Lumped Parameter Impedance Measurements

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Abstract—This paper is intended to be tutorial in the specific area of lumped parameter immittance measurement at radio frequencies. Included is a brief background discussion with particular emphasis upon the important recent developments of precision coaxial connectors and coaxial air dielectric transmission lines as immittance standards. Special emphasis is given to precision coaxial connectors and their necessity in achieving highest accuracies. Other sections of the paper deal with standards, techniques of measurement, and instruments. The present state-of-the-art is presented in graphical form wherein the accuracies attainable by best practices are compared with the best capabilities found in specifications for commercial instruments. The state-of-the-art presentation includes two-terminal as well as three-terminal measurements. The paper concludes with some recommendations for improving the state-of-the-art in this measurement area.

I. Introduction

THIS PAPER deals with the measurement of impedance in "lumped" circuits at radio frequencies. The frequency range of interest extends from the upper limit of the audio range, approximately 30 kHz, to the upper limit of usefulness of lumped circuit techniques, which is perhaps 100 to 300 MHz. There is no clear-cut dividing line between the areas where lumped analysis and distributed analysis are appropriate, each being applied wherever it is useful. For example, it is sometimes convenient to think of a probe extending through the wall of a coaxial line as forming a capacitive voltage divider at frequencies above 1 GHz and, on the other hand, distributed parameter analysis is applied to sections of precision coaxial line to provide the NBS standards of impedance at frequencies as low as 30 kHz [1]. Because the mathematical manipulations required are relatively simple, and the lumped parameter approach is a powerful one, the approximate equations of ordinary circuit theory are almost always used when they will yield the required accuracy over a sufficiently broad frequency range. When the effective values of circuit elements change rapidly with frequency—typically at high frequencies—or when the highest accuracy is needed at any frequency, it is usually best to use an analysis based upon the exact relations obtained from Maxwell's field equations. Ramo, Whinnery, and VanDuzer [2] and Carson [3] should be consulted for a detailed discussion of the approximations involved in lumped circuit theory.

In this discussion, impedance is considered to be a proportionality constant relating voltage and current in an electrical circuit. The relationship implied here is a linear one, and holds only for sinusoidal voltages and currents. The impedance of the two-terminal (or one-port) device of Fig. 1(a) is thus the ratio of the voltage across the terminals

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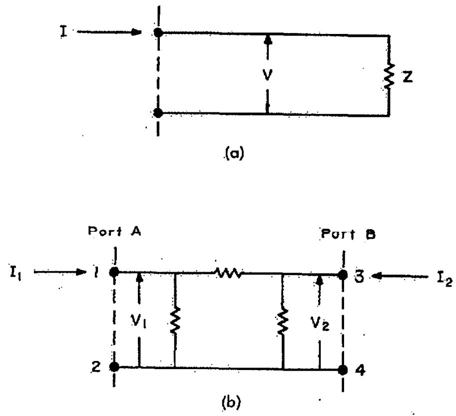


Fig. 1. (a) One-port network. (b) Two-port network.

to the current flowing through them, $Z=V/I$. The voltage-current relationships for the linear two-port of Fig. 1(b) may be expressed by the equations

$$V_1 = Z_a I_1 + Z_{ab} I_2$$
$$V_2 = Z_{ba} I_1 + Z_b I_2$$

from which are obtained the four impedances

$$\left.\begin{aligned} Z_b &= \frac{V_2}{I_2} \\ Z_{ab} &= \frac{V_1}{I_2} \end{aligned}\right\} I_1 = 0 \qquad \left.\begin{aligned} Z_a &= \frac{V_1}{I_1} \\ Z_{ba} &= \frac{V_2}{I_1} \end{aligned}\right\} I_2 = 0.$$

For reciprocal networks [4] $Z_{ab}=Z_{ba}$, and only three impedances are required to characterize the network.

It should be realized that defining impedance in this way does not necessarily imply that it is best measured in terms of voltage-current ratios. In fact, specific values of impedance may be calculated from a geometrical configuration of materials and the electromagnetic properties of the surrounding space, and impedance obtained in this way is at present much more accurately related to the basic quantities[1] than is either voltage or current.

In this article we will attempt a survey of the field of impedance measurement as applied to linear passive lumped circuits. The intent is to be general enough in scope to provide a good overview of the field, but at the same time provide enough detail to be useful in specific instances.

II. Background

The techniques of lumped parameter immittance[2] measurement at radio frequencies were primarily developed during the era between World Wars I and II. Since the 1940's, attention has been focused upon higher frequency work and the development of microwave techniques, with the result that the lower frequencies have received relatively less attention. Instruments such as RF bridges and Q-meters have undergone only minor modifications over the past two decades. Much of the instrumentation used at radio frequencies was developed through modifications to dc and audio-frequency instrumentation. An obvious example of this is the Wheatstone bridge circuit commonly used in modern RF immittance bridges. There are some notable exceptions which include the twin-T and bridged-T instruments and those employing the principles of resonance which were developed primarily for use at radio frequencies. However, all of the circuits mentioned have in common the fact that lumped parameter analysis is sufficiently exact for practical purposes. Advances in the state-of-the-art have been more toward the extension of existing techniques to higher frequencies than in the improvement of accuracies at frequencies where capabilities already existed.

A significant departure from this trend occurred in the 1950's when Woods [5], [6] of the United Kingdom introduced the concept of precision coaxial connectors and advocated using coaxial air dielectric transmission lines as immittance standards. These contributions resulted in accuracy improvements of one or even two orders of magnitude in many instances. For example, at 50 MHz a capacitance of 20 picofarads (pF) equipped with a precision coaxial connector can be measured with an uncertainty of only 0.01 percent as compared to an uncertainty of the order of one percent where a nonprecision connector is used.

III. Precision Coaxial Connectors

Connectors and their effect upon measurement accuracy is a subject of the greatest importance in immittance measurements [7]. Every immittance measurement is made in terms of some sort of electrical measuring circuit, such as that of Fig. 2. Because the unknown is an integral part of the measuring circuit, it is necessary to distinguish, and mechanically separate, the part of the circuit being measured from the rest of the circuit if the measurement is to be meaningful and useful. This is conveniently done by establishing a mechanical plane of separation which is coincident with the "reference plane" separating the two parts of the circuit. If the connection is made in a plane perpendicular to the axis of a uniform transmission line, the two parts of the circuit may be separated very precisely. If the measured immittance is to be insensitive to changes in its environment, the connection must be mechanically and thermally stable and well-shielded electrically. If the measurement is to be repeatable, the connection must be such that it may be precisely repeated.

These characteristics of a connector—well-defined reference plane, mechanical and thermal stability, good shielding, and repeatable connection—are all that are required in those practical situations where only precision is required. Any good, repeatable, shielded connector system can be used for *precise* measurements but, in addition, accurately known reference conditions are necessary for *accurate* absolute measurements. The *immittance* of the short circuit or open circuit commonly used as references can be calculated for coaxial structures whose inner and outer conductors terminate in a common plane perpendicular to

[1] In this paper, "basic quantities" refers to the quantities mass, length, time, and μ_0.

[2] To avoid writing "impedance and admittance" the two quantities are assigned one name, immittance.

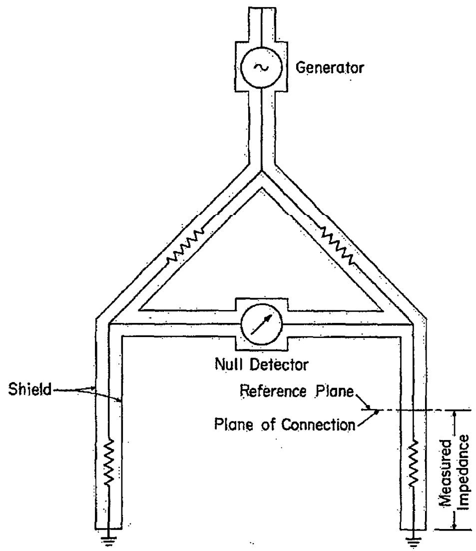


Fig. 2. Electrical measuring circuit.

their axis [8], [9]. Furthermore, both immittances may be verified by measurement if the connectors are sexless, that is, if any two connectors of the same line size are capable of being mated to each other without adaptors.

The IEEE Subcommittee on Precision Coaxial Connectors has adopted specifications [10] for precision connectors in 14-mm and 7-mm line sizes for use to 8.5 GHz and 17 GHz, respectively. Connectors in both line sizes are commercially available. While these connectors were developed primarily for use at the higher frequencies, they have the characteristics which are desirable in a connector for use in lumped circuit measurements.

The effect of connectors on immittance measurements will be demonstrated by considering a typical measurement situation. In measuring an unknown capacitor, a capacitance bridge is nulled initially with its terminals open circuited. The unknown capacitor is then connected, and the bridge standards are adjusted to restore the null. Figure 3(a) represents the "unknown" terminals of a capacitance bridge equipped with banana plugs or binding posts, and Fig. 4(a) represents the terminal of a similar bridge equipped with a precision coaxial connector. Figures 3(b) and 4(b) represent the same terminals with the unknown capacitor C_x connected for measurement.

In the figures, C_0 represents the fixed component of the terminal capacitance plus the capacitance of the internal connecting leads, and is a characteristic of the bridge. In Fig. 3(a), C_{g1} is the capacitance from the ungrounded terminal to the instrument case and the surroundings. Its value varies with changes in the location of conductors in the vicinity of the connector. C_f is the fringe capacitance, defined for precision coaxial connectors to be the capacitance which is removed when two connectors are joined, forming a uniform coaxial line through the plane of connection. For banana plugs or binding posts, the fringe capacitance is not well defined. It has the same effect as a change in C_{g1}, which in the usual configuration is unknown

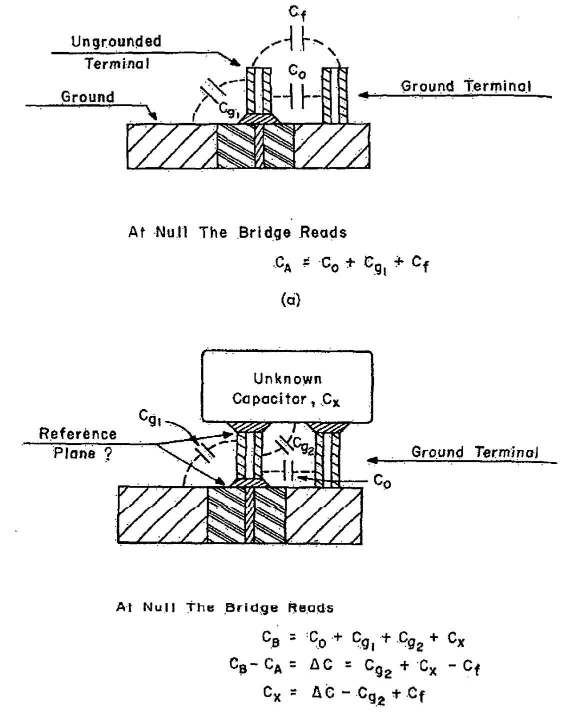


Fig. 3. (a) Open-circuit binding post connectors. (b) Binding post connector with capacitor attached.

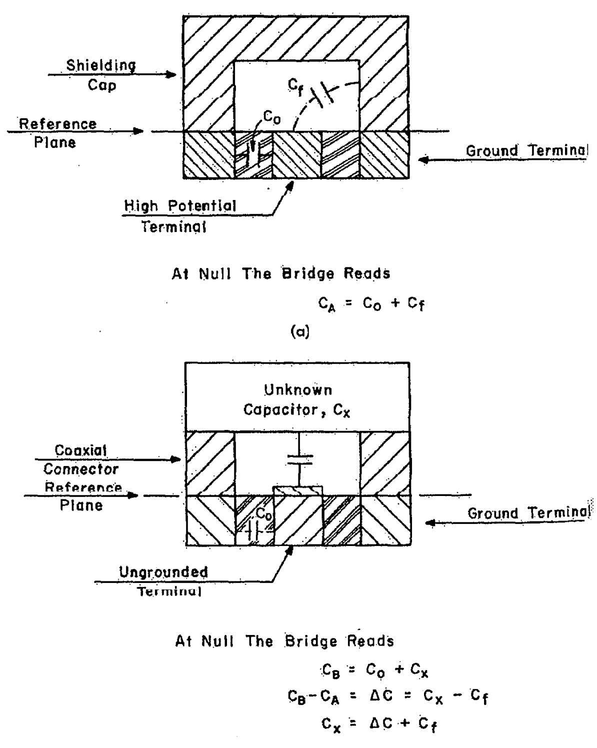


Fig. 4. (a) Open-circuit precision coaxial connector. (b) Precision coaxial connector with capacitor attached.

and unknowable. C_{g2} is the capacitance from the ungrounded terminal to the case of the unknown capacitor.

If C_{g2} is lumped with and considered a part of C_x, and if C_{g1} is truly unchanged when C_x is connected, the equations for the measurement with binding posts are identical to those for the measurement with precision connectors. The difference lies in the precision of connection and the accuracy with which C_f can be determined. C_{g2} is affected by the length and diameter of the binding posts and by how well the capacitor is seated for measurement. Unless these are standardized, the measured value of C_x will vary from one setup to another. Attempts to measure the fringe capacitance of one particular type of binding post at 1-inch spacing have yielded a value of 0.3 pF, with an uncertainty of perhaps 50 percent. By contrast, the fringe capacitance of the shielding cap of Fig. 4(a) has been determined to be 0.2074 pF with an uncertainty of 0.3 percent. A precision connector developed and used by NBS permits capacitance measurements to be repeated with a 3-sigma[3] value of less than 0.001 pF. The practical consequence is that a 20-pF capacitor equipped with banana plugs cannot be measured with an error less than about 0.75 percent, while the same capacitor could be measured to within 0.005 percent if it were equipped with a precision connector.

A similar situation exists for inductance measurements, where the measurement is referenced to a "short" which is removed when the unknown inductor is connected. For a typical banana plug arrangement, the short might have an inductance of 0.01 μH which may be calculated with an error of about 50 percent. This means that a 1-μH inductor may be measured with an error of about 0.5 percent. The shorting disk used with the 14-mm precision connector has an inductance of less than 0.000016 μH at 1 MHz [11], which if neglected entirely would cause an error of only 0.002 percent in measuring 1 μH.

We have not discussed the advantages of precision connectors in the measurement of resistance and conductance, or in fixing residual impedances[4] in inductance and capacitance standards and in three-terminal measurements. We do not wish to belabor the point, but do want to make a convincing case for using precision connectors wherever accurate and precise immittance measurements are required. There are many immittance measurements which are not compatible with coaxial connectors, and it is necessary to compromise precision and accuracy in order to make the necessary connections. The change from a precision coaxial system can be accomplished with suitable adaptors, and this is preferably done only when it becomes necessary. The spectacular increase in accuracy of lumped immittance measurements in the past few years has resulted almost entirely from improved standards, instruments, and techniques made possible by precision connectors. This accuracy cannot be realized by the ultimate user of the measurement unless he is willing to accept the small added cost of using precision connectors.

[3] Sigma, the standard deviation, is a measure of the precision of the measurement.

[4] Residual impedance is defined in Section IV.

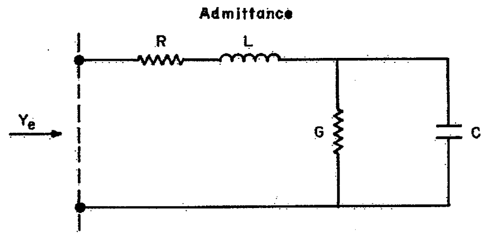
IV. Standards

When attempting to verify the accuracy of an immittance measurement in the 30 kHz to 300 MHz frequency range, an interesting dilemma arises concerning what to use for a standard. Various manufacturers produce components which are useful in determining the agreement between two instruments of the same model or manufacture, but beyond this, standards which are commonly accepted for use with all commercial instruments are nonexistent. This situation has caused a large amount of unnecessary expense and inconvenience which will continue until appropriate standards and standardization procedures are adopted on an industry-wide basis. To accomplish effective industry-wide standardization, two important initial steps must be taken. First, agreement is needed on specific values and frequencies for which standards are needed and second, precision coaxial connectors must be utilized on both instruments and standards. The following discussion pertains to standards for use as interlaboratory transfer standards.

An immittance standard for general use should have certain characteristics if it is to fulfill its purpose in maintaining uniform measurement agreement. These characteristics are long-term stability, high purity, value independent of frequency and environmental change, and convenience in use. High purity and frequency independence are related characteristics which depend upon the degree to which residual impedances are present in a capacitor, a resistor, or an inductor. A standard or a component is usually called a capacitor, resistor, or an inductor in accordance with whichever of these three parameters is predominant at low frequencies. The other parameters, which are always present in a practical situation, are called residual impedances. A capacitor of high purity has a high ratio of susceptance to conductance (high Q) and exhibits minimum change in capacitance value as the frequency is varied. Similarly, a high-purity inductor has a high ratio of reactance to resistance (high Q) and changes little in inductance value with frequency change. A high-purity resistor (or conductor) exhibits a near-zero phase angle (low Q) and only small changes in resistance or conductance with frequency.

At sufficiently low frequencies, a two-terminal capacitance or conductance may usually be represented by the equivalent circuit of Fig. 5(a) and a two-terminal inductance or resistance by the equivalent circuit of Fig. 5(b). The equations in the figures show that the effective values of a component depend upon the frequency and the residual parameters. Furthermore, precision connectors are seen to be important because they permit accurate definition and repeatability of the residuals by shielding and strict control of the circuit geometry in the vicinity of the connection. Field and Sinclair [12] have described a method for determining the residual series inductance and resistance of variable air capacitors; other methods, based upon resonance, are commonly used to evaluate the residual series inductance [13], [14].

As the frequency is increased to the vicinity of self-resonance in a standard or component, simple equivalent

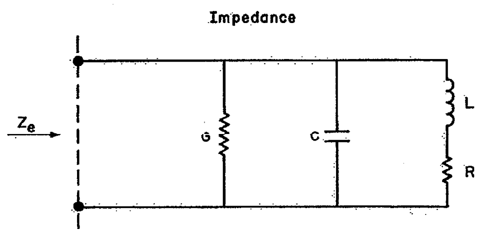


$$Y_e = G_e + j\omega C_e$$

$$G_e = \frac{G(1+RG) + R\omega^2 C^2}{(1+RG-\omega^2 LC)^2 + (R\omega C + G\omega L)^2}$$

$$C_e = \frac{C(1-\omega^2 LC) - G^2 L}{(1+RG-\omega^2 LC)^2 + (R\omega C + G\omega L)^2}$$

(a)



$$Z_e = R_e + j\omega L_e$$

$$R_e = \frac{R(1+RG) + G\omega^2 L^2}{(1+RG-\omega^2 LC)^2 + (G\omega L + R\omega C)^2}$$

$$L_e = \frac{L(1-\omega^2 LC) - R^2 C}{(1+RG-\omega^2 LC)^2 + (G\omega L + R\omega C)^2}$$

(b)

Fig. 5. (a) Admittance equivalent circuit. (b) Impedance equivalent circuit.

circuits such as those in Fig. 5(a) and (b) no longer adequately represent the actual distribution of the various parameters, and more complex equivalent circuits must be employed. At this point lumped parameter analysis is usually abandoned and we must rely upon calculable standards such as coaxial air dielectric transmission lines.

At the Radio Standards Laboratory of NBS, capacitance is the parameter selected as the foundation for the system of lumped parameter immittance standards [1]. This is because capacitors have been constructed which have the aforementioned desired characteristics to a higher degree than either inductors or resistors. Because an air dielectric capacitor stores energy primarily in free space, its value is essentially unaffected by the properties of the materials used in its construction, and the capacitance is determined by its geometry and the relative permittivity of air. For this reason the stability of the capacitor is largely determined by the mechanical stability of the device. Capacitors can be made which have simple geometric configurations, resulting in short current paths with correspondingly small inductive and resistive residual impedances. The principal advantage of capacitors as standards is the accuracy to which their values may be obtained from the basic quantities. Two-terminal capacitance at high frequencies is calculated [15]–[17] from the dimensions of a section of coaxial line and three-terminal capacitance is obtained from the Thompson-Lampard [18] capacitor in terms of length and the permittivity of free space. The coaxial lines have been compared to the Thompson-Lampard capacitors at audio frequencies to confirm the accuracy of calculation. Such comparisons have resulted in agreements to within 1×10^{-15} farads for values between 5 and 50 pF.

Another advantage of capacitors is that variable elements can be made which are not only highly pure but also provide essentially infinite resolution. There is often a choice of measurement circuits for a particular application wherein one circuit containing a variable air capacitor may provide the same measurement capability as another circuit containing a variable resistor or a variable inductor. Where such an alternative exists, the choice is usually made in favor of the circuit containing the variable air capacitor.

Inductors are not as desirable as capacitors for primary standards of RF impedance because a greater number of factors affect their values, making calculation in terms of basic quantities more difficult. For example, at lower frequencies current is not confined to the outer surfaces of the conductors and therefore material properties become important. The residual impedances in inductors are usually greater than in capacitors, resulting in a more pronounced frequency dependence. This is especially true of wire-wound inductors. The circuit of Fig. 5(b) indicates the residual parameters as series resistance and parallel capacitance and conductance, but there are still other factors which affect the inductance. These include the mutual inductance effect of a shield and the proximity effect of adjacent windings [19]. In inductors containing high permeability core materials, the inductance is dependent upon the current magnitude so that it is necessary to specify the current in the inductor when measured values are obtained. Good air-core inductors have all the other characteristics of desirable standards and make very good transfer standards.

High-frequency resistance is the most difficult quantity to obtain from the basic quantities because of the dependence upon material properties. Some resistance materials exhibit a long-term aging effect so that stability cannot be relied upon. This problem is largely avoided by using wire-wound resistors of stable alloys, but this creates problems at high frequencies because of large residual reactances. In recent years techniques in the manufacture of deposited metal film resistors have improved so that good transfer standards of resistance are feasible.

The NBS standards for RF immittance measurement are derived in approximately the manner represented by the chart in Fig. 6. This chain of traceability is only for a typical case and is somewhat different for other specific values and frequencies. The standards most directly related to length, time, and μ_0 are the smaller values of inductance (≤ 0.1 μH) and capacitance (≤ 50 pF). Excellent standards for small values of inductance and capacitance are provided by sections of coaxial air dielectric transmission line. For induc-

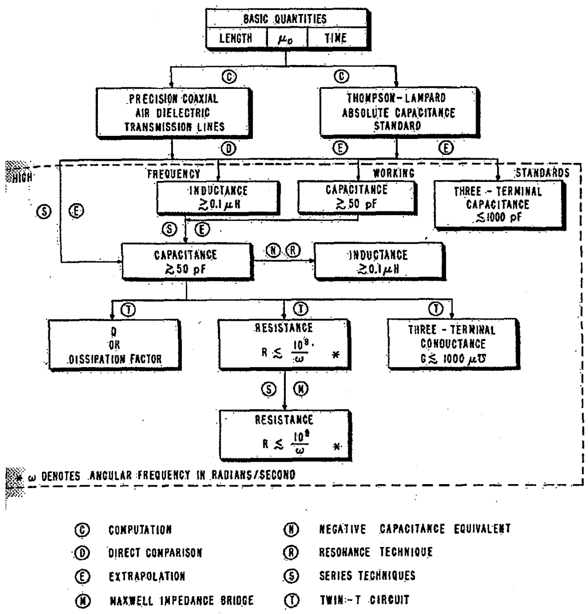


Fig. 6. Derivation of NBS immittance standards.

tance standards the lines are short circuited, and for capacitance standards the same lines are used in the open-circuit condition. At the higher frequencies ($\geq$300 MHz), where a quarter wavelength is of a practical size, such coaxial lines are used for a wide range of values of inductance and capacitance.

The so-called open and short circuits play an important part as reference immittances. Since their impedance values are only nominally an open or a short, accurate knowledge of these values are required. Such immittance values can be calculated for coaxial structures whose inner and outer conductors terminate in a common plane perpendicular to their axis [8], [9].

V. Techniques

The techniques for measuring immittance have been classified in a number of ways, but we will confine the discussion to those which have been found most useful. One classification distinguishes between direct measurements—by the voltmeter/ammeter method, for example—and measurements in which the unknown immittance is compared to a standard of known value. While instruments which determine immittance from the ratio of voltage to current are available [20], they are not at present capable of the accuracy attainable by comparison to a standard and are not used at radio frequencies when high accuracy is required.

Another worthwhile distinction may be made between techniques which use the measuring instrument as the standard, and comparator techniques in which the instrument simply serves to indicate small differences between a standard and an unknown which are nearly identical immittances. The first approach is used in most commercial immittance measuring instruments. These instruments contain internal standards to which the unknown immittance is compared. The range covered by the standards typically extends from short circuit to a finite impedance, or from open circuit to a finite admittance, and the instrument usually operates over a very wide frequency range. The continuous coverage of immittance value and frequency makes these instruments extremely versatile, but also makes them extremely difficult to calibrate.

The principal advantage of the comparator approach is that even relatively inaccurate instruments can be used to make highly accurate measurements if a sufficiently accurate standard is available. For example, a one percent measurement of a difference of one percent corresponds to 0.01 percent error in comparing an unknown to a standard. The practical result is that very accurate measurements can be obtained without investing in instruments which are themselves very accurate and therefore expensive. Many commercial instruments are capable of one to three percent measurements over a broad frequency range, and would be suitable for this type of immittance measurement if they were equipped with a suitable connector.

The principal disadvantage of the comparator approach is that the necessary standards must be maintained, one near each immittance value to be measured, and the value of each standard must be known at each frequency at which it is used. This may not be as serious as it might seem, since a relatively small number of standards can give good coverage of a wide range of values. If the common 1-2-5 sequence of values is used, there are only three standards per decade. Furthermore, if these standards are used with instruments capable of 1 percent measurements, and which have sufficient resolution, the measurement uncertainty will vary from perhaps 0.001 percent for "identical" standards to at worst 0.4 percent when measuring values midway between standard values. High-quality standards vary predictably with frequency, so that it is not strictly necessary to calibrate them at every frequency at which a measurement may be made. Often sufficient accuracy may be obtained by measuring at a few standard frequencies and interpolating for intermediate frequencies.

Another useful classification of techniques distinguishes between null methods and resonance methods. The null methods use some sort of nulling circuit, such as a Wheatstone bridge or the twin-T, to indicate that a definite relationship exists between the circuit elements. Resonance techniques use inductors and capacitors to form a series or parallel resonant circuit, and a voltmeter or a current meter to determine when resonance exists [13], [21]. Instruments based on either technique may be used for direct measurement or for comparing nearly identical immittances. In general, the null condition can be more precisely determined than can the resonance condition, making null measurements most useful for precise immittance measurements.

VI. Instruments

In general, there is a class of impedance measuring instruments corresponding to each measurement technique. Which instrument is best suited for a particular measure-

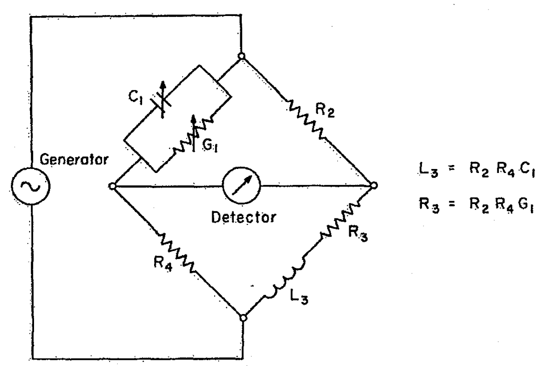


Fig. 7. Basic Maxwell bridge.

ment depends on the parameters to be measured, their magnitudes, the frequency at which they will be measured, and the accuracy required. In this section, some of the more useful instruments are discussed together with the advantages and disadvantages of each. Voltmeter/ammeter [20] or ohmmeter techniques for measuring impedance are generally not suited to accurate measurements, and will not be discussed. The null instruments which use active elements, such as amplifiers, as standards [22] are likewise not suited to accurate measurements, so the discussion will be limited to instruments using null or resonance techniques in which all the circuit elements are linear, passive devices. (The signal source, or generator, and the detector are not considered part of the instrument.)

Most null instruments use a variation of the familiar four-arm Wheatstone circuit or the twin-*T* null circuits described by Tuttle [23], but there are exceptions. All null instruments have in common the characteristics that one or more of the impedance elements in the circuit can be adjusted to provide zero transmission between generator and detector (null condition), and detector and generator may be interchanged without affecting the null condition.

Null instruments which have been found useful for two-terminal measurements at radio frequencies include the four-arm bridges of Figs. 7, 8, and 9, the twin-*T* of Fig. 10, and the transformer ratio bridge of Fig. 11. Most RF immittance measuring instruments are modifications of these basic instruments. The Maxwell bridge of Fig. 7, and the Schering bridge of Fig. 8(b) are impedance bridges, that is, they measure *impedances* between zero and a finite value and can be nulled with the terminals short circuited. The Schering bridge of Fig. 8(c), the resistance ratio bridge of Fig. 9, and the twin-*T* of Fig. 10 are admittance bridges which measure *admittances* between zero and a finite value, and can be nulled with the terminals open circuited. The transformer ratio bridge of Fig. 11 can be used as either an impedance bridge or an admittance bridge.

The Maxwell bridge has been used at frequencies to 5 MHz [24] but is limited in that it measures resistance in terms of an incremental conductance. The Schering bridge, which measures both resistance and reactance in terms of capacitance increments, and which measures either impedance or admittance, is the most widely used RF bridge. Most

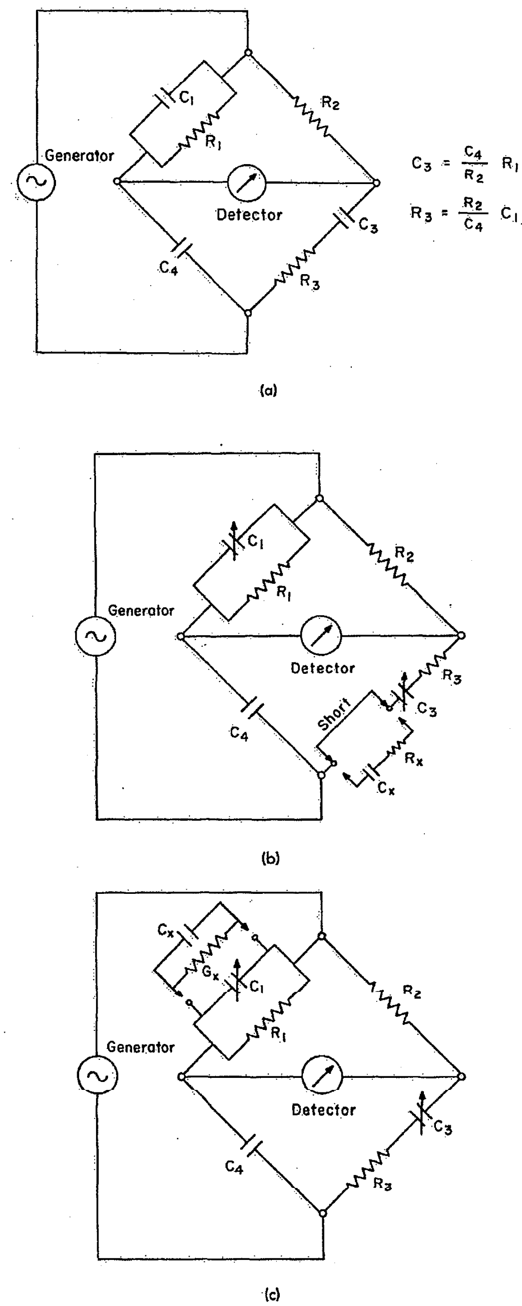


Fig. 8. (a) Basic Schering bridge. (b) Schering impedance bridge. (c) Schering admittance bridge.

commercial RF bridges use this circuit [25], and it has been successfully used to 250 MHz [26]. The ratio bridge has been used to measure admittance to 20 MHz [24]. The major weakness of this bridge is that it uses an incremental conductance standard to measure conductance. The Radio Standards Laboratory of NBS has constructed a modular [27] ratio bridge for use as an immittance comparator [Fig. 9(b)]. In the figure, $R_1 = R_2$, G_0 and C_0 balance the

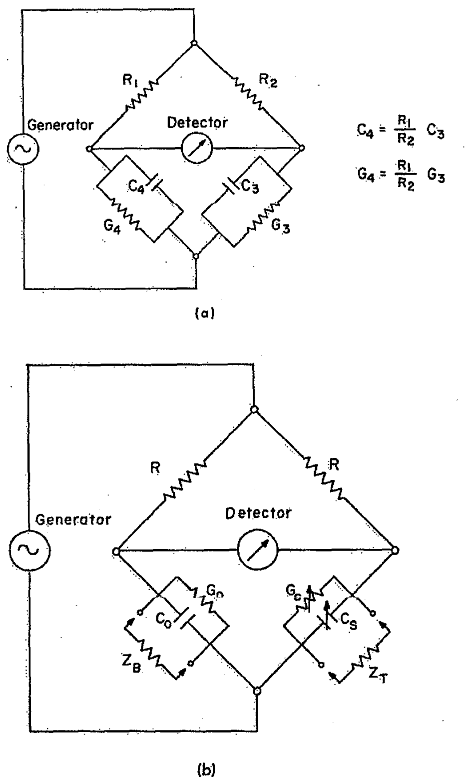


Fig. 9. (a) Basic resistance ratio bridge. (b) Modular resistance ratio bridge (NBS Comparator).

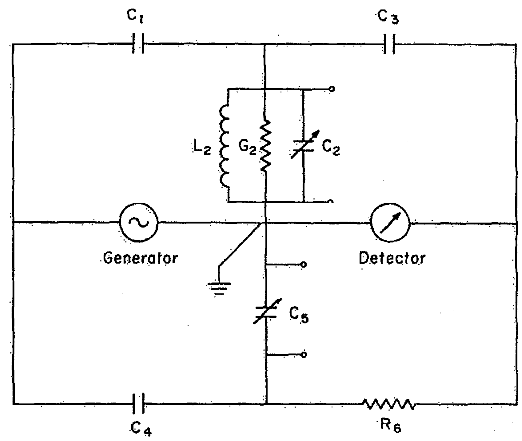


Fig. 10. Twin-T circuit.

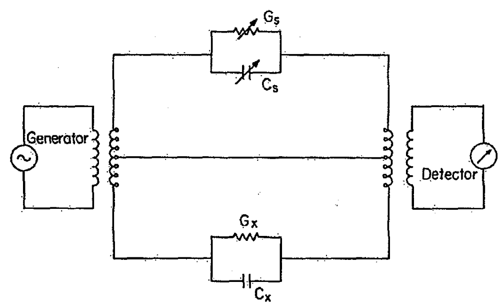


Fig. 11. Transformer ratio bridge.

initial nonzero G_s and C_s, and Z_b is nearly equal to the test impedance Z_t. The instrument measures small differences between test impedances in terms of small changes in G_s and C_s, so that G_s and C_s need not be high-quality standards. The Maxwell and Schering bridges cover an immittance range which depends upon the frequency and provide accuracies of typically 1 to 3 percent.

The commercial version of the twin-T, developed by Sinclair [28], was used to measure admittance to 40 MHz, and a dual admittance bridge developed by Woods [29] measures admittance with a basic uncertainty of 0.1 percent to 100 MHz which is degraded to 0.3 percent at 300 MHz. The Radio Standards Laboratory has constructed a twin-T useful to 15 MHz, primarily for measuring conductance in terms of capacitance increments [30]. This instrument measures conductance with errors of about 0.05 percent at 1 MHz. The advantages of the twin-T instruments include the facts that incremental capacitors are used to measure both conductance and capacitance, and the generator, the detector, the measured immittance, and the incremental standards are all connected to a common ground. The advantages are offset by the fact that the bridge balance is frequency sensitive, making twin-T instruments relatively inconvenient to use.

The transformer ratio bridge (Fig. 11) is one of the exceptions which cannot be classified as a Wheatstone, or a twin-T instrument. In this bridge, null is obtained by adjusting the input or output turns ratio, or the immittance standards, to provide zero current in the detector transformer [31]. A line of commercial instruments uses this circuit for admittance measurements at frequencies to 250 MHz.

A basic difference between admittance bridges and impedance bridges, which is not obvious from the simple circuits, is the relative complexity of the shielding required for the two types of instruments. The subject of shielding is far too complex [32], [33] to be entered into here beyond pointing out that impedance bridges usually require more complex shielding than do admittance bridges. The practical result is that impedance bridges cannot be readily improved by a simple application of precision connectors. This, plus the fact that good absolute standards of low-valued impedance are not easily obtainable, have resulted in the accuracy of measurement of small impedance lagging behind that of small admittance measurements.

While resonance methods are not at present capable of the same accuracy as null methods, they are widely enough used to justify some discussion. The simple circuits in Fig. 12 illustrate the essentials of a resonance instrument: a signal source, a capacitor and an inductor connected in series or parallel, and an ammeter or a voltmeter for detecting the resonant condition. Resonance measurements often combine the techniques of direct measurement and comparison to a standard. The resistive component is obtained directly by measuring voltage ratios, and the reactive com-

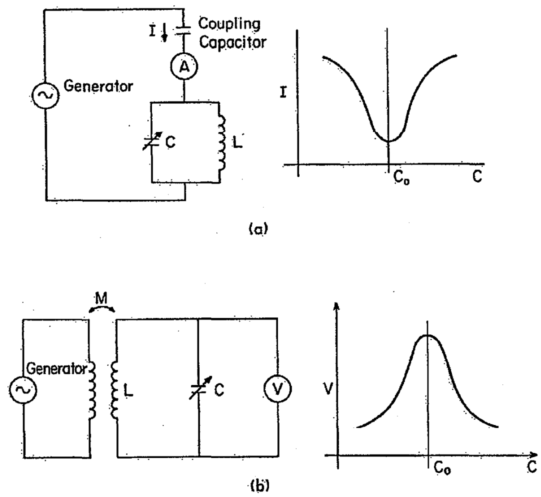


Fig. 12. (a) Series resonance method. (b) Parallel resonance method.

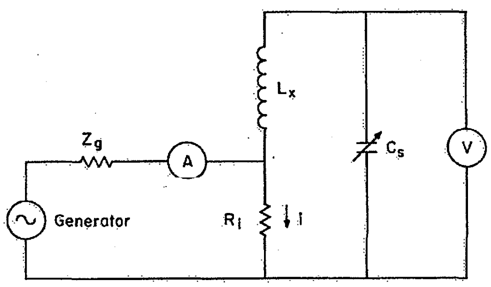


Fig. 13. Q-meter circuit.

ponent is obtained by comparison to the standard capacitor. Because resonance methods work best when the coupling to the generator is kept small, they are best suited to measurements in high-Q circuits. Resonance measurements are complementary to null measurements in that it is difficult to measure the resistive component of high-Q circuits with null instruments.

The Q meter [34], [35], represented schematically in Fig. 13, is a widely used resonance instrument. A small voltage, $e=iR_i$, appears across the series combination of L_x and C_s. The standard capacitor is tuned to the resonant value C_0, which maximizes the voltage across the capacitor as indicated by the voltmeter V. Since the voltage across either component of a series resonant circuit is Q times the voltage across the series combination, Q may be obtained from the ratio V/e. The voltage e is set to a predetermined value by adjusting the current through the known insertion resistor R_i, the current being monitored by the ammeter A. The unknown resistance R_x is obtained from the relationship

$$Q = \frac{\omega L_x}{R_x}.$$

Q meters are used at frequencies as high as 610 MHz [36].

A line of resonance instruments, which are not Q meters, measure both conductance and capacitance in terms of internal standards. A smoothly varying incremental conductance is obtained by varying the bias on a diode connected in parallel with the resonant circuit. These instruments measure admittance at frequencies between 0.1 and 100 MHz [37]. Accuracies of 1 percent for capacitance and 5 to 20 percent for resistance are claimed.

VII. Signal Generators and Detectors

In addition to the circuitry of RF impedance measuring instruments, it is necessary to give careful consideration to the signal generators and detectors used with them.

Good frequency stability, adequate power output, and low harmonic content are the main requirements for signal generators. The frequency stability required of a generator depends upon the measuring instrument with which it is used, and the item being measured and the accuracy desired. In circumstances where bridge balance equations involve frequency, or where resonant circuits are involved, stabilities of the order of 1 part in 10^6 are sufficient for accuracies of 1 part in 10^3. This is the case for the twin-T circuit and the Q meters. When a component is being measured at a frequency near self-resonance, frequency stability is especially necessary. In this situation the frequency must be accurately known, as well as stable. Bridge circuits which do not involve frequency in the balance equations do not impose critical frequency requirements, and stabilities of the order of 1 part in 10^4 are usually adequate. The required frequency stability is a criterion which must be established for specific measurement situations and can vary widely depending upon the measurement accuracies desired. This is also true for power output and harmonic content. In general, power output should be no more than that amount required to realize sufficiently sharp bridge balance conditions, and both bridge and detector can be determining factors. Increasing power output to gain sensitivity can lead to instabilities due to temperature fluctuations or to the more serious problem of damaging components. Higher generator output does not necessarily improve measurement resolution where a significant amount of leakage exists between generator and detector.

Harmonic content and frequency modulation are of serious concern in some instances and can be neglected in others. Measuring circuits whose balance equations involve frequency are subject to errors from both sources. To avoid problems arising from harmonics it is advisable to filter the generator output and use narrowband detectors.

Detectors should have the characteristics of high sensitivity and high selectivity, be well shielded to guard against leakage from the generator, and have good signal-to-noise ratio. Detector sensitivities which allow detection of signals in the range of a few microvolts are usually sufficient so that the full resolution of a measuring instrument can be utilized.

Ground loops and leakage are problems which are not solely related to either the generator or detector but are associated with the measurement setup as a whole. Ground loops are most effectively avoided by having a single low-

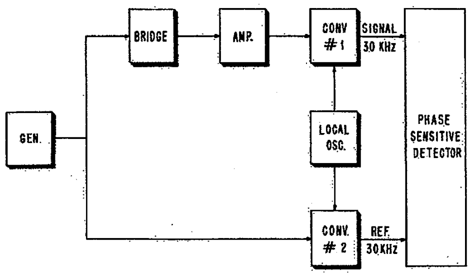


Fig. 14. Measurement setup using phase sensitive detector.

impedance ground path connecting the generator, bridge, and detector, as opposed to having a separate ground for each. Leakage can be reduced by placing added shielding around the generator and detector, and by employing semi-rigid coaxial cable and threaded connectors wherever possible.

Phase sensitive detectors are finding increasing application in measurements involving immittance bridges and offer some distinct advantages. In addition to providing greater sensitivity, they allow the operator to distinguish between unbalanced voltages due to real and imaginary immittances. An interesting result of this is that one gains an appreciation for the purity of the bridge standards because as the reactance standard is varied the variation in its resistance is displayed or vice versa. Especially when making measurements of low-Q components, balance may be difficult to locate because the reactance of the resistance standard in the bridge may vary appreciably with setting. Such "sliding null" conditions present little difficulty with phase sensitive detectors. The greater sensitivity of phase sensitive detectors comes about as a result of a much narrower effective bandwidth which results in improved signal-to-noise ratio. These detectors are not currently available for wide frequency ranges, but can be readily adapted for application at higher frequencies by using a local oscillator-mixer arrangement such as that shown in Fig. 14. The phase sensitive detector requires a reference signal which is in phase with the output from the bridge. This requirement is fulfilled by feeding the same generator signal into each converter. Under these circumstances the local oscillator is free running and need not be highly stable.

VIII. State of the Art (Two-Terminal)

The application of precision connectors to the measurement of lumped immittance has resulted in very substantial increases in measurement accuracy and precision. Better precision is a direct result of a more repeatable connection, while improved accuracy comes from two principal sources. One improvement in accuracy results from the fact that the open- and short-circuit reference conditions are accurately known. Another improvement comes from the fact that residual impedances, which cause the value of a standard to vary with frequency, are more precisely fixed by precision connectors.

Figures 15, 16, and 17 present, in graphical form, the

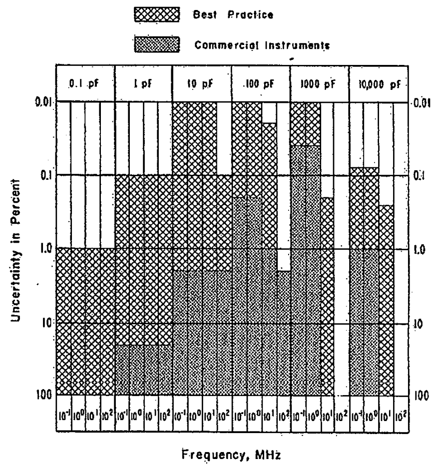


Fig. 15. State-of-the-art (two-terminal capacitance).

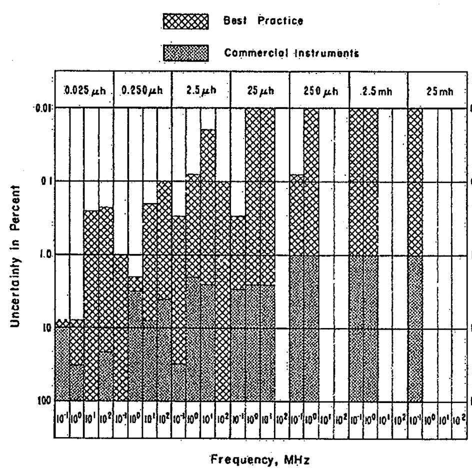


Fig. 16. State-of-the-art (two-terminal inductance).

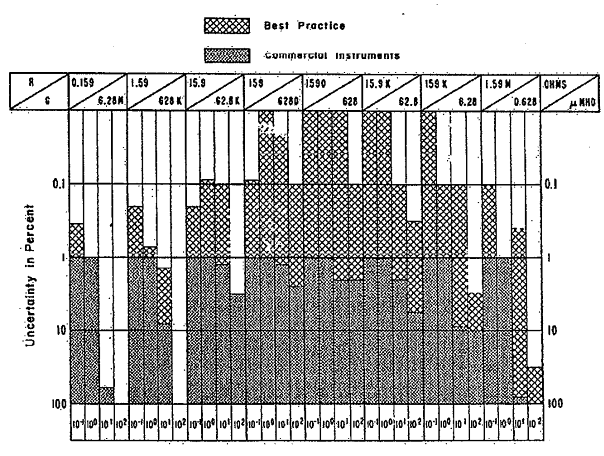


Fig. 17. State-of-the-art (two-terminal resistance).

authors' estimations of the existing state-of-the-art in two-terminal measurements of capacitance, inductance, and resistance at radio frequencies. Two classes of measurements are represented, the best possible with existing equipment and those possible with readily obtainable commercial instruments.[5] Usually, the best techniques use precision connectors. However, techniques for exploiting precision connectors in measuring low impedance have not been perfected, so that instruments equipped with banana jacks or binding posts represent the state-of-the-art in this area. One commercial instrument, the commercial version of Woods' dual admittance bridge, is equipped with a sexless, reference plane connector and represents the state-of-the-art for certain values of conductance and capacitance above 10 MHz.

IX. Three-Terminal Measurements

Present applications for three-terminal measurement are primarily confined to the measurement of small admittances, and the measurement instruments may employ either a ratio transformer or a differential capacitor [31], [38]. The technology for three-terminal measurement in the RF range is not as well developed as it is for two-terminal measurements, and at present there appears to be very little application above 5 MHz. The accuracy to which three-terminal measurements can be made is affected by such factors as the purity of the standards within the intrument, transformer ratio uncertainties, the effect of impedances from each electrode to ground, and the inductance of the leads which connect the unknown to the instrument. Each of these factors becomes increasingly important at higher frequencies.

Figures 18 and 19 are estimates of the state-of-the-art for three-terminal capacitance and conductance measurement based upon accuracy specifications published by the manufacturers of commercial three-terminal instruments. In these figures, the accuracies claimed for commercial instruments also represent best practice primarily because there has been little effort by other than commercial laboratories to improve the state-of-the-art. The verification of accuracies is difficult because of the absence of generally accepted standards. The problems in standardization, although similar in many respects to those associated with two-terminal measurement, are much more complicated.

Three-terminal measurement at radio frequencies may be considered as a special case of the more general situation where the unknown is considered as a two-port such as that represented in Fig. 1(b). Such a two-port is completely described if the impedance values of its equivalent pi or equivalent T network are known. If the two-port is represented as a pi network, as shown in Fig. 20, the values Y_A, Y_B, and Y_C may be obtained by two-terminal measurements. These two-terminal measurements are made looking into port 1 with port 2 alternately open and short circuited and looking into port 2 with port 1 alternately open and short circuited. Any three of the resulting four two-terminal admittances may be used to solve for Y_A, Y_B, and Y_C. For best results, precision connectors are required at the ports so that the open- and short-circuited conditions are accurately known. Although two-port devices may be measured in this manner, simpler and more accurate measurements would be made possible by the development of special two-port standards.

[5] The commercial capabilities shown are based upon manufacturer's specifications.

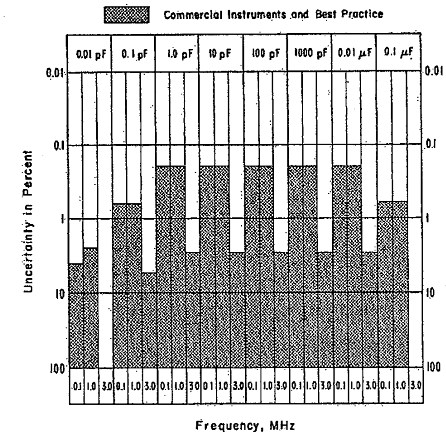


Fig. 18. State-of-the-art (three-terminal capacitance).

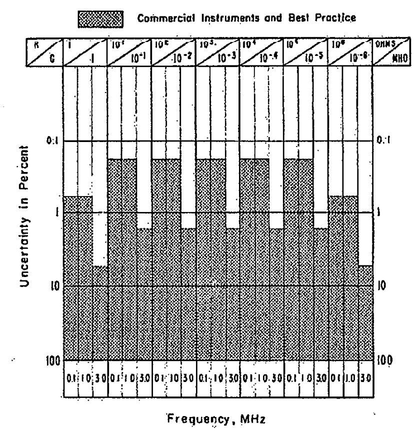


Fig. 19. State-of-the-art (three-terminal conductance).

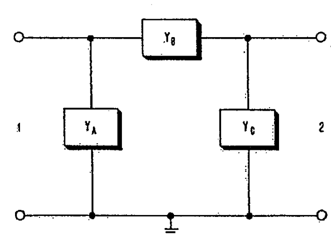


Fig. 20. Two-port (equivalent pi network).

X. Conclusions and Future Trends

The large differences in the state-of-the-art for commercial two-terminal instruments, as compared to best practices, are due almost entirely to the fact that precision coaxial connectors have not yet been utilized in commercial instruments manufactured for the measurement of lumped parameter immittance. It is expected that this situation will change rapidly, especially where there is evidence of sufficient demand. If appropriate standards are made available along with improved instruments, the differences will be sharply reduced with very significant improvements realized over the entire frequency range of measurement for lumped immittances. Longer term benefits can be expected as well because new techniques in the construction of instruments will be made possible. For example, several different types of instruments have been constructed from one- and two-port immittance components which can be readily disconnected from one another and calibrated individually [27]. Such modular instruments offer many advantages including compactness, versatility, and ease of calibration and maintenance; however, they are not yet commercially available.

There are two areas where measurement capabilities are noticeably absent. These are for small two-terminal impedances at frequencies above 10 MHz and for three-terminal admittances above 5 MHz. It appears that there are no urgent requirements for such measurements, but it is often the case that there is no strong evidence of need for a particular measurement capability until it is developed, and then numerous applications arise.

To achieve the most effective and efficient standardization program agreement is needed regarding the specific frequencies and specific values for which standards are to be maintained. In this way, the advantages of comparator techniques can be utilized for the accurate determination of differences and measurements could be subjected to statistical control. Because of the lack of agreement in these matters such statistical control is not now possible.

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