OPERATING INSTRUCTIONS
FOR

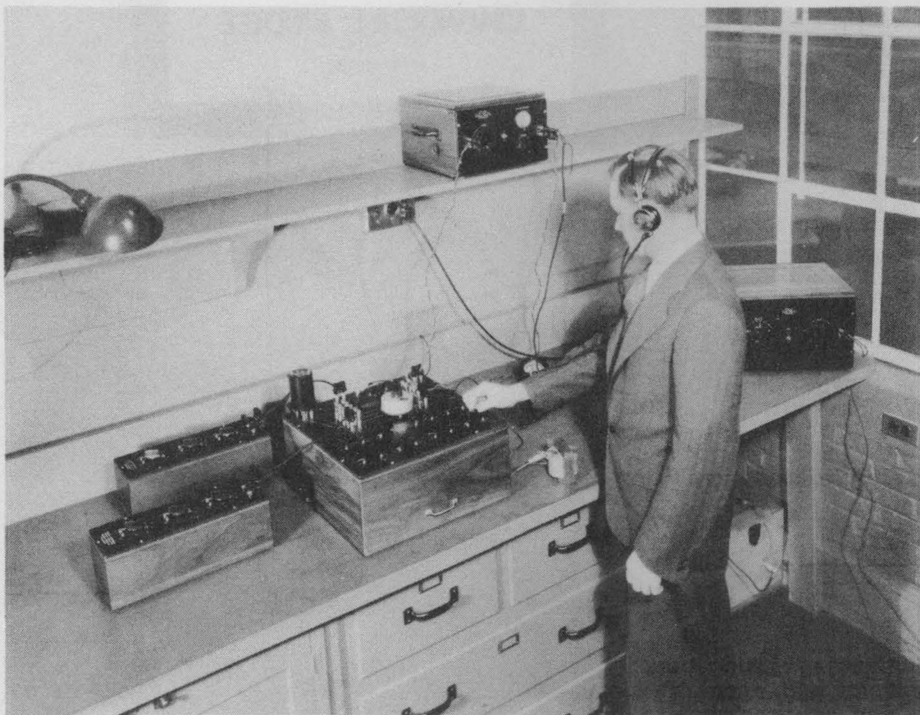
TYPE 293-A
UNIVERSAL BRIDGE

FORM 292C

GENERAL RADIO COMPANY
CAMBRIDGE A, MASSACHUSETTS

TABLE OF CONTENTS

	Page
SECTION 1 - Purpose of the Instrument - - - - - - - - - -	1
SECTION 2 - Theory of the Alternating-Current Bridge- -	1
SECTION 3 - Construction of the Instrument- - - - - - -	7
SECTION 4 - Suggestions for Use - - - - - - - - - - - - -	10
TABLES AND DIAGRAMS - - - - - - - - - - - - - - - - - - -	13



Measuring the inductance and effective resistance of a choke coil by means of the Owen bridge arrangement of the Type 293-A Universal Bridge. A Type 293-P2 Transformer is plugged in at the "IN" terminal of the bridge. The cylindrical aluminum case near the center of the panel is a Type 293-P3 Slide-Wire Resistor.

OPERATING INSTRUCTIONS

FOR

TYPE 293-A UNIVERSAL BRIDGE

SECTION 1
PURPOSE OF THE INSTRUMENT

The Type 293 Universal Bridge is designed to provide a flexible bridge circuit from which may be constructed any one of the various bridge circuits available for the measurement of resistance, self and mutual inductance, capacitance, and frequency. The limits imposed on the magnitude and accuracy of measurement of each of these quantities are, in general, those set by the particular bridge used. This bridge may be used for both direct-current and alternating-current measurements.

SECTION 2
THEORY OF THE ALTERNATING-CURRENT BRIDGE

The four-branch network devised by Wheatstone for use with direct current is applicable to the comparison of impedances by the use of alternating current. This bridge is shown in Figure 1a. For the condition of no current in the telephones or other detecting element, the four imped-

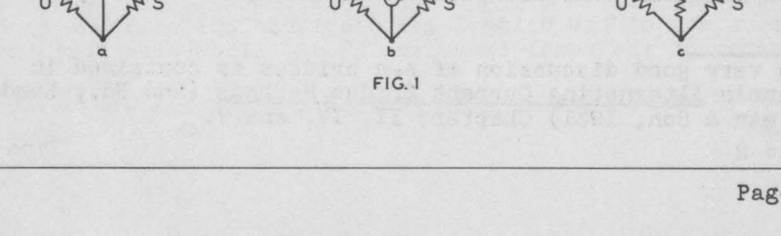


FIG. 1

ances are related by the equation*

$$\frac{Z_A}{Z_B} = \frac{Z_U}{Z_S},$$

or

$$Z_A Z_S = Z_B Z_U. \tag{1}$$

These impedances are, in general, vectors, containing both resistance and reactance, being of the form

$$Z = R + jX. \tag{2}$$

Expanding Equation (1)

$$\frac{A + jX_A}{B + jX_B} = \frac{U + jX_U}{S + jX_S} \tag{3}$$

and separating the real and imaginary components

$$AS - X_A X_S = BU - X_B X_U$$

$$AX_S + SX_A = BX_U + UX_B\ . \tag{4}$$

If the arms A and B are pure resistance, so that

$$X_A = X_B = 0,$$

Equations (4) reduce to their well known form

$$AS = BU$$

$$AX_S = BX_U \tag{5}$$

$$\text{or}\quad \frac{A}{B} = \frac{U}{S} = \frac{X_U}{X_S}. \tag{6}$$

When all four arms are pure resistances, as is always the

* A very good discussion of a-c bridges is contained in Hague's Alternating Current Bridge Methods (2nd Ed.; London: Pitman & Son, 1931) Chapters II, IV, and V.

case when the bridge is used on direct current, Equations (6) reduce to

$$AS = BU$$

$$\text{or} \quad \frac{A}{B} = \frac{U}{S}. \tag{7}$$

Whenever any of the branches contains impedances in parallel, it is usually easier to substitute the expression for their equivalent series impedance directly in Equation (1) than (4). The series impedance of two parallel impedances Z_1 and Z_2 is

$$Z = \frac{\left(R_1R_2 - X_1X_2\right) + j\left(R_1X_2 + R_2X_1\right)}{\left(R_1 + R_2\right) + j\left(X_1 + X_2\right)}. \tag{8}$$

For the frequently used case of a capacitance in parallel with a resistance, for which

$$R_1 = R; \quad X_1 = 0; \quad R_2 = 0; \quad X_2 = -\frac{1}{\omega C}, \tag{9}$$

the impedance is given by

$$Z = \frac{R}{1 + jR\omega C}. \tag{10}$$

The six-branch method used in the Anderson bridge is shown by Figure 1b. Its balance condition is given by

$$Z_Q\left(Z_BZ_U - Z_AZ_S\right) = Z_P\left[Z_P\left(Z_A + Z_B\right) + Z_AZ_B\right]. \tag{11}$$

It will be noted that the Wheatstone four-branch network of Figure 1a is a special case of this larger network, obtained by setting $Z_P = 0$ and Z_Q = infinity.

Mutual inductances are frequently introduced between the various branches of the four-branch network of Figure 1a. The general case is discussed by Hague.* The balance condition for the simple case shown in Figure 1c is

$$Z_AZ_S - Z_BZ_U - j\omega M\left(Z_A + Z_B\right) = 0, \tag{12}$$

* B. Hague, Alternating Current Bridge Methods, pp.59-62.

which also reduces to Equation (1) if $M = 0$.

Practically all of the bridge circuits which have been devised for the intercomparison of impedances at a given frequency make use of one of these three networks. A complete discussion of the various bridge circuits is given by Hague.* The choice of the proper bridge circuit for the measurement of a particular impedance depends on its magnitude, on the standards available, and on the frequency at which the measurement is to be made. The present discussion classifies bridge circuits according to the relation of the standard to the unknown impedance and briefly touches upon certain sources of error, which are frequently encountered.

When the unknown impedance and the standard are similar, the bridge to be used is the four-branch network shown in Figure 1a. Two of the arms, A and B, are made pure resistances and the other two arms, U and S, contain the unknown and standard, respectively. Equation (6) becomes for inductances

$$\frac{A}{B} = \frac{U}{S} = \frac{L_U}{L_S} \tag{13}$$

and for capacitances

$$\frac{A}{B} = \frac{U}{S} = \frac{C_S}{C_U} \tag{14}$$

while for pure resistances the first two terms of either equation suffice. These equations are independent of frequency. If the various impedances in the bridge are constant with frequency, the bridge will be balanced for the harmonics of the fundamental frequency when it is balanced for the fundamental itself. In this rare case a true null point will exist at balance even when a power source rich in harmonics is used. This condition will exist when the four arms contain only pure resistances, when the two reactances are pure, or when the two reactances have the same phase angle, i.e., ratio of reactance to resistance. In general, it is desirable to have the power source as nearly a pure sine wave as possible. The use of a low-pass filter, such as the General Radio Type 330 Filter Sections, suitably chosen for cut-off frequency and characteristic impedance, or a tuned circuit, will minimize the effect of harmonics. Such a device is more effective between the bridge and null detector than between the

* B. Hague, <u>Alternating Current Bridge Methods</u>, Chapters IV and V.

power source and bridge because the impedance of the null detector is usually higher than that of the bridge.

Since there are two conditions for balance, one containing only resistances and the other containing the reactances, there must be at least two variables in the bridge arms. These variables should be independent in the sense that each should appear in only one of the balance equations. Since the ratio arms A and B occur in both equations, both components, S and X_S, of the standard must be variable in order to comply with this condition. When the standard of reactance X_S is fixed, one of the ratio arms must be variable and the two balance conditions, resistive and reactive, are no longer independent. Each time the ratio arm is adjusted in order to improve the reactive balance, the previous resistive balance obtained by adjusting S is disturbed. If the reactance of the standard is large compared to its resistance, i.e., large phase angle or small phase difference, complete balance of the bridge may be obtained with a few successive adjustments of the ratio arm and S. If, on the other hand, the resistance component is the larger, as is likely to happen with small inductances or large capacitances at low frequencies, many successive adjustments are required and exact balance can be determined only by the quantitative comparison of successive minima.

The resistance balance may also be made by introducing variable reactance into one or both of the ratio arms, as suggested by Grover.* These reactances may be either inductances in series or capacitances in parallel. This method is usually adopted only for the comparison of reactances having small power factors or phase differences, because in that case some of the correction terms of Equation (4) are negligible.

No impedances can be built which are pure. All contain a trace of the quadrature component, sometimes termed a residual. Resistances are slightly reactive, the small units being inductive and the large units capacitive. Capacitances have energy losses due to the solid dielectric used for insulation, which give them resistances or phase differences. Self inductances have relatively large resistances due to the ohmic resistances of their windings, increased at the higher frequencies by skin effect in the conducting wires and by energy losses in the distributed capacitance of the winding. Mutual inductances have mutual capacitances between primary and secondary, which introduce a resistive term and make them mutual impedances. By analogy frequency may be called impure when it contains harmonics. Of the four kinds of impedance

* B. Hague, Alternating Current Bridge Methods, p. 275.

mentioned, the capacitance obtained from an air condenser is most free from residuals over the widest frequency range. Certain types of resistances are next, while the residuals of self inductances are the largest.

It is necessary when measuring small reactances or the resistance of large reactances to consider the effect of these residuals. When the standard and unknown are in adjacent arms, the numerical magnitudes of the residuals must be known and then subtracted from the results obtained from the balance equations. Their effect may be eliminated by a substitution method, in which the standard and unknown are introduced in turn into the same bridge arm. A double set of balance equations is thus obtained, from which many of the residuals may be eliminated. A number of examples of this sort of measurement are given in the Instruction Book for the General Radio Type 216 Capacity Bridge.*

When the unknown and the standard are different kinds of impedances, any of the three networks shown in Figure 1 may be used. A list of the more important bridges is given in Table I. The type of network used, the unknown and standard impedances, the use of two impedances in parallel in one bridge arm, and the independent variables, are shown. The first three bridges, impedance, Grover, and Schering, belong in the class just discussed, in which the unknown and standard are similar. Grover's bridge is used when it is undesirable to obtain the resistance balance by means of a resistance in series with the unknown or standard reactance, because this added resistance makes it impossible to keep one side of each capacitance at ground potential. Schering's bridge is merely a modification of Grover's, in which a single parallel capacitance provides the resistance balance. The ground is placed between the two ratio arms, so that high voltages may be used with safety and the standard condenser is frequently made to have no losses by suitable shielding of the dielectric supporting the high potential plates.

An inductance may be compared with a capacitance by the use of Maxwell's or Owen's bridge. The balance for these bridges is independent of frequency. In Maxwell's bridge, the standard capacitance must be variable to allow the two balance conditions to be independent. In Owen's bridge it may be fixed.

The other three bridges of the four-branch network type are not independent of frequency. Hay's bridge was devised for the measurement of large inductances in terms of a capacitance. It is frequently used in the measurement of iron

* Obtainable on request from General Radio Company.

core inductances with direct current in their windings. There is only one independent variable. The resonance bridge and Wien's bridge depend directly on frequency and may be used as frequency meters. Wien's bridge is preferable for this use because only the resistances need be variable and there can be no magnetic pickup. The General Radio Type 434-B Frequency Meter uses this bridge circuit. For the measurement of inductance or capacitance in terms of resistance and frequency, this bridge can be made to yield accurate results, but its adjustment is tedious because there is only one independent variable. The resonance bridge provides for the measurement of inductance in terms of capacitance and frequency. It also gives an easy method of determining the combined resistance of the inductance and capacitance at their resonant frequency.

The six-branch network of Figure 1b was devised by Anderson to provide Maxwell's bridge with two independent variables not including the standard capacitance. Its residuals give more trouble than those in Owen's bridge. Hay's modification provides for the measurement of the residual capacitance of a resistance in a manner similar to that by which the residual inductance of a resistance may be measured on the original Anderson's bridge.

The last two bridges in the list make use of mutual inductance. Campbell's bridge provides for the comparison of a self inductance with a mutual inductance, which must be variable to provide two independent variables. The use of equal ratio-arms and a center tap on the primary of the mutual inductance was suggested by Heaviside. A capacitance may be compared with a mutual inductance on Carey Foster's bridge. Residuals in the mutual inductance prevent the determination of the resistance of large capacitances.

SECTION 3
CONSTRUCTION OF THE INSTRUMENT

The Type 293 Universal Bridge consists of three variable resistances connected to a terminal board so arranged that they may be connected together and to input and output circuits by means of short links or flexible cables in order to form the various bridge circuits discussed in Section 2. Two of the resistances consist of four decades: units, tens, hundreds, and thousands of ohms. The third resistance has five steps varying by factors of 10 from 1 to 10,000 ohms, inclusive. The terminal board is built up with Type 138-V Binding Posts having jack tops. They are arranged with standard spacing of 3/4 inch to allow interconnection by means of Type 274 Plugs.

The principle on which the jacks are arranged is shown graphically in Figure 2. The three resistances, A, B, S, and the external circuit element U form the four arms of a simple Wheatstone bridge. The connecting links shown make this diagram equivalent to Figure 1a. There are twenty posts forming the closed circuit of the bridge, Nos. 7-13, 15-18, 20-21, 23-29, inclusive. The extra twelve posts in excess of the eight necessary for the terminals of the four arms allow extra circuit elements to be placed in series with, and on either side of, any arm. There are ten posts, Nos. 1, 2, 5, 6, 14, 22, 30, 31, 34, 35, which are used for the introduction of input and output transformers and the connection of the input or output to any part of the closed circuit of the bridge. There are five posts, Nos. 3, 4, 19, 32, 33, which serve to connect the shields of the input and output transformers to the shields separating the three internal resistances, the panel, the cabinet shield, and ground. The closed bridge circuit may be connected to ground at any point by a flexible link. The actual arrangement of the jacks and the order of connection of the decades is shown in Figure 3.

The three internal resistances are similar to General Radio Type 602 Decade-Resistance Boxes in their construction and electrical characteristics. Their accuracy of adjustment is 0.1% for all values except the one-ohm units, for which the accuracy is 0.25%. The contact resistance of the switches themselves is not included in the values as marked, but must be added whenever it is of importance. It amounts to about 0.0015 ohm per switch. Plug resistances are about 0.002 ohm. These contact resistances will therefore usually amount to 0.014 ohm for the A and B arms and 0.010 ohm for

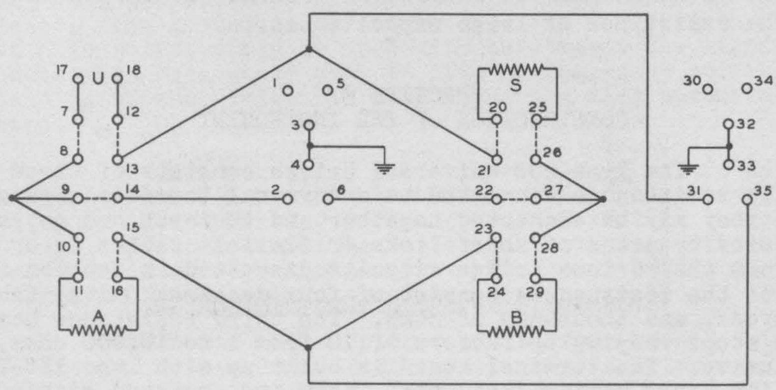


FIG. 2

the S arm. Their capacitances to the shields are of the order of 60 μμf for the four-decade resistances A and B, or roughly 15 μμf per decade, and 10 μμf for the resistance S. The effect of these capacitances depends on the type of bridge circuit used and the position of the resistance in the bridge with reference to ground.

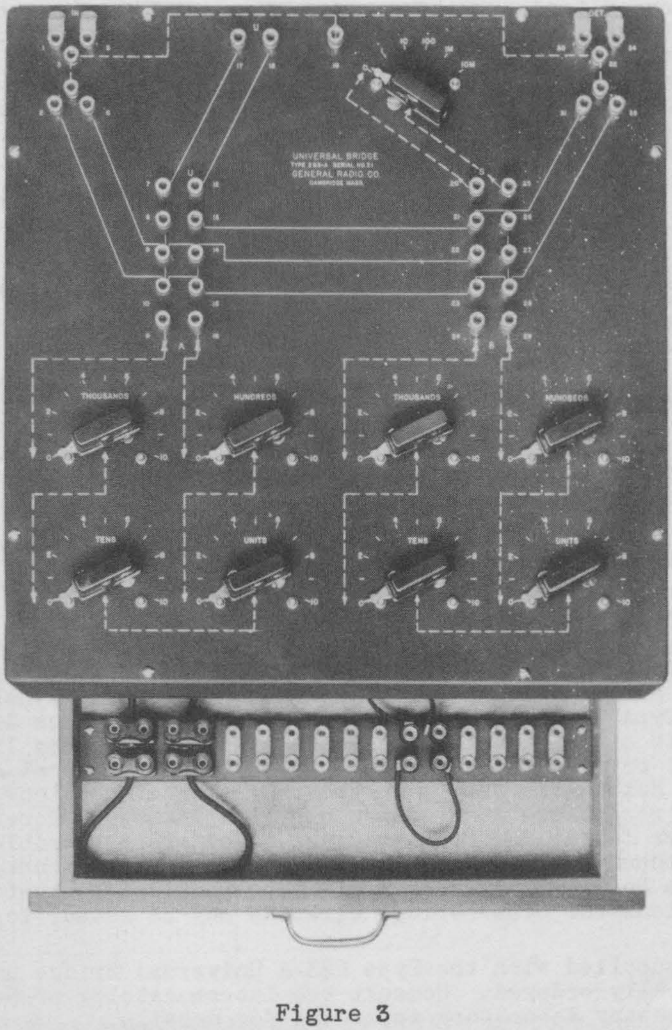


Figure 3

See the table on page 11 for current-carrying capacities of resistors used in the bridge.

Type 293-P1 and P2 Transformers* are shielded transformers covering a frequency range from 50 to 500 cps. They have a magnetic shield of soft iron to eliminate inductive pickup, instead of being wound astatically. There is an electrostatic shield between the two windings which is also connected to the iron core. The turns ratios, inductances, direct capacitances between primary and secondary, and capacitances to shield, both total and as divided when the shield is halfway in potential between the ends of each winding, are given in Table II. Since these transformers may be connected to the bridge either step-up or step-down, the two types cover the range of impedances likely to be measured. Other types for higher frequencies can be constructed.

In the measurement of low impedances it is frequently desirable to vary the resistance arms in steps smaller than one ohm, and at least one resistance should be continuously variable. The Type 293-P3 Slide Wire* is a bifilar resistor having a total resistance of 1.2 ohms. Its two parallel wires are 0.01 inch in diameter, spaced 0.06 inch apart, and wound around the periphery of a 2-3/8-inch bakelite drum. A sliding contact rotates around the drum, short-circuiting the loop of wire beyond the contact. The inductance of this resistor at its maximum resistance setting is about 0.3 μh. It is completely shielded and is provided with plug terminals for mounting on the terminal board of the bridge in series with any resistance arm.

SECTION 4
SUGGESTIONS FOR USE

Schematic diagrams of the various bridge circuits described in Section 2 are shown in the accompanying appendix. A sketch of the twenty jack posts of the terminal board of the Type 293 Universal Bridge is given below each diagram and on it are marked the positions of the connecting links for that bridge, together with the permanent internal connections. Below this are given the two balance equations, solved for the resistance and reactance of the unknown. Equations for power factor and frequency are added where possible. Another appendix similar to this, containing blank schematic diagrams and terminal boards, is also provided so that the connections for other bridge circuits may be added, together

* Not supplied with the Type 293-A Universal Bridge unless specifically ordered. Consult the latest catalog of General Radio Company laboratory apparatus for details.

with the positions of the connecting links and balance equations.

At least one shielded transformer is necessary, connected to either the input or output of the bridge, in order to eliminate the effects of unsymmetrical capacitances to ground of the power source or detector. Its position is determined by the point of grounding of the bridge. It is connected to the input if the detector is grounded, and to the output if the source is grounded. The capacitance to the shield of the winding of the transformer connected to the bridge is placed in parallel with the two arms of the bridge between which the ground is connected. Its division between these two arms depends on the design and construction of the transformer. The Type 293-P1 and P2 Transformers designed for use with this bridge have been described in Section 3.

The effect of these capacitances depends on the magnitude of the impedances of the bridge arms with which they are in parallel. These effects may be eliminated by the use of a Wagner ground,* as shown in Figure 4. This is a device for adjusting the capacitances to ground of the shielded transformer and the various arms of the bridge to have the same ratio as the bridge arms themselves at balance. In its most general form it consists of pairs of variable resistances and capacitances connected across the transformer. The auxiliary bridge, formed by these impedances and two arms of the bridge, such as A and B, is balanced.

TABLE
Current for Temperature Rise of 20° C. and 40° C.

Decade	*20° C. Rise*	*40° C. Rise*
0.1-ohm steps	1 a	1.5 a
1 -ohm steps	600 ma	1 a
10 -ohm steps	170 ma	250 ma
100 -ohm steps	50 ma	80 ma
1000 -ohm steps	5 ma	23 ma
10,000 -ohm steps	5 ma	7 ma

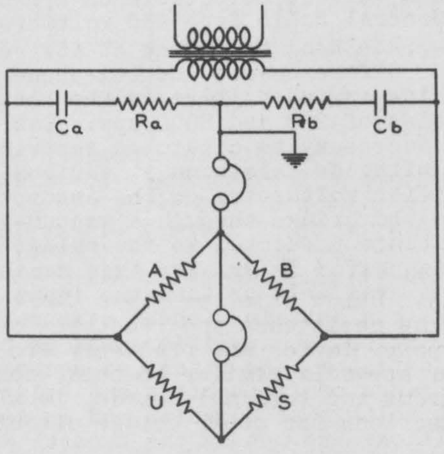


FIG.4

* B. Hague, Alternating Current Bridge Methods, pp.367-371.

The Type 293 Universal Bridge requires as external equipment an a-c power source, a null detector, and the necessary standards. Table III lists General Radio Company equipment of this type. The choice of standards is determined mainly by the magnitude and kind of the unknown impedance and the accuracy of measurement desired. The choice of null detector, whether telephone or meter, is determined by the frequency range used and the accuracy desired. The frequency range of the usual head telephone extends from 300 to 5000 cps. It is most sensitive at its natural frequency, which occurs at about 900 cps. This fact makes the use of the telephone difficult at frequencies less than half its natural frequency when the harmonic content of the power source is large. The choice of power source and its partial equivalent, amplification between bridge and null detector, is determined by the accuracy of measurement desired. The ratio of the voltage across the null detector to the input voltage for an unbalance of the bridge equal to the accuracy desired for a four-arm bridge, all of whose arms are equal pure resistances, is given by

$$\frac{E_o}{E_i} = 1/4 \frac{D/A}{1 + D/A} d \qquad (15)$$

where D and A are the resistances of null detector and bridge arms respectively and d is the error allowable. Their ratio therefore lies between 1/8 d and 1/4 d for ratios of detector and bridge-arm resistance between one and infinity. The minimum voltage detectable on a rectifier voltmeter, such as the General Radio Type 488 Voltmeter,* is 0.1 volt; on a high-grade head telephone at its resonant frequency, 0.002 volt. Off resonance the telephone loses sensitivity rapidly, becoming as insensitive as the rectifier voltmeter at frequencies of 200 and 5000 cps. Table IV gives the input voltages necessary to obtain an accuracy of balance of 1% and of 0.1% with the telephone at various frequencies and with a rectifier voltmeter, on the assumption that both are connected to the bridge through a vacuum-tube amplifier, so that the resistance presented to the bridge is infinite. Whenever the voltage given is greater than can be obtained from the power source available or than the input transformer or arms of the bridge can sustain without overheating or changing their characteristics, an amplifier must be used between the bridge and null detector. To attain an accuracy of 0.1% over a reasonable range of frequencies and bridge-arm ratios requires an input voltage of 30 volts and an amplification of 200. These conditions are met by the General Radio Type 508 Oscillator* and the General Radio Type 514 Amplifier.*

* Consult the latest catalog of General Radio Company laboratory apparatus for details.

TABLE I

Bridge	I Network	II U	III S	IV Parallel	V Independent Variables
Impedance	a	R L C	R L&R C&R		S L_S & S or U C_S & S or U
Grover	a	C C	C&R C&R	 R & C	 C_S or A & L_A C_S or A & C_A
Schering	a	C	C&R	R & C	A & C_A
Maxwell	a	L	C&R	R & C	C_S & S or U
Owen	a	L	C&R		A & C_A or U
Hay	a	L	C,R&f		S
Resonance	a	L f	C&f L&C		C_S & S or A C_S or L&S or A
Wien	a	C L f	R&f R&L C&R		A A A
Anderson	b	L	C&R		C_S or A & A'
Anderson-Hay	b	C	C&R	R & C	C_S or A & A'
Campbell	c	L	M&R		M_S & U
Carey Foster	c	C M	M&R C&R		A & U A & S

Explanation of Table

Column I: a, b, c, refer to Fig.1a, Fig.1b, Fig.1c, respectively.

Columns II & III: Symbols refer to circuit elements -- R resistance, L self inductance, M mutual inductance, C capacitance, f frequency.

Column IV: R & C indicate resistance and capacitance in parallel.

Column V: Symbols refer to bridge arms L_S, C_S, M_S, the standards, S the resistance in arm containing the standard, U the resistance in arm containing the unknown, A the resistance in any other arm.

TABLE II

Transformer	Turns Ratio	Winding	L h	Capacitances in μμf Direct	Shield	Divided	
193-P1	3-1	Low	.28	3	160	30	130
		High	2.5		150	45	105
193-P2	2.55-1	Low	3.8	6	160	50	110
		High	25		200	35	165

TABLE III

OSCILLATORS

Type	Instrument	Frequency Range		
213	Audio Oscillators (tuning fork)	400	or	1,000
241	Microphone Hummer			1,000
377-B	Low-Frequency Oscillator	25	to	70,000
508-A	Oscillator	200	to	4,000
513-B	Beat-Frequency Oscillator (A.C.)	10	to	10,000
613-B	Beat-Frequency Oscillator (D.C.)	10	to	10,000

TRANSFORMERS AND FILTERS

359	Variable Ratio Transformers
166	Telephone Transformers
285	Transformers
585	Transformers
330	Filter Sections
530	Band-Pass Filter
534	Band-Pass Filter

AMPLIFIERS

514-A	Amplifier	25	to	70,000

TABLE III (Continued)

Type	Instrument	Frequency Range
	NULL DETECTORS	
	Western Electric Head Telephones W E Type Number 1002-C	200 to 10,000
338-G	Vibration Galvanometer	50 to 1,000
426-A	Thermionic Voltmeter	10 to 3,000,000
626-A	Vacuum-Tube Voltmeter	10 to 3,000,000
483	Output Meters	0 to 20,000
488	A-C Voltmeters	0 to 20,000
	STANDARDS AND BALANCING REACTORS	
602	Decade-Resistance Boxes	
133	Standard Resistances	
500	Resistors (plug-in type)	
106	Standard Inductances	
107	Variable Inductors	
219	Decade Condensers	
222	Precision Condensers	
246	Condensers	
505	Condensers (plug-in type)	

TABLE IV

Detector	f	E in volts for d = 1%	d = 0.1%
Telephones	100 cps	80 volts	800 volts
	200 "	8 "	80 "
	500	1.0 "	10 "
	1 kc	0.4 "	4 "
	2 "	0.8 "	8 "
	5 "	12 "	120 "
	10 "	80 "	800 "
Voltmeter	any	80 "	800 "

APPENDIX

1. The number assigned to each bridge in the following diagrams corresponds to the order in which it is listed in Table I.

2. The name given is that of the discoverer or early user of the bridge, or is descriptive of its use.

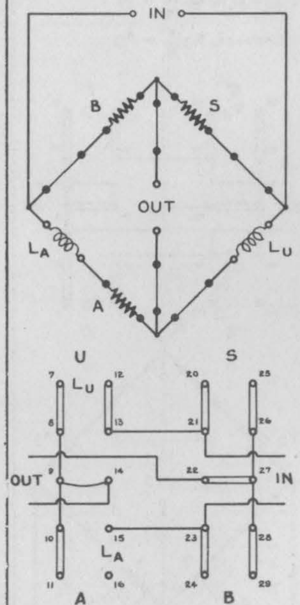
3. A conventional bridge diagram is shown, in which input and output terminals and all connected impedances are indicated by standard symbols. Terminals of internal resistors are shown solid, while those of externally connected impedances are shown as circles. The arrangement of all impedances is made on the assumption that the output terminals will be at ground potential.

4. The internal wiring of the twenty jack posts of the terminal board is shown, together with the connecting link necessary to form each bridge. Flexible connectors are indicated by curved lines.

5. The formulae given are for the resistive component R, the reactive component L or C of the unknown impedance, its energy factor, $Q = \frac{X}{R}$, and its dissipation factor, $D = \frac{R}{X}$. Resistances which are connected in series in the same bridge arm are not separated except where indicated.

6. The page numbers given at the bottom of each diagram are those on which each bridge is described in this instruction book and in Hague's <u>Alternating Current Bridge Methods</u>, 2nd Edition.

CIRCUIT NO. 1c
VARIABLE ARMS
One Variable Resistance



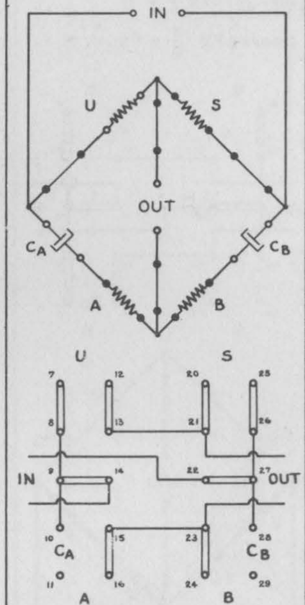
$$L_U = \frac{S}{B} L_A$$

$$\left(C_U = \frac{B}{S} C_A\right)$$

$$U = \frac{S}{B}(A + R_A)$$

SEE PAGE 2, 4; HAGUE: PAGE 210, 226

CIRCUIT NO. 1b
FIXED ARMS
Capacitance

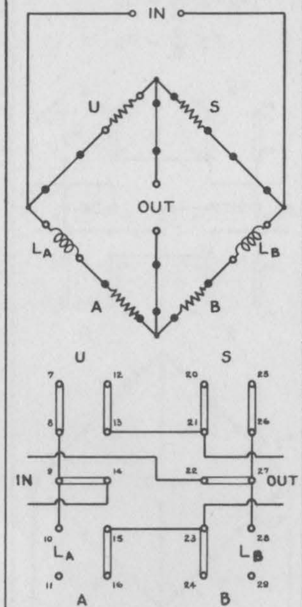


$$C_A = \frac{S}{U} C_B$$

$$A = \frac{U}{S} B$$

SEE PAGE 2, 4; HAGUE: PAGE 226

CIRCUIT NO. 1b
FIXED ARMS
Inductance

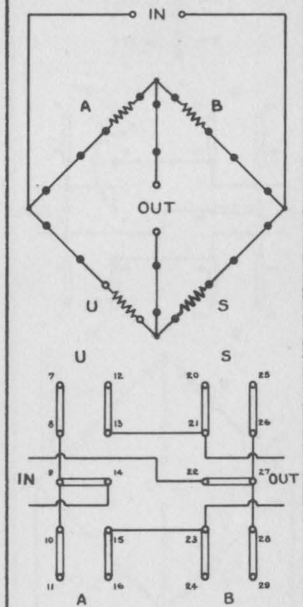


$$L_A = \frac{U}{S} L_B$$

$$A = \frac{U}{S} B$$

SEE PAGE 2, 4; HAGUE: PAGE 210

CIRCUIT NO. 1a
VARIABLE ARMS
Fixed Resistance

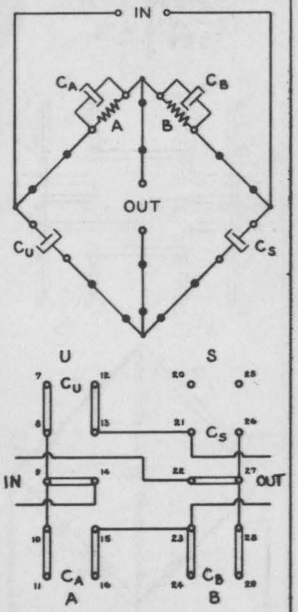


$$U = \frac{A}{B} S$$

SEE PAGE 2, 4; HAGUE: PAGE 210

CIRCUIT NO. 2b

GROVER
Parallel Capacitance



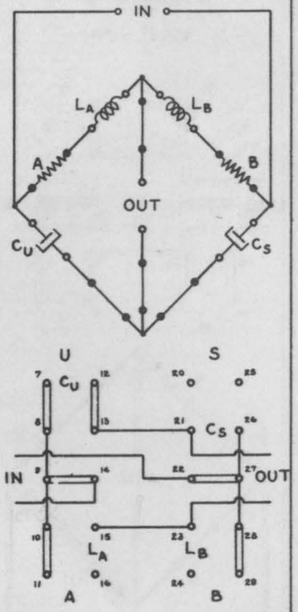
$C_U = \frac{B}{A} C_S$ (APPROX.)

$U = \frac{A}{B} S + A\left(\frac{C_B}{C_S} - \frac{C_A}{C_U}\right)$

SEE PAGE 2, 5 ; HAGUE : PAGE 275

CIRCUIT NO. 2a

GROVER
Series Inductances



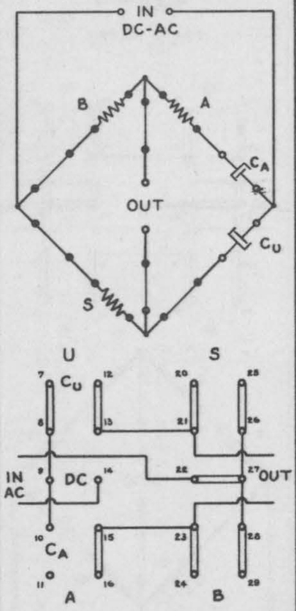
$C_U = \frac{B}{A} C_S$ (APPROX.)

$U = \frac{A}{B} S + \frac{1}{B}\left(\frac{L_A}{C_S} - \frac{L_B}{C_U}\right)$

SEE PAGE 2, 5 ; HAGUE : PAGE 275

CIRCUIT NO. 1d

VARIABLE ARMS
Combined DC & AC



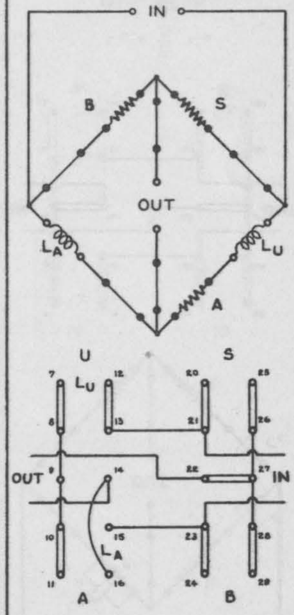
$C_U = \frac{B}{S} C_A$

$U = \frac{S}{B} (A + R_A)$

SEE PAGE 2, 4 ; HAGUE : PAGE 226

CIRCUIT NO. 1c

VARIABLE ARMS
One Variable Resistance



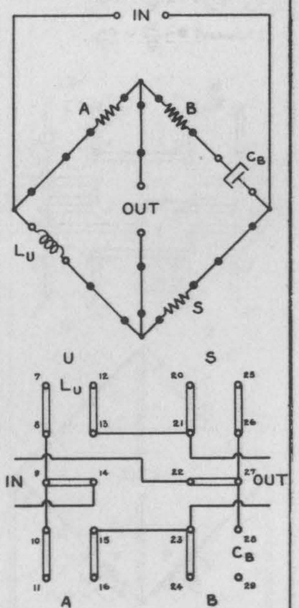
$L_U = \frac{S}{B} L_A$

$\left(C_U = \frac{B}{S} C_A\right)$

$U = \frac{S}{B} R_A - A$

SEE PAGE 2, 4 ; HAGUE : PAGE 210, 226

CIRCUIT NO. 6a
HAY



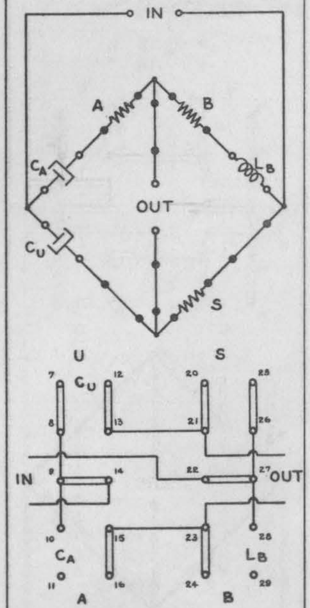
$$L_U = \frac{ASC_B}{1+B^2\omega^2C_B^2}$$

$$U = \frac{ABS\omega^2C_B^2}{1+B^2\omega^2C_B^2}$$

$$Q = \frac{1}{B\omega C_B}$$

SEE PAGE 6[2)] ; HAGUE : PAGE 266

CIRCUIT NO. 5
OWEN

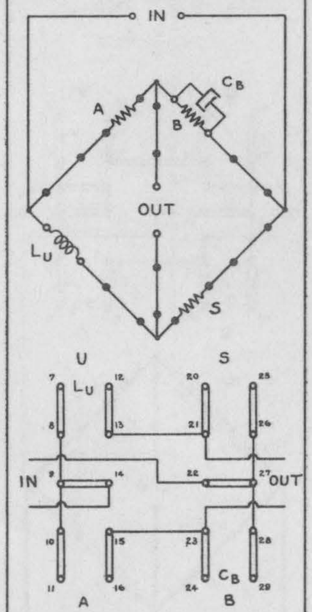


$$L_B = ASC_U$$

$$R_B = \frac{C_U}{C_A}S - B$$

SEE PAGE 6[2)] ; HAGUE : PAGE 277

CIRCUIT NO. 4
MAXWELL



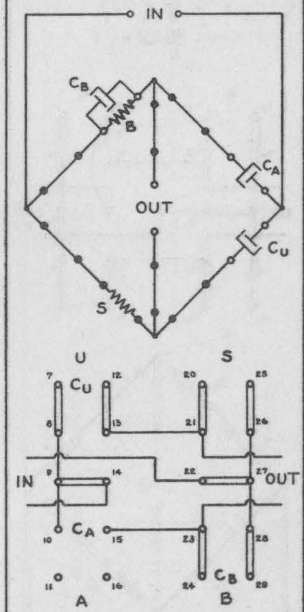
$$L_U = ASC_B$$

$$U = \frac{A}{B}S$$

$$Q_U = B\omega C_B$$

SEE PAGE 6[2)] ; HAGUE : PAGE 252

CIRCUIT NO. 3
SCHERING



$$C_U = \frac{B}{S}C_A$$

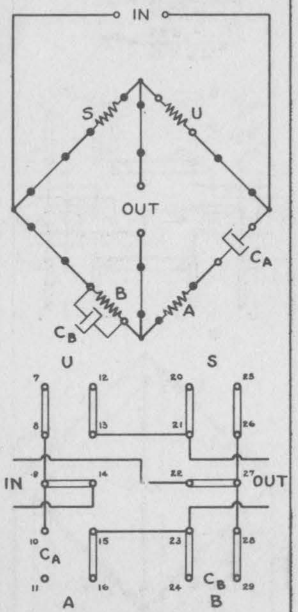
$$U = \frac{C_B}{C_A}S$$

$$(pf)_U = B\omega C_B$$

SEE PAGE 6[2)] ; HAGUE : PAGE 241

CIRCUIT NO. 8 b

WIEN
Frequency Meter



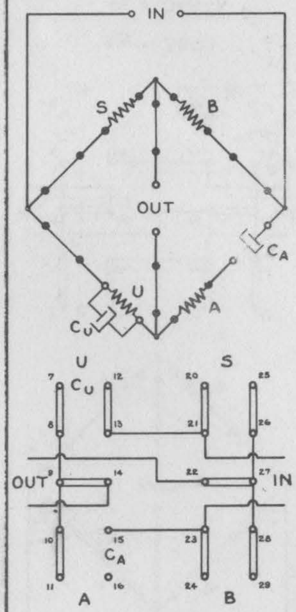
$$\omega^2 = \frac{1}{ABC_AC_B}$$

$$\frac{C_B}{C_A} = \frac{U}{S} - \frac{A}{B}$$

SEE PAGE 2/7; HAGUE: PAGE 235

CIRCUIT NO. 8 a

WIEN
Capacitance



$$C_U^2 = \frac{BU-AS}{SU^2A\omega^2}$$

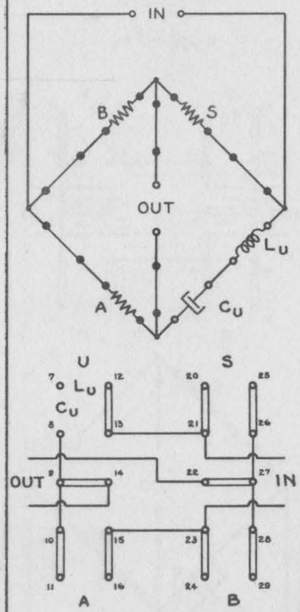
$$C_A^2 = \frac{S}{(BU-AS)A\omega^2}$$

$$\omega^2 = \frac{1}{AUC_AC_U}$$

SEE PAGE 2/7; HAGUE: PAGE 235

CIRCUIT NO. 7

RESONANCE



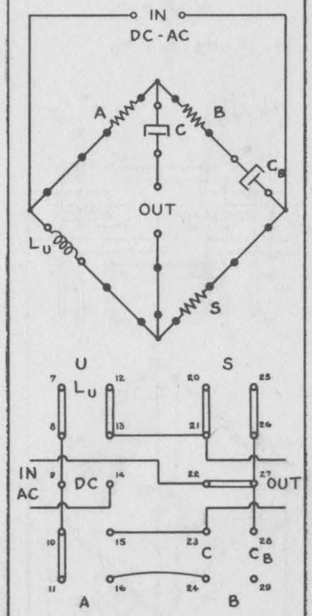
$$U = \frac{S}{B}A$$

$$\omega^2 = \frac{1}{L_UC_U}$$

SEE PAGE 2/7; HAGUE: PAGE 270

CIRCUIT NO. 6 b

HAY
Combined DC & AC



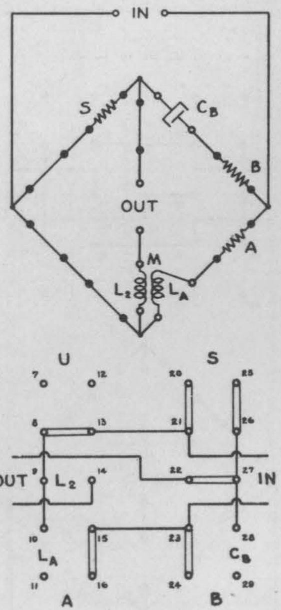
$L_U = ASC_B$ (APPROX)

$U = ABS\omega^2C_B^2$ (APPROX)

$$Q_U = \frac{1}{B\omega C_B}$$

SEE PAGE 2/6; HAGUE: PAGE 266

CIRCUIT NO. 12
CAREY FOSTER MUTUAL

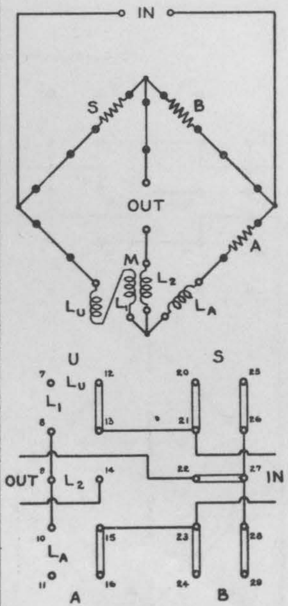


$$C_B = \frac{M}{SA}$$

$$B = S\left(\frac{L_A}{M} - 1\right)$$

SEE PAGE 3/7; HAGUE: PAGE 317

CIRCUIT NO. 11
CAMPBELL MUTUAL

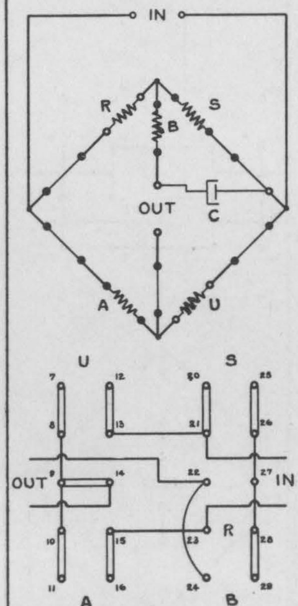


$$L_U = \frac{S}{B}L_A - L_1 - \left(1 + \frac{S}{B}\right)M$$

$$U = \frac{S}{B}(A + R_A) - R_1$$

SEE PAGE 3/7; HAGUE: PAGE 298

CIRCUIT NO. 10
ANDERSON-HAY

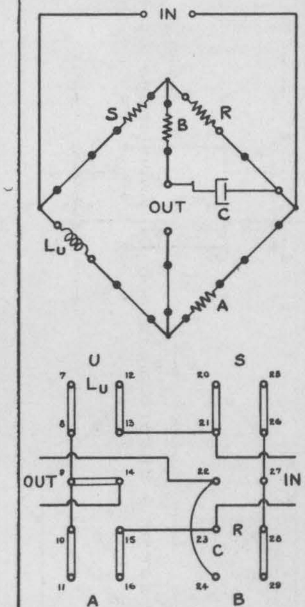


$$C_U = \frac{C}{A}\left[B\left(1 + \frac{R}{S}\right) + R\right]$$

$$U = \frac{R}{S}A$$

SEE PAGE 3/7; HAGUE: PAGE 240

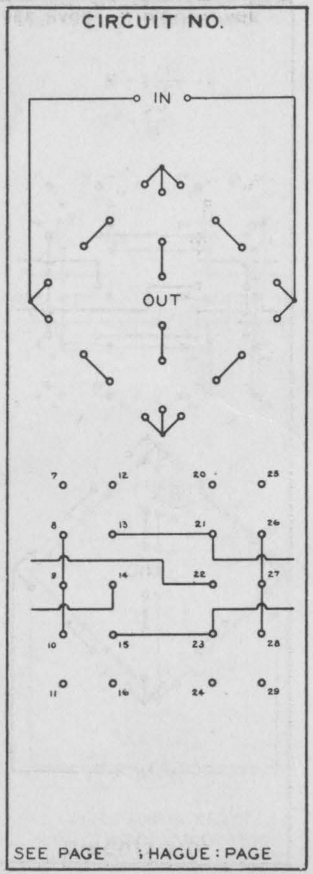
CIRCUIT NO. 9
ANDERSON

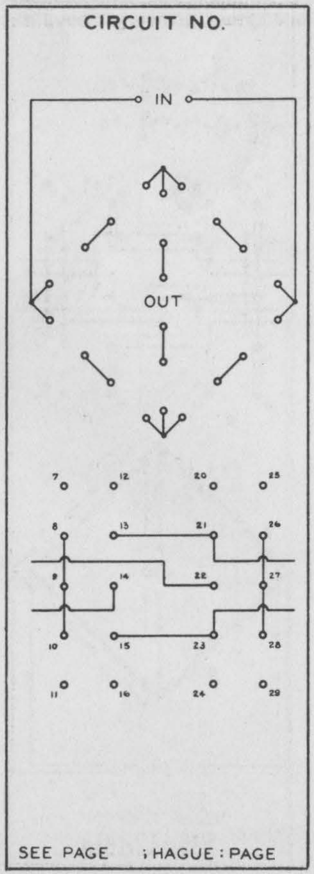


$$L_U = AC\left[B\left(1 + \frac{S}{R}\right) + S\right]$$

$$U = \frac{S}{R}A$$

SEE PAGE 3/7; HAGUE: PAGE 257


CIRCUIT NO.
IN
OUT
7 12 20 25
8 13 21 26
9 14 22 27
10 15 23 28
11 16 24 29
SEE PAGE ; HAGUE : PAGE


CIRCUIT NO.
IN
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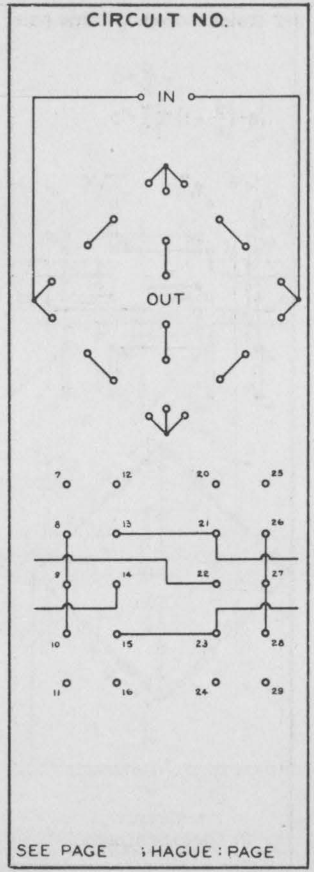
8 13 21 26
9 14 22 27
10 15 23 28
11 16 24 29
SEE PAGE ; HAGUE : PAGE


CIRCUIT NO.
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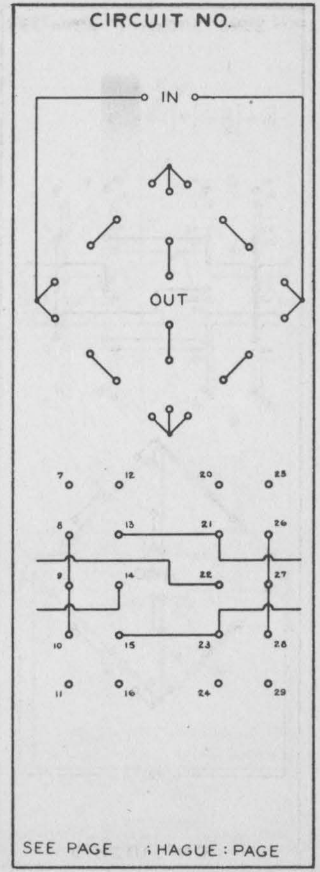
9 14 22 27
10 15 23 28
11 16 24 29
SEE PAGE ; HAGUE : PAGE


CIRCUIT NO.
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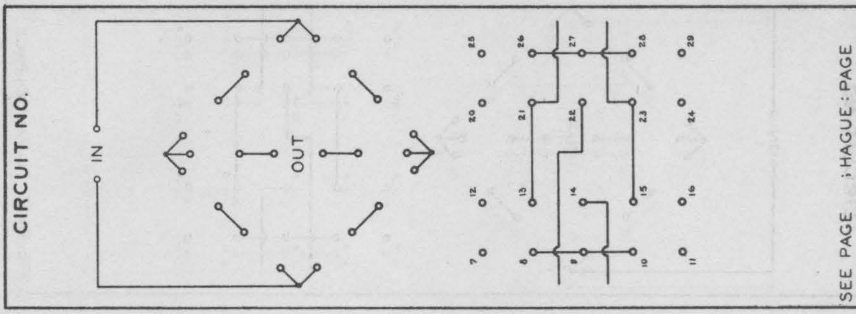
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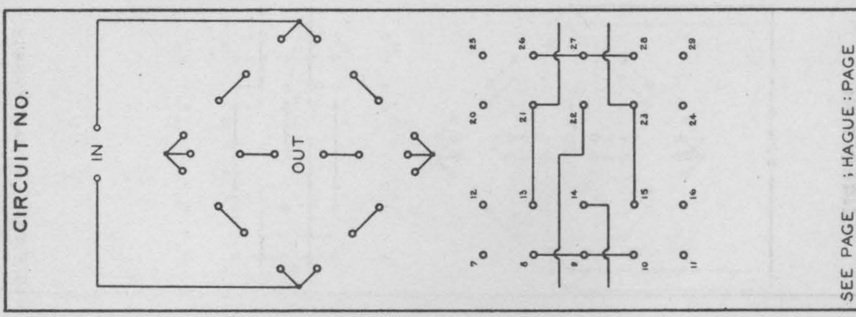
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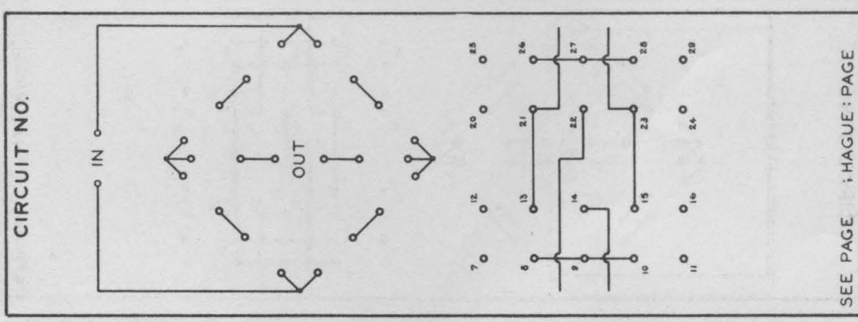
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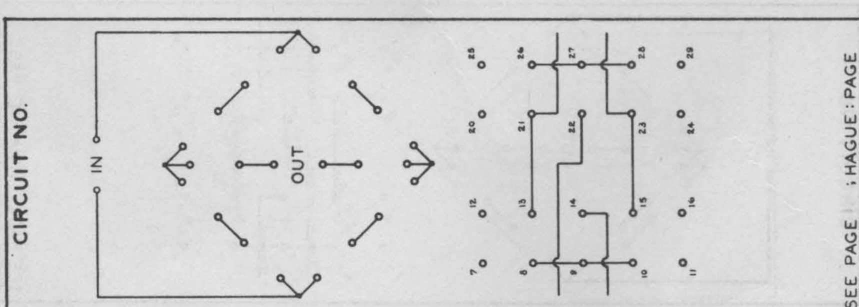
CIRCUIT NO.
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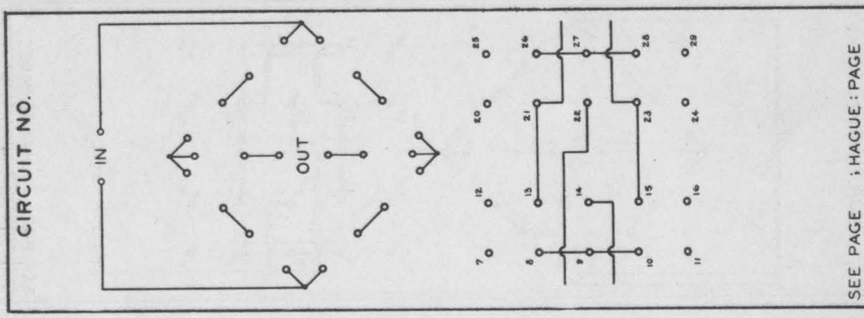
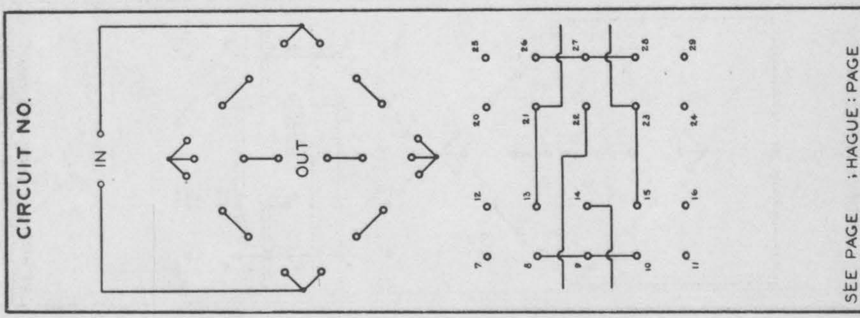

CIRCUIT NO.
IN
OUT
7 8 9 10 11
12 13 14 15 16
20 21 22 23 24
25 26 27 28 29
SEE PAGE ; HAGUE : PAGE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IN
OUT
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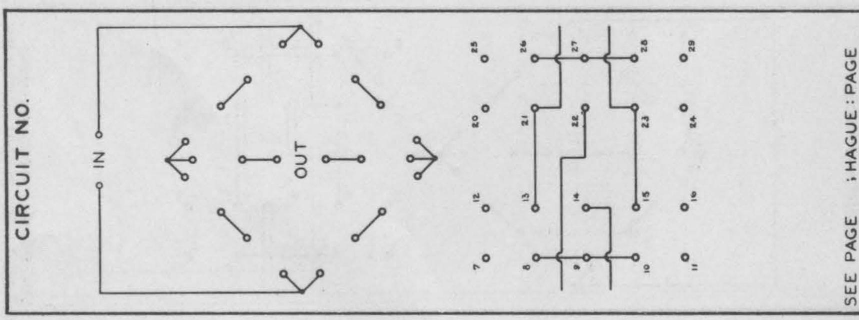
12 13 14 15 16
20 21 22 23 24
25 26 27 28 29
SEE PAGE ; HAGUE : PAGE


CIRCUIT NO.
IN
OUT
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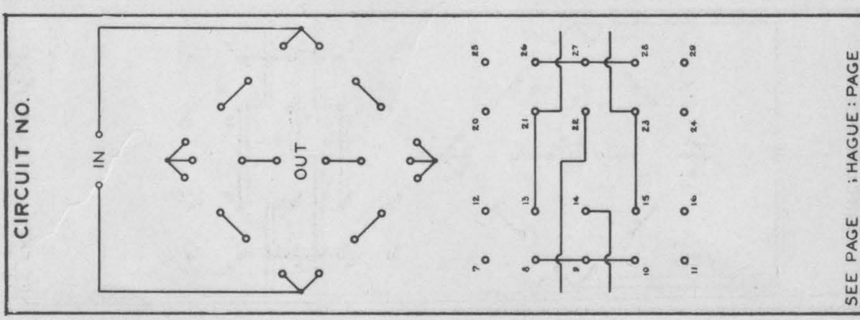
12 13 14 15 16
20 21 22 23 24
25 26 27 28 29
SEE PAGE ; HAGUE : PAGE


CIRCUIT NO.
IN
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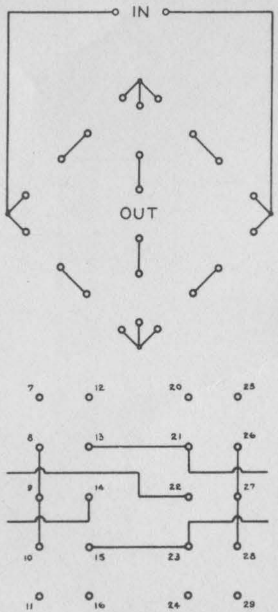
7 8 9 10 11
12 13 14 15 16
20 21 22 23 24
25 26 27 28 29
SEE PAGE ; HAGUE : PAGE

CIRCUIT NO.



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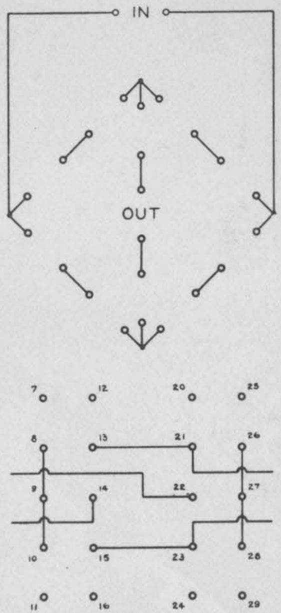
CIRCUIT NO.



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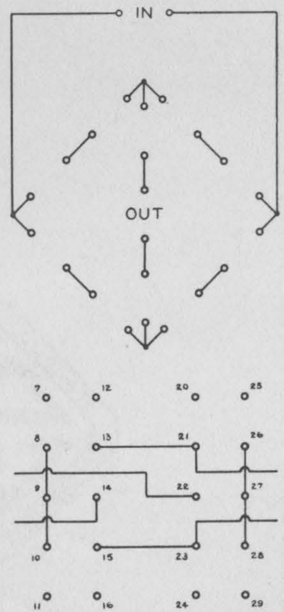
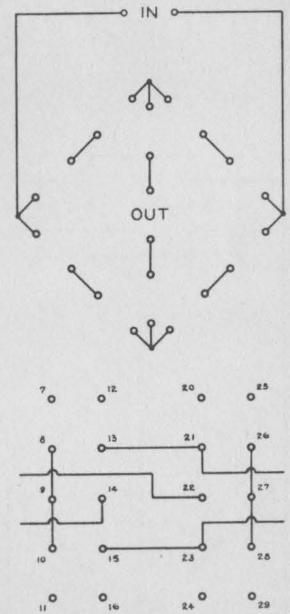
CIRCUIT NO.



SEE PAGE ; HAGUE : PAGE

CIRCUIT NO.



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