and inter-relation of these three bridge methods, it is helpful to plot their ranges on a Slonczewski reactance/frequency chart[17] shown in Fig. 3. In this chart, the top frequency shown for the ratio-arm bridge is three megacycles, and for the Maxwell bridge is one megacycle, as these are considered boundaries



(a) ADMITTANCE BRIDGE

(b) SERIES REACTANCE BRIDGE



(c) MAXWELL INDUCTANCE BRIDGE

Fig. 1—Simplified schematics showing the basic circuits of three existing bridges for use at frequencies up to about three megacycles.

for their best performance, even though both bridges are useable at higher frequencies. It will be observed that while there is some overlapping of the three ranges, all three methods are necessary to obtain the impedance coverage shown. It should be emphasized that all the ranges shown cover both capacitive and inductive reactances. In the case of the admittance and series-reactance bridges, inductive impedances are measured by using a resonating capacitor, in parallel or series, respectively, with the apparatus being measured. In the Maxwell inductance bridge, capacitive impedances are measured by using a fixed resonating inductor in series with the impedance under test. A complete accuracy statement for these bridges is necessarily complex, but in general accuracies of ±0.25 per cent for the major component

Fig. 2—One-megacycle Maxwell inductance bridge, shown schematically in Fig. 1c, designed for relay-rack mounting.

was obtained over most of the range plotted on the reactance chart. These bridges have been very successful for the purpose for which they were designed, but they are not useable up to the eight megacycles or higher required by the L3 system.

REQUIREMENTS OF BRIDGES FOR L3 SYSTEM

When the L3 system was contemplated, it was evident that new bridges would be needed. It was required to be able to measure virtually any impedance value at frequencies up to and beyond the second harmonic of the 8.4 megacycle upper limit of the system. Accordingly, a top

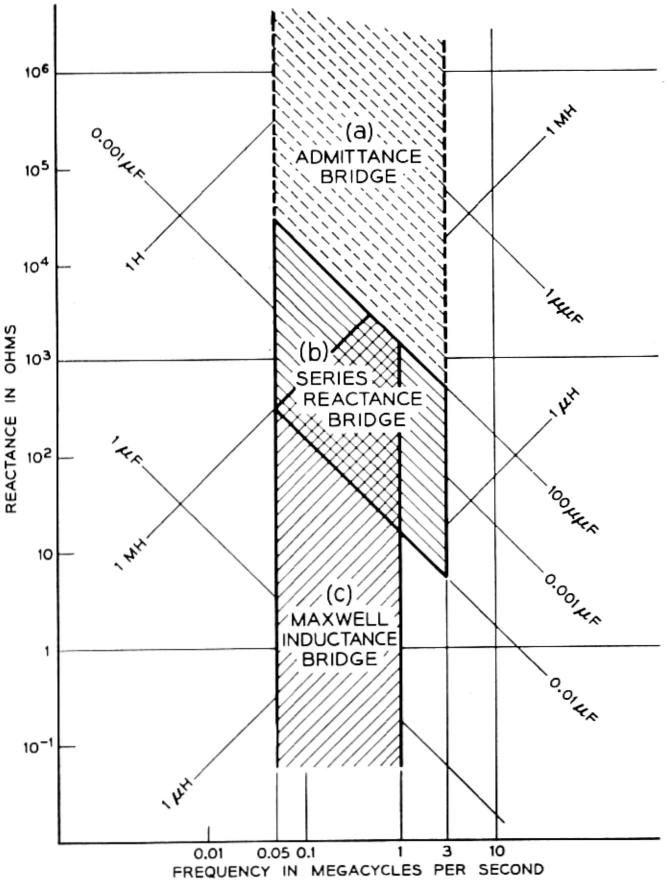


Fig. 3—Reactance/frequency chart showing the measurement range of the bridges shown in Fig. 1.

frequency of twenty megacycles was decided upon as a design objective with a basic accuracy of ±0.5 per cent for the major component. The immediate need was for a general-purpose bridge, but it was expected that special-purpose bridges having better accuracy would be required later.

GENERAL PURPOSE 20-MEGACYCLE BRIDGE

It was decided first to develop a single bridge unit which would embrace both admittance and series impedance methods, and thereby cover a reactance range from a few ohms up to nearly a megohm, as shown in Fig. 4. Such a bridge would combine the features of (a) and (b) of Fig. 1. There were numerous departures from the earlier designs, however, including the use of a series range capacitor to reduce the size of the series capacitance standard, the use of deposited carbon resistors,[18] the form and construction of both conductance and resistance standards, and especially the use of transformer-coupled inductive ratio arms.

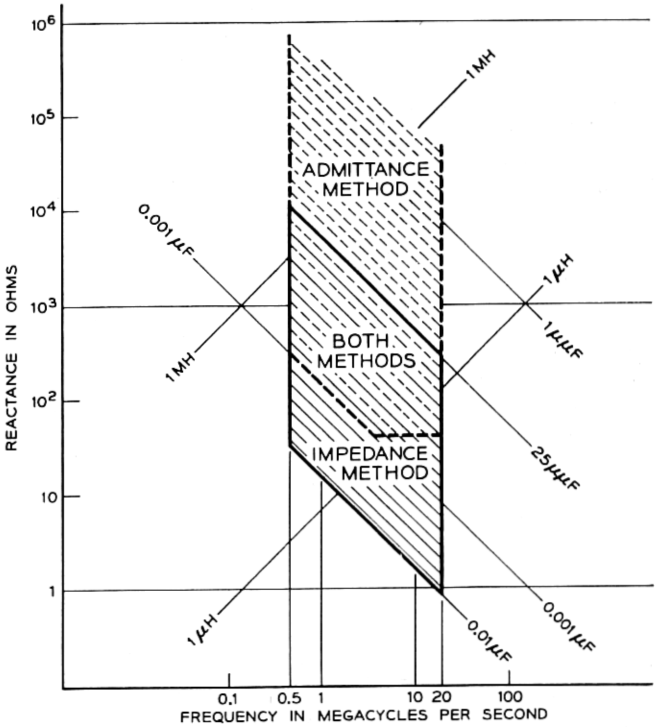


Fig. 4—Reactance/frequency chart applying to the general-purpose bridge shown in Fig. 5.

The successful use of a center-tapped transformer for ratio arms in a 465-KC direct capacitance bridge[13] indicated that the resistance ratio arms R1, R2 of Fig. 1 might be omitted if a suitable transformer could be developed for higher frequencies. The transformer group of the Laboratories succeeded in producing a transformer with a deviation from unity ratio of less than 0.1 per cent over a frequency range from 0.5 to 20 megacycles. This was made possible by precise location of the windings in fine milled grooves in the form of reversed helices, cut on a longitudinally-split brass cylinder for the inner winding, and on a surrounding phenol fibre cylinder for the bifilar outer winding which serves as the bridge ratio arms. Electrostatic shielding limits the direct capacitance between primary and secondary to less than 0.01 $\mu\mu f$. The core material is compressed powdered molybdenum permalloy. This transformer was the nucleus around which the general purpose bridge was built, and the resulting bridge is shown schematically in Fig. 5.

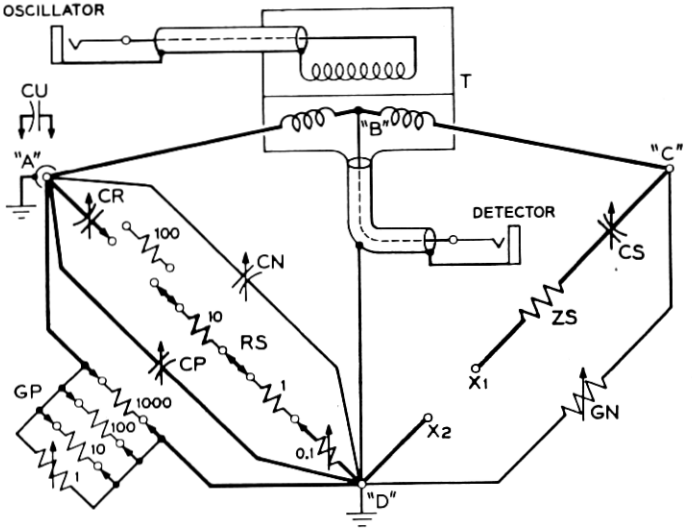


Fig. 5—Schematic of the 20-megacycle general-purpose bridge showing both the series (impedance) and parallel (admittance) bridge circuits combined in a single unit.

In Fig. 5, the letters A, B, C and D designate the four bridge corners, and T is the ratio-arm transformer already described. Apparatus to be measured by the admittance method is connected to terminals C and D, and is balanced by the calibrated capacitor CP and conductance standard GP. To use the series reactance method, CP and GP are set at minimum settings, apparatus to be measured is connected to terminals X1 and X2, and is balanced by the calibrated capacitor CS and resistance standard RS. The range capacitor CR consists of several mica capacitors for extending the range of CS, as will be described below; and ZS is merely a compensating impedance, essentially an inductive two-ohm resistor. The circuit is thus basically quite simple and avoids the use of switches or other complications which would impair performance at these high frequencies.

Capacitors CP and CS are worm-driven air capacitors with a range of about 220 $\mu\mu f$, and were specially designed for this bridge. In the case of CS, any direct conductance between rotor and stator would result in an effective series resistance which would vary both with frequency and capacitor setting, and therefore require laborious correction. This was avoided by arranging the construction so that the rotor and stator are mounted on independent insulating supports to the ground panel, thereby completely eliminating direct conductance from rotor to stator. While this results in some conductance from test terminal X1 to ground, the amount is small and its effect is negligible because of the relatively low impedance values measured. In the case of CP, on the other hand, it is important to minimize series resistance and inductance to avoid conductance and capacitance corrections which would change both with frequency and capacitor setting. This was accomplished by careful design of the rotor brush using silver contact surfaces and center-fed connections to both rotor and stator.

The conductance standard, GP, and resistance standard, RS, were designed to emphasize high-frequency performance. Deposited carbon resistors[18] on ceramic rods $\frac{1}{8}''$ in diameter and $\frac{3}{4}''$ long mounted on small decade rotors were used, so arranged that only one resistor on a rotor is in the circuit at any time, and that adjacent resistors are short-circuited by means of auxiliary shorting brushes to eliminate shunting admittance which might vary with frequency. For GP the resistance values are such that the two lower decades and the slide-wire rheostat each have a residual conductance of 333 micromhos, thereby avoiding the use of resistors exceeding 3,000 ohms in value which would be more likely to vary with frequency. The structure is designed to minimize series inductance and to maintain constant capacitance for all settings. For RS, on the other hand, it is necessary to maintain constant inductance for all settings. This was accomplished by adding small wire-loop compensating inductors in series with individual resistors in the 10-ohm and 100-ohm decades when necessary. To minimize the over-all inductance, the resistor rotors are placed very close together and are driven by gearing from the corresponding dials.

The range capacitor, CR, has already been mentioned. It consists of a rotor switch on which are mounted five uncalibrated mica capacitors which enable CS to measure both positive and negative reactance values up to 10,000 $\mu\mu f$ without additional switching. The 20 $\mu\mu f$ CR capacitor covers capacitance measurements up to 60 $\mu\mu f$; the 40 $\mu\mu f$ capacitor covers up to 150 $\mu\mu f$; the 80 $\mu\mu f$ up to 600 $\mu\mu f$; the 140 $\mu\mu f$ up to 10,000 $\mu\mu f$; and the 200 $\mu\mu f$ capacitor covers all the positive series reactance measurements. Since the CR capacitor permits the bridge to be balanced with the test leads short-circuited, the value of the effective resistance under test is simply equal to the difference between RS readings for the measurement balance and the short-circuit balance, and the reactance under test is determined from a computation of the two readings of CS.

A front view of the general purpose bridge is shown in Fig. 6. The four lower dials are for GP; above them are the four RS dials; and above them is the CR dial. The capacitors CS and CP are located adjacent to the test terminals, but are operated remotely by the dial knobs at the extreme right end of the bridge. This was done to remove the operator's hands as far as possible from the test terminals. Near the test terminals is a coaxial connector engraved A. This allows plug-in capacitors (CU in Fig. 5) to be added in parallel with CP for extending the capacitance range. Compact silvered mica capacitors in steps of 200 $\mu\mu f$ are used. Fig. 7 shows the interior of the same bridge with CP and CS in the lower foreground, GP at the left and RS in the upper right.

Fig. 6—Front view of the general-purpose bridge shown in Fig. 5. The bridge is approximately 10½ inches high and 19 inches wide.

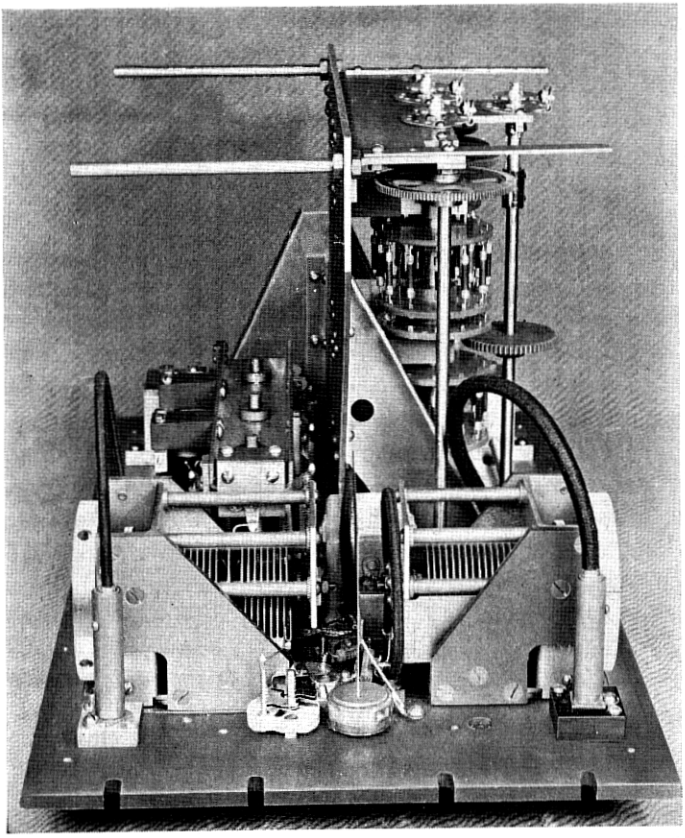


Fig. 7—Interior view of the general-purpose bridge. The panel edge shown in the foreground is the left edge of the bridge shown in Fig. 6.

FIVE-MEGACYCLE MAXWELL INDUCTANCE BRIDGE

To facilitate the measurement of low-valued inductors, there was need for a direct-reading inductance bridge inasmuch as such measurements entail considerable computation effort when using the general-purpose bridge. Accordingly, it was decided to build a five-megacycle Maxwell inductance bridge to cover a range from 0.001 microhenry up to 10 microhenries, and effective resistance values up to 11 ohms. The basic circuit is the same as the Maxwell bridge in Fig. 1, but the design embraces such refinements as glass-sealed deposited-carbon resistors for the conductance standard, and a worm-driven center-fed variable air capacitor. Special woven-wire resistors on spools of Teflon are used for the two fixed arms, and are compensated to give a constant product of practically zero

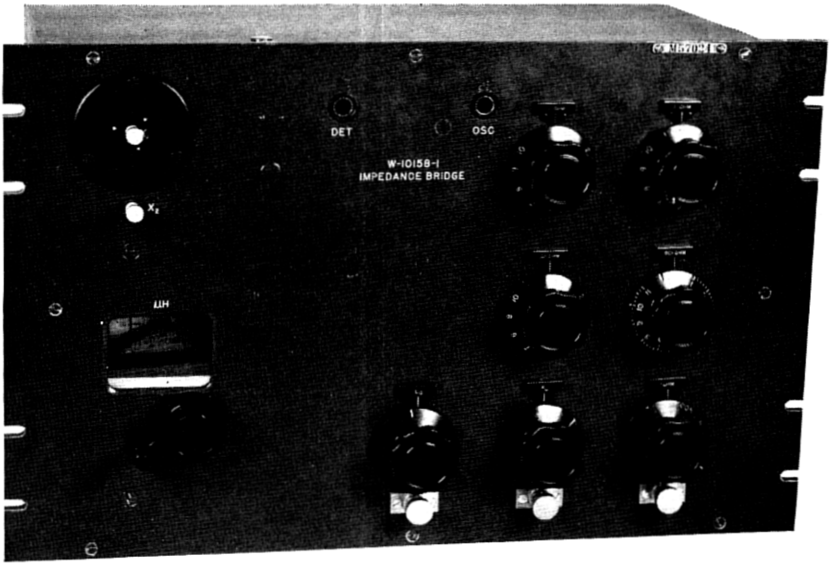


Fig. 8—The five-megacycle Maxwell inductance bridge is approximately 12¼ inches high and 19 inches wide. Test terminals are at upper left, and the three knobs at lower right are zero-balance adjusters.

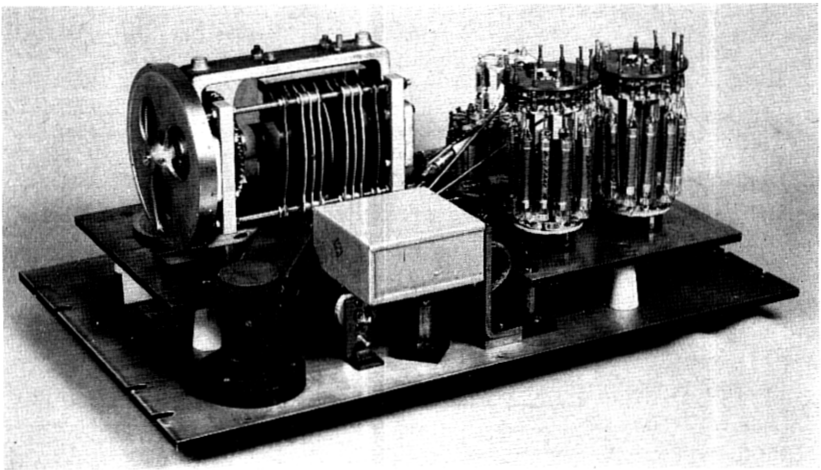


Fig. 9—Interior of bridge of Fig. 8 showing the shielding for test terminal X1 in foreground; at the left is the calibrated air capacitor; at the right are the conductance decades using glass-sealed deposited-carbon resistors.

phase angle over the entire frequency range. The result is a direct-reading bridge shown in Figs. 8 and 9 which has greatly facilitated the development of inductors in the megacycle range. The accuracy for major component varies from ±0.25 per cent at one megacycle up to ±1 per cent at five megacycles.

TEN-MEGACYCLE ADMITTANCE BRIDGE

Development of capacitors for the L3 coaxial system has required a new ten-megacycle admittance bridge. Intended especially for determining temperature coefficient and frequency characteristics of small capacitors, the bridge is capable of measuring capacitance values up to 200 $\mu\mu f$ with a precision of ± 0.01 $\mu\mu f$, and a wide range of conductance values. Unlike the other two bridges described which make grounded measurements only, this bridge is arranged for direct and balanced-to-ground measurements as well. This is accomplished by using the ratio-arm transformer already described in combination with a simple grounding circuit using a three-position key, as shown in the bridge schematic of Fig. 10.

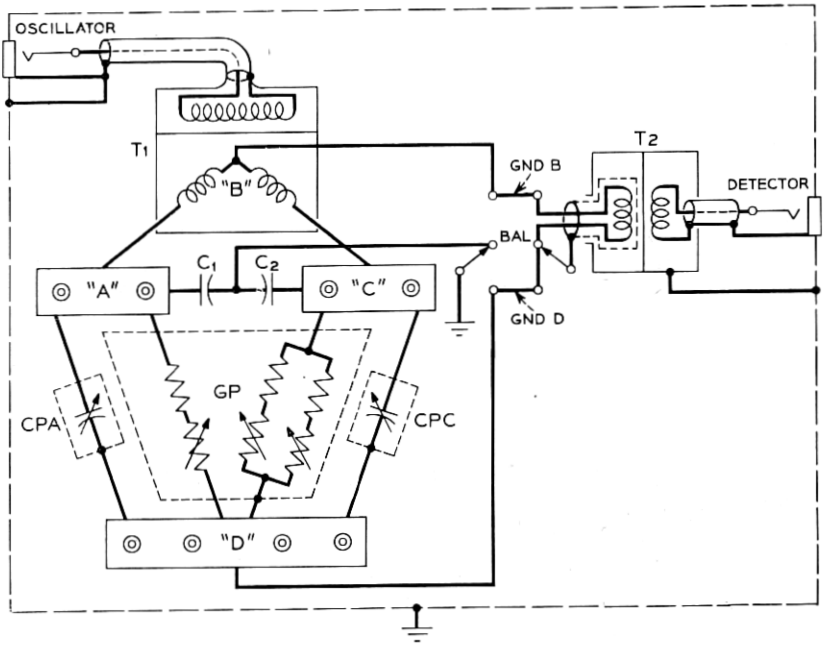


Fig. 10—Ten-megacycle admittance bridge with three-position key for shifting ground to B for measuring direct admittance, to junction of C1 and C2 for balanced admittance, and to D for grounded admittance. Unknowns may be connected from A to D or C to D.

The direct-capacitance measurements are useful in the development of low valued capacitors, and the balanced-to-ground measurements are helpful in evaluating low-admittance off-ground networks.

CONCLUSION

Bridges have been developed for the measurement of impedance and admittance parameters at megacycle frequencies with accuracies heretofore possible only at much lower frequencies. Several of the twenty-megacycle general-purpose bridges have been built and are furnishing useful measurements of networks and components. Experience with these bridges has indicated ranges for which supplementary special-purpose bridges would be desirable, and two such bridges have been built: a Maxwell bridge for low-valued inductors, and an admittance bridge for low-valued capacitors. One feature of all of these bridges not generally available in commercial measuring instruments for megacycle frequencies is the provision of standards having a range of several decades. These allow balances to be made with greater precision over a wider range of phase angles in the apparatus under test, and assure that the absolute accuracy will not be limited by readability. This added precision is very useful in comparing similar components or in measuring characteristics such as temperature coefficient.

ACKNOWLEDGMENTS

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REFERENCES

1. W. J. Shackelton, "A Shielded Bridge for Inductive Impedance Measurements," *Bell System Tech. J.*, **6**, pp. 142–171, Jan., 1927.
2. W. J. Shackelton and J. G. Ferguson, "Electrical Measurement of Communication Apparatus," *Bell System Tech. J.*, **7**, pp. 70–89, Jan., 1928.
3. J. G. Ferguson, "Measurement of Inductance by the Shielded Owen Bridge," *Bell System Tech. J.*, **6**, pp. 375–386, July, 1927.
4. S. J. Zammataro, "Impedance Bridges," *Bell Labs. Record*, **8**, pp. 167–170, Dec., 1929.
5. J. G. Ferguson, "Shielding in High-Frequency Measurement," *Bell System Tech. J.*, **8**, pp. 560–575, Aug., 1929.

6. J. G. Ferguson and B. W. Bartlett, "The Measurement of Capacitance in Terms of Resistance and Frequency," *Bell System Tech J.*, **7**, pp. 420–437, July, 1928.
7. W. D. Voelker, "An Improved Capacitance Bridge for Precision Measurements," *Bell Labs. Record*, **20**, pp. 133–137, Jan., 1942.
8. J. G. Ferguson, "Classification of Bridge Methods for Measuring Impedances," *Bell System Tech. J.*, **12**, pp. 452–468, Oct., 1933.
9. S. J. Zammataro, "An Inductance and Capacitance Bridge," *Bell Labs. Record*, **16**, pp. 341–346, June, 1938.
10. H. T. Wilhelm, "Impedance Bridge with a Billion-to-One Range," *Bell Labs. Record*, **23**, pp. 89–92, Mar., 1945.
11. H. T. Wilhelm, "Measuring Inductance of Coils with Superimposed Direct Current," *Bell Labs. Record*, **14**, pp. 131–135, Dec. 1935.
12. H. T. Wilhelm, "A Bridge for Measuring Core Loss," *Bell Labs. Record*, **19**, 92–96, Nov. 1940.
13. C. H. Young, "Measuring Inter-Electrode Capacitances," *Bell Labs. Record*, **24**, pp. 433–438, Dec., 1946.
14. H. T. Wilhelm, "Maxwell Bridge for Measuring Loading Coils," *Bell Labs. Record*, **28**, pp. 453–457, Oct., 1950.
15. Carl Englund, "Note on Radio Frequency Measurements," *Proc. Inst. Radio Engrs.*, **8**, pp. 326–333, Aug., 1920.
16. C. H. Young, "A 5-Megacycle Impedance Bridge," *Bell Labs. Record*, **15**, pp. 261–265, Apr., 1937.
17. T. Slonczewski, "A Versatile Nomagram for Circuit Problems," *Bell Labs. Record*, **10**, pp. 71–73, Nov., 1930.
18. R. O. Grisdale, A. C. Pfister, W. van Roosbroeck, Pyrolitic Film Resistors—Carbon and Borocarbon," *Bell System Tech. J.*, **30**, pp. 271–314, Apr., 1951.
19. R. A. Kempf, "Coaxial Impedance Standards," *Bell System Tech. J.*, **30**, pp. 689–705, July, 1951.