Electrical Measurement of Communication Apparatus[1]

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Synopsis: This paper describes precision high-frequency measurements of a fundamental type, special emphasis being placed on the measuring circuits rather than on the types of apparatus measured. Standards of frequency, resistance, capacitance, and inductance are discussed briefly. Bridge measurements are described for the measurement of frequency, inductance, effective resistance, capacitance, dielectric loss, capacitance balance and inductance balance. Circuits for the measurement of other high-frequency characteristics such as attenuation, gain, and cross-talk are included.

Introduction

LONG DISTANCE electrical communication is now being effected by means of frequencies embracing the audible range and extending from there to the so-called short wave-lengths employed in radio transmission. According to the field of usefulness, this whole range has been subdivided into the audio, the carrier, and the radio ranges. From the viewpoint of the power engineer, all of the frequencies embraced in these ranges are high frequencies, but to the communication engineer, only those frequencies in the upper regions are considered high.

This paper discusses methods of measurement and measuring instruments adapted to the measurement of communication apparatus over this complete range. Most of the measuring apparatus described is designed particularly for use at audio and carrier frequencies. The measuring methods which are discussed are intended primarily for laboratory use in connection with the development and inspection of telephone apparatus prior to its application in the field.

Many of the transmission problems in the communication field involve the impedance characteristics of apparatus and circuits. In the manufacture of apparatus, impedance limits are used to a very great extent in inspection tests. Consequently, quantities of prime importance are those defining impedance characteristics; that is, inductance, capacitance and resistance at specified conditions, of course, such as temperature, frequency, and current or voltage. Other characteristics, of a less fundamental nature but nevertheless of considerable importance, are attenuation, gain, inductance and capaci-

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[1] Presented at the Regional Meeting of District No. 1 of the A. I. E. E., Pittsfield, Mass., May 25–28, 1927.

tance balance, cross-talk, flutter and modulation. Since the three impedance components mentioned above, together with frequency, are probably of more general interest, this paper will be devoted largely to a discussion of their measurement, only brief reference being made to the methods used for the measurement of the latter group of characteristics.

As in all measurement work, standards representing the quantity are required, and these are of two classes, prime standards and secondary or working standards. In our case, the prime standards are resistance and frequency. From these we derive inductance and capacitance. Working standards are stable types of inductance coils, air and mica condensers, adjustable resistances, and for frequency, resonance type meters and highly stable oscillators.

PRIME STANDARDS

Frequency. The standard of frequency used is that described by Horton, Ricker and Marrison.[2]

Briefly, it comprises a special self-driven fork held at constant temperature and having all other conditions of operation so thoroughly controlled that a high degree of frequency stability is obtained. The exact frequency is measured by driving synchronously a phonic wheel for determining the number of cycles occurring in a given time interval. This time interval is usually a period of 24 hr. as measured by time signals received from Arlington. The average frequency of this fork is capable of being held constant and measured in this way with an accuracy of about 0.001 per cent.

The frequency of 100 cycles obtained from this fork is used to drive a 1000-cycle slave fork from which an equally constant 1000-cycle frequency is obtained. Having these frequencies, all other frequency measurements may be made with as high an accuracy as desired by direct comparison, using the cathode-ray tube as described in detail by Rasmussen.[3]

Resistance. Resistance standards specially designed for use with direct currents and having a very high degree of stability may be readily purchased or constructed and calibrations to a high degree of accuracy may be obtained from the Bureau of Standards. These resistance standards are not suitable for precision measurements at high frequencies, usually being wound on metal spools, and the value of the phase angle receiving only secondary consideration. It is

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[2] Horton, Ricker and Marrison, "Frequency Measurement in Electrical Communication," *A. I. E. E. Transactions*, 1923.

[3] F. J. Rasmussen, "Frequency Measurements with the Cathode Ray Oscillograph," *A. I. E. E. Journal*, January, 1927.

necessary, therefore, to use resistance standards of special construction, depending upon the particular application to be made. In all cases, constancy of resistance with variations in atmospheric conditions, frequency and time is imperative. Generally as small a phase angle as possible is also highly desirable, although for some uses a suitable degree of constancy may be sufficient provided that the angle is known, and not large enough to affect appreciably the magnitude of the impedance of the resistance over the frequency range used.

To obtain the highest degree of stability of both resistance and phase angle, it has been found desirable to wind the wire on a spool made of a material not affected appreciably by atmospheric conditions, for example, phenol fiber, and to immerse the complete resistance in a sufficient amount of a suitable sealing compound to exclude all moisture. Resistances meeting all of the requirements outlined have been constructed as described in a recent paper by one of the authors.[4] Coils such as described there, having a resistance of approximately 1000 ohms, may be constructed to have an effective inductance of less than five microhenrys, and this inductance is practically independent of frequency up to at least 100 kc. Coils having lower values down to about 10 ohms can be made with equally small phase angles. Below this value of resistance, it is more difficult to hold a low phase angle.

Coils constructed as described may be considered to have so small a change in resistance with frequency that a calibration with direct current may be used without appreciable error for all frequencies at which they are used. Both the variation in resistance with frequency and the phase angle may be most readily measured by comparison with some simple type of resistance of such geometrical form that the phase angle may be readily computed. Satisfactory resistances for this purpose are short lengths of fine wire of definite shape, sputtered metal films on glass or other insulating material, and carbon in the form of rod or film.

SECONDARY STANDARDS

Capacitance. The value of our capacitance standards is determined in terms of the prime standards of frequency and resistance. This determination may be made in several ways, the following bridge method being a simple and accurate one. The circuit, as shown in Fig. 1, consists of two equal resistance ratio arms, a resistance and capacitance in parallel in the third arm and a resistance and capacitance in series in the fourth arm. When this bridge is balanced at any particular frequency, the relations between the impedance arms

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[4] W. J. Shackelton, "A Shielded A-C. Inductance Bridge," *A. I. E. E. Journal*, February, 1927.

of the bridge are such that the value of each capacitance may be determined in terms of the frequency and the two resistances.

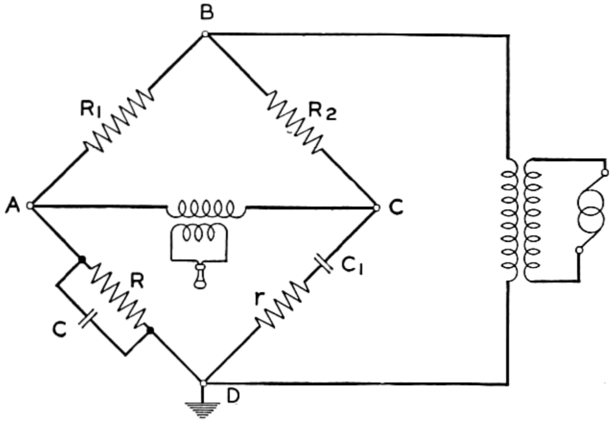

Fig. 1—Bridge circuit for measuring capacitance in terms of resistance and frequency

The requirements for a capacitance standard are high constancy with variations in frequency, time, voltage, and atmospheric conditions, and a small phase difference. Mica has been found to be the best solid dielectric, used either alone or impregnated with a high quality wax such as paraffin. If mica alone is used, the condenser must be sealed to prevent the entrance of moisture.

Good mica condensers can be obtained with a temperature coefficient below 0.005 per cent per deg. cent., and having a variation of less than 0.1 per cent over a frequency range from 500 cycles to 100 kc. Variations in capacitance with voltage are also negligible provided voltages below 100 volts are used. It has been our experience that the paraffin-impregnated condensers generally have a negative change of capacitance with temperature. This change is smaller than that of the unimpregnated type which has a positive change with temperature. The paraffin-impregnated condensers, however, usually change more with time than the unimpregnated condensers.

Air condensers may be used as standards in small sizes. For the larger values, the air condensers become large and cumbersome and are not as stable as the mica condensers. Even in the smaller sizes, very special precautions must be taken to obtain air condensers which have appreciably smaller phase differences than the mica condensers, which may be made with phase differences considerably less than one minute.

Inductance. Requirements for inductance standards are high constancy with variations in time, current or saturation, atmospheric conditions, and frequency. It is also desirable that they be made with a small external field. Otherwise, very great care must be taken to avoid errors due to this cause.

In order to obtain stability with variations in saturation, it is usual to make inductance standards with air cores. This requires standards of large physical size if a time constant as large as the average iron core coil is desirable. This large size results in large capacitance distributed in the coil itself and from the coil to ground. These capacitances cause large variations in inductance with frequency and with the position of the coil with respect to ground. On account of this difficulty with air core coils, permalloy[5] as core material has been used with considerable success as described by one of the authors.[4]

The calibration of these inductance standards may be made by comparison with any two of the quantities, capacitance, resistance and frequency. Comparison with frequency and resistance may be made in a bridge circuit exactly similar to the one used for capacitance determination, substituting inductances for capacitances. A comparison with frequency and capacitance may be made by means of a resonant method, and comparison with capacitance and resistance may be made by means of the Owen bridge.[6] The resonant method is used generally except for those cases requiring large capacitance, in which cases the Owen bridge is used.

Frequency. As a secondary standard of frequency for use with th cathode ray tube, where practically only one standard frequency is required, a special 1000-cycle oscillator is used, designed particularly for high stability of frequency with ordinary variations in external conditions. This oscillator is shown in Fig. 2. It allows the use of a cathode ray tube for frequency measurements with a high degree of accuracy under conditions where the prime standard of frequency is not accessible.

Where a portable frequency standard is desirable, for instance, as a means of shop frequency checks, a resonance type of meter is used. This is shown in Fig. 3. It is essentially a resonance bridge circuit consisting of two equal resistance ratio arms, a third arm containing a resonant circuit, and a variable resistance as the fourth arm. The capacitance and resistance are variable over wide ranges by means of decade switches, and the capacitance is capable of fine variations by the use of a form of precision variable air condenser having provision for fine control. There are four air-core inductance coils which give,

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[5] H. D. Arnold and G. W. Elmen, *Franklin Institute Journal*, Vol. 195, 1923.

[6] D. Owen, "A Bridge for the Measurement of Self-Inductance," *Proceedings of the Physical Society of London*, October, 1914.

in conjunction with the variable capacitance, a frequency range of about 100 cycles to 150 kc.

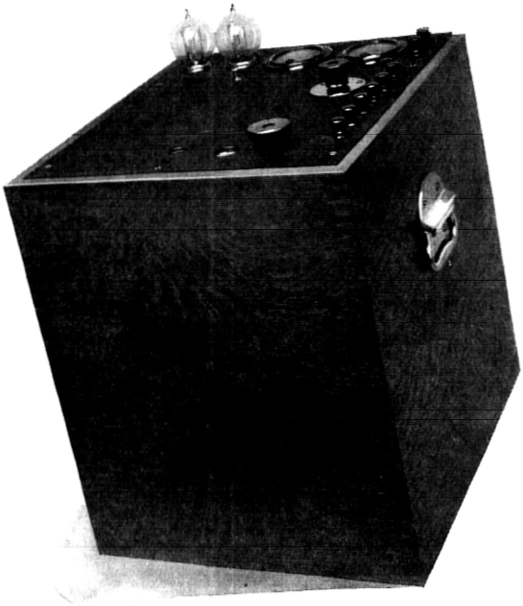

Fig. 2—Single-frequency vacuum tube oscillator used as secondary standard of frequency

The meter is calibrated by balancing the circuit by means of the variable resistance and capacitance with a known frequency input, and recording the coil and condenser settings. It is used for checking frequencies by reversing the process, that is, connecting the source of unknown frequency to the bridge, balancing as before, and determining the frequency by reference to the calibration. There are no input or output transformers connected to this circuit and on this account certain precautions must be taken in connecting the output and input circuits to it; but it is a relatively low impedance circuit, and troubles due to this cause have not been found serious.

Resistance. A convenient secondary standard of resistance is a dial box having the resistance units designed to meet the same requirements as the prime standards. Commercial dial boxes are available, having satisfactory stability with variations in frequency and atmospheric conditions, and having sufficiently small phase angles for all frequencies but the highest radio frequencies.

A dial box, requiring, as it does, a certain amount of wiring between dials, and having all of the dials connected permanently whether they are used or not, always has more capacitance and inductance associated with it than a single resistance of the same value. A certain amount of compensation between the capacitance and inductance may be effected by proper design, but it may be generally accepted that the inductance of the wiring makes the phase angle of the low resistance values comparatively high and the capacitance between dials and between units of each dial makes the phase angle of the high values comparatively high. This effect can only be overcome by a compact design using coils of small physical size. This sets a limitation on coils for use in dial boxes which is not present to such an extent in the case of single resistance units or single value prime standards.

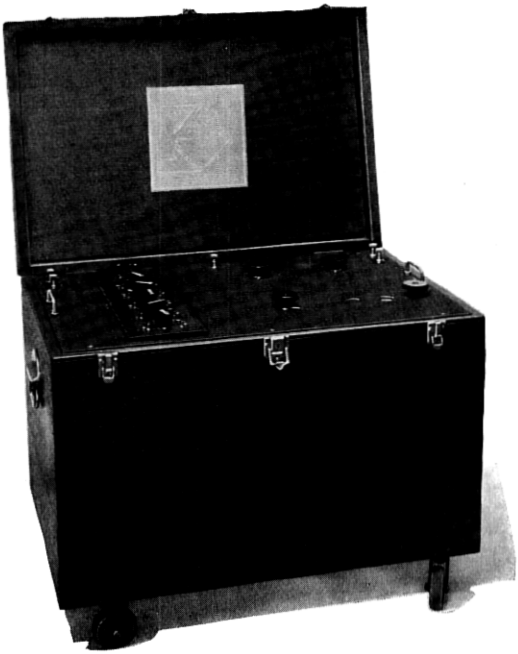

Fig. 3—Resonance-type frequency meter

Methods of Measurement

We have discussed already measurements of frequency and resistance in connection with the description of standards, and we will not discuss them further here. We are particularly concerned with the measurement of impedance of all types, it being understood that any resistance having a phase angle which is not negligible or which is of special interest is to be considered a special type of impedance.

In measuring impedances, we have found that those methods which determine the unknown in terms of circuit constants are superior to those requiring the measurement of current and voltage. Accordingly, bridge methods are used almost exclusively and, furthermore, the bridge type which is used wherever possible is the equal ratio arm bridge in which a direct comparison is made of the unknown impedance with a known impedance adjusted to that same value. This type of measurement has the disadvantage of requiring standards of the same value as the quantity measured over the whole range of impedances used, but it has the compensating advantages that, having standards whose value is known, this circuit is extremely simple, very easy to check at any time, and may be made extremely accurate.

Auxiliary Apparatus. Without going into details regarding the auxiliary apparatus used in connection with bridge measurements, we may state briefly that vacuum tube oscillators are used almost exclusively for furnishing all frequencies, and that the telephone receiver is used almost exclusively as a detector, due to its simplicity and the rapidity with which it may be used. For frequencies below 200 cycles, it is used with a chopper to give a tone of about 1000 cycles, and above 3000 cycles, it is used with a heterodyne detector to give a beat note of about 1000 cycles. In the audio frequency range, it is used alone or with an amplifier, if necessary.

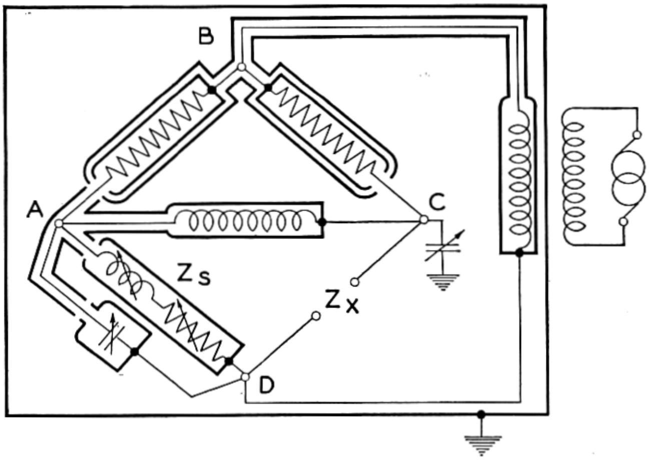

Fig. 4—Shielded impedance bridge circuit

While it is impossible to draw a distinct line between the methods of measurement of different types of impedances, certain bridge circuits have been designed primarily for certain types of measurements, and we will therefore classify them in this way, although in general they have a considerably wider sphere of usefulness than indicated.

Inductance. A simple shielded bridge for the measurement of inductance and resistance has been described by one of the authors[4] and is shown in schematic form in Fig. 4. It comprises two equal resistance ratio arms, an adjustable standard of self-inductance, an adjustable resistance standard, a thermocouple milliammeter, two reversing switches, two transformers, and two air condensers. This apparatus is grouped into three separate units, as shown in Fig. 5, one comprising the standards of inductance, one the resistance standard, and one the remaining parts of the circuit. Each of these units is shielded electrostatically. The last assembly constitutes the balance element of the system, by means of which the unknown and standard impedances are compared. This unit may be used alone for the comparison of two impedances of any type since the only condition for balance is the exact equality of impedances in the two arms. Using in addition the standard inductance and resistance shown, it is adapted particularly for measuring inductance and effective resistance. The inductance

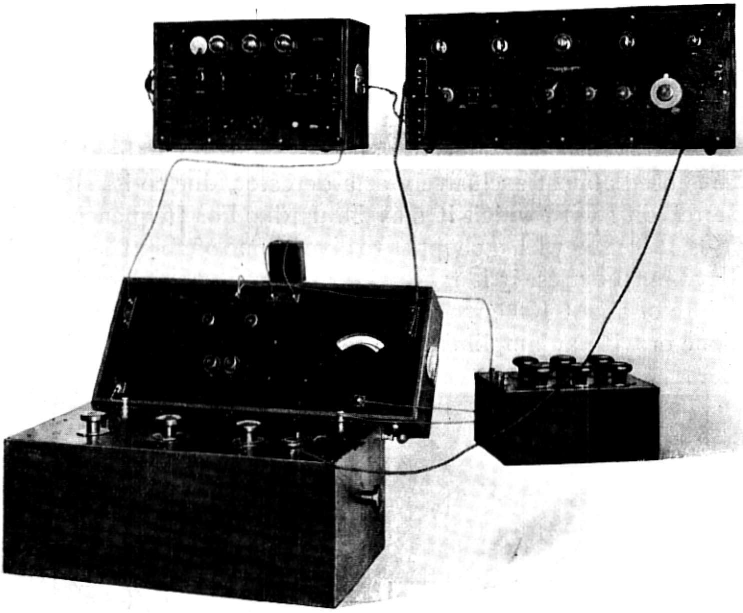

Fig. 5—Shielded impedance bridge and standards, connected to vacuum tube oscillator and heterodyne detector

standard may be made with a range of 10 henrys to a minimum of two millihenrys, using an inductometer having a minimum scale division of 0.1 millihenry, or the range may be any simple multiple of this. Values as low as one microhenry at frequencies as high as 150 kc. are measured in this way.

By connecting the resistance in one arm of the bridge and a capacitance in series with an inductance in the other arm, we may use it to indicate resonance, and if we measure the frequency we may use this method for the comparison of capacitance with inductance. This is the method actually used for the calibration of the inductance standard used with the bridge. The bridge may be used for the comparison of capacitance. The bridge described later for the measurement of capacitance, however, has certain special features which make it peculiarly adapted to the measurement of capacitance and conductance.

Inductance with Superposed Direct Current. In telephone work, it is often of value to know the performance of apparatus, particularly of iron core impedances, when used at telephone frequencies while at the same time carrying direct current. The bridge shown in schematic form in Fig. 6 will measure the inductance of the coil at audio frequency

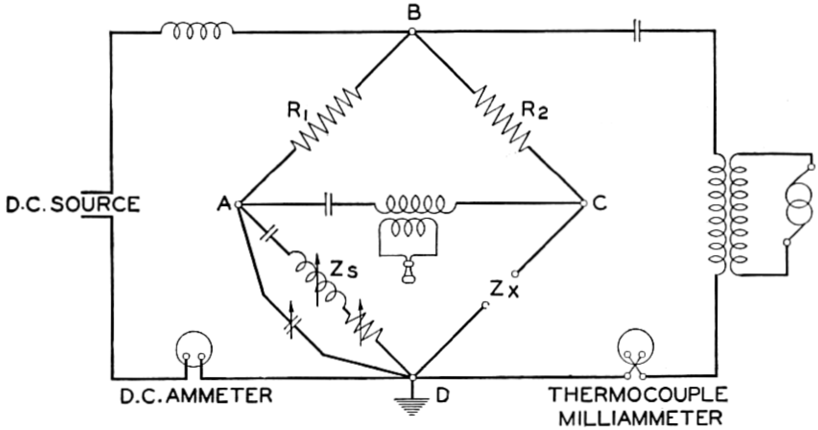

Fig. 6—Bridge circuit for measuring impedances with superposed direct current

with a direct current flowing through it. As shown in the figure, the direct current is kept out of all of the arms of the bridge except one ratio arm and the test arm, by means of condensers, and the alternating measuring current is separated from the direct current by means of a choke coil. None of these added features affect the bridge balance except the capacitance in the standard arm, and this is made large enough (26 μ f.) to have an impedance small compared with the impedance measured. In any case, a correction may be made by taking first a zero reading which will be slightly positive due to the inductance necessary to compensate for the capacitance in this circuit. This correction will vary with frequency but at 1800 cycles, for instance, with 26-μ f. capacitance, the correction is only about 0.3 millihenry and the inductances measured are usually considerably larger than this.

The circuit is extremely simple and convenient to use. The values of alternating current and direct current can each be measured separately outside of the bridge circuit and the inductance standards do not need to be constructed to carry the direct current. The only part of the bridge required to carry the direct current is one ratio arm and, in consequence, it is a comparatively simple matter to construct such a bridge to carry several amperes of direct current. Where very high direct currents are required, the ratio arms may be reactances wound on a single core, instead of resistances, thus reducing the loss due to the passage of the direct current.

Flutter. In telephone circuits used for joint telephone and telegraph service, it is desirable to know the effect of the telegraph impulse on the telephone frequency inductance and effective resistance of the loading coils used on the lines. This effect, known as "flutter," with a method of measuring it, is described in detail by Fondiller and Martin.[7] The measuring circuit consists of a double bridge, the inner one consisting of two similar loading coils on which the flutter effect is to be measured and two other coils of comparatively high impedance approximately equal in value and which have negligible flutter effects, the four coils being connected to form a balanced bridge. The low frequency corresponding to the telegraph impulse is introduced at two diagonal corners and the other two corners, which are at a common potential with respect to the low frequency, are connected to the usual test terminals of an impedance bridge of the type already described. With no low-frequency current passing through the coils, a continuous balance may be obtained on the main or high-frequency bridge using an audio frequency input. From this, the normal effective resistance and inductance of the coils may be obtained.

When the low-frequency current passes through the coils, the inductance and effective resistance are different for every point of the low-frequency cycle. Thus, only an instantaneous balance of the outer bridge is possible. This instantaneous balance for any particular point in the low-frequency cycle may be made by the use of an electro-

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[7] W. Fondiller and W. H. Martin, *Transactions of the A. I. E. E.*, 1921, Vol. 40, p. 553.

magnetic oscillograph. By this means as described in the paper already mentioned, it is possible to obtain the curve of variation of inductance and effective resistance of the coil over one low-frequency cycle.

Another method used at the present time employs the same bridge circuit but an entirely different method of detecting the cyclic variation in the balance. This method of detection uses the cathode-ray oscillograph and is as follows. The low-frequency source is connected across a high resistance and condenser in series, the two having equal impedances. The potentials across the condenser and resistance are then placed respectively across the horizontal and vertical plates of the oscillograph. These two potentials, being equal in magnitude but 90 deg. apart in phase, give a circle on the screen. The output of the main bridge is now connected through a transformer whose secondary is connected in series with the oscillograph cathode potential. Due to the fact that the sensitivity of the tube to deflections by the plate potentials varies with the cathode potential, the radius of this circle produced by the low frequency is a function of the telephone frequency input from the bridge, and instead of a circle we get a band, the width of which is a measure of the degree of unbalance of the bridge. The point in the cycle at which the bridge is balanced, is indicated on the screen as the point where this band diminishes to a line, and the angular position of this point in the band determines the phase position of this balance with respect to the low-frequency cycle. It is possible in this way to balance the bridge for any angular position corresponding to any point in the low-frequency cycle, and by taking sufficient points, to obtain a curve of variation of the coil constants over a complete cycle. This method is found to be simpler and faster than the method using the mechanical oscillograph.

Inductance Balance. A simple form of bridge for measuring inductance balance of the two windings of a transformer or other coil uses the two windings of the transformer for two arms, the other two arms being resistances, one of which at least is variable. The balance is made by means of the variable resistance, the ratio of the two resistances at balance then giving the unbalance of the transformer. If one of these resistances is made 100 ohms, the variation of the other from 100 ohms at balance gives directly the percentage unbalance. Any unbalance in resistance is usually comparatively small and may be taken care of by low resistances in series with the transformer windings.

Ratio of Transformation. A similar bridge may be used for the measurement of ratio of transformation. There are many cases where the secondary of a step-up transformer has an inductance which is inconveniently large to measure directly, and the ratio of transformation circuit eliminates this necessity. The circuit used is practically the same as that already described for measuring inductance balance, the ratio of transformation being equal to the ratio of the resistance arms of the bridge at balance.

Capacitance. The direct comparison of capacitance is made in a special bridge known as the Campbell [8]-Colpitts [9] capacitance and conductance bridge. The ratio arms, input and output circuits, and the shielding are similar to the impedance bridge already described. The unique feature of this bridge is the method of connecting the standard air condenser to eliminate the dielectric loss in the measurement of capacitance. The schematic diagram of the bridge is shown in Fig. 7. Instead of connecting the standard condensers in the arm *AD* as in the case of the impedance bridge already described, a special switch is used to switch these condensers from *AD* to *CD*, and in the case of the continuously variable condenser, the three-plate construction is used, causing a decrease in the capacitance in *CD* as the capacitance in *AD* is increased.

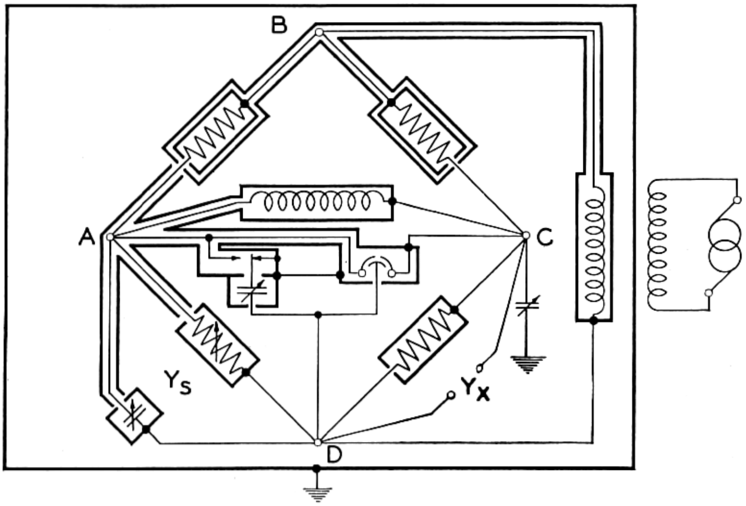

Fig. 7—Schematic circuit of capacitance and conductance bridge

The method of construction of the unit air condensers is shown in

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[8] G. A. Campbell, "The Shielded Balance," *Electrical World and Engineer*, April 2, 1904, p. 647.

[9] G. A. Campbell, "Measurement of Direct Capacities," *Bell System Technical Journal*, July, 1922, p. 18.

Fig. 8. It may be seen from this figure that all capacitances which include dielectric material are permanently connected across *CD* or *AC* and so are not changed when the condenser is switched, or else they are switched so that capacitances across *AC*, which do not enter into the bridge balance, are short-circuited on switching. This scheme eliminates all dielectric loss in the standards when measuring condensers by comparison with them. It has the additional advantage that the capacitances in the bridge have twice the effect they would have if simply switched in and out of the circuit.

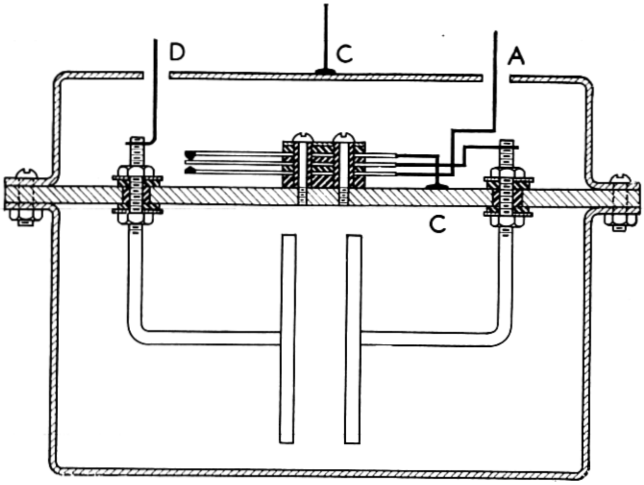

Fig. 8—Air-condenser construction employed in the capacitance and conductance bridge

By the use of this bridge, it is possible to measure capacitances up to the maximum limit of the range of the air condensers with a negligible loss in the standard condensers. This capacitance range is usually up to 0.01 μ f. and for condensers above this value the conductance is measured by comparison with that of the maximum value of the air condenser, assuming it to have negligible conductance. Of course this method of eliminating dielectric loss is not applicable to the use of mica condenser standards and if a range greater than 0.01 μ f. is desired, the mica condensers are simply connected in the usual way across *AD*.

Another feature of this bridge is the method of measuring conductance. The connection of a variable resistance, either in series or in shunt, with the standard condenser for the measurement of loss in the test condenser has objections due to the wide range of resistance values required to cover the possible variations in losses. A compromise is effected in this bridge by connecting a 10,000-ohm shunt across each of the arms *CD* and *AD*. A slight difference in the losses in these two arms can then be measured by varying one of these resistances slightly. Since the standard condenser practically always will have lower losses than the condenser tested, it is usual to place a fixed 10,000-ohm resistance across *CD* and a resistance across *AD* variable in 0.01-ohm steps to 10,000 ohms. A change of one ohm in this resistance, when balancing a condenser, is equivalent to shunting it with a resistance of 100 megohms or 0.01 micromho. Accordingly, the conductance of a condenser may be measured in micromhos by simply dividing the resistance change in ohms by 100. This, of course, is only approximate in the case of large conductances, but is correct to 1 per cent for values up to one micromho.

Due to the condensers forming such an integral part of the bridge circuit, they are all built into the bridge. The complete bridge is shown in Figs. 9 and 10. Fig. 9 is a top view showing the capacitance and resistance dials for effecting a balance, and Fig. 10 is a view with the cover removed, showing the method of shielding the individual parts. The range of capacitance is from 0.1 $\mu\mu$ f. up to three μ f., and the frequency range is from about 10 cycles up to about 150 kc., the only modifications required in the bridges to cover this whole frequency

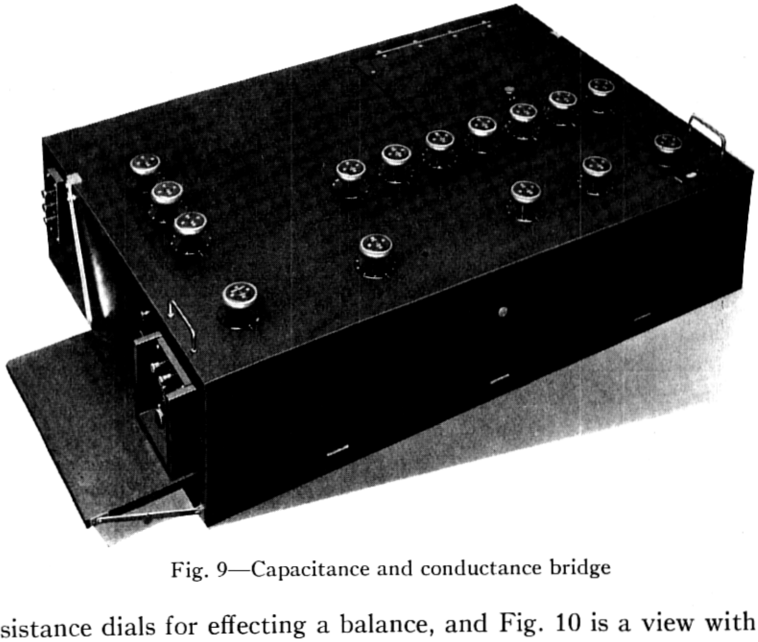

Fig. 9—Capacitance and conductance bridge

range being a change in input and output transformers, as it is not found practicable to design these transformers to give efficient operation over such a wide frequency range.

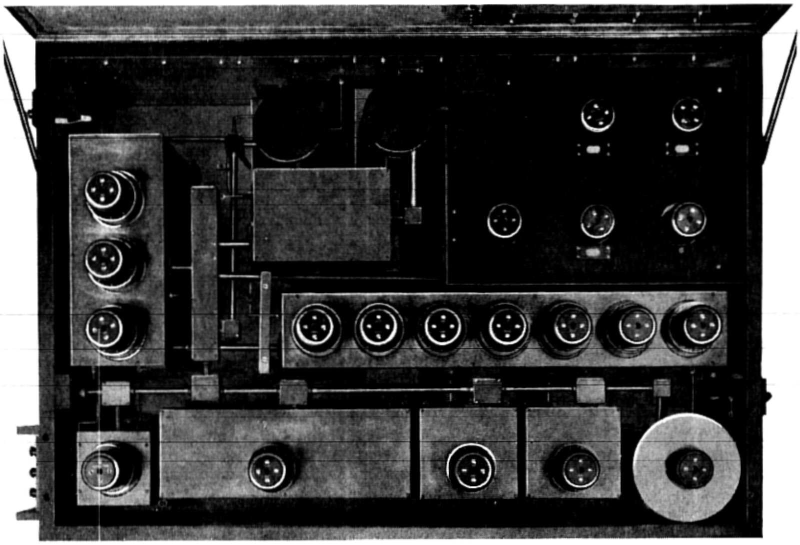

Fig. 10—Capacitance and conductance bridge with cover removed, showing method of assembly and shielding

A comparison of this bridge with the impedance bridge already mentioned shows it to be essentially the same circuit, the capacitance bridge having conductance shunts not included in the impedance bridge which allow a conductance balance to be made more readily. It is obvious that any two impedances can be compared on this bridge. Inductances may be measured by parallel resonance by simply placing them in the *AD* arm in parallel with the standard condenser and effecting a balance with it. This method is used to some extent for the measurement of large inductances.

Capacitance Unbalance. In order to keep cross-talk low in long cable circuits, it is necessary to have a high degree of capacitance balance between the various conductors in the cable, more particularly between the four conductors of a phantom group. The unbalances of interest are the phantom to each side circuit and the side-to-side unbalances. These may be measured on a capacitance bridge by measuring all of the direct capacitances [9] associated with the group and computing the unbalances required. A special circuit, however, is generally used which measures directly the particular unbalances in which we are interested. It consists of an input and an output transformer, two equal resistance ratio arms, a variable air condenser of the three-plate type, four binding posts for connecting the four conductors of the quad, and switches for making the various connections. By means of the switches, the cable conductors are connected to the circuit in such a way that the reading of the air condenser when a balance is obtained indicates directly the unbalance, either side-to-side or phantom-to-side, according to the switch positions. This circuit when used as a laboratory instrument is capable of measuring capacitance unbalance as low as 1 $\mu\mu$ f.

Attenuation and Gain. So far, we have discussed the measurement of the fundamental impedance characteristics of apparatus. When the component parts have been found to meet their individual impedance requirements and are assembled to form the completed apparatus, it is desirable to have tests made of the over-all performance of this apparatus. In a large number of cases, the requirement of greatest importance is the attenuation frequency characteristic. It is fairly obvious that this characteristic, of all apparatus used in telephone lines, is of interest, and this is particularly true of all types of filter circuits which are designed primarily for the purpose of furnishing definite attenuation frequency characteristics. These measurements are particularly required on apparatus used in carrier-current telephony and telegraphy.

From the very nature of the measurements, it is difficult to obtain a null method of measuring attenuation. The most direct method is to measure the input and the output of the apparatus under test simultaneously, from which the attenuation may be computed. The practical difficulty in doing this is to measure the extremely small outputs which are obtained from apparatus having high attenuations, where the characteristic must be obtained with the normal input, which is usually low. In general, it has been found necessary to use some form of amplifying device in the output circuit and it has not been found desirable to rely on the constancy of amplification of this device. Accordingly, the usual method used for the measurement of attenuation is a substitution one. The circuit is shown in Fig. 11A. There are two branches in this circuit, one of which includes the apparatus under test and the other, a variable standard attenuator. The output of each branch is arranged to connect either to a detector of impedance Z_1 equal to the impedance of the standard attenuator or to a fixed impedance of the same value. If the apparatus under test has the same impedance as the standard attenuator, the input impedances Z_1 and Z_3 are made equal and the matching impedance Z_2

is omitted. Then the two branches of the circuit will be identical, provided the attenuation of the standard attenuator is equal to that of the apparatus under test. Accordingly, the method of measurement is to switch the detector first to one and then to the other branch, adjusting the standard attenuator until an equal output is obtained for either switch position. The attenuator then reads directly the loss in the apparatus. The total input of the circuit is independent of the switch position, since the impedance conditions remain unchanged in switching.

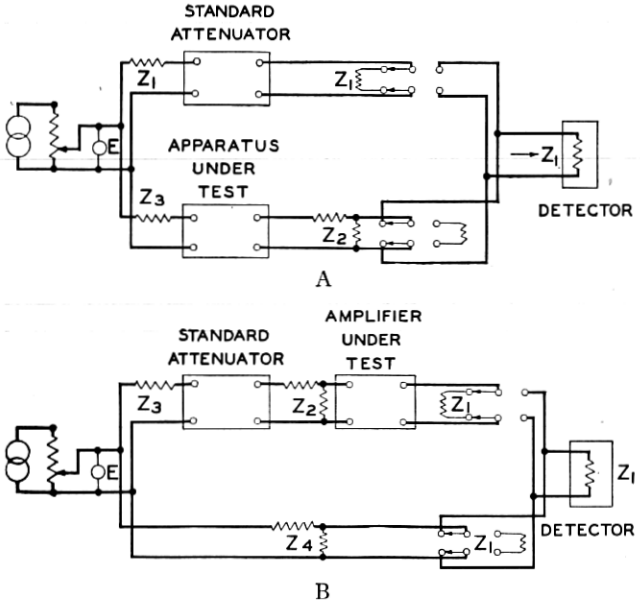

Fig. 11—Circuits for measuring attenuation and gain. A. Arrangement for measuring loss. B. Arrangement for measuring gain

If the apparatus under test has not the same impedance as the standard attenuator, the input impedance Z_3 and the matching network Z_2 are adjusted so that the circuit still reads directly.

The standard attenuator is a resistance network capable of variation in small steps, each step consisting of a network of the *L*, *T* or *H* type, the resistance values being such as to give the desired attenuation between the output and input terminals. It is usually calibrated in 0.1-T.U. steps and may read as high as 100 T.U. corresponding to a ratio of power output to power input of ten billion to one or, if the impedances are the same, which is usually the case, corresponding to a current or voltage ratio of 100,000 to 1.

The calibration of these attenuators is based on the measurement of the individual resistances. Of course, sufficient measurements are made to determine that any capacitances which enter do not affect appreciably the accuracy of the attenuator at the maximum frequency used, which may be as high as 150 kc.

By modifying the circuit of Fig. 11A, we may use it to measure gain as shown in Fig. 11B. In this arrangement, the lower branch contains an impedance Z_4 that is adjusted to introduce a loss equal to that of the matching impedance Z_2 in the upper branch. In other words, with the amplifier under test out of the circuit and the standard attenuator set at zero, the detector will read the same for either position of the output switch. Then when the amplifier is introduced into the circuit, the attenuator is adjusted until the detector reads the same for either switch position, which means that the gain of the amplifier is just neutralized by the attenuator and the setting of the latter is read as gain.

This circuit is used principally for the measurement of gain of audio frequency amplifiers, and is capable of measuring gain as high as 120 T.U. corresponding to a power output of 1,000,000,000,000 times the power input.

Cross-Talk. When there is an appreciable amount of coupling between two telephone circuits, any mutual interference which results is known as cross-talk. It is measured in cross-talk units, a cross-talk unit being defined as the relation existing between the two circuits when the current in the disturbed circuit is one millionth of the current in the disturbing circuit, the impedances of the two circuits being the same. Under these conditions, one cross-talk unit may be assumed the same as 120 T.U. An interesting form of cross-talk is that due to loading coils and is of a complex type, produced by a combination of capacitance, inductance and resistance unbalances in the windings. Since the actual cross-talk caused by an unbalance in the coil is dependent upon all of the conditions of the circuit, it is necessary that any measurement of cross-talk made on the individual coils be made in a circuit as nearly as possible the equivalent of the line in which the coil is to be used. Consequently, all cross-talk circuits for the measurement of loading coil cross-talk consist of networks simulating the impedance of an ideal line of the type for which the loading coil is designed. The principle of the method is to apply to the disturbing circuit a definite input of a single frequency, usually 900 cycles, and to measure the cross-talk in the disturbed circuit at the desired point in it by comparing the tone heard in the telephone receiver connected at this point with the tone obtained from a cross-talk meter which is simply a device for obtaining a definite part of the input, and having a scale reading in millionths, that is, in cross-talk units. The measurement is made by switching from the cross-talk meter to the disturbed line and adjusting the cross-talk meter until the tone heard in each case is the same. The method is therefore not a null method and depends to some extent on the judgment of the operator, but results accurate to one or two cross-talk units may be obtained by this method. The coils as commercially produced after adjustment for this requirement are usually within 10 cross-talk units, representing an unbalance in the circuit due to the coil unbalance of less than one part in 100,000.

CONCLUSION

We have described in this paper a number of the more important high-frequency methods of measurement and measuring circuits. It has been impossible to cover all of the different methods and circuits used, but we believe that the information given will be of value to those interested in this field of work.

We have not been able, in a paper of this type, to go into details concerning any specific circuits used, but we have referred to papers which describe in greater detail some of these methods and circuits, and it is expected that other papers will be published in the future covering other circuits which have received only brief mention here.