OPERATING INSTRUCTIONS

for

AUTOBALANCE UNIVERSAL BRIDGE B642

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WAYNE KERR
Meter Sensitivity
Auto
Calibrate
Zero
FSD
G Term
C Term
Range
µH
µF
nF
pF
Trim
Polarity
On
Supply
Link Neutrals
Unknown
External Standards

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The Reference Number of this Publication is TP41

INTRODUCTION

The B642 is an autobalance transformer ratio arm bridge for the measurement of admittance or impedance at audio frequencies, generally to an accuracy of 0.1%. The instrument is self-contained and simple to operate; it also incorporates facilities for the operation of recorders, digital voltmeters or printers.

Capacitance and conductance are displayed simultaneously on two meters as soon as the test component is connected. Eight decades—four for capacitance and four for conductance—are operated in succession, each decade being provided with a numbered readout. Decimal points are indicated by small signal lamps mounted between the Decade Control knobs, the correct lamp being selected automatically by operation of the RANGE switch.

The sensitivity of the instrument can be adjusted manually by setting the METER SENSITIVITY switch to one of the three manual positions, engraved 1, 2 and 3. Alternatively by setting the METER SENSITIVITY switch to Auto, the meter sensitivity will change automatically as the first two Decade Controls are set. In this instance the meters always indicate the last two significant figures.

Since the instrument is continuously balanced automatically, it can be used for the observation of changing values. The third and fourth Decade Controls allow the whole or part of the C and G meter indications to be backed off, a facility that can be used to obtain enhanced discrimination or to offset the meter deflection by a controlled amount.

Sockets are provided for the connection of EXTERNAL STANDARDS, and full instructions are given for their use in various types of measurement.

Although the instrument standards are of capacitance and conductance, resistance and inductance can also be measured, reciprocal tables being provided at the end of this manual. To simplify the derivation of those values which are frequency-dependent, the oscillator is adjusted to 1591.5Hz (at which frequency $\omega = 10^4$*).*

The instrument has provision for operation with an external source and detector; this is necessary if operation is required at any frequency other than that given by the internal source. Under these conditions the Autobalance feature does not operate, the bridge being manually balanced by means of all the Decade Controls.

The instrument may only be used with a 50 or 60Hz a.c. supply in the voltage ranges 100–125V or 200–250V.

SPECIFICATION

OVERALL RANGE

C 1fF (0.001pF)—10F G 10p℧ —100k℧

L 1nH—10MH R 10μ Ω—100G Ω (100,000M Ω)

RANGES FOR 0.1% ACCURACY

1pF—10μF 10n℧ —100m℧

1mH—10kH 10 Ω—100M Ω

The above coverage is obtained as follows:

(a) DIRECT PARALLEL READOUT

× 1G			RANGE	× 1C		
1st div.	Min. for 0.1%	Max. (0.1%)		1st div.	Min. for 0.1%	Max. (0.1%)
.01m℧	10m℧	100m℧	4	.001μF	1μF	10μF
.001m℧	1m℧	10m℧	5	.1nF	100nF	1000nF
.1μ℧	100μ℧	1000μ℧	6	.01nF	10nF	100nF
.01μ℧	10μ℧	100μ℧	7	.001nF	1nF	10nF
.001μ℧	1μ℧	10μ℧	8	.1pF	100pF	1000pF
.1n℧	100n℧	1000n℧	9	.01pF	10pF	100pF
.01n℧	10n℧	100n℧	10	.001pF	1pF	10pF

(b) DIRECT SERIES READOUT (in equivalent SERIES components)

R			RANGE	L		
1st div.	Min. for 0.3%	Max. (0.3%)		1st div.	Min. for 0.3%	Max. (0.3%)
10μΩ	10mΩ	100mΩ	1	1nH	1μH	10μH
100μΩ	100mΩ	1Ω	2	10nH	10μH	100μH
1mΩ	1Ω	10Ω	3	100nH	100μH	1mH

Note: 0.3% accuracy applies after correction for systematic error.

(c) DERIVED PARALLEL VALUES (using reciprocal tables)

R			RANGE	L ($\omega=10^4$)		
Min. (0.1%)	Max. for 0.1%	1st. div.		Min. (0.1%)	Max. for 0.1%	1st div.
10Ω	100Ω	100kΩ	4	1mH	10mH	10H
100Ω	1kΩ	1MΩ	5	10mH	100mH	100H
1kΩ	10kΩ	10MΩ	6	100mH	1H	1kH
10kΩ	100kΩ	100MΩ	7	1H	10H	10kH
100kΩ	1MΩ	1GΩ	8	10H	100H	100kH
1MΩ	10MΩ	10GΩ	9	100H	1kH	1MH
10MΩ	100MΩ	100GΩ	10	1kH	10kH	10MH

Note: Parallel L ranges are frequency dependent ($L=1/\omega^2C$).

(d) DERIVED SERIES VALUES (using reciprocal tables)

RANGE	Min. (0.3%)	Max. for 0.3%	1st. div.
1	1mF	10mF	10F
2	100μF	1mF	1F
3	10μF	100μF	100mF

Note: 0.3% accuracy applies after correction for systematic error.
Series C ranges are frequency dependent ($C = 1/\omega^2 L$).

ACCURACY — Figures quoted above in (a), (b) and (c) (±0.1% and ±0.3%) apply at 1591.5Hz. At other frequencies accuracy is ±0.5% 200Hz–10kHz, ±1% 10–20kHz. With frequency-dependent values the source frequency must be known to ±0.05% for the specified accuracy to be realised.
For table (d), the accuracy (±0.3%) applies at 1591.5Hz. At other frequencies accuracy is ±1.5% 200Hz–10kHz, ±2% 10–20kHz.

Frequency — Internal source/detector 1591.5 ±0.5Hz ($\omega = 10^4$).
External source/detector 200Hz–20kHz.

Comparator — Bridge gives direct measurement of difference between Unknown and External Standard(s) of values 100pF–100nF and 1μ℧–1m℧ (1k Ω–1M Ω).

Outputs — 0–100mV from C and G meter circuits, available at rear panel. Output impedance 10k Ω. Preset adjustments for setting up.

Ambient Temperature Range — Operates over temperature range 0–40°C.

Power Supply — 100–125V/200–250V, 50–60Hz.

Dimensions — Width 482 mm (19 in.).
Height 311 mm (12.25 in.).
Depth 152 mm (6 in.).

Weight — Approx. 11 kg. (24.25 lb.).

ANCILLARY ITEMS

BNC connectors for external source/detector	Greenpar GE37570C (2 off)
D.V.M. Plugs	Belling Lee L378/A/4/Red (2 off)
	,, ,, ,, Black ,,
Measurement leads (complete) (BML12)	D10065A (2 off)
Low Capacity Clip leads (LCC3)	D10642B (2 off)
Power lead (complete)	D10879 (1 off)
Reciprocal Tables	D12461 (1 off)
Instrument stand	D12466 (1 off)
*Power input connector	Bulgin P430
*Measurement connectors (E & I)	Greenpar GE37570C (2 off)†

*Available as optional extra

†Same as supplied for external source/detector.

CONTROLS

OPERATING CONTROLS

RANGE Switch

This ten-position switch provides the necessary multiplying factor for the Decade Controls, and selects the appropriate decimal point signal lamp.

Decade Controls

Eight Decade Controls are provided, in two groups. Four for the G term and four for the C term. The three left-hand controls in each group are 12-position switches, the right-hand one in each group is a potentiometer. The two left-hand switches in each group are calibrated 0 to 10, the twelfth position marked with a red 0 is the RESET position. The Decades control the sensitivity of the Autobalance circuits when the METER SENSITIVITY switch is in the AUTO position. A symbol ⊕ is adopted to replace 10, on all but the first Decade switch in each group. The third Decade switch from the left in each group, has its twelfth position engraved -1; in conjunction with the POLARITY switches this provides overlap, which is useful in dealing with awkward values. The potentiometer (right-hand) controls enable a precise value to be set on the scales. They are calibrated -1 to $+10$. The zero positions on the 3rd and 4th controls are coloured red for easy identification.

The Decade Controls select a combination of standards and transformer taps.

POLARITY Switches

These controls enable the operator to change the sign of the voltage applied to the standards, thus enabling measurements to be made in all four quadrants of the complex plane.

TRIM Potentiometers

Capacitance or leakage between measurement cables or jigs would give rise to false zero readings. The TRIM potentiometers enable these effects to be balanced out.

LINK NEUTRALS Switch

The two neutral leads are connected internally when this switch is in the up, LINK NEUTRALS position. This facility simplifies the connection of Wayne Kerr Conductivity and Permittivity cells, since the majority of these cells are not fitted with a neutral link. This switch may also prove useful when using special jigs or fixtures for the connection of the test component, and for normal two terminal measurements where manual linking of the neutrals may be inconvenient.

METER SENSITIVITY Switch

This switch has five positions. The function in each position is as follows:—

AUTO

In this position the meter sensitivity is controlled by the Decade Controls.

1, 2 AND 3

In these positions the meter sensitivity switch overrides the control of sensitivity provided by the Decade Controls. Sensitivity is at a minimum on 1 (maximum range) and at a maximum on 3 (minimum range).

Lamps are provided adjacent to the positions engraved 1, 2 and 3, to indicate the selected sensitivity. When AUTO is selected, the lamps will be under the control of the Decade Controls.

CALIBRATE

In this position a standard current is selected for the unknown arm, which enables the gain and phase response of the Autobalance circuits to be adjusted.

ZERO Control

This control is used to set the G meter to zero during the calibration procedure.

F.S.D. Control

Used to set the C meter to full scale deflection during the calibration procedure.

SUPPLY Switch

The instrument is operational when this switch is in the up ON position.

PRESET CONTROLS

A number of preset controls are contained within the instrument, the settings of which are carefully adjusted during manufacture and do not normally require further adjustment. It is important to note that none of these controls should be adjusted except as detailed in the Maintenance Manual. Failure to heed this warning may result in improper or inaccurate operation.

OPERATION

PRELIMINARY

Ensure that the voltage selector is set to the correct voltage tapping. The selector is a small two position slide switch mounted above the fuse in a cut-out in the back of the cabinet. A locking plate is fitted to prevent accidental operation of the switch. To alter the voltage range, remove the locking plate and slide the switch to the opposite position; reverse the locking plate and refit. Engraving on this plate indicates the voltage range available, 120V for the range 100–125V, and 240V for the range 200–250V. The fuse mounted just below the switch is the power supply fuse; a suitable replacement (for 120V or 240V supplies) is Beswick type TDC 134, 0.5A 'slow blow'.

SWITCHING ON

The instrument is supplied with a three wire connecting lead for the a.c. supply, terminated with a three pin free socket at one end. This should be inserted into the input plug at the rear of the instrument. The free end of the lead should be fitted with a suitable three pin plug. Connect red (or brown) to live, black (or blue) to neutral and green (or green striped yellow) to ground. (Two colour codes are in use.) Before switching on, set the mechanical zero of each meter, with the adjustment provided.

With no UNKNOWN connected, set the SUPPLY switch to ON, and allow the instrument to stabilise for 1 minute.

MEASUREMENT CABLES

The instrument is supplied with two pairs of measurement cables. One pair is terminated with crocodile clips at the test component end, the second being fitted with special low capacity clips. This latter type should be used to obtain maximum accuracy when measuring small values of capacitance on Ranges 9 or 10.

The cables are connected to the UNKNOWN sockets E and I.

The legend E signifies the voltage or source side of the instrument, while I signifies the current or detector side. In each case the green lead is the neutral connection. The exposed metal sleeve between the two moulded sections is also connected to neutral.

IMPORTANT: Under no circumstances must the inner of either measurement lead be connected to Ground while the green wire of the Bridge power cable is grounded. The Neutral circuit of the Bridge is grounded internally and such action would render the Bridge inoperative.

When it is necessary to connect either measurement lead (inner of E or I) to the chassis or framework of the equipment under test, this equipment must first be isolated from Ground. If this is not practicable, the bridge must be isolated from Ground by disconnecting the green wire of the power cable from the Ground pin of the plug. Care must be exercised while operating the Bridge in this condition and the Ground connection should be replaced when isolation is no longer necessary.

TRIMMING AND CALIBRATION (Normal Measurements - Ranges 4 - 10)

Connect the measurement cables to be used, to the UNKNOWN sockets E and I. Connect together the two green neutral leads as shown in Fig. 1, or alternatively, set the LINK NEUTRALS switch to the upper position.

At this stage Yu in Fig. 1 should not be connected.

Select RANGE 4 and set all decade controls to the red positions. Set METER SENSITIVITY

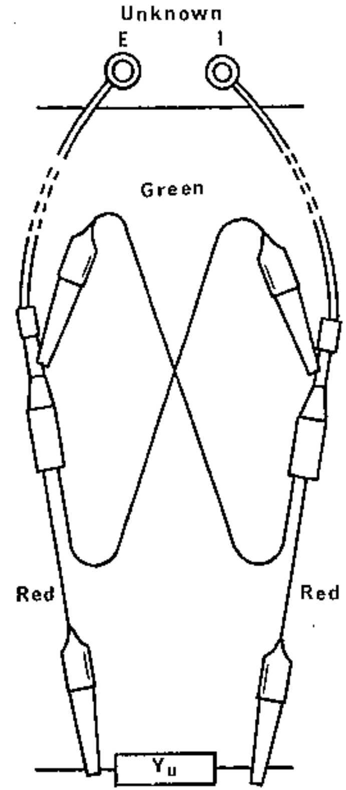


Fig. 1 Normal Measurement Connections

switch to 3. Set C and G POLARITY switches to +.

Adjust: TRIM C for zero reading on the C meter.
TRIM G for zero reading on the G meter.

Set the METER SENSITIVITY switch to CALIBRATE.

Adjust the F.S.D. control until the C meter indicates +10, and adjust the ZERO control until the G meter indicates zero. As there is slight interaction between these controls the adjustments should be repeated.

Set the METER SENSITIVITY switch to AUTO. The instrument is now ready for use and the UNKNOWN may be connected between the two red leads. Although the trimming conditions established on RANGE 4 will be approximately correct on RANGES 4–10, it is desirable always to check the trim on the RANGE finally selected for measurement, with the settings of both POLARITY switches determined and any special jigs connected. This is particularly important when measuring small values of capacitance and when changing from the standard leads to the Low Capacitance Clip Leads. This check can be made very quickly as described below.

Disconnect either of the red leads (or either of the Low Capacity Clips) from one end of the UNKNOWN. (If a jig is in use, leave the measurement leads connected to the jig but disconnect one lead of the component from the jig).

With all Decade Controls in the red positions, and the METER SENSITIVITY switch set to 3, adjust TRIM C and TRIM G for zero reading on the associated meters.

Reconnect the UNKNOWN. The final measurement can now be made, in accordance with the appropriate instructions which follow.

TWO TERMINAL MEASUREMENTS - RANGES 4-10

Normal Measurements

The following operations cover normal two terminal measurements at 1591.5Hz. Low Impedance measurements and three or four terminal measurements are dealt with under their respective headings. For measurements at other frequencies, see External Source and Detector on page 36. For measurements on polarized capacitors, energised inductors and other special conditions, see Bridge Measurement Techniques on page 45.

The basic procedure for normal measurements is the same regardless of the nature of the component under test. When the measurement is completed, interpret the displayed result as described in the next section. The user is advised to read through these two sections before commencing to use the bridge.

Having trimmed as described on page 15, set the METER SENSITIVITY switch to the AUTO position.

With all Decade Controls in the red positions and RANGE 4 selected, connect the unknown component between the two red leads (or between the special clips if Type D10642B cables are being used).

N.B.—When all Decade Controls are thus set, meter sensitivity indicator lamp No. 1 will light.

Ensure that C and G POLARITY switches are set to '+'.

Observe the meter indications. If both are between zero and +1, change to RANGE 5* and, if necessary, to higher Ranges in sequence until the larger of the two meter indications is between +1 and +10. If during this operation either of the two meter indications is negative, change the appropriate POLARITY switch to '—' and check the trim. If a reading of greater than +10 is obtained on RANGE 4, this indicates that the component is of low impedance, and requires to be measured using the procedure detailed under 4 TERMINAL MEASUREMENTS—Ranges 1–3 on page 23.

Check the trim as described on page 15.

If an indication to two significant figures is satisfactory, no further operations are necessary. Multiply the C and G meter indications by the factor appropriate to the RANGE in use (the units are given by the RANGE switch, the decimal point being indicated by the signal lamps on the Decade display) and refer to Interpretation of Results on page 18. If greater accuracy is required proceed as follows.

Note the first figure of the G meter indication and set the first (left-hand) G Decade control to the appropriate position as indicated by the G meter. Repeat for C. If the indication on one of the meters was less than 1, set the appropriate decade to the black zero. When both first decades have

*When measurements are made on Ranges 4 or 5, see the section 'Lead Corrections', on page 42.

been set, the METER SENSITIVITY lamp 2 will light to indicate an increase in meter sensitivity. At this stage the display (first Decades plus meter indications†) is a three-figure indication of the C and G values of the component under test, requiring only the application of the RANGE units for the range in use.

Note the first figure of the new G meter indication and select the appropriate position on the second G decade. Repeat for C, again selecting the black zero for a meter indication of less than 1. The METER SENSITIVITY indicator lamp will light in position 3 when both second decades have been selected, indicating a further increase of meter sensitivity. The resulting display† (after application of the RANGE units) gives the C and G values with the full accuracy of 0.1%.

In the event of a negative meter indication being obtained, after adjustment of the 1st and 2nd Decade Controls; a positive on-scale reading may be obtained by the use of the —1 position on the appropriate 3rd Decade Control. The —1 positions provide overlap, which is useful in dealing with awkward values. Their use prevents the need to select the alternative POLARITY switch position, when the negative meter indication is small.

†A negative meter reading must be subtracted from the Decade display before applying units of measurement indicated by the RANGE switch.

If the POLARITY switch has to be changed during a measurement, the instrument should be retrimmed with the UNKNOWN disconnected.

When the values given by the display have been noted, return all Decade Controls to the red positions in readiness for the next measurement. Disconnect the test component.

Interpretation of Results

The foregoing procedure applies basically to the measurement of any normal component (i.e. one whose value is within the scope of RANGES 4 to 10 inclusive).

If the component under test is a capacitor, the value of C is read directly from the display. The loss term given by the G display is the parallel conductance of the component. To interpret this value in terms of parallel resistance, take the reciprocal of the G reading and multiply by the appropriate RANGE factor for R.

The dissipation factor of a capacitor and the Q factor of an inductor, at the internal frequency of 1591.5Hz, can be found by taking the direct ratio of the C and G readings.

$$\tan \delta = \frac{\text{G reading}}{\text{C reading}}$$

$$Q = \frac{\text{C reading}}{\text{G reading}}$$

In nearly all cases the G polarity switch will be set to '+' for a positive indication on the G meter. However, some networks have a negative resistance characteristic in certain circumstances; in such cases the G polarity switch may require setting to '−'.

If the test component is a resistor having a small reactance, the C meter indication will probably be less than 1 initially, in which case the first decade should be set to zero. However, a wire wound resistor may have an inductive reactance and this will require the C Polarity switch to be set to '−'. In this case it will be necessary to take the reciprocal of both displays since

$$R = \frac{1}{G} \text{ and parallel } L = \frac{1}{\omega^2 C}$$

where $\omega^2 = 10^8$ at 1591.5Hz.

Alternatively, it may be more useful to interpret this as negative capacitance since this is a direct measure of the (positive) capacitance which, if connected in parallel with the UNKNOWN, would cancel out the inductive term at the measurement frequency. To obtain negative capacitance, take the reading from the C Decade Controls, note the units of measurement indicated by the RANGE switch and prefix the result with a minus sign.

If it is desired to express the reactance term in the series form, conversion formulae (parallel to series) are given in the section PARALLEL TO SERIES CONVERSIONS on page 28.

If the test component is an inductor, the C POLARITY switch can be set to '−' before commencing the measurement procedure. To determine the value of the inductance, use the expression given above. Note that, for accurate results, the value of the self-capacitance (if known) of the inductor should be added numerically to the C meter reading (making the reading more negative) before using the above expressions. The value of most inductors is modified by their proximity to metal objects and so a free air space around the component should be ensured.

THREE TERMINAL MEASUREMENTS - RANGES 4 - 10

In-Situ Measurements

It is often convenient to be able to measure an impedance in situ, without disconnecting any other components that may be associated with it. This applies particularly when components form part of a printed circuit or encapsulated assembly. Moreover, with certain test jigs, it is often impossible to 'disconnect' the effective shunt and stray capacitances. Generally speaking, any circuit can be resolved into a three-terminal network, the arrangement being as shown in Fig. 2.

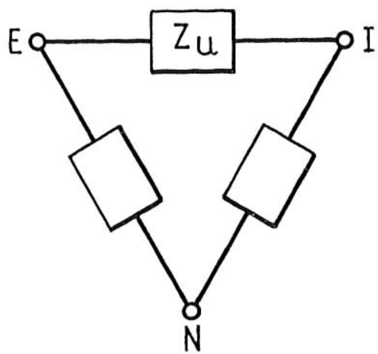


Fig. 2 Three-terminal Network

The impedance to be measured is Z_u and the effect of impedances E-N and I-N must be removed. The arrangement can be considered as a π-network and is shown in Fig. 3 in this form, connected to the bridge. Z_{EN} shunts the E circuit and Z_{IN} shunts the I circuits. In many instances these shunting effects can be disregarded. In Fig. 4, for example, it may be possible to measure the impedance between A and B without disconnecting the other components, simply by connecting point C to the bridge neutral.

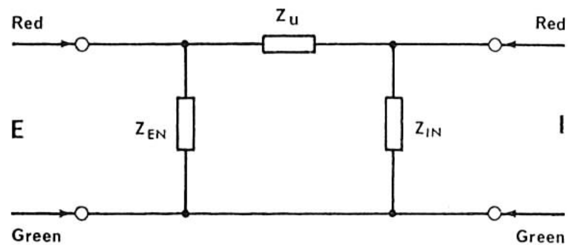


Fig. 3 Three-terminal Measurements

When the shunting effects (Z_{EN} and Z_{IN} of Fig. 3) cannot be ignored, the series resistance and leakage inductance of the bridge circuits must be taken into account. The measurement circuit must now be drawn as in Fig. 5 and a simple calculation, described in succeeding paragraphs, must be made to correct the readings obtained.

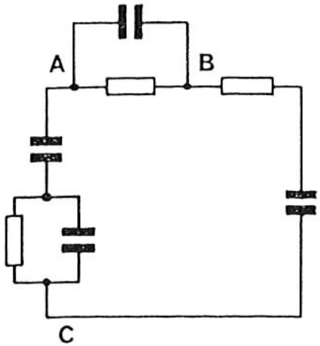


Fig. 4 In-situ Measurements

The loading effect of the UNKNOWN impedance itself is small and can be ignored. It is only when the shunt impedances are low compared with Z_u that errors arising are of importance. Therefore Z_u can be considered as an open-circuit and the shunting effects on either side of the UNKNOWN can be considered separately.

The fall in potential at E caused by the load Z_{EN} will depend on the ratio of Z_{EN} to the impedance of R_e and L_e, the effective series resistance and inductance at the E socket. A similar argument applies to the detector (I) side of the bridge and the two effects are additive.

Table 1 gives the average values of effective resistance and inductance for each range. When it is necessary to correct for shunt loading the following formulae can be used to calculate the true value of impedance, Z_u, from the value read on the bridge, Z_m.

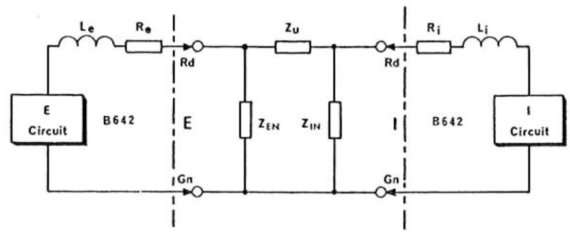


Fig. 5 Shunting Effects

With shunt loading on the E socket only:

$$Z_u = (1 - Z_e/Z_{EN}) . Z_m$$

where $Z_e = R_e + j\omega L_e$ ($\omega = 10^4$ at 1591.5 Hz).

With shunt loading on the I socket only:

$$Z_u = (1 - Z_i/Z_{IN}) . Z_m$$

where $Z_i = R_i + j\omega L_i$.

With shunt loading on E and I sockets:

$$Z_u = [1 - (Z_e/Z_{EN} + Z_i/Z_{IN})] . Z_m.$$

RANGE	E SOCKET		I SOCKET	
	Re	Le	Ri	Li
4	40mΩ	1.1μH	38mΩ	1.1μH
5	41mΩ	1.1μH	64mΩ	1.3μH
6	68mΩ	2.7μH	66mΩ	1.4μH
7	67mΩ	2.5μH	1.02Ω	3.0μH
8	1.17Ω	9.0μH	1.03Ω	3.0μH
9	1.20Ω	10.0μH	10.0Ω	30.0μH
10	12.6Ω	11.0μH	10.0Ω	30.0μH

Table 1 Internal R and L for each Range (Typical)

Network and Attenuator Characteristics

The facility for three-terminal measurements and the readiness with which either or both the conductance and reactance Standards can be made effectively negative by setting the appropriate polarity switch to '—', make the bridge a most efficient instrument for measuring the characteristics of networks. Transfer admittance, for example, is measured simply by the arrangement shown in Fig. 6. The input of the network is connected between the red and green E leads. The output is connected, in series with its terminating resistance R_T, between the red and green I leads. If there is no internal connection between the neutrals in the circuit being measured, the LINK NEUTRALS switch may be set to the upper position. The right-hand side of R_T will be at Neutral potential when the bridge is balanced and the network will then be correctly terminated.

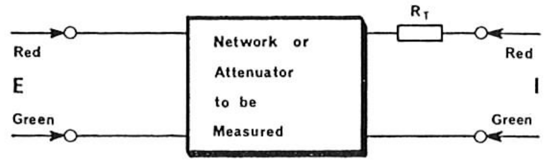


Fig. 6 Network and Attenuator Characteristics

Let the transfer admittance, defined as the current flowing in the terminating resistor for unit input voltage, be $|Y|\angle\theta$. Then, at balance:

$$|Y|\angle_m = \pm G_m \pm j\omega C_m$$

where G_m and C_m are the values of conductance and capacitance read on the bridge.

Then

$$|Y| = (G_m^2 + \omega^2 C_m^2)^{\frac{1}{2}}$$

and

$$\angle\theta = \tan^{-1}(\pm\omega C_m/G_m).$$

The characteristics of attenuators can be measured on the bridge using the same circuit arrangement as shown in Fig. 6. With the resistor R_T in the position shown the attenuator is correctly terminated at balance, when the right-hand side of R_T will be at Neutral potential.

If the bridge is balanced with the attenuator set to zero, a value equal to the matching impedance R_T will be measured. If the attenuator steps are now switched in, the voltage attenuation can be calculated accurately from the ratio of the apparent change in value of R_T.

Measurement of Screened Components

When a component, such as a small-value capacitor, is mounted in a screening box, the neutral connection from the bridge should be connected to the box. One green lead should remain cross-connected (from E to I, or vice versa) and the second green lead provides the desired neutral connection.

Measurement of Three Terminal Capacitors

When measuring sub-standard three-terminal capacitors, care must be taken to ensure that the conditions of measurement are the same as those under which the capacitor was calibrated. A three-terminal capacitor is shown schematically in Fig. 7.

Where the case has been connected to one

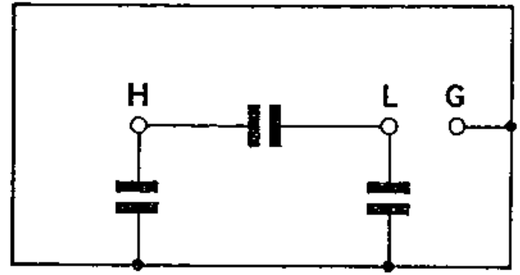


Fig. 7 Three-terminal Capacitor

terminal during calibration, then the L and G terminals should be connected to the I lead. If, however, the direct capacity only is required, then the G terminal should be connected to the neutral.

FOUR TERMINAL MEASUREMENTS - RANGES 1 - 3

General

This section describes four terminal measurement of low impedance components. At 1591.5Hz the coverage provided by this method is capacitance exceeding 10μF, conductance exceeding 100mMho (resistance less than 10 Ω) and inductance less than 1 mH. For values outside these limits, refer to the section headed TWO TERMINAL MEASURE-

MENTS—RANGES 4–10 on page 16. For operation at other frequencies, see EXTERNAL SOURCE AND DETECTOR, page 36.

Trimming and Calibration (Low Z)

Ensure that the LINK NEUTRALS switch is in the lower position. Connect the crocodile-clip leads to the UNKNOWN sockets. Remove any connections from all other front-panel sockets.

Clip the red and green leads from the left-hand cable (looking at the front-panel connectors) one to either side of the component to be measured, at least ¾ inch from the body (see Fig. 8).

Clip the green lead from the right-hand cable to the component wire between the body and the left-hand green lead clip.

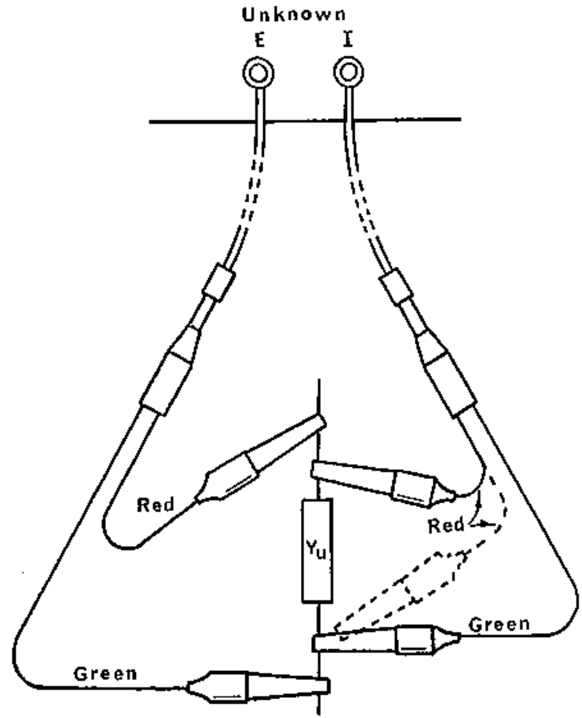
Clip the red lead of the right-hand cable on to the clip of the green lead from the same cable.

Select RANGE 1 and set all Decade Controls to the red positions.

Set the METER SENSITIVITY switch to position 3.

Adjust: TRIM C for zero reading on the C meter.
TRIM G for zero reading on the G meter.

Set the METER SENSITIVITY switch to CALIBRATE.



Component connected while trimming but with right-hand Red lead in dotted position

Fig. 8 Low Impedance Measurement Connections

Adjust the F.S.D. control until the C meter indicates +10, and the ZERO control until the G meter indicates zero.

There is slight interaction between these controls and the adjustments should be repeated.

Set the METER SENSITIVITY switch to AUTO.

Transfer the red lead of the right-hand cable to the other side of the component body so that the clip is between the body and the left-hand red clip (Fig. 8).

The instrument is now ready for use. Set the RANGE switch, commencing on RANGE 1 and advancing from 1–3 as required, until both meters are on scale. When the correct range has been selected, the instrument should be retrimmed, and recalibrated. Measurements are then made as detailed on page 16 under Normal Measurements.

N.B.—The measurement is ALWAYS that between the two clips from the right-hand cable (the other pair of clips being always outside these). Thus, for example, it is possible to measure the resistance per unit length of conductors.

Resistance Measurement (Low Impedance)

The procedure is basically the same as for NORMAL MEASUREMENTS—page 16—(Resistance) except that:

(a) on LOW IMPEDANCE only, the C POLARITY switch should be set to '−' if any capacitance is present, and to '+' for any inductance (i.e. opposite settings to those for Normal Measurements).

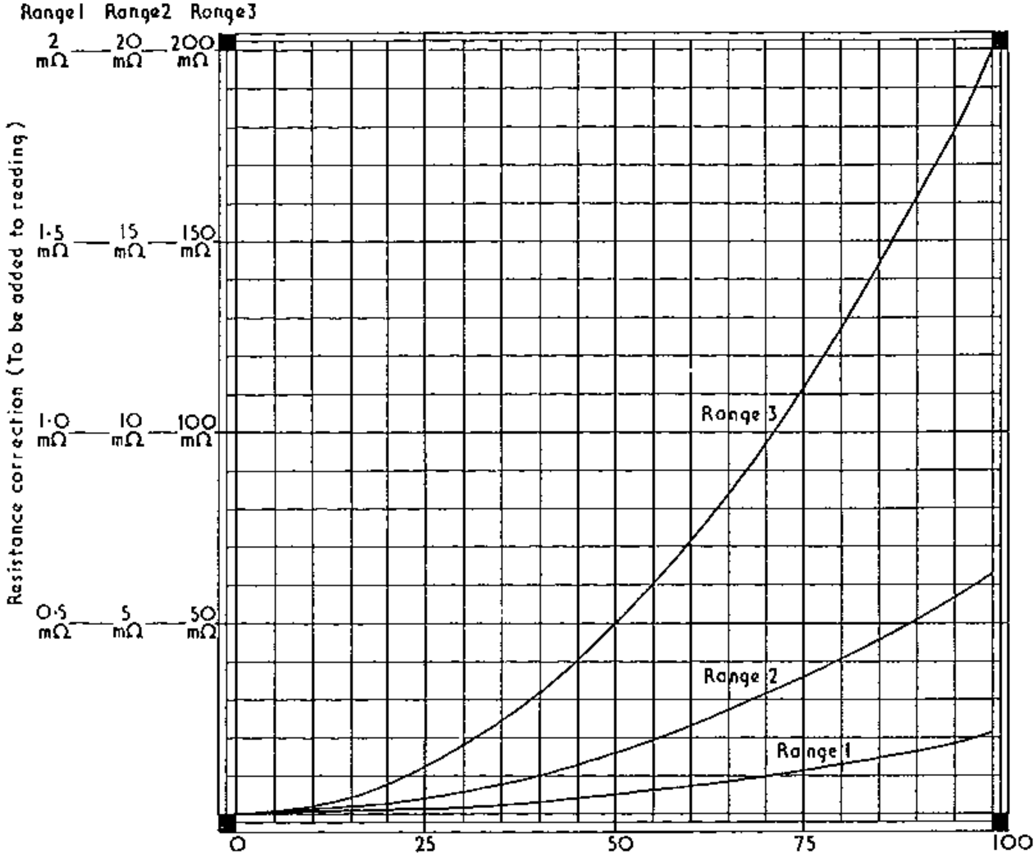
(b) the bridge reads the equivalent SERIES impedance of the UNKNOWN.

The sequence of operations, commencing with all Decade controls in the red 0 positions is as follows:

Note both meter readings and set the first C and G Decade Controls accordingly. For readings between 0 and +1, set the first Decade Control to zero. If the C meter indication is negative, reverse the setting of the C POLARITY switch.

Set in the first figure of the new meter readings on the second Decade Controls (again selecting zero for readings below 1).

The G display reads in resistance units as indicated on the Range switch, in conjunction with



Graph 1 Resistance Correction Ranges 1–3

the decimal point indicator lamps.

On the Low Impedance Ranges 1–3, the values derived from the bridge readings are the equivalent SERIES components of R and L, or R and C.

Inductance Measurement (Low Impedance)

The procedure is the same as given in preceding paragraphs for resistance measurement, bearing in mind that, on RANGES 1–3 only, the C POLARITY switch is set to '+' for inductance measurements. The value is obtained from the C display by using the units of inductance indicated on the RANGE switch.

Capacitance Measurement (Low Impedance)

The procedure is the same as that given for Resistance Measurement, bearing in mind that, on Low Impedance Ranges 1–3 only, the C POLARITY switch is set to '–' for capacitance measurements. The value is obtained from the C display by using the expression:

$$C = \frac{1}{\omega^2 L}$$

where L is given in RANGE switch units, in conjunction with the decimal point indicator lamps.

$$\omega^2 = 10^8 \text{ at } 1591.5\text{Hz}.$$

Accuracy of Low Impedance Measurements

The simplified expressions for deriving R, L and C values on the Low Impedance Ranges 1–3 ignore a systematic error. This can easily be allowed for, as shown below, to give results accurate to $\pm 0.3\%$; alternatively, refer to the resistance correction curves on graph 1.

To avoid errors arising from the uncertainty of lead and contact resistances, Low Impedance measurements are made by connecting the UNKNOWN as the shunt arm of a T-network. This technique gives a small inherent error which, however, is known and can be allowed for by adding to the measured value a percentage derived as follows:

Correction to be added:

RANGE 1 $= 2 \times Rm\%$
RANGE 2 $= 0.63 \times Rm\%$
RANGE 3 $= 0.2 \times Rm\%$

where R_m is the measured value in ohms.

Example:

Measured value $= 8\,\Omega$

Correction to be added $= 0.2 \times 8$ (RANGE 3)

$= 1.6\%$ which is the percentage by which R_m must be increased.

Therefore the true value

$$R = 8 + \frac{1.6}{100} \times 8.$$

$$= 8.128\,\Omega$$

If the UNKNOWN is not purely resistive, but a complex impedance, i.e. $Zu = Ru + j\omega Lu$, then the bridge indications Cb and Gb will represent Lu and Ru.

The true equation relating these is:—

$$Zu = Ru + j\omega Lu = \frac{R^2(Gb + j\omega Cb)}{1 + 2R(Gb + j\omega Cb)}$$

where $R = 1\text{k}\,\Omega$ for Range 3

$= 316\,\Omega$ for Range 2

$= 100\,\Omega$ for Range 1.

Analysis of this equation shows that the error incurred is always most serious in the resistive term, amounting to a maximum of 2% on Range 3. At the internal source frequency, the maximum error in the reactive term is 0.02%. When using an external source and detector however, the reactive term error can become considerable.

The worst case occurs when measuring an inductor of 1mH, with a source frequency of 20kHz. This will read 2.6% in error on the major term, and 24% resistive error. All low impedance errors can be corrected to give 0.3% accuracy by using the above equation.

PARALLEL TO SERIES CONVERSIONS

Any impedance (or admittance) can be expressed in two ways:

(a) Parallel components of the in-phase and quadrature terms.

(b) Series components of the in-phase and quadrature terms.

Given values for the components in one form—(a) or (b)—values for the alternative form can be calculated to give an exact equivalent circuit at any one specified frequency of operation.

Because the Standards of the B642 Bridge are in parallel, the Unknown is measured in form (a).

Expressions for obtaining the equivalent series components are given below. In the case of Low Impedance measurements, Ranges 1–3, the bridge readings are in form (b).

$$R_s = \frac{1}{G(1 + Q^2)} \qquad [Q = \frac{\omega C}{G}]$$

$$C_s = C[1 + \frac{1}{Q^2}]$$

$$L_s = -1/[\omega^2 C(1 + \frac{1}{Q^2})] \quad \omega = 10^4 \text{ at } 1591.5\text{Hz}$$

$$X_s = \frac{X}{1+(1/Q^2)} \qquad X = \omega L \text{ or } \frac{1}{\omega C}$$

where C and G are the values of the parallel components obtained from the bridge.

If $Q \gg 1$:

$$R_s \simeq \frac{1}{Q^2 G}; \; C_s \simeq \frac{1}{\omega^2 C}; \; X_s \simeq X.$$

If $Q \ll 1$:

$$R_s \simeq \frac{1}{G}; \; C_s \simeq \frac{C}{Q^2}; \; L_s \simeq \frac{Q^2}{\omega^2 C}; \; X_s \simeq Q^2 X.$$

DVM OUTPUTS

Voltage outputs proportional to the C and G meter readings are provided on the rear panel. They provide 100mV at full-scale deflection, and the digital voltmeter connected to them should have an input impedance of not less than 100k Ω. Controls are provided for setting up each output to the precise level required.

FURTHER USE OF METER SENSITIVITY SWITCH

A general description of the function of the METER SENSITIVITY switch is given on page 13 under Operating Controls. For most normal measurements this control will be set to AUTO, in which position the meter sensitivity will be controlled by the first and second Decade Controls.

With all Decade Controls correctly set so that both meters indicate zero, the C and G terms may be read from the Decade Controls only. This is dealt with in the next section—3rd and 4th Decade Controls. The range of meter indication from 0 to +10 will now represent +1.0% of the full range capability of the RANGE in use (assuming that the first and second Decade Controls are not in the red zero positions). This may prove to be too sensitive for some measurements, for example, the selection of a ±5% capacitor from ±10% stock. In this case the METER SENSITIVITY switch may be set to 1, 2 or 3 as appropriate. The range of meter indications from 0 to +10 will now represent +100%, +10% or +1% of the full range capability of the RANGE in use on 1, 2 or 3 respectively of the METER SENSITIVITY switch. In order to obtain + or − indications on the meter it is necessary to offset the meter so that the required centre value indicates at +5, this is achieved with the Decade Controls and the METER SENSITIVITY switch. The following example for a ±5% selection of a 3n3 capacitor illustrates the method used.

Set the RANGE switch to the required range, in this instance RANGE 7. If the C Decade Controls are set to read 3300, a 3n3 capacitor would produce a zero reading on the C meter. For the present purposes, it is required that the meter shall read +5. To achieve this it is necessary to subtract one-half of the full scale meter capability from the Decade readout. The full scale meter capability for each RANGE depends upon the position of the METER SENSITIVITY switch, it is therefore necessary to decide the correct position, before the correct Decade settings can be ascertained. For RANGE 7 the meter coverage for each position of the METER SENSITIVITY switch is as follows:—

Position 1— 10nF (+100% of f.r.c.)
Position 2— 1nF (+ 10% of f.r.c.)
Position 3—100pF (+1% of f.r.c.)

Required percentage tolerance ±5% = ±165pF
Meter coverage required = 330pF

Position 2 will therefore be satisfactory.

Subtracting one-half of the meter coverage for position 2:

3n3−500pF = 2n8.

The C Decade Controls should therefore be set to 2800, at which setting a 3n3 capacitor will give a C meter reading of +5. A deviation of −5% will now read +3.35, and +5% will read +6.65.

USE OF 3rd AND 4th DECADES

During Normal Measurements the 1st and 2nd Decade Controls are set, and the reading is taken from these plus the meter indications, the 3rd and 4th Decade Controls having been left in the red zero positions. These last two Decade Controls have the following three functions.

1. They permit a meter deflection to be offset.

2. Used to 'back-off' a meter reading to zero, they provide enhanced discrimination.
3. When the instrument is operated with an external source/detector they are the fine balance controls.

Function 1 is particularly valuable for the batch-testing of components and when a varying value is to be recorded. The third and fourth Decade Controls are used to adjust to zero or mid-scale. The Autobalance facility will then give continuous readings (and the monitoring outputs) for changes in either sense. Also, the meter scale could be marked for acceptable upper and lower limits to meet a required component tolerance.

Function 2 arises because the linearity of the third and fourth Decade Controls considered jointly, is better than that normally obtainable from a moving-coil meter. The Decade reading taken when the meter deflection has been backed to zero is about five times improved in resolution.

Function 3 arises because the Autobalance meter circuits are inoperative when an external source and detector are used. The operating procedure is given in the section EXTERNAL SOURCE AND DETECTOR on page 36.

The coverage provided by the 3rd and 4th Decade Controls is equivalent to the full-scale range of a meter when the first and second Decade Controls are in use, in the most sensitive condition (Meter Sensitivity indicator lamp No. 3 alight).

EXTERNAL STANDARDS

General

The purpose of the two front-panel B.N.C. connectors above the legend EXTERNAL STANDARDS is to permit the connection of external components into the 'standards' side of the bridge. Such externally connected components DO NOT replace the internal bridge standards, but there are circumstances—discussed in the following paragraphs—where it is advantageous to be able to modify them.

By connecting external standards to these points, a large part of any reading can be 'backed off' allowing the bridge to be set to a more sensitive RANGE to provide increased discrimination. Further uses include the accurate comparison of two components (for example, an external standard in stabilized conditions could be compared with an UNKNOWN subjected to various environmental conditions), components can be measured against external preset standards which could be switched in the form of a programme, also—over a wide range—two components can be compared, or matched, on a direct 1 : 1 basis.

The backing-off provides a discrimination of up to 100 times better than on a normal measurement. This is extremely valuable for the plotting or observation of small variations. It must be appreciated, however, that the same order of discrimination is applied to the external standard component.

For this reason it is usually necessary to use a component that is highly stable and whose value is known precisely or is adjustable. Also the quality of the component must be sufficient to prevent its minor term—which may be magnified 10 or 100 times by the system—from causing errors. This is particularly important when an external standard is being used to balance out the major term of an UNKNOWN in order to allow closer examination of its minor term.

The operation of the bridge with external standards is described (a) as a Comparator, (b) for increased discrimination. This is followed by (c) interpretation of results, and (d) extension of trim controls. The section incorporates a table giving the values of the external standards required for backing-off.

All information on this facility applies equally to capacitance and conductance measurements. In principle, the use of this facility is equally applicable to inductance, but in this case signs must be changed and ratios must be inverted. To avoid confusion, it is preferable to consider inductance as a negative capacitance component and convert to actual inductance units only for the final results.

Comparator - Ranges 4 - 10

The bridge can be used for direct 1 : 1 comparison of capacitors, with normal discrimination, on Range 7 only. Before commencing the measurement, the bridge should be trimmed (with all the red positions selected in the usual way) with all the leads connected to the appropriate sockets. The Decade Controls should be set to the red positions before either component is connected. The UNKNOWN should be connected in the normal way and the comparison component should be connected between the two inner connections of the EXTERNAL STANDARDS sockets (see Table 2).

The full sensitivity of the instrument can then be achieved by setting the decades (zero or digits as appropriate) and the resulting indication, in conjunction with the relevant RANGE multiplier,

UNKNOWN ARM				EXTERNAL STANDARD Value equivalent to full scale on Normal Range of Unknown				
Unknown Value	Normal Range	E & I turns in Unknown Arm	Normal Discrimination	For Normal Discrimination (Select Normal Range)	10 × Normal Discrimination (Select 1 Range above Normal)		100 × Normal Discrimination (Select 2 Ranges above Normal)	
					New Range		New Range	
1μF-10μF 10m℧–100m℧	Range 4	E+1, I+1	1nF, 10μ℧	10nF 100μ℧	Range 5	100nF 1m℧	Range 6	1μF 10m℧
100nF–1μF 1m℧–10m℧	Range 5	E+1, I+10	100pF, 1μ℧	10nF 100μ℧	Range 6	100nF 1m℧	Range 7	1μF 10m℧ (Direct comparison)
10nF–100nF 100μ℧–1m℧	Range 6	E+10, I+10	10pF, 100n℧	10nF 100μ℧	Range 7	100nF 1m℧ (Direct comparison)	Range 8	1μF 10m℧
1nF–10nF 10μ℧–100μ℧	Range 7	E+10, I+100	1pF, 10n℧	10nF 100μ℧ (Direct comparison)	Range 8	100nF 1m℧	Range 9	1μF 10m℧
100pF–1nF 1μ℧–10μ℧	Range 8	E+100, I+100	100fF, 1n℧	10nF 100μ℧	Range 9	100nF 1m℧	Range 10	1μF 10m℧
10pF–100pF 100n℧–1μ℧	Range 9	E+100, I+1000	10fF, 100p℧	10nF 100μ℧	Range 10	100nF 1m℧	NO RANGE AVAILABLE	
1pF–10pF 10n℧–100n℧	Range 10	E+1000, I+1000	1fF, 10p℧	10nF 100μ℧	NO RANGE AVAILABLE		NO RANGE AVAILABLE	

One minor division on the meter always equals $1/10^4$ of the selected range maximum.

Table 2 External Standards

will be the difference in value of the two components.

An initially negative meter indication shows that the UNKNOWN component has a smaller capacitance or conductance than the EXTERNAL STANDARD component.

Increased Discrimination - Ranges 4 - 10

The discrimination of the bridge is improved by increasing the RANGE position but, in so doing, the balance of the UNKNOWN goes outside the range of the internal standards. All or part of the UNKNOWN admittance can then be backed-off by connecting to the EXTERNAL STANDARDS sockets a component that is selected as follows:—

1. Select the normal RANGE for the UNKNOWN component (i.e. one that gives an initial reading between 10% and 100% of f.s.d. on the meter).
2. Refer to Table 1 to determine the discrimination available on this normal RANGE and decide on the number of orders of increased discrimination required (a limit of two orders is recommended).
3. From the table, select the appropriate column giving the required discrimination. This also specifies the increase in RANGE setting required (the RANGE position is increased by one for each extra order of discrimination).
4. The three columns give the values of EXTERNAL STANDARD equivalent to full scale on the normal range of the UNKNOWN component.

If the UNKNOWN value is less than full scale the EXTERNAL STANDARD value must be reduced proportionally.

The above method holds in principle for any RANGE – 4 to 10. In practice, however, a limit is reached on the high ranges when no further ranges are available to increase the discrimination and, on the low ranges, when the heavy loading that occurs will exaggerate the errors caused by internal and lead impedances.

Having determined the correct value for the EXTERNAL STANDARD, and the required RANGE, the measuring procedure is the same as before, i.e. trim the bridge on the new range with the leads only connected, select the red positions on the decade controls, connect both components and proceed as detailed under Normal Measurements on page 16.

Interpretation of Results

Within the limits of accuracy obtainable, the bridge always indicates the difference between the admittance of the UNKNOWN arm and the admittance of the EXTERNAL STANDARD arm transformed up or down to the level of the UNKNOWN arm.

The EXTERNAL STANDARD is reflected into the UNKNOWN arm as an admittance transformed by the ratio of the UNKNOWN E and I turns product to the EXTERNAL STANDARD E and I turns product.

Thus:

Effective Value of EXTERNAL STANDARD reflected into UNKNOWN arm

$$= \frac{\text{Ext. Std. value} \times \text{Ext. Std. turns product}}{\text{Unknown turns product}}$$

The turns product of the UNKNOWN arm is dependent only on the RANGE setting and can be found from Table 2. The turns on the EXTERNAL STANDARD arm are E_{-100} and I_{+10}.

For positive polarity:

Bridge indication = Unknown value—

$$\frac{\text{Ext. Std. value} \times \text{Ext. Std. turns product}}{\text{Unknown turns product}}$$

The bridge indication is always taken in conjunction with the multiplier of the range actually in use.

When a polarity switch is turned to negative to balance the bridge, this implies that the UNKNOWN admittance is less than the reflected admittance of the EXTERNAL STANDARD. The above equation holds if the bridge indication is taken as a negative value.

EXTENSION OF TRIM

It is sometimes necessary to trim out the effects of special clips, jigs, etc., or even an unwanted shunt path that appears, effectively, across the UNKNOWN. In cases where the coverage of the TRIM controls provided is inadequate or inconvenient, a suitably chosen component may be connected to the EXTERNAL STANDARDS sockets. The required value is best obtained by measuring the shunt path on the bridge and referring to the 'Normal Discrimination' columns in Table 2, exactly as though a comparator measurement were intended.

EXTERNAL SOURCE AND DETECTOR

General

The B642 Autobalance circuits operate at a fixed frequency which is, normally, 1591.5Hz ($\omega = 10^4$). When operation is essential at other frequencies, an external source and detector must be employed. The illuminated decimal points associated with the decades will still be operational, but the 3rd and 4th C and G Decade Controls must be used for fine balance to give the last two significant figures, in place of the meters.

The B.N.C. connectors for the external source and detector are fitted on the rear panel. Beside these is a switch which must be set to EXT: this disconnects the internal source and detector circuits and brings the external connectors into circuit.

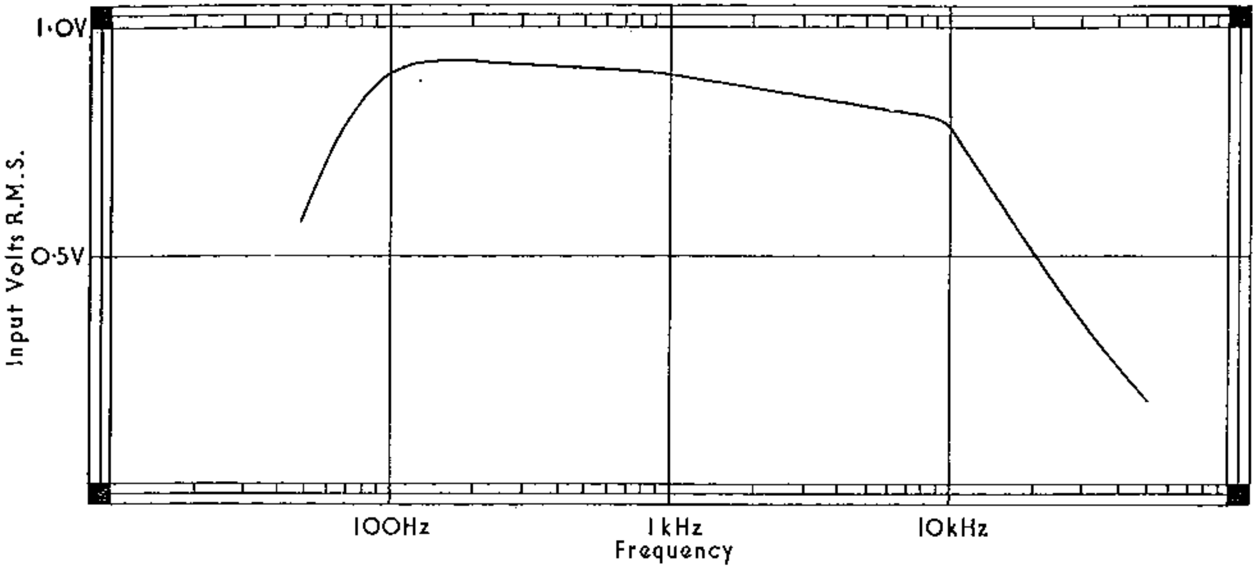
Source

The correct external source level for any frequency can be found by reference to Graph 2. Higher levels can cause errors and possible damage to the instrument, while lower levels will reduce the sensitivity. The output from the Source must be free of d.c. The input impedance at the EXTERNAL SOURCE socket is 15k Ω at all frequencies.

DETECTOR

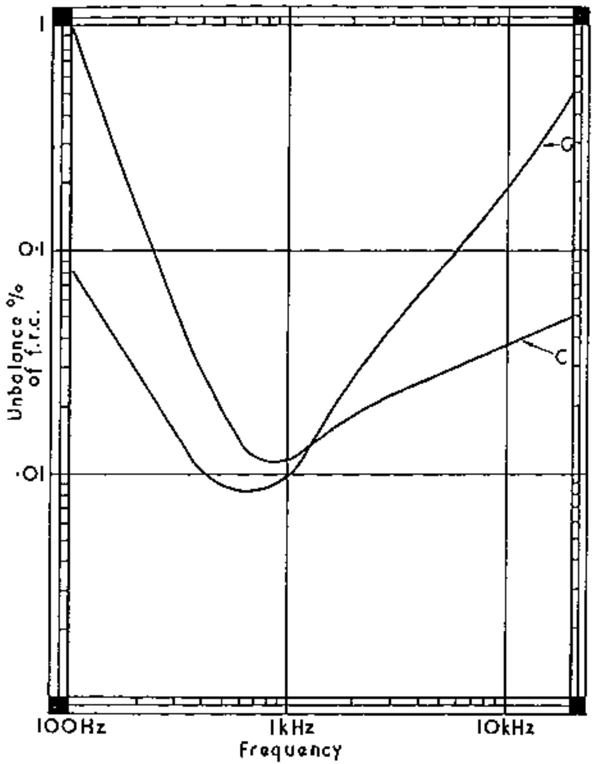
The choice of Detector will depend to a large extent on the degree of discrimination required, which in turn dictates the accuracy of the final result. In general the greater the detector sensitivity, the greater the degree of discrimination available. In practice, however, there is a limit to the sensitivity that can be used, due to residual hum and noise both within the bridge and in the external detector. The residual noise level is not constant over the useful frequency range, most notable being peaks at the fundamental, and low order harmonics of the a.c. line frequency. Any detector used should be tuned, since this will reduce unwanted noise. A single tuned circuit, having a Q of 20, will provide adequate rejection. In general, a Detector providing full scale deflection for 1µV at the EXTERNAL DETECTOR socket, will realise the maximum useful sensitivity, since hum and noise may represent 0.5µV at some frequencies.

Graph 3 illustrates the sensitivity of the system over the useful frequency range, and should be interpreted as follows. If the instrument is at exact



Graph 2 Maximum Drive at External Source Socket plotted against Frequency (Typical)

balance, there will be zero output at the EXTERNAL DETECTOR socket (excluding residual noise). If however the balance is in error by an amount sufficient to produce 1μV at the EXTERNAL DETECTOR socket, then graph 3 will show the size of the imbalance, i.e. the discrimination for 1μV output, and pro rata. This Graph should be consulted when interpreting the accuracy of results. It is important to note that the percentage figures given are a percentage of the full range capability (f.r.c.) of the RANGE in use.



Graph 3 Typical % Unbalance for 1μV R.M.S. at External Detector Socket when B642 is fed with maximum input voltage

Operation

Set the METER SENSITIVITY switch to the AUTO position.

When the source is first adjusted to the desired measurement frequency, and before the bridge is balanced, the detector should be tuned to the point of maximum response. The bridge must be retrimmed whenever the frequency of operation is changed.

N.B.—When operating with an external source and detector, the detector must be grounded at the input socket.

The bridge is trimmed exactly as described on page 15 (Ranges 4–10) or page 24 (Ranges 1–3), except that Trim C and Trim G are adjusted for minimum indication on the external detector (or minimum signal for an aural detector output). The FSD and ZERO controls are inoperative when an external detector is used.

N.B.—The disposition of the leads during trimming and measurement, the use of Low Capacity Clips, and allowance for the series inductance of the leads and the bridge circuits all become increasingly important at the higher frequencies.

Method 1 (with Detector Amplifier). Connect the test component. Set the first C and G Decade Controls to 2. Commencing at RANGE 4, rotate the RANGE switch step by step in the direction of RANGE 10 until a reduction in detector output indicates that the correct range has been engaged. Alternatively, the probable RANGE can be determined by first making the measurement with Autobalance at 1591.5Hz. Having determined the correct RANGE, balance is achieved by setting the 1st and 2nd C and G Decade Controls to obtain minimum detector output. Finally the 3rd and 4th Decade Controls are operated until full balance is achieved.

Method 2 (with Oscilloscope as Detector). Connect the 'E' EXTERNAL STANDARD socket (approximately 400mV pk-pk) to the X input of the oscilloscope and the external Detector socket to the Y input. Adjust the oscilloscope controls to produce a convenient Lissajous figure (this will be a single stationary loop since X and Y inputs are derived from the same frequency source). With the bridge measuring leads, but no UNKNOWN connected, use the TRIM controls to balance the instrument, i.e. the display must be reduced to the nearest approach to a horizontal line. Set the first C and G Decade Controls to 10 in turn. This will establish the maximum deflection obtainable under the worst out-of-balance condition; if necessary, adjust the Y sensitivity of the oscilloscope. Connect the UNKNOWN and use the C and G Decade Controls to balance the instrument as before. Note that the C and G controls affect the amplitude of the minor axis of the Lissajous figure and the angle of its major axis to the horizontal. Thus, a little practice will quickly establish which controls need adjustment to effect the balance.

INTERPRETATION OF RESULTS

Measurements of inductance and resistance Ranges 1–3 and conductance and capacitance Ranges 4–10 are not frequency dependent. The results are therefore interpreted as with internal source and detector, in conjunction with the RANGE switch units and the decimal point indicator lamps.

For measurements of inductance Ranges 4–10, and measurements of capacitance Ranges 1–3, a factor dependent on frequency must be applied.

For inductance, Ranges 4–10, $L = \frac{1}{\omega^2 C}$

where $\omega = 2\pi f$ and C is the value obtained after using the RANGE multiplying factor. The units are basic (L in Henrys, C in Farads). Thus, 10^{-6} must be included if C is in μF, 10^{-9} for nF, 10^{-12} for pF and 10^{-15} for fF. The expression can be written as:

$$L = \frac{1}{39.48f^2C}$$

For capacitance, Ranges 1–3, $C = \frac{1}{\omega^2 L}$

where $\omega = 2\pi f$, and L is the value obtained after using the RANGE multiplying factor. The units are again basic (L in HENRYS, C in FARADS).

Accuracy

Bridge accuracy using the internal source/detector is 0.1% on C and G provided all decades are in use. Measurement of L is dependent on a precise knowledge of the bridge frequency, which is accurate to ±0.5Hz. The C and G accuracy obtainable at other frequencies is better than:

±0.5%	200Hz – 10kHz
±1%	10 – 20kHz

These figures apply also to L measurement where frequency is known accurately: otherwise allowance must be made [L value will vary as $\frac{1}{(\text{frequency})^2}$]. Low Impedance accuracy is given by adding '1' to the % figures quoted above. In this case the figures apply to L and R. For C, measure frequency or make due allowance [C value will vary as $\frac{1}{(\text{frequency}^2)}$]. The internal source frequency is accurate to ±0.5Hz.

Note:–On the Low Impedance Ranges 1–3, correction for systematic error must be made. (See Graph 1 and the section Accuracy of Low Impedance Measurements on page 27).

RANGE LIMITATIONS

Permissible bridge loading restricts the maximum capacitance that can be measured accurately at frequencies above 1591.5Hz on Ranges 4–10. However, it should be noted that as the frequency is increased, this restriction in the bridge coverage is accompanied by a corresponding extension in the measurement range of the Low Impedance Ranges 1–3.

Source Frequency	Maximum Capacitance	Minimum Inductance
50Hz	10μF	1H
60Hz	10μF	0.7H
100Hz	10μF	250mH
200Hz	10μF	63mH
400Hz	10μF	16mH
800Hz	10μF	4mH
1000Hz	10μF	2.5mH
1592Hz	10μF	1mH
2kHz	8μF	0.8mH
4kHz	4μF	0.4mH
8kHz	2μF	0.2mH
10kHz	1.6μF	0.16mH
15kHz	1μF	0.11mH
20kHz	0.8μF	0.08mH

Table 3 Range Limitations with Frequency (Ranges 4–10)

Table 3 provides a guide to the maximum capacitance and minimum inductance values that can be measured accurately, on the bridge at selected frequencies throughout the band, on Ranges 4–10. In all instances lead corrections must be applied when the admittance of the UNKNOWN exceeds 10 millimhos (i.e. when the impedance is less than 100 ohms)—see LEAD CORRECTIONS on page 42.

When the bridge is used on Ranges 9 or 10 (for the measurement of large values of resistance and/or reactance) at frequencies above 2000Hz, particular care must be taken to avoid heavy shunt loading to the Neutral from either the voltage or current leads. If such loading is present, the measured value of the UNKNOWN should be corrected using the formulae given under In-Situ Measurements on page 21.

MEASUREMENT CONDITIONS

The voltage applied to the UNKNOWN during measurement is approximately as follows:

Ranges 4 and 5	20mV pk-pk
Ranges 6 and 7	200mV pk-pk
Ranges 8 and 9	2V pk-pk
Range 10	20V pk-pk

On the Low Impedance Ranges 1–3, measurements are made using a constant current source. The current passed through the UNKNOWN is approximately as follows:

Range 3	2mA pk-pk
Range 2	6mA pk-pk
Range 1	20mA pk-pk

LEAD CORRECTIONS

When the instrument is used for the measurement of conductance exceeding 10 millimhos (resistance of less than 100 ohms), capacitance exceeding 1 microfarad* or inductance of less than 10 millihenrys*, an allowance must be made for the series resistance and inductance of the measurement cables and bridge circuits.

Typical values are 130 milliohms and 2.3 microhenrys for Range 4, and 180 milliohms and 2.8 microhenrys for Range 5†. These figures are the sum of the measurement cables and the internal bridge circuits. The series resistance and inductance of the internal bridge circuits can be found from Table 1, in the section In-Situ Measurements on page 22. For extreme accuracy, or when using leads other than those supplied with the instrument, it is advisable to measure the series resistance and inductance as described below.

*That is, reactance less than 100 ohms. Values quoted apply at 1591.5 Hz and must be computed for other measurement frequencies. The effect of shunt loading is described under In-Situ Measurements on page 20.

†The values quoted are for measurement cables Type D10065A

The simplest method of making the correction is dependent on the availability of a second component whose value is within 2% of the value of the UNKNOWN. The Bridge is trimmed and the UNKNOWN measured normally, the conductance and capacitance values being noted (G1 and C1). A further measurement is made with the UNKNOWN remaining in position, but the second component connected between the red and green leads of the E cable. New readings (G2 and C2) are noted.

The second component is then transferred to the red and green leads of the I cable (the UNKNOWN remaining across the two red leads) and readings again noted (G3 and C3). The effect of the second component is given by adding the two variations from the original, i.e. (G1−G2) + (G1−G3) and (C1−C2) + (C1−C3). The original reading is corrected by adding the appropriate sum. If the loading component is a capacitor, the effect will be to increase the C reading. The correction must be added to the original reading.

An alternative method relies only on the availability of two 10 Ω±2% resistors. However, although the result is general, a calculation is necessary with each new measurement in order to apply the correction. The sequence of operations is similar to the previous method:

(i) Measure one 10 Ω resistor, noting G1 and −C1.

(ii) Add second 10 Ω between red and green leads of E cable. Rebalance. Note G2 and −C2.

(iii) Leaving first resistor across red-red transfer second resistor to red and green of I cable. Rebalance. Note G3 and −C3.

The differences that occur on adding the second resistor are a measure of the series resistance and inductance of the leads and bridge circuits.

Resistance. When measuring 10 ohms on RANGE 4, using all decades, the difference between two conductance readings in mhos × 100 gives the series resistance directly in milliohms.

Total series resistance = [(G1−G2) + (G1−G3)] × 100m Ω. To apply the correction, the measured value of the UNKNOWN should first be converted to the series form (see PARALLEL TO SERIES CONVERSIONS on page 28) and the total series lead and circuit resistance subtracted.

Inductance. When measuring 10 ohms on RANGE 4, using all decades, the difference between two capacitance readings × 100 will give the series inductance directly in microhenrys.

Total series inductance = $\{[(-C1)-(-C2)] + [(-C1)-(-C3)]\} \times 100\mu H$.

To apply the correction, the measured value of the UNKNOWN should first be converted to a series inductance and the total series lead and circuit inductance subtracted for inductance measurements. For capacitive UNKNOWN measurements on RANGE 4, the capacitance value measured must be converted to a series capacitive reactance, and the inductive reactance of the leads and circuits added. The true series or parallel capacitance can then be calculated.

NOTE:

$$L_s\,(\text{true}) = \frac{1}{\omega^2 C_p(1+1/Q^2)} - L_T$$

For capacitance

$$X_s\,(\text{true}) = \frac{1}{\omega C_p(1+1/Q^2)} - \omega L_T$$

$$C_s\,(\text{true}) = \frac{1}{\omega X_s\,(\text{true})}$$

where L_T is the total series inductance of leads and circuits.

Worked Example for RANGE 4:

1. Measurement of 10 Ω resistor:
   $G1 = 98.31\text{m℧}$; $-C1 = -0.038\mu F$
2. Measurement with E cable loaded:
   $G2 = 97.49\text{m℧}$; $-C2 = -0.054\mu F$
3. Measurement with I cable loaded:
   $G3 = 97.77\text{m℧}$; $-C3 = -0.051\mu F$

Total series resistance

$= [(98.31 - 97.49)+(98.31 - 97.77)] \times 100\text{m}\,\Omega$

$= (0.82+0.54)\times 100\text{m}\,\Omega$

$= (1.36)\times 100\text{m}\,\Omega$

$= 136\text{m}\,\Omega$

Total series inductance

$= [(-0.038+0.054)+(-0.038+0.051)] \times 100\mu H$

$= (0.016+0.013)\times 100\mu H$

$= 2.9\mu H$

Assume hypothetical bridge indications such as might be obtained when measuring a small inductor.

$$G = 97.43\text{m℧ and } C = -2.706\mu F$$

These are parallel components and must be converted to equivalent series values.

$$Q = \omega C/G = \frac{10^4\times 2.706\times 10^{-6}}{97.43\times 10^{-3}}$$

$$= \frac{27.06}{97.43}$$

$$= 0.278$$

$$\therefore Q^2 = 0.077$$

Equivalent series resistance

$$Rs = 1/G(1+Q^2)$$
$$= 1/97.43\times 10^{-3}(1+0.077)$$
$$= 9.53\,\Omega$$

Equivalent series inductance

$$Ls = 1/[-\omega^2 C(1+\frac{1}{Q^2})]$$

$$= 1/10^8\times 2.706\times 10^{-6}(1+\frac{1}{0.077})$$

$$= 1/10^2\times 2.706(1+12.99)$$
$$= 1/270.6\times 13.99$$
$$= 0.0002641$$
$$= 264.1\mu H$$

Corrected series resistance

$$\text{True } R_s = 9.530 - 0.136\,\Omega$$
$$= 9.394\,\Omega$$

Corrected series inductance

$$\text{True } L_s = 264.1 - 2.9\mu H$$
$$= 261.2\mu H$$

If desired, these values can be converted back to parallel values by applying the formulae:

$$Rp = Rs(1+Q^2)$$

$$Cp = Cs[1/(1+\frac{1}{Q^2})]$$

When measuring capacitance, it is convenient to convert the lead reactance to a series capacitance. The required value of the UNKNOWN is then given by

$$Cu = \frac{Cl \times Cb}{Cl - Cb}$$

where Cl is the equivalent series capacitance of the leads, and Cb is the indication given by the bridge.

Corrections for RANGE . The method for obtaining the series resistance of leads and bridge circuits is exactly the same as described for RANGE 4 but in this case a 100 Ω resistor ±2% or better is measured with 10 Ω±2% resistor loading.

The appropriate expressions for RANGE 5 are:

Series Resistance in milliohms = Total change in reading (mMho)×1000.

Series Inductance in microhenrys = Total change in reading (μF)×1000.

BRIDGE MEASUREMENT TECHNIQUES

Introduction

The Operating Instructions given for this instrument describe the basic procedure for directly measuring the quantities C and G and deriving values for the quantities L and R on Ranges 4–10. However, there are many cases where other parameters or conditions can be measured by adapting the basic procedure to meet the requirements of the individual case. While it is difficult to foresee every possible measurement, the intention in the following paragraphs is to indicate the approach to some of the more common applications so that users can obtain the full benefits of a.c. bridge measurement techniques. The Wayne Kerr Company is always interested in, and would be grateful for any information concerning novel applications of this instrument. Users are also invited to consult the Company concerning problems arising in the course of such applications.

Measurements on Non-Linear Resistive Elements

When measuring the characteristics of non-linear resistive elements (e.g. thermistors) it must be borne in mind that the voltage applied to the UNKNOWN varies according to the measurement range in use. The applied voltage is given under MEASUREMENT CONDITIONS on page 41.

NOTE—An external source may be used to provide a variable level for measurements of non-linear components.

Ceramic Capacitors - Ranges 4 - 10

With certain capacitors, the value changes considerably with the value of d.c. polarizing voltage. In such instances a polarizing potential can be applied as shown in Fig. 9. The blocking

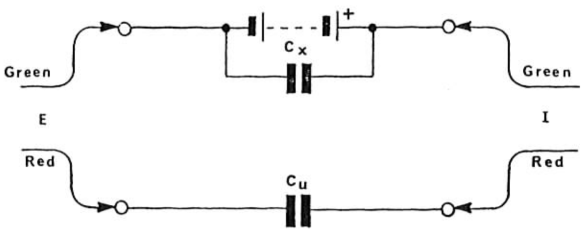


Fig. 9 Polarising Ceramic Capacitors (Ranges 4–10)

capacitor should have a value at least 1000 times that of the UNKNOWN in order to reduce the additional error introduced to 0.1%.

Electrolytic Capacitors - Ranges - 1 - 3

In practice it has been found that measurements of electrolytic capacitors may be made without using a polarizing voltage. In the majority of cases, the impedance of the component under test will require a four terminal measurement. Should it be desired to use a polarizing voltage, the connection should be made as in Fig. 10 and the measurement made in the normal manner. The source of d.c.

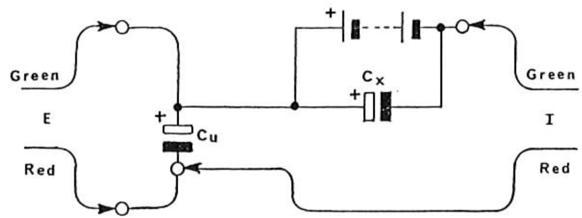


Fig. 10 Polarising Electrolytic Capacitors—Ranges 1–3

employed must not exceed an e.m.f. of 10V. A capacitor C_x is required to by-pass the series impedance of the polarizing supply. The value of this may be found from Table 4. When operating

RANGE	VALUE OF Co
1	1000μF
2	300μF
3	100μF

Table 4 C_o = Value of C_x at 1591.5Hz for Circuit of Fig. 10

at frequencies other than the bridge internal frequency, the value of C_x must be calculated from the following formula.

$$C_x = C_o \times \frac{fo}{f}$$

where fo = 1591.5Hz

This will give an additional error of not more than 0.1%.

Loss Angle

The loss angle or power factor of capacitors can be computed from the values measured on the bridge.

$$\tan \delta = G/\omega C$$

$$\cos \theta = G/Y \simeq G/\omega C = \tan \delta$$

An allowance for the impedance of the measuring leads must be made when dealing with large-value capacitors.

The internal capacitance standards have a small loss term that will cause an error in the displayed G value of the test component. While this error is not normally significant (less than 1% offset of the final meter reading) it may become so if an accurate measurement of a small loss term is required. The error will always be negative, i.e. the displayed G value will be less than the true value, but its magnitude can be simply determined as follows.

A standard air-dielectric capacitor, having either a negligible or known angle term, is measured on the bridge. The known loss angle (if any) is subtracted from the loss angle calculated from the displayed G and C values, and the result is the error caused by the loss angle of the internal standard. The final value thus obtained must be numerically added to any loss angle subsequently derived.

Iron-Cored Inductors

Great care must be taken when interpreting the results obtained from measurements on iron-cored coils and transformer windings. With power transformers, for example, the core will have only its initial permeability due to the low value of the a.c. potential applied from the bridge. The effective permeability at full operating voltage may be as much as twenty times higher.

With high-permeability materials such as mumetal, the effective permeability changes so rapidly with excitation, even at very low levels of magnetization, that widely different values of inductance may be obtained on different ranges of the bridge or even on two bridges of the same pattern. Therefore, unless the operating conditions are simulated, the measurements made are of value only for comparison purposes.

Inductors Carrying D.C.

It is often necessary to measure inductors carrying a known value of direct current and this may be accomplished with the circuit of Fig. 11.

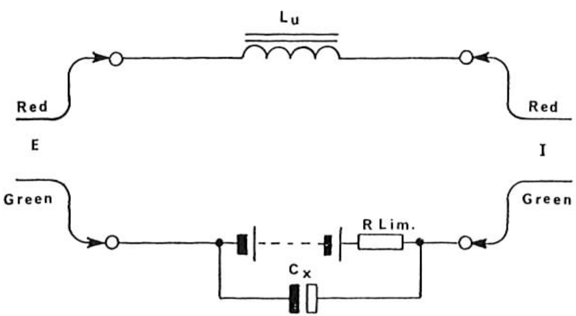


Fig. 11 Inductors Carrying D.C. (Ranges 4–10)

With the arrangement shown, the d.c. supply is connected between the two neutral leads. The limiting resistor R LIM must be calculated so that the current flowing does not exceed the value given for each range in Table 5. Alternatively a current limited supply may be employed. If the reactance of the bypass capacitor C is significant, it can be allowed for by calculating its equivalent inductance value at the frequency in use, and adding this to the effective series value derived from the measurement. If one side of the d.c. supply is grounded, this should be connected to the green lead on the E side of the bridge.

Range	4	5	6	7	8	9	10
Max. d.c.	1.0A	1.0A	1.0A	0.5A	0.5A	50mA	50mA

Table 5 Maximum Permissible Current through Bridge

Temperature Coefficients

Since leads of any length may be used without their capacitance affecting the accuracy of the reactance measurement, and as lead resistance can be allowed for, the bridge is ideal for the measurement of temperature and other coefficients of components placed in an oven, refrigerator, pressure chamber, humidity chamber, etc. If full use is made of the decades, normal discrimination of balance is 0.01 % of maximum for the range in use. If greater discrimination is required, see Increased Discrimination—Ranges 4–10 on page 34.

Measurements on Transformers

Turns Ratios

The turns ratio of a.f. transformers can be obtained by using an arrangement similar to that shown in Fig. 6 on page 22, substituting the transformer for the network. The value of R_T must be high compared with the output impedance of the transformer. Assuming the transformer has a primary: secondary turns ratio of 1 : N and that the primary is connected to the E lead of the bridge, the voltage produced across the secondary will be N.E. The secondary current (at balance) is given by I = NE/R_T. The conductance reading of the bridge, G_b, is equal to I/E. Therefore, the turns ratio, N, is given by $R_T \times G_b$.

Effectiveness of Transformer Screens

The effectiveness of screens between transformer windings can be determined using the arrangements shown in Fig. 12. The method of measurement when the transformer has a single inter-winding screen is shown in Fig. 12(A) and, in Fig. 12(B) the method of connection when each winding has a separate screen is shown.

With perfect screening there should be no feed through the transformers if connected as shown.

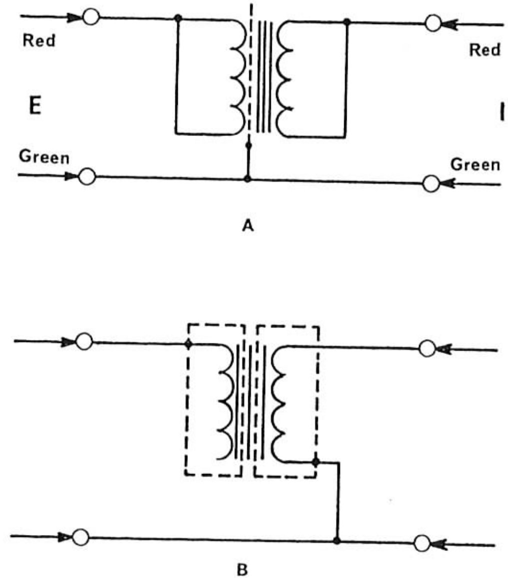


Fig. 12 Transformer Screens

RECIPROCAL TABLES

Reproduced from Tables of Mathematical Functions by J. B. Dale (Edward Arnold Ltd) by permission of the Publishers.

Note: Numbers in difference columns to be subtracted, NOT added.

	0	1	2	3	4	5	6	7	8	9
1·0	1·00000	99010	98039	97087	96154	95238	94340	93458	92593	91743
1·1	90909	90090	89286	88496	87719	86957	86207	85470	84746	84034
1·2	83333	82645	81967	81301	80645	80000	79365	78740	78125	77519
1·3	76923	76336	75758	75188	74627	74074	73529	72993	72464	71942
1·4	71429	70922	70423	69930	69444	68966	68493	68027	67568	67114
1·5	66667	66225	65789	65359	64935	64516	64103	63694	63291	62893
1·6	62500	62112	61728	61350	60976	60606	60241	59880	59524	59172
1·7	58824	58480	58140	57803	57471	57143	56818	56497	56180	55866
1·8	55556	55249	54945	54645	54348	54054	53763	53476	53191	52910
1·9	52632	52356	52083	51813	51546	51282	51020	50761	50505	50251
2·0	50000	49751	49505	49261	49020	48780	48544	48309	48077	47847
2·1	47619	47393	47170	46948	46729	46512	46296	46083	45872	45662
2·2	45455	45249	45045	44843	44643	44444	44248	44053	43860	43668
2·3	43478	43290	43103	42918	42735	42553	42373	42194	42017	41841
2·4	41667	41494	41322	41152	40984	40816	40650	40486	40323	40161
2·5	40000	39841	39683	39526	39370	39216	39063	38911	38760	38610
2·6	38462	38314	38168	38023	37879	37736	37594	37453	37313	37175
2·7	37037	36900	36765	36630	36496	36364	36232	36101	35971	35842
2·8	35714	35587	35461	35336	35211	35088	34965	34843	34722	34602
2·9	34483	34364	34247	34130	34014	33898	33784	33670	33557	33445
3·0	33333	33223	33113	33003	32895	32787	32680	32573	32468	32362
3·1	32258	32154	32051	31949	31847	31746	31646	31546	31447	31348
3·2	31250	31153	31056	30960	30864	30769	30675	30581	30488	30395
3·3	30303	30211	30120	30030	29940	29851	29762	29674	29586	29499
3·4	29412	29326	29240	29155	29070	28986	28902	28818	28736	28653
3·5	28571	28490	28409	28329	28249	28169	28090	28011	27933	27855
3·6	27778	27701	27624	27548	27473	27397	27322	27248	27174	27100
3·7	27027	26954	26882	26810	26738	26667	26596	26525	26455	26385
3·8	26316	26247	26178	26110	26042	25974	25907	25840	25773	25707
3·9	25641	25575	25510	25445	25381	25316	25253	25189	25126	25063
4·0	25000	24938	24876	24814	24752	24691	24631	24570	24510	24450
4·1	24390	24331	24272	24213	24155	24096	24038	23981	23923	23866
4·2	23810	23753	23697	23641	23585	23529	23474	23419	23364	23310
4·3	23256	23202	23148	23095	23041	22989	22936	22883	22831	22779
4·4	22727	22676	22624	22573	22523	22472	22422	22371	22321	22272
4·5	22222	22173	22124	22075	22026	21978	21930	21882	21834	21786
4·6	21739	21692	21645	21598	21552	21505	21459	21413	21368	21322
4·7	21277	21231	21186	21142	21097	21053	21008	20964	20921	20877
4·8	20833	20790	20747	20704	20661	20619	20576	20534	20492	20450
4·9	20408	20367	20325	20284	20243	20202	20161	20121	20080	20040
5·0	20000	19960	19920	19881	19841	19802	19763	19724	19685	19646
5·1	19608	19569	19531	19493	19455	19417	19380	19342	19305	19268
5·2	19231	19194	19157	19120	19084	19048	19011	18975	18939	18904
5·3	18868	18832	18797	18762	18727	18692	18657	18622	18587	18553
5·4	18519	18484	18450	18416	18382	18349	18315	18282	18248	18215
	0	1	2	3	4	5	6	7	8	9

PROPORTIONAL PARTS OF MEAN DIFFERENCES

	1	2	3	4	5	6	7	8	9
1·0									
1·1									
1·2									
1·3									
1·4									
1·5	42	83	125	167	209	250	292	334	375
1·6	37	74	110	147	184	221	258	294	331
1·7	33	65	98	131	164	196	229	262	294
1·8	29	58	88	117	146	175	204	234	263
1·9	26	53	79	105	132	158	184	210	237
2·0	24	48	71	95	119	143	167	190	214
2·1	22	43	65	86	108	130	151	173	194
2·2	20	40	59	79	99	119	139	158	178
2·3	18	36	54	72	91	109	127	145	163
2·4	17	33	50	67	84	100	117	134	150
2·5	15	31	46	62	77	92	108	123	139
2·6	14	29	43	57	72	86	100	114	129
2·7	13	26	40	53	66	79	92	106	119
2·8	12	25	37	49	62	74	86	98	111
2·9	12	23	35	46	58	69	81	92	104
3·0	11	22	32	43	54	65	76	86	97
3·1	10	20	30	40	51	61	71	81	91
3·2	10	19	29	38	48	57	67	76	86
3·3	9	18	27	36	45	53	62	71	80
3·4	8	17	25	34	42	50	59	67	76
3·5	8	16	24	32	40	47	55	63	71
3·6	8	15	23	30	38	45	53	60	68
3·7	7	14	21	28	36	43	50	57	64
3·8	7	14	20	27	34	41	48	54	61
3·9	6	13	19	26	32	38	45	51	58
4·0	6	12	18	24	31	37	43	49	55
4·1	6	12	17	23	29	35	41	46	52
4·2	6	11	17	22	28	33	39	44	50
4·3	5	11	16	21	27	32	37	42	48
4·4	5	10	15	20	26	31	36	41	46
4·5	5	10	14	19	24	29	34	38	43
4·6	5	9	14	18	23	28	32	37	41
4·7	4	9	13	18	22	26	31	35	40
4·8	4	9	13	17	22	26	30	34	39
4·9	4	8	12	16	20	25	29	33	37
5·0	4	8	12	16	20	24	27	31	35
5·1	4	8	11	15	19	23	26	30	34
5·2	4	7	11	15	18	22	25	29	33
5·3	3	7	10	14	18	21	24	28	31
5·4	3	7	10	14	17	20	24	27	30
	1	2	3	4	5	6	7	8	9

	0	1	2	3	4	5	6	7	8	9
5·5	18182	18149	18116	18083	18051	18018	17986	17953	17921	17889
5·6	17857	17825	17794	17762	17731	17699	17668	17637	17606	17575
5·7	17544	17513	17483	17452	17422	17391	17361	17331	17301	17271
5·8	17241	17212	17182	17153	17123	17094	17065	17036	17007	16978
5·9	16949	16920	16892	16863	16835	16807	16779	16750	16722	16694
6·0	16667	16639	16611	16584	16556	16529	16502	16474	16447	16420
6·1	16393	16367	16340	16313	16287	16260	16234	16207	16181	16155
6·2	16129	16103	16077	16051	16026	16000	15974	15949	15924	15898
6·3	15873	15848	15823	15798	15773	15748	15723	15699	15674	15649
6·4	15625	15601	15576	15552	15528	15504	15480	15456	15432	15408
6·5	15385	15361	15337	15314	15291	15267	15244	15221	15198	15175
6·6	15152	15129	15106	15083	15060	15038	15015	14993	14970	14948
6·7	14925	14903	14881	14859	14837	14815	14793	14771	14749	14728
6·8	14706	14684	14663	14641	14620	14599	14577	14556	14535	14514
6·9	14493	14472	14451	14430	14409	14388	14368	14347	14327	14306
7·0	14286	14265	14245	14225	14205	14184	14164	14144	14124	14104
7·1	14085	14065	14045	14025	14006	13986	13966	13947	13928	13908
7·2	13889	13870	13850	13831	13812	13793	13774	13755	13736	13717
7·3	13699	13680	13661	13643	13624	13605	13587	13569	13550	13532
7·4	13514	13495	13477	13459	13441	13423	13405	13387	13369	13351
7·5	13333	13316	13298	13280	13263	13245	13228	13210	13193	13175
7·6	13158	13141	13123	13106	13089	13072	13055	13038	13021	13004
7·7	12987	12970	12953	12937	12920	12903	12887	12870	12853	12837
7·8	12821	12804	12788	12771	12755	12739	12723	12706	12690	12674
7·9	12658	12642	12626	12610	12594	12579	12563	12547	12531	12516
8·0	12500	12484	12469	12453	12438	12422	12407	12392	12376	12361
8·1	12346	12330	12315	12300	12285	12270	12255	12240	12225	12210
8·2	12195	12180	12165	12151	12136	12121	12107	12092	12077	12063
8·3	12048	12034	12019	12005	11990	11976	11962	11947	11933	11919
8·4	11905	11891	11876	11862	11848	11834	11820	11806	11792	11779
8·5	11765	11751	11737	11723	11710	11696	11682	11669	11655	11641
8·6	11628	11614	11601	11587	11574	11561	11547	11534	11521	11507
8·7	11494	11481	11468	11455	11442	11429	11416	11403	11390	11377
8·8	11364	11351	11338	11325	11312	11299	11287	11274	11261	11249
8·9	11236	11223	11211	11198	11186	11173	11161	11148	11136	11123
9·0	11111	11099	11086	11074	11062	11050	11038	11025	11013	11001
9·1	10989	10977	10965	10953	10941	10929	10917	10905	10893	10881
9·2	10870	10858	10846	10834	10823	10811	10799	10787	10776	10764
9·3	10753	10741	10730	10718	10707	10695	10684	10672	10661	10650
9·4	10638	10627	10616	10604	10593	10582	10571	10560	10549	10537
9·5	10526	10515	10504	10493	10482	10471	10460	10449	10438	10428
9·6	10417	10406	10395	10384	10373	10363	10352	10341	10331	10320
9·7	10309	10299	10288	10277	10267	10256	10246	10235	10225	10215
9·8	10204	10194	10183	10173	10163	10152	10142	10132	10121	10111
9·9	10101	10091	10081	10070	10060	10050	10040	10030	10020	10010
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5·9	3	6	9	11	14	17	20	23	25
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