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COMPLETE SPECIFICATION

Improvements relating to the Measurement of Electrical Impedance

I, EDMUND RAMSEY WIGAN, a British subject, of "Kerry", Barnham, Bognor Regis, Sussex, do hereby declare the invention, for which I pray that a patent may be granted to me, and the method by which it is to be performed, to be particularly described in and by the following statement:—

The present invention relates to apparatus and methods for detecting and measuring electrical impedance and concerns particularly, but not exclusively, the measurement of resistance, especially the resistance of circuit components for example (inductors and capacitors) which have a high ratio of reactance to effective series resistance.

Conventional methods of measuring such resistance require careful adjustment of the measuring circuit before each measurement is made and in particular before measurement is made at differing frequencies. It has also been necessary that the stability of the test frequency is carefully controlled. The testing and checking of large numbers of components as in factory production is therefore difficult and specially trained labour is required.

One object of the invention is to provide an apparatus and method for testing reactive circuit components which is particularly useful where they are tested at high speed or in large numbers.

According to the present invention there is provided a network consisting of purely resistive components, purely reactive components or components of complex impedance which all have the same time constant, and first, second and third pairs of terminals, the network having the property that, when an oscillator is connected to the first pair of terminals so as to cause a voltage or short-circuit current to appear at the third pair of terminals, the voltage or current is reduced to zero when an impedance matching that seen looking into the second pair of terminals (with the oscillator connected as described) is connected across these latter terminals.

It is another property of the network defined that the modulus of the voltage or current at the third pair of terminals is the same when the second pairs of terminals is open circuited and short circuited.

The network is theoretically completely frequency-independent and in practice is substantially frequency-independent over a certain range of frequencies.

The impedance looking into the second pair of terminals is purely resistive when the network components are purely resistive and is in this case hereinafter denoted R_0 in this specification. Similarly the impedance is purely reactive when the network components are purely reactive and is complex when the network components are complex. In this latter case the impedance has a characteristic time constant and is matched by a complex impedance having the same time constant. Further description is restricted to the cases of purely resistive and purely reactive impedances, the extension to complex impedances being obvious.

A resistive network, wherein the voltage at the third pair of terminals is reduced to zero, may comprise a transformer with the input to the primary winding forming the first pair of terminals and having a tapped secondary winding, the two ends of the secondary winding being connected through three resistors in series, the second pair of terminals being the junction of two of the resistors and the tapping point of the secondary winding, and the third pair of terminals being the other junction of resistors and the tapping point.

Another form of the network, wherein the voltage at the third pair of terminals is reduced to zero, may comprise three resistors connected in series between the first pair of terminals and two further resistors connected in parallel with the three resistors. The second pair of terminals is then the junction of two of the three resistors, and the junction of the two further resistors, and the third pair of terminals is the junction of the other two of the three resistors, and the junction of the two further resistors.

One network wherein the current through a short circuit connected across the third pair of terminals is reduced to zero when a resistance equal to the resistance looking into the second pair of terminals is connected to these terminals, comprises a transformer with a tapped secondary winding, the input to the primary winding forming the first pair of terminals, two resistors each connected to one end of the secondary winding and a third resistor connected to the tapping point of the secondary winding, the second pair of terminals being the unconnected end of one of the two resistors and the unconnected end of the third resistor, and the third pair of terminals being the unconnected end of the other of the two resistors and the unconnected end of the third resistor. Many other forms of the network can be built.

In those networks which comprise transformers, in series with the secondary windings of which resistors are connected, the said resistors may be replaced by resistive attenuators of equivalent output resistance. In addition one of these attenuators may be designed so as to incorporate the resistance of a measuring device utilised to detect voltage or current changes at the third pair of terminals.

Also according to the invention there is provided a method of measuring or detecting resistance in the presence of reactance in a circuit component, using on of the aforementioned resistive networks, by finding the modulus of the voltage or current at the network's third pair of terminals when the circuit or a component to be tested is connected to the second pair of terminals, and comparing this modulus with the modulus of the voltage or current at the third pair of terminals when the second pair of terminals is open circuited or short circuited. For convenience the circuit or component being tested will be called the test object.

The ratio of moduli so derived has the value unity if the test object is purely reactive whilst, if the object contains resistance the ratio falls short of unity, by a small number which number is related to the resistance of the object unless the reactance is zero and the resistance is close to R_o, when the ratio approaches zero and is zero for the resistance equal to R_o.

A purely reactive network, in contrast to the already mentioned resistive network may be used to measure or detect reactance in the presence of resistance. A network in which all the components have the same time constant may be used to measure the time constant of components or detect components having the same time constant as the components of the network. That is the components of the network must all have the same resistance/reactance ratio. It will be appreciated that this same requirement applies equally to the purely resistive and the reactive networks where the ratio is of course, infinite and zero respectively.

In measuring or detecting resistance using a resistive network of the type in which measurements are made in terms of the voltage or current at a third pair of terminals, a measuring device may be used to which is applied a uni-directional voltage proportional to the alternating voltage or current at the third pair of terminals, together with a second uni-directional voltage which acts as a reference and is proportional to the alternating voltage at the first pair of terminals, the measuring device being arranged to register the difference between these two uni-directional voltages, and thus to respond to the presence of resistance in the test object when it is connected to the second pair of terminals.

For example the conversion from alternating to uni-directional voltage may be made by amplifiers associated with rectifiers, or by thermo-junctions and the like, and the difference between these voltages may be derived by connecting the sources of the said voltages in series, with the junction point earthed, the loop being completed with a resistor provided with a sliding tap. A D.C. meter connected between earth and the tap can then be used to give the required indication, its zero reading being adjusted by moving the tap.

The resistance of the test object may be derived in terms of a first variable (and known) resistance connected in series with the test object, the said known resistance being initially set to zero and the deflection of the meter brought to zero by connecting an adjustable uni-directional voltage in opposition to the voltage causing the deflection, the first variable resistance then being adjusted to a known value and the meter deflection being adjusted to a convenient value by means of a second variable resistance connected across the meter (so calibrating the meter in terms of the said known resistance), the required resistance of the test object being then read by reducing the first variable resistance to zero and observing the new meter deflection.

Embodiments of the invention will now be described by way of example only with reference to the drawings accompanying the provisional specification in which:—

Fig. 1 is a block diagram showing a test object (T) and the equipment required to check its resistance,

Fig. 2 shows a network used in testing the object, T,

Fig. 3 shows the similarity between the

network of Fig. 2 and a conventional bridge,

Fig. 4 shows the network of Fig. 2 after modification to reduce the effect of unwanted reactive impedance associated with the transformer,

Fig. 5 shows a circuit for measuring the voltage output from the network,

Fig. 6 shows the current dual of the circuit of Fig. 2,

Fig. 7 shows the circuit of Fig. 6 in a form suitable for practical use,

Fig. 8 shows another network satisfying the required conditions,

Fig. 9 shows the dual circuit of Fig. 8,

Fig. 10 shows a four arm bridge circuit developed from the circuit of Fig. 9, and

Fig. 11 shows the circuit of Fig. 5 modified to allow the resistance of the test object to be read directly and to make a further connection for the reactive effect of the transformer.

An embodiment of the invention will now be described with reference to Figs. 1. A purely resistive network 10 has three pairs of terminals a, a′, b, b′ and c, c′. A high impedance voltmeter 11 is connected at the terminals a, a′, an oscillator 12 at the terminals c, c′ and a test object T, with unknown resistance, at the terminals b, b′. The network is designed to meet both the following conditions:—

the first condition is that a resistance of value R_o can be found which when connected at the terminals b, b′ will reduce the voltage at the terminals a, a′ to zero (which implies that the circuit is of the bridge type), and

the second condition is that the resistance so found equals the resistance looking into the terminals b, b′, when the oscillator and the voltmeter are connected.

If these conditions are fulfilled then the voltage at the terminals a, a′ when the terminals b, b′ are open circuit will equal the voltage at the terminals a, a′ when the terminals b, b′ are shorted, there being however a 180° difference in phase between the two voltages.

To understand why this is so, imagine that T is removed and a resistance equal to R_o substituted and consider that voltage changes $\Delta_1 b$ and $\Delta_2 b$ occur at the terminals b, b′ when R_o is first short circuited and then removed. When R_o is shorted the voltage at b, b′ falls from a value e_b to zero; thus $\Delta_1 b = -e_b$. Now consider the voltage change $\Delta_2 b$ at the same terminals when the resistance R_o is removed and the terminals become open circuit. Since R_o equals the resistance looking back into the terminals b, b′, the voltage at these terminals rises from e_b to $2e_b$, that is $\Delta_2 b = +e_b$.

By the "principal of superposition", the voltage at any point in a circuit is the sum of the voltages at that point due to each voltage source in the circuit taken one at a time the e.m.f.'s of the other sources being made zero. The voltage changes $\Delta_1 b$ and $\Delta_2 b$, could equally be caused by the connection one at a time of voltage sources having voltages $\Delta_1 b$ and $\Delta_2 b$ at terminals b, b′ terminals c, c′ being shorted. Thus by the principle of superposition these voltage changes are accompanied by voltage changes $\Delta_1 a$ and $\Delta_2 a$ at terminals a, a′ which are equal and opposite to one another as were $\Delta_1 b$ and $\Delta_2 b$. Since the voltage at the terminals a,a′ was initially at zero when the external resistance R_o was connected, it must follow that when the terminal b, b′ are open circuited and short circuited, the voltages at a, a′ induced by $\Delta_1 b$ and $\Delta_2 b$ must also be equal and opposite.

In order to show how the network can be put to practical use, consider the quantities $(e_a/e_c)_T$ and $(e_a/e_c)\infty$ which relate the voltage at terminals a, a′ to the voltage at terminals c, c′ when a test object T is connected at terminals b, b′ and when terminals b, b′ are open circuited.

It can be shown that, writing $M=(e_a/e_c)_T/(e_a/e_c)\infty$:—

in the case that T contains series resistance r_s and reactance x_s then

$$M=\frac{1-(r_s+jx_s)/R_o}{1+(_s+jx_s)/R_o}$$

or if

$$\frac{r_s}{R_o}=\alpha,$$

and

$$\frac{x_s}{R_o}=\beta$$

$$M=\frac{1-\alpha-j\beta}{1+\alpha+j\beta}$$

Thus if $x_s=0$ and the unknown is purely resistive and small compared with R_o, α is small and

$$|M| \simeq 1-2\alpha \ . \ . \ . \ . \ . \ (1)$$

Thus is α is vanishingly small $|M|=1$; but from the general equation is is clear than $|M|=1$ when $\alpha=\infty$, also, provided β remains zero.

If the unknown is purely reactive, $\alpha=0$ and from the general equation

$$M=\frac{1-j\beta}{1+j\beta} \text{ for all values of } \beta \ . \ . \ . \ (2)$$

and $|M|=1.0$ again.

If, however both α and β are finite, β being $\gg\alpha$, and $\alpha\ll$ unity, as will nearly always be the case in practice:—

then $|M| \simeq 1-2\alpha/(1+\beta^2)$ . . . . . (3)

If α is not small relative to β this approximation is modified by terms in α and α^2, which appear below the line, and complicate the expression beyond the point of usefulness. Note that the amount by which $|M|$ falls short of unity is proportional to α when α and β have the sort of magnitudes likely to be met in practice. The fall is, however rapidly reduced as β grows; and when $\beta=1$ the fall is equal to α.

The equations (1) to (3) show how the network can be used to detect or measure resistance, by making use of the fact that by equation (2) ratio $|M|$ will equal unity unless the unknown contains resistance, and further that by equations (1) and (3) the difference between unity and $|M|$ will be proportional to the resistance of the unknown. There are a variety of ways in which the resistance can be fully determined. One of these will be described later.

When large number of components having reactance x_s always in a certain range are being tested it will often be sufficient to set a limit on the permissible change in $|M|$. In this way the Q (quality factor) of components of known reactance may be checked.

Any network which fulfils the above mentioned conditions may be employed in utilising the invention. One such network is shown in Fig. 2. A transformer 13 with a primary winding 14 and secondary windings 15 and 16 applies voltages from the oscillator 12 to the network which consists of three resistances R_1, R_2 and R_3, the voltmeter 11 and the test object T. If the voltage across the secondary winding 15 is E_1 and that across the secondary winding 16 is E_2, then when the terminals b, b′ are open circuit or short circuit the voltage e_a across terminals a, a′ is given by:—

$$\left.\frac{e_a}{E_1}\right|_{T=0}=(-1)\left.\frac{e_a}{E_1}\right|_{T=\infty}=\frac{R_2}{R_1+R_2}.$$

When $e_a=0$, the resistance of the unknown T equals the resistance looking into terminals b, b′, that is when

$$e_a=0,\ T=R_o.$$

The value of R_o is given by:—

$$\frac{1}{R_o}=\frac{1}{R_3}+\frac{1}{R_1+R_2},$$

since R_o is found by looking into the terminals b, b′, voltage sources E_1 and E_2 being replaced by short circuits.

The values of R_1, R_2 and R_3 appropriate to a given voltage ratio E_2/E_1 in Fig. 2 can be found from the following equation:—

$$\frac{E_2}{E_1}=\frac{R_3+R_2\left(2+\frac{R_3}{R_1+R_2}\right)}{R_1}\quad\ldots(4)$$

For the network to give the desired performance it is necessary that the ratio of the voltages E_2 and E_1 is a real number. This can sometimes be achieved by using a transformer with interleaved secondary windings when the secondary voltages can be arranged to be very nearly in phase with one another over the range of frequencies to be used.

The best method of using a transformer to obtain a "real" ratio is to use a transformer with a secondary winding having the same number of turns as the primary and centre tapped, such as the transformer 13 in Fig. 2. In this case $E_1=E_2=\frac{E_o}{2}$ where E_o is the voltage of the oscillator 12.

It can be shown that if $E_1=E_2$ in Fig. 2, values of $R_1=15r$, $R2=5r$ and $R_3=4r$, where *r* is any real positive number, satisfy equation (4) but this solution is not unique since if we write $K=\frac{R_1}{R_2}$, then if $E_1=E_2$

$$\frac{K+2}{(K-2)(K+1)}=\frac{R_2}{R_3}\quad\ldots.(5)$$

The above quoted values of R_1, R_2 and R_3 are derived from $K=3.0$, but by putting $K=2.5$, the values of $R_1=45r$, $R_2=18r$, and $R_3=7r$ are obtained. Although K may have any value whatever provided $K>2$, it is usually advantageous to keep K as small as possible. Again as *r* can have any value, the network can be designed so that R_o suits the impedance of the components likely to be tested.

It is not necessary that the transformer 13 be centre tapped, and in fact the sensitivity of the circuit can be increased if an adjustment off-centre is made. In this instance E_1 will not equal E_2 and equation 5 will not apply.

For the network to function correctly the parts of the network immediately adjacent to the detector and test object must appear to be substantially resistive and therefore to minimise the effects of using a less than ideal transformer two resistive attenuators 25 and 26 shown in Fig. 4 are used.

This circuit is of the transformer "bridge" type and has the advantages that the oscillator, the unknown and the common terminal of the measuring circuit may be earthed, thus reducing the influence of stray voltages and currents upon the meter 11. If the resistors R_4, R_5, R_6 and R_7 have the values n_1p, n_2p, n_1q and n_2q respectively, then the ratio n_1/n_2 should be greater than 5 in order that the network shall function correctly in spite of transformer deficiencies.

In Fig. 4 resistors R_4 and R_5 have an effect equivalent to R_1 in Fig. 2, that is $1/R1=1/n_1p+1/n_2p$, and R6 and R7 have an effect equivalent to R3 in Fig. 2 that is $1/R3=1/n_1q+1/n_2q$.

In practice R5 would be made to include the resistance of the voltmeter 11, and in tests made at radio-frequencies the voltmeter impedance can form part of the termination of a transmission line, the input impedance of the line then being arranged to be resistive, and forming all or part of R5. The parallel combination of the voltmeter and any additional terminal impedance should be the characteristic (resistive) impedance of the line.

The ratio of the voltages E_1 to E_2 need not necessarily be unity. Even using a transformer with a centre tapped secondary winding having the same number of turns as the primary and thus ensuring that the secondary voltages are in phase with one another, the ratio of the voltages applied to the effective network need not be unity since the attenuators can be designed to attenuate the secondary voltages by different amounts.

The above described network and any network according to the invention will, of course, be subject to frequency limitations. What these limitations are, will be determined by network design and by choice of components. An example of the frequency range of one network is given later in the specification.

The circuit of Fig. 2 is equivalent to the four arm bridge of Fig. 3 if the transformer secondary windings are replaced by two resistors R_9 and R_{10}. If transformer 13 has a centre tapped secondary of the same number of turns as the primary then, on replacement, the resistors R_9 and R_{10} are equal and resistors R_{41} and R_{43} are not the same as resistors R_1 and R_3. The equations for the circuit of Fig. 2 do not apply to the circuit of Fig. 3. However a similar set of equations can be found which apply to Fig. 3.

The current dual of the circuit of Fig. 2 is shown in Fig. 6. A current sensitive detector 20, with theoretically zero resistance, a test object S, and two current generators 21 and 22 are used instead of the high impedance voltmeter, the test object T and the transformer secondary windings. If S equals $\left(\frac{F}{T}\right)$ where T as before equals the resistance of the test object and F is a normalising factor, and is $R_9=\frac{F}{R_1}$, $R_{10}=\frac{F}{R_2}$ and $R_{11}=\frac{F}{R_3}$, then this network conforms to the equations (1) to (4), the quantity M in the new equations representing the ratio of the current flowing in the detector 20 when the unknown is connected to the current flowing in the detector when the test terminals are open circuit. Here T, R_1, R_2 and R_3 are taken as numbers without dimensions and the normalizing factor F is any real positive number and has the dimensions of resistance.

The current generators 21 and 22 with the resistors R_9 and R_{11} respectively in parallel can be replaced by voltage generators with resistors R_9 and R_{11} in series. Such a circuit is shown in Fig. 7 where the two halves 24 and 25 of the transformer secondary winding are the voltage generators. It should be noted that the voltages V_1 and V_2 from the secondary winding are in opposition to one another round the loop, unlike the voltages E_1 and E_2 in Fig. 2, and also that $\frac{V_1}{V_2}=\frac{R_9}{R_{11}}$.

Practical values of R_9, R_{10} and R_{11} can be found from $R_9=\frac{F}{R_1}$, $R_{10}=\frac{F}{R_{11}}$ and $R_{11}=\frac{F}{R_3}$ or from an equation similar to equation (5) which can be found from the circuit of Fig. 7.

Such values are $R_9=\frac{F}{15}$, $R_{10}=\frac{F}{5}$ and $R_{11}=\frac{F}{4}$, with these values $\frac{V_1}{V_2}=\frac{R_9}{R_{11}}=\frac{4}{15}$. Hence, again there are many values of resistance which could be used to make a network of this type, the only restriction being $\frac{R_{10}}{R_{12}}>2$.

Another network of the type in which the current at the third terminals is reduced to zero when R_o is connected to the second terminals, its current dual and a four arm bridge equivalent will now be briefly mentioned. The network is shown in Fig. 8 and a low resistance current sensitive detector 20 is used. The sense of the voltages across the two halves of the secondary winding are as shown by the arrows. If also these voltages are equal and $R_{14}=mR_{12}$, where *m* is any real number, then

$$2R_{13}=\frac{R_{12}}{1+m} \text{ or } R_{13}=\frac{R_{12}}{2(1+m)} \quad \ldots (6)$$

and also

$$R_o=R_{12}-R_{13}=\frac{1+2m}{2(1+m)}R_{12} \quad \ldots (7)$$

The number *m* may therefore have any real value and therefore there are again many values of the resistances.

The dual form of this circuit is shown in Fig. 9, with two current generators 21 and 22, and a high resistance voltage detector 11. If the resistances and the test object in this network are proportional to the reciprocals of those in the network of Fig. 8, and

$$\frac{F}{R_{14}}=m'\frac{F}{R_{12}}$$

then equations (5) and (6) apply if *m* is replaced by *m'*.

The bridge form of the dual circuit of Fig. 9 is shown in Fig. 10. Here a voltage sensitive detector 11 is used and the resistances R_{15}

and R_{16} will be equal if the currents from the generators 21 and 22 in Fig. 9 are equal. Equations rather similar to (5) and (6) will apply to the bridge but only after they have been modified to allow for the presence of R_{15} and R_{16}.

In all the circuits illustrated it can be arranged that the detector and the test object have a common terminal. This terminal may be earthed.

It can be seen that there are many networks of different types which satisfy the conditions laid down. Any of these networks can be used in exercising the invention.

From equations (1) and (2) it can be seen that, in order to detect or measure the resistance of the unknown, it is necessary to measure the small quantity by which a voltage ratio fall short of unity. A circuit for making this measurement accurately is shown in Fig. 5.

A reference voltage from the terminals c, c′ is applied to an amplifier A_1 whose output is rectified by rectifier B_1 and applied to a capacitor C_1 which consequently has a unidirectional voltage V_1 developed across it. In the same way a capacitor C_2 has a voltage V_2 dependent on the alternative voltage at terminals a, a′ developed across it. Voltages V_1 and V_2 are added and combine to drive current through a resistor R_8. The point 16 of connection between the two capacitors is connected to earth. A tapping point 18 on the resistor R_8 can therefore be found which is at zero potential to earth and a milliammeter 17 connected between the tapping point 18 and earth is used to find this point.

In operation the tapping point on resistor R_8 for zero current in the milliammeter 17, is found with the terminals b, b′ open circuit, that is with T absent. The circuit can be checked by short circuiting the terminals b, b′ when the meter 17 should still read zero. The unknown T is then connected and a deflection in meter 17 results which is in accordance with the terms other than unity of equation (3) or an equation derived in a similar way. The voltages V_1 and V_2 are, in one embodiment, about 5 volts, R_8 has the value 1000Ω and the meter 17 reads from 0 to 50 μA. The oscillator delivers about 1 volt to a 1 : 1 transformer associated with a network in which $R_o=68\Omega$ and the gain of the amplifiers is about 30dB. Successful measurements have been made in the frequency range 100 c/s to 50,000 c/s.

The only requirement for the stability of the zero reading of the meter 17 is that the component circuits A_1, A_2, B_1, B_2 and the capacitors C_1 and C_2 retain their performance. Even gross deficiencies in performance can be corrected by moving the tapping point on resistor R_8. The frequency characteristics of the rectifier B_1 and B_2 and the amplifiers A_1 and A_2 are unimportant though it is an advantage that they behave alike if the frequency is changed but if they do not the tapping point can be readjusted.

From equation (3) it can be seen that r_s cannot be found directly from the change in $|M|$ unless β is known. However $|M|-1$ is proportional to r_s if β is constant, that is at a fixed frequency, and consequently it is possible to derive r_s by a substitution test, as follows.

If a deflection d_1 is measured on the meter 17 in Fig. 5 with the test object connected and then a known resistance R_B is connected in series with the test object and a new deflection d_2 is measured then, from equation (3),

$$\frac{d_1}{d_2}=\frac{2\left(\dfrac{r_s}{R_o}\right)/(1+\beta^2)}{2\left(\dfrac{r_s+R_B}{R_o}\right)/(1+\beta^2)}$$

and thence,

$$r_s=\frac{R_B}{\dfrac{d_2}{d_1}-1};$$

this, however, is an awkward formulation.

In Fig. 11, variable resistors RV4, RV5 are provided which allow r_s/R_B to be determined as the ratio of two deflections of meter 17.

Switch SW1 is first moved to the left hand position and then, by adjustment of the variable tap on potentiometer RV5 a voltage is applied across the meter equal to and in opposition to the voltage causing deflection d_1, thus reducing the deflection of the meter 17 to zero.

The resistance R_B in series with the test object is then adjusted to a known value (say one ohm). The deflection d'_2 now shown by meter 17 is adjusted to some convenient value, say 10 divisions, by a variable shunt resistance RV4. R_B is then reduced to zero and the new meter deflection d'_1 measured; as each division now corresponds to 1/10 ohm, f_s is measured as $d'_{1:10}$ ohms. To measure larger values of r_s, R_B is increased as required.

The circuit of Fig. 11 also includes elements for reducing errors in the measured value of r_s due to the network not being entirely resistive. These errors mainly arise from the ratio of the voltages of the transformer secondaries not being unity and from small reactive terms in the transformer output impedances.

A variable resistance RV2 is used to correct for changes in circuit performance due to the departure of the voltage ratio from unity and the reference voltage at the rectifier B_1 is derived not from the oscillator as in Fig. 4 but from one half of the transformer secondary; this makes the circuit performance largely independent of the transformation ratio. Since this reference voltage may change slightly with frequency a small variable resistance RV3 is included to allow the initial zero setting of 17 to be adjusted precisely.

The procedure for setting up the circuit of Fig. 11 is as follows:—

(1) Set R_B to zero,

(2) short the terminals b-b',

(3) Put SW1 to the right, thus disconnecting battery Bb,

(4) Adjust the tap R8 (course control) or RV3 (fine control) until 17 reads zero.

(5) Open circuit the terminals b—b', and

(6) Adjust RV2 until the meter again indicates zero.

(If large adjustments were called for, repeat from the third item)

The circuit is then ready, the test object may be connected and its resistance r_s measured, SW1 put to the left and 17 being calibrated by RV4, RV5 and RS as already described.

WHAT I CLAIM IS:—

1. A network consisting of purely resistive components, purely reactive components or components of complex impedance which all have the same time constant, and first, second and third pairs of terminals, the network having the property that, when an oscillator is connected to the first pair of terminals so as to cause a voltage or short-circuit current to appear at the third pair of terminals, the voltage or current is reduced to zero when an impedance matching that seen looking into the second pair of terminals (with the oscillator connected as described) is connected across these latter terminals.

2. A resistive network according to claim 1, wherein the voltage at the third pair of terminals is reduced to zero, including a transformer with the input to the primary winding forming the first pair of terminals and having a tapped secondary winding, the two ends of the secondary winding being connected through three resistors in series, the second pair of terminals being the junction of two of the resistors and the tapping point of the secondary winding, and the third pair of terminals being the other junction of resistors and the tapping point.

3. A network according to claim 1, wherein the voltage at the third pair of terminals is reduced to zero, including three resistors connected in series between the first pair of terminals, and two further resistors connected in parallel with the three resistors, the second pair of terminals being one of the junctions between two of the three resistors, and the junction of the two further resistors, and the third pair of terminals being the other of the junctions between two of the three resistors and the junction of the two further resistors.

4. A network according to claim 1 wherein a current in a short circuit between the third pair of terminals is reduced to zero, including a transformer with a tapped secondary winding, the input to the primary winding forming the first pair of terminals, two resistors each connected to one end of the secondary winding and a third resistor connected to the tapping point of the secondary winding, the second pair of terminals being the unconnected end of one of the two resistors and the unconnected end of the third resistor, and the third pair of terminals being the unconnected end of the other of the two resistors and the unconnected end of the third resistor.

5. A network according to claim 2 or 4 further comprising a voltage or current measuring means connected to the third pair of terminals and wherein resistive attenuators are connected in place of the resistors connected to the secondary windings, one of these attenuators incorporating the resistance of the measuring means, whereby the network impedance as seen looking into the second pair of terminals appears substantially resistive.

6. A network according to claim 5 wherein the measuring means include a first amplifier and a first rectifying circuit to provide a first unidirectional voltage proportional to an alternating voltage appearing at the third pair of terminals, and further comprising a second amplifier and a second rectifying circuit to provide a second unidirectional voltage proportional to an alternating voltage applied at the first pair of terminals, the two unidirectional voltages being applied to two capacitors respectively, which are connected in series across a potentiometer, and the tapping point of the potentiometer being connected through a d.c. meter to the junction of the two capacitors, whereby the voltage across the third pair of terminals when a test object is connected to the second pair of terminals can be compared with the voltage across the third pair of terminals when the second pair of terminals are open circuit.

7. A network according to claim 6, wherein one of the resistances connected to the ends of the transformer secondary winding is shunted by a variable resistor.

8. A network according to claim 6 or 7 wherein a first variable resistance is connected to one of the second terminals to be in series with the test object when connected, and further comprising a variable voltage source connected across the d.c. meter whereby its deflection can be set to zero when the first variable resistance has been adjusted to zero, and a second variable resistance connected across the d.c. meter whereby its deflection can subsequently be set to some convenient reading when the first variable resistance is set to a known value.

9. A method of measuring or detecting resistance in the presence of reactance by applying an alternating voltage to the first pair of

terminals of a resistive network according to any of claims 1 to 4, finding the modulus of the voltage or short circuit current appearing at the third pair of terminals when a test object is connected to the second pair of terminals, and comparing this modulus with the modulus of the voltage or current at the third pair of terminals when the second pair of terminals is open circuited or short circuited.

10. A method according to claim 9, wherein the modulus voltages are compared further comprising converting the alternating voltage appearing at the third pair of terminals to a first uni-directional voltage, providing a second uni-directional voltage proportional to alternating voltage applied at the first pair of terminals, combining the uni-directional voltages in such a way as to produce a predetermined voltage when the second pair of terminals is open or short circuited and finding the difference between the uni-directional voltages combined in the same way and the predetermined voltage, when a test object is connected to the second pair of terminals.

11. A method of measuring or detecting reactance in the presence of resistance by applying an alternating voltage to the first pair of terminals of a purely reactive network according to claim 1, finding the modulus of the voltage or the short circuit current appearing at the third pair of terminals when a test object is connected to the second pair of terminals, and comparing this modulus with the modulus of the voltage or current at the third pair of terminals when the second pair of terminals is open circuited or short circuited.

12. A method of measuring the characteristic time constant of a test object or detecting when the time constant of a test object differs from a predetermined value, the method comprising an alternating voltage to the first pair of terminals of a network according to claim 1 made up of components having complex impedances and all having the same time constant, finding the modulus of the voltage or the short circuit current appearing at the third pair of terminals when a test object is connected to the second pair of terminals, and comparing the modulus with the modulus of the voltage or current at the third pair of terminals when the second pair of terminals is open circuited or short circuited.

13. A network substantially as hereinbefore described with reference to and as shown in Figs. 1, 2, 4, 5 and 11 of the drawings accompanying the provisional specification.

14. A network substantially as hereinbefore described with reference to and as shown in Fig. 3 of the drawings accompanying the provisional specification.

15. A network substantially as hereinbefore described with reference to and as shown in Figs. 5 and 7 of the drawings accompanying the provisional specification.

16. A network substantially as hereinbefore described with reference to and as shown in Fig. 8 of the drawings accompanying the provisional specification.

17. A network substantially as hereinbefore described with reference to and as shown in Figs. 9 and 10 of the drawings accompanying the provisional specification.

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Fig. 1.

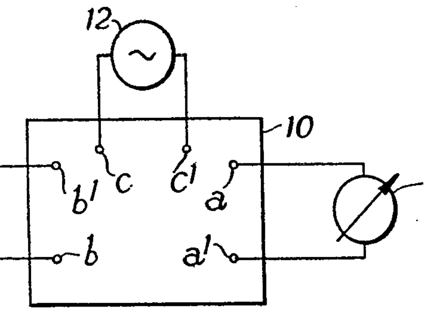
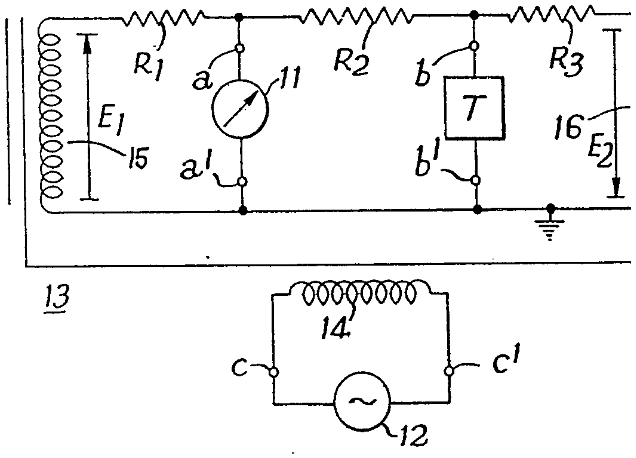


Fig. 2.



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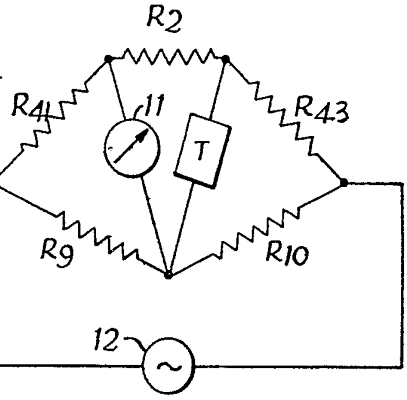

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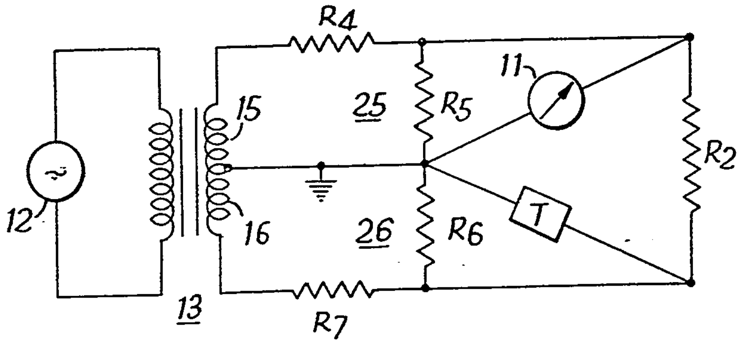
Fig. 4.



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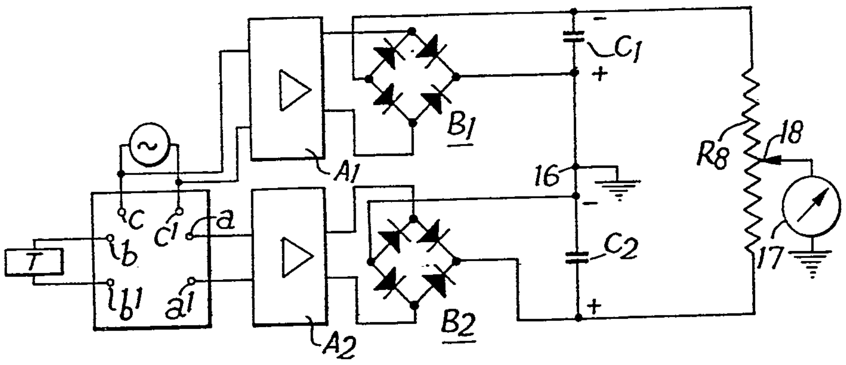

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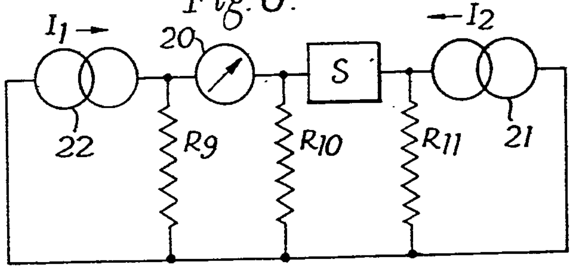

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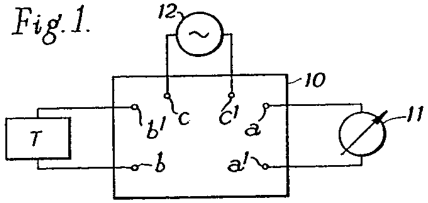

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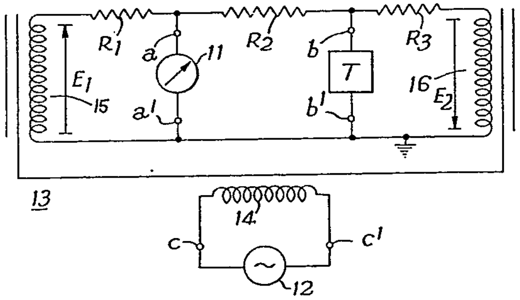

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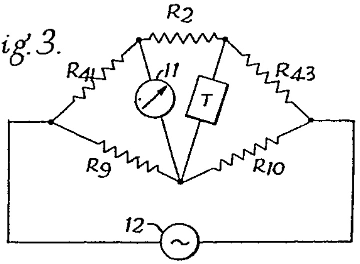

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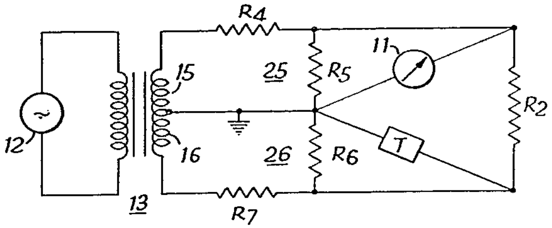

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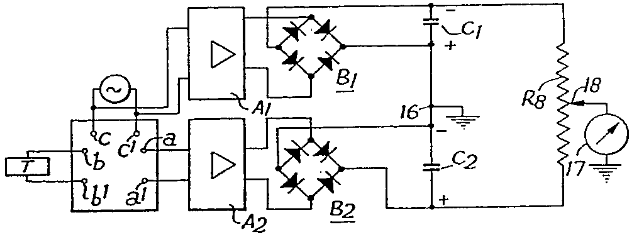

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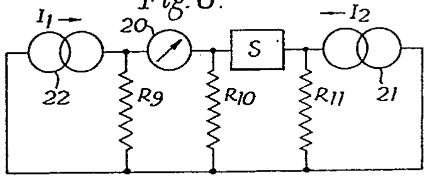

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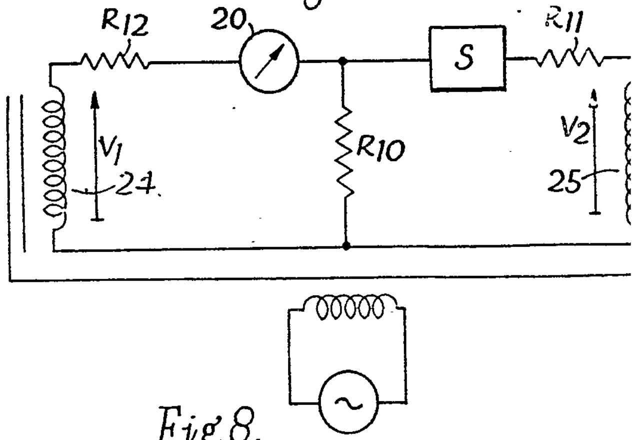

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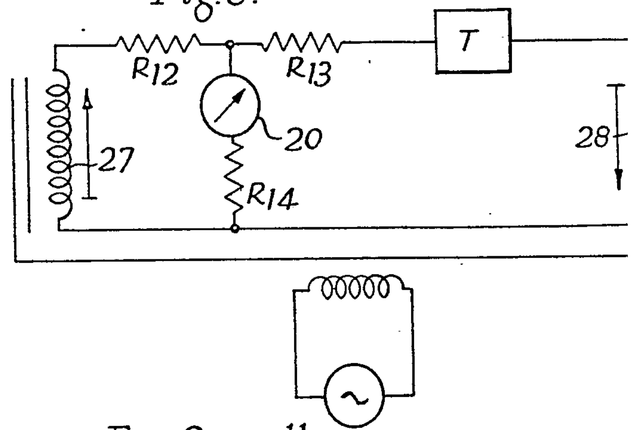

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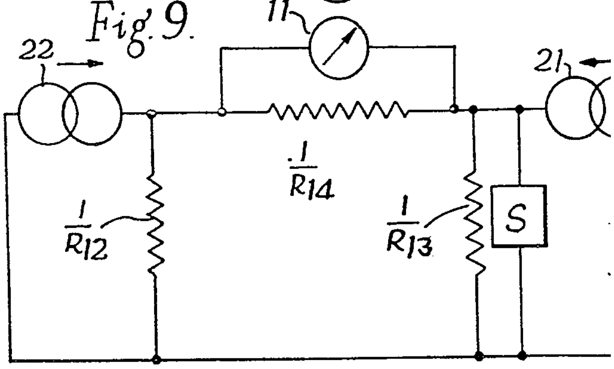

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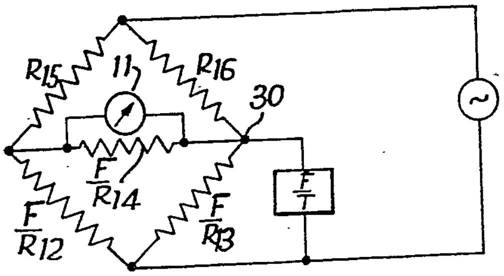
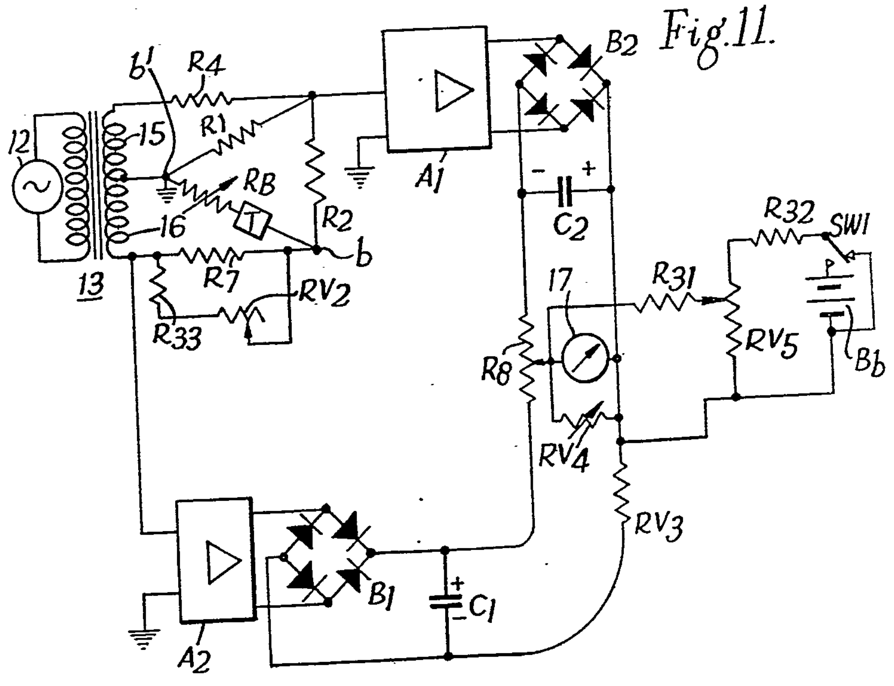

R15
11
R16
30
F/R14
F/R12
F/R13
F/T

Fig. 11.


b'
R4
R1
12
15
RB
T
16
R2
b
13
R7
RV2
R33
A1
B2
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C2
17
R31
R32
SW1
RV5
Bb
R8
RV4
RV3
A2
B1
+
C1

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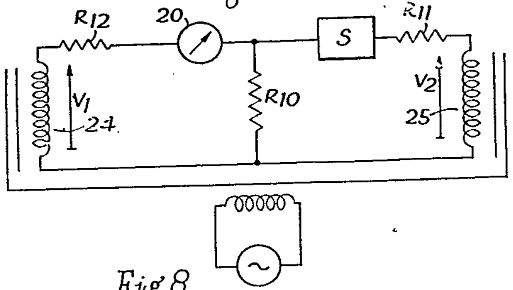
Fig. 7.



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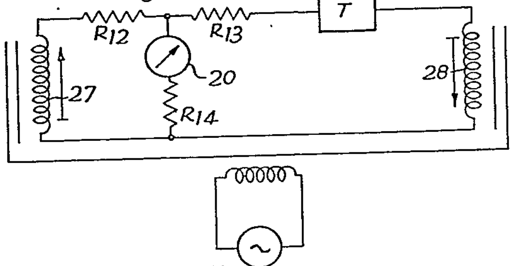
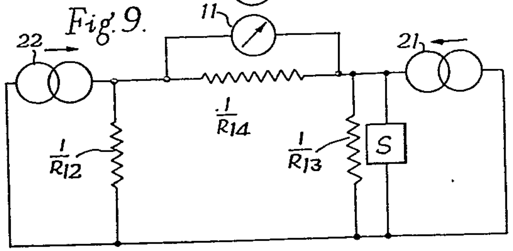


Fig. 9.



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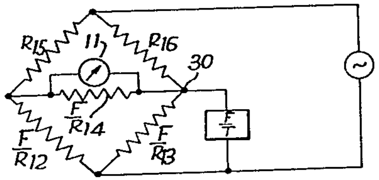

Fig. 11.