O P E R A T I N G
I N S T R U C T I O N S

S U L L I V A N

F9200

Two-Stage Inductive Voltage Divider

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TRANSFORMER RATIO STANDARDS

by

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1.0 GENERAL DESCRIPTION

TWO-STAGE INDUCTIVE VOLTAGE DIVIDER

Introduction

The following gives operating details for the Sullivan Two-Stage Inductive Voltage Divider, Type F9200. This is a highly accurate instrument and is used for the measurement of voltage ratios.

Details for connecting into a suitable test circuit are given, additionally further design considerations are contributed along with additional test circuits, by Mr. A.H. Silcocks under the title 'Transformer Ratio Standards'.

This instrument is easily connected into circuit using the terminals provided. The eight decade dials are easily read when balance has been achieved. The panel carries all terminals and decade dials, which are plainly marked as to their function.

General

The design considerations of inductive voltage dividers are directly related to the frequency band at which they operate. At low frequency the problem is to obtain a high accuracy from a design of suitable input voltage rating (input voltage = constant x frequency). This effectively requires that the ratio windings present a very high shunt input impedance with a corresponding limiting of their copper resistance (i.e. winding resistance). This effect is realised in the Sullivan F9200 Inductive Voltage Divider by a two stage design which facilitates a "pre-magnetising" of part of the core with a separate magnetising winding (hence a five terminal divider). Use of this technique eliminates, to a large extent, the errors introduced by external connecting leads.

2.0 SPECIFICATION

Ratios	0,00000001 to 0,99999999 in eight decades with facilities of -1 and +10 on the last four decades.
Accuracy	3 to 4 parts in 10^8 at 1 kHz depending upon ratio.
Frequency Range	50 Hz to 10 kHz
Max. Voltage	0,2f (where f is the frequency in Hz) or 200 V whichever is the least.
Dimensions	686 x 229 x 254 mm (27 x 9 x 10 ins.)
Weight	25,4 kg (56 lb)

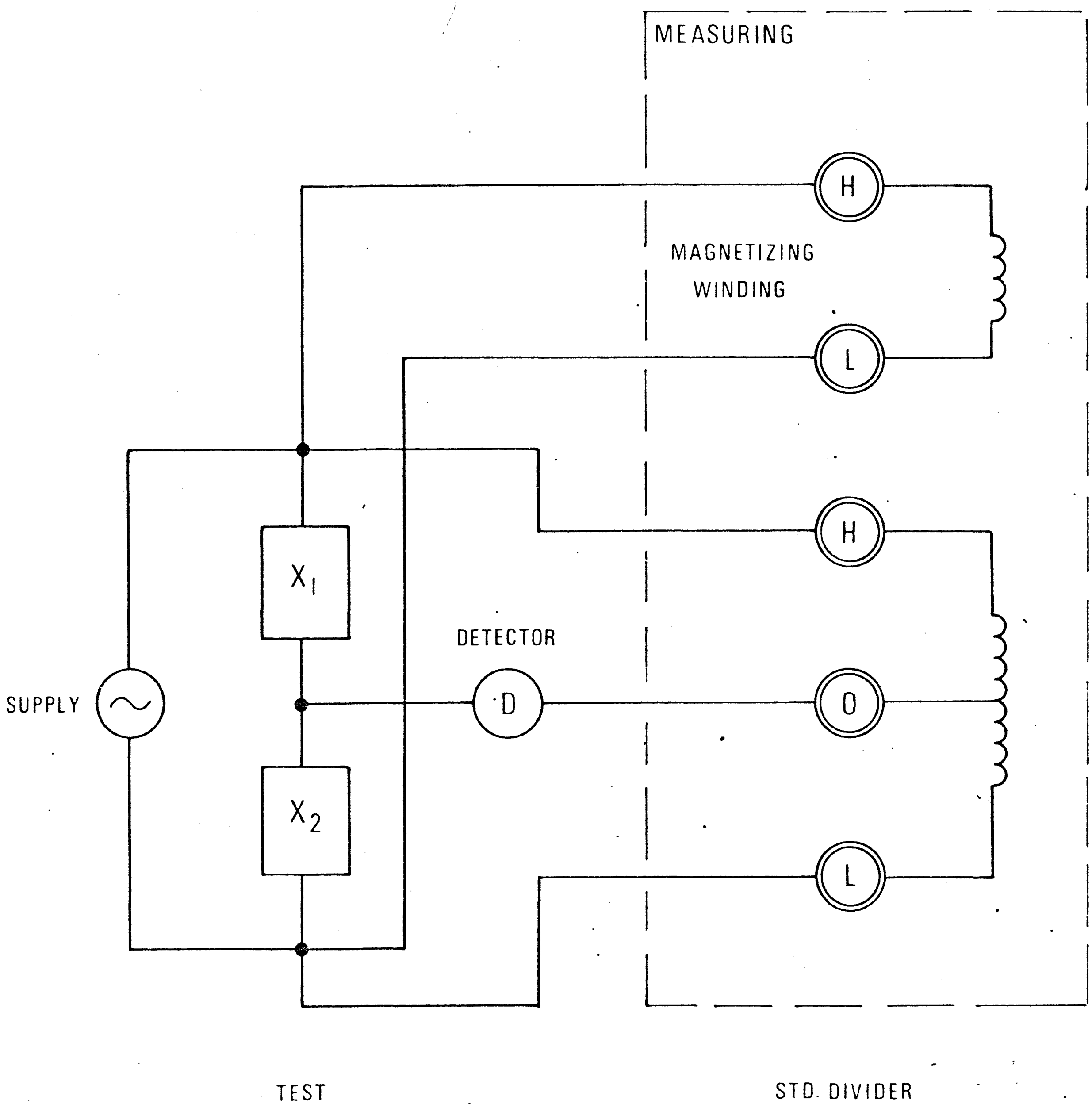
MEASURING
H
MAGNETIZING
WINDING
L
H
X1
DETECTOR
SUPPLY
D
O
X2
L
TEST
STD. DIVIDER

Fig. 1

TRANSFORMER RATIO STANDARDS

by A.H. Silcocks, Technical Director of H.W. Sullivan Ltd., Dover.

General Most physical parameters can be expressed by the equation:

$$A = n\,A_s$$

where n is a pure number without dimension, and A_s is a standard whose value or magnitude can be obtained by direct transfer from a national standardising authority. In the case of voltage the magnitude can be transferred directly by means of a Weston cell calibrated at N.P.L. Sometimes A_s is a standard that must be transferred indirectly; an example is the standard current that is obtained from standards of resistance and emf.

In either case, without means of generating the pure number "n" our ability to measure would be hopelessly limited.

Since the equality between two resistors can be established quite precisely by reversal methods, pure number ratios can be established with chains of equal resistors. An example of this is the D.C. potentiometer which has been spoken of in another lecture.

In A.C. work the transformer has long been known as an accurate source of ratios. It is well known that the ratio between primary and secondary emf's in a transformer is in the ratio of the turns, but it requires further examination to realise the accuracy that can be achieved.

Types of Transformers

We can divide transformers into two main classes: these are auto transformers and what I shall call multi-winding transformers.

Fig. 1 shows a simple transformer and fig. 2 shows a three winding transformer. Both of these can be used to provide voltage ratios, but in different ways.

The Auto Transformer

Firstly, we will consider the auto transformer of fig. 1. Normally such an auto transformer will be constructed so that the same magnetic circuit cuts each turn on the auto transformer, and in this case one would expect the emf associated with each turn to be the same. To ensure that this is so, precision auto transformers are often wound on toroidal cores.

Consider a transformer divided into N windings as in fig. 3b, all connected in series aiding.

The potential difference across each winding can be considered as being made up of two parts. The first of these is the emf due to the flux in the core, the second of these is the volt drop caused by the magnetising current flowing in that part of impedance of the winding that is not coupled in the core.

Now for a perfect toroidal core, the flux cutting each winding will be the same. If this were the only source of emf in each winding then, the emf generated in winding "r" would be:

$$v_r = -n_r \frac{d\phi}{dt} \qquad (1)$$

where n_r is the number of turns and ϕ is the flux. The ratio between the various emf's would be in the ratio of the turns. However, if the permeability of the core is not infinite, the core reluctance can cause some of the flux to take paths outside the core as shown by the dotted line in fig. 3a. This means that the flux will not be the same through all the windings, and consequently the ratio will be in error.

To avoid this error, the following precautions are taken:

(a) A toroidal core is used.

(b) The core must be very uniform, and have a high permeability.

(c) Every attempt must be made to ensure that the windings are as near coincident as possible. Usually, each winding is made a strand, of a rope of conductors.

As has already been said, there is a voltage drop due to the magnetising current flowing in the leakage impedance associated with each winding. These voltage drops are very small compared with the main emf's in the windings, but for the highest accuracies it is essential that these are in the same ratio as the turns ratio.

To minimise errors from this source it is essential that the magnetising current be kept low; after all if there were no magnetising current there would be no error. This means a high permeability core is used. To minimise the effect of the copper resistance it is essential that the "Q" of the magnetic material should be as high as possible.

For a given core, the best results will be obtained when all the windings are as alike as possible. Again this means that they should be strands of the same gauge of wire made up into a rope of conductors.

Fig. 4a and b shows a ten sectioned winding on a toroidal core. Each winding in 4b is a strand in the rope shown in 4a. Such a transformer can be designed to have a ratio accuracy of 1 in 10^7 of the input.

The transformer in fig. 4 gives one decade of ratio; should more decades be required a Kelvin/Varley arrangement of transformers is possible, as shown in fig. 5. In this the various windings are on separate cores.

A multi-decade divider can be constructed on these lines giving an accuracy at least as good as 1 in 10^7. Other arrangements are possible giving a variety of accuracies; the possible accuracies are so good that sometimes it makes good commercial sense to go to a cheap arrangement and sacrifice some in accuracy.

Transformer dividers are characterised by a high input impedance and a low output impedance. Typical figures at 1 kHz are greater that 70 k ohms for the input and less than 3 ohms for the output impedance.

The two winding transformer.

Let us consider the transformer of fig. 2. Here the ratio of V_1 to V_2 is not affected by the magnetising current, as this current does not flow in the secondary windings. This means that the accuracy of this ratio is potentially better than for the auto transformer. However, even if the turns ratio from primary to secondary is 1 : 1, the secondary voltage will differ from the generator voltage, because of the leakage impedances associated with the two windings. This limits the use of this type of transformer to A.C. bridge applications.

Construction

As has been said, the optimum shape of core is the toroid or ring, as it is the shape most likely to cause uniformity of flux. Usually, when the lowest frequency of use is below about 30 kHz, the material is a tape of Mumetal or Supermumetal wound in the form of a clock spring.

The thickness of the tape is governed by the frequency at which the core is used; the thinner the material the less its effective permeability reduces with frequency due to eddy current shielding. Tapes down to ,001" thickness are readily available, but, since the packing factor is poorer for thin tapes than for thick, the effective permeability of the material is reduced for thin tape.

The size of the core and the number of turns is a compromise between input impedance, output impedance and the input voltage that can be applied without approaching saturation.

The peak flux density in the core is given by:

$$\hat{B} = \frac{E}{4{,}44\ A.f.n.} \quad \text{tesla} \qquad (2)$$

Where E is the applied voltage.
A is the cross sectional area in square metres
f is the frequency in Hertz, and n is the number of turns.

For Supermumetal 100 it is usual to keep this under 5 mT. As can be seen, the area of core units, input voltage, number of turns and frequency are inter-related.

It is usual to rate a ratio transformer for voltage, by specifying a maximum input voltage as

V max. = K.f where f is the frequency in Hertz.

That is, if a transformer is rated as 0,2f Hz, then at 50 Hz the maximum input voltage is

V max. = 10 volts

In addition, an over-riding maximum voltage, determined by the insulation, is also specified.

If the specified input voltage is exceeded, distortion can result, and more important, the accuracy of the ratio drops off in an alarming fashion.

The very high permeability materials, such as Supermumetal 100, are very susceptible to shock; violent mechanical shock can soon reduce the permeability. For this reason the cores are usually cushioned in silicone grease and mounted in a nylon core box.

Care must be taken to see that the core is not magnetised by the production of D.C. flux. When sorting out the windings on a ratio transformer we should avoid using a D.C. continuity tester, such as a buzzer, since this can cause an amount of magnetism that can reduce the usefulness of the core.

A core can be demagnetised by applying a large A.C. signal and gradually reducing it. However, even when demagnetised the original permeability may not be regained if the magnetic shock was too great.

Most often, the winding consists of the series connection of the strands of some kind of rope. The strands are, of course, insulated from each other and the ordinary solderable enamels are found quite satisfactory for this purpose.

Application

The uses of the ratio transformer are many; in any A.C. measurement where an accurate ratio is required a transformer is the best tool to use. A multi-decade transformer divider can be used to calibrate attenuators, measure transformer ratios and compare impedances of all sorts.

Fig. 6 shows such a divider being used to compare two resistors. Here R_1 is given by

$$R_1 = R_2 \frac{n}{1 - n} \qquad (3)$$

The resistors could be replaced by capacitors, inductors, etc. In this diagram it will be noted that the screen of the detector is connected to the transformer tap. Since the impedance to ground at this point is a few ohms only, the capacitance to ground can usually be neglected. When the highest accuracy is desired the screen can be connected to the tapping point of a second divider as in fig. 7. Here the second divider acts as a Wagner earth.

Sometimes, with the circuits shown, a complete balance cannot be obtained because the ratio being measured has a quadrature component. Fig. 8 is such a case. The loss component here is being balanced out by the addition of a resistor in series with the tapping point of the transformer and an adjustable capacitor.

Auto transformer dividers such as these are used to calibrate potentiometers, and potential dividers, for use with D.C. The technique is to measure at several low frequencies and by assuming the type of frequency law, calculate an extrapolation to zero frequency. With care, this is a powerful method.

A less well understood application of this type of ratio transformer is the conversion of a fixed impedance standard into a variable one, and since this has very considerable utility it is worthwhile examining it in some detail.

Fig. 9a shows a "T" network consisting of an auto transformer 1 - 2 - 3, and an impedance Z_3. If the transformer is ideal, this "T" network can be replaced by the Δ in fig.9b where:

$$Z_4 = \frac{N_1 + N_2}{N_2} \cdot Z_3 \qquad (4)$$

$$Z_5 = \frac{N_1 + N_2}{N_1} Z_3 \qquad (5)$$

$$Z_6 = \frac{-(N_1 + N_2)^2}{N_1 \quad N2} Z_3 \qquad (6)$$

In Fig. 9a the tapping point 2 divides 1 - 3 internally.

Fig. 10 is similar to fig. 9 but with 2 dividing 1 - 3 externally. In this case, since the turns from 1 - 3 must equal the turns 1 - 2 plus the turns 2 - 3, N_2 must be taken as negative. If this is done, equation 4, 5 and 6 will be found to hold.

As an example of fig. 9 consider fig. 11. Fig. 11a is fig. 9a, where Z_3 has been replaced by a capacitor C_4. Then in fig. 11b.

$$C_1 = \frac{N_2}{N_1 + N_2} C_4 \qquad (7)$$

$$C_2 \quad \frac{N_1}{N_1 + N_2} C_4 \qquad (8)$$

$$C_3 \quad \frac{-N_1 \cdot N_2}{(N_1 + N_2)^2} C_4 \qquad (9)$$

This combination of an impedance and an auto transformer can be used in certain resistive ratio arm bridges, either as an internal standard or as an external standard with which to calibrate the bridge.

Fig. 12 shows a transformer/capacitor combination being used to calibrate a unity ratio resistance ratio arm bridge. The turns ratio 1 - 2 : 2 - 3 is unity and the winding 2 - 3 is divided into ten sections.

The initial balance is carried out with the switch set to the centre or zero point. In these circumstances, capacitance across the AD arm and the capacitance across the CD arm are both C4/2. If, now, the capacitor is switched to a tap N, the capacitance thrown across the AD and CD arms will be

$$C_{AD} = C_4 \left(\tfrac{1}{2} + \frac{N}{20}\right) \qquad (10)$$

and

$$C_{CD} = C_4 \left(\tfrac{1}{2} - \frac{N}{20}\right) \qquad (11)$$

To rebalance the bridge, C_s must then be changed by

$$C_s = C_{AD} - C_{CD}$$

$$= \frac{C_4 N}{10} \qquad (12)$$

Thus a decade of capacity has been formed, and by cascading transformers in a Kelvin-Varley arrangement, or by using a multiplicity of separately switch capacitors in place of C_4, several decades could be formed. If the bridge ratio is other than unity, the turns ratio 1 - 2 : 2 - 3 must be the same as the bridge ratio.

There are few low frequency applications where a ratio transformer and a capacitor cannot be used in place of a variable capacitor.

Transformer Ratio Bridges

We have considered the case where a transformer divider, that is an auto transformer, is used in a bridge circuit; there are many such circuits. However, at this point I would mention the more common type of bridge transformer, which uses a transformer with separate windings. Such a bridge circuit is shown in fig. 13.

In this form of circuit the open circuit ratio is independent of the magnetising current. An equivalent circuit can be drawn as in fig. 14.

In this, z_1 is the impedance of winding 1 - 2 with a short circuit across 1 - 4, and z_2 is the impedance of 3 - 4 with a short circuit across 1 - 4.

In general z_1 and z_2 will be very low impedances, a few ohms at the most. However, if Y_1 and Y_2 are large admittances one should allow for the effects of z_1 and z_2.

It is the fact that z_1 and z_2 are so low that makes it possible to load the winding 1 - 2 and 3 - 4 with shunt impedances.

New devices

Transformer devices have been around so long that it is surprising that there are new advances still being made. We will consider two of these. Firstly, two core devices:-

As has been said already a potential source of error in auto transformers, such as shown in fig. 1, is the voltage drop in the leakage impedances caused by the magnetising current flowing in them. This error shows itself up more and more as the ratio deviates from unity.

This form of error is not present in a multi-winding transformer such as that in fig. 2, between the various secondaries: however, in these, leakage impedances prevent the primary to secondary voltages being in the ratio of the turns.

The device to be described combines the best of the two types of transformers.

Consider fig. 15. In this there are two transformers T_1 and T_2.

T_1 has a primary and two secondaries; the number of turns in the primary is equal to the total secondary turns, and 3 - 4 is in the same sense as 5 - 6.

T_2 has two windings, 1 - 2 being in the same sense as 3 - 4. The ratio of turns n_3/n_4 is the same as the ratio n_1/n_2 in the transformer T_1.

Now if the secondary windings of T_1, had been left open circuit, the sum of the induced emf's would be nearly equal to e. The difference δv, which for a well designed transformer will be small, will be the result of the voltage drop in the primary leakage impedances due to the magnetising current flowing in them.

Now as the circuit is wired, in fig. 15, the difference voltage, just referred to, will be shared by the leakage impedances of the secondaries, and the windings of T_2. The impedances of the windings of T_2 are arranged to be high compared with the leakage impedances of the secondaries of T_1.

$$\text{Since} \quad \frac{n_3}{n_4} = \frac{n_1}{n_2}$$

the difference voltage δv, is divided up by T_2 in nominally the correct ratio, and the accuracy of division of T_2 can be high.

This means that

$$v_1 + v_2 = e \text{ very precisely}$$

and

$$\frac{v_1}{v_2} = \frac{n_1}{n_2} \quad \text{with an accuracy relatively}$$

unaffected by the leakage impedances of T_1.

Since the ratio of T_2 is unlikely to be exactly unity, it is necessary to measure its insertion loss separately and to allow for it. However, this introduces a possibility of error as the insertion loss of T_2 will vary with load and the load may change with the setting of the attenuator.

Using a Longitudinal stop coil

See fig. 20. T_2 is a unity ratio transformer. Here T_2 takes the potential difference 2-D and reflects a voltage equal to it in series with the detector. This ensures that the voltage appearing across the detector is simply the difference between the voltage appearing across 2 - 3 of the IVD and CD of the attenuator.

It is usual to make the windings 1 - 2 and 3 - 4 the inner and outer of a co-axial cable. Since this transformer is used to stop a longitudinal signal, i.e. one that flows in the outer conductor only, it is called, in the telecommunication industry, a longitudinal stop coil. Lately this type of transformer has been discovered by the measurement industry, which calls them "co-axialisers". This is a poor term as some longitudinal stop coils are not co-axial, i.e. where used in balance outs.

Accuracy

IVD's have their accuracy specified in terms of the input voltage e.g. a divider may have an uncertainty of 10 p.p.M of input.

In the circuits shown:

$$A = \text{Attenuation} = 20 \log_{10} n = \frac{20}{2,303} \log_e n$$

$$dA = \frac{20}{2,303} \frac{dn}{n}$$

e.g. If $A = 120$ db

$n = 10^{-6}$

$\therefore$ if we want $dA = 0,1$ db

$$0,1 = \frac{20}{2,303} \frac{dn}{10^{-6}}$$

$$\therefore \quad dn = \frac{2,303}{2} 10^{-8}$$

$$= 1,1515 \; 10^{-8}$$

APPENDIX

Use of Inductive divider to calibrate attenuators

General

Since both inductive dividers and attenuators are ratio devices it seems an obvious step to calibrate attenuators, at low frequency, using an inductive divider. However, considerable care needs to be exercised since an attenuator is a four terminal device, and an IVD is a three terminal device.

Fig.17 shows the circuit most commonly given for calibrating attenuators. The fixed resistor R and the variable capacitor C are included so that a phase balance may be achieved. Zo is the terminating impedance for the attenuator. With an ordinary IVD, such as the F9100, the difficulty comes in connecting the lead from terminal 2 to the attenuator. If it is connected to attenuator terminal D, the magnetising current for the 1st transformer of the IVD will flow through the wiring of the attenuator. If it is connected to B then the voltage drop D to B within the attenuator will be included with the output voltage of the attenuator.

In either case, unacceptable errors will be obtained when measuring high values of attenuation.

There are three methods of avoiding these errors.

Using an IVD with a two stage input, i.e. F9200

Probably the simplest method of avoiding this error is to use an inductive divider which has a two stage input transformer, which enables the magnetising current to be kept out of the measuring circuit.

Fig. 18 illustrates the method. Notice the way the two staging is illustrated schematically. Winding 4 - 5 embraces core 1 only, while winding 1 - 2 embraces both cores.

In this circuit, the inductive divider measures only the PD across CD.

Using an isolating transformer

This method is shown in Fig. 19.
Here T_2 is an isolating transformer having a unity turns ratio.

In practice T_1 and T_2 are made one transformer as illustrated in Fig. 16. This shows a section through the transformer which has two toroidal cores. Winding 1 - 2 of T_1, is wound on core A. Core B is then taped on to core A, and windings 3 - 4 and 5 - 6 are wound on both cores together. It is easy to see that these last windings not only provide windings 3 - 4, 5 - 6 by coupling with core A, but provide windings 1 - 2, 3 - 4 of T_2 by coupling with core B.

Such a transformer is capable of much greater accuracies than the usual auto transformer when ratios are required that differ greatly from unity.

These transformers are being used in multi decade inductive dividers and in A.C. bridges.

Lastly, we will just mention the use of ratio transformers for D.C. measurements. This can be done by chopping the D.C., or by using harmonic devices as in reference No.2.

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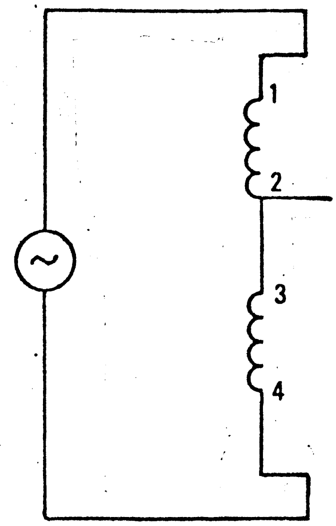

Fig.1

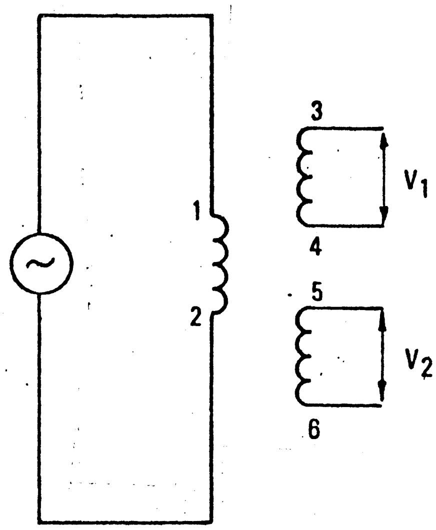

Fig.2

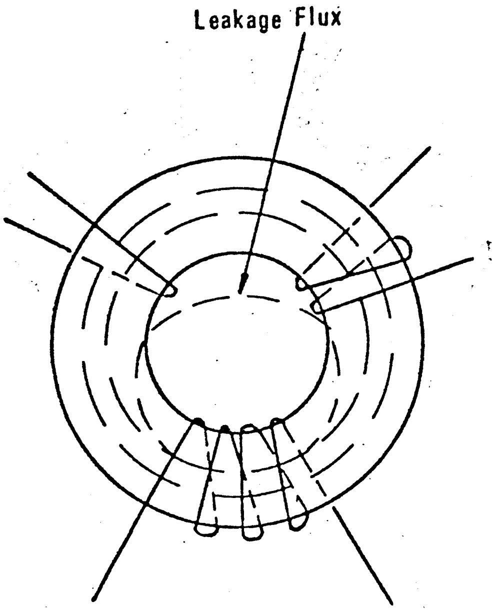

Fig.3a

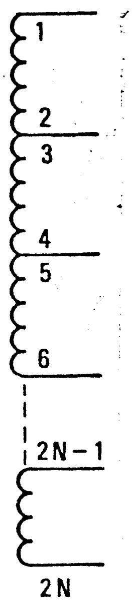

Fig.3b

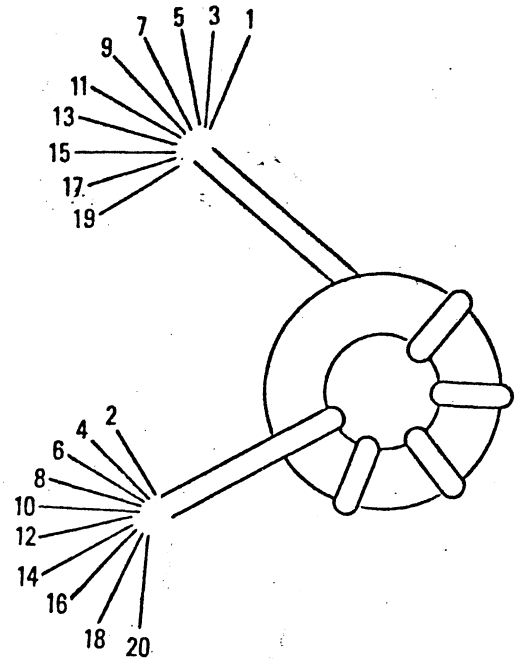

Fig. 4a

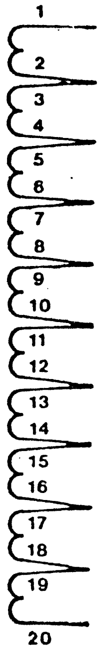

Fig. 4b

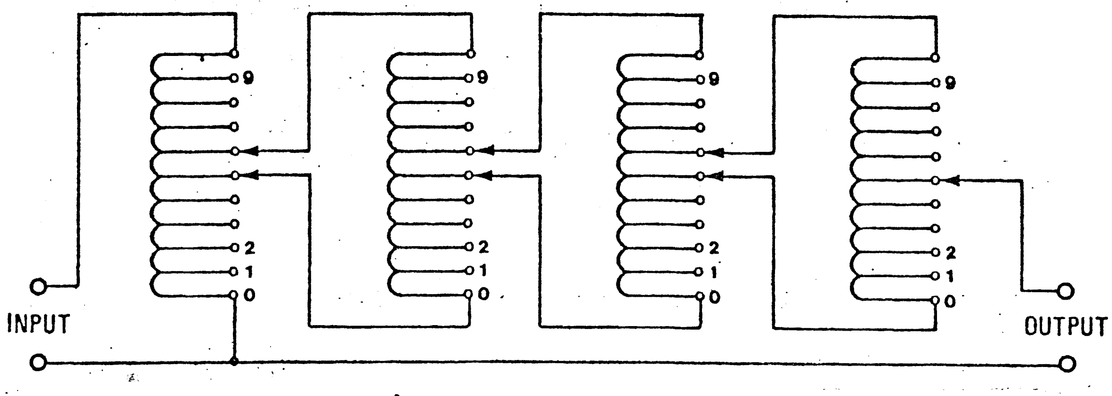

Fig. 5

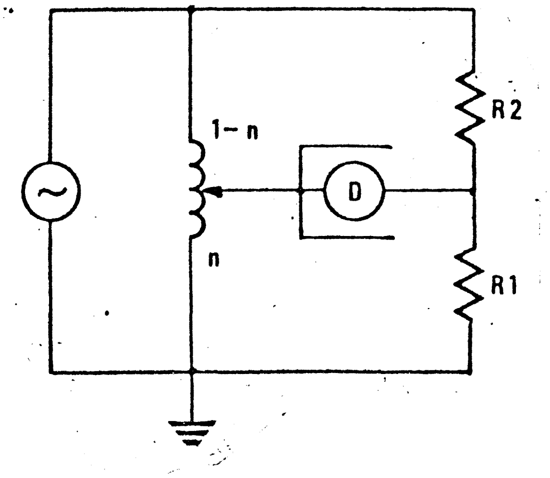

Fig.6

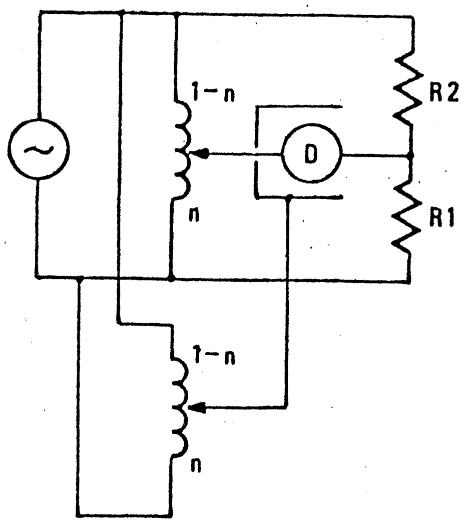

Fig.7

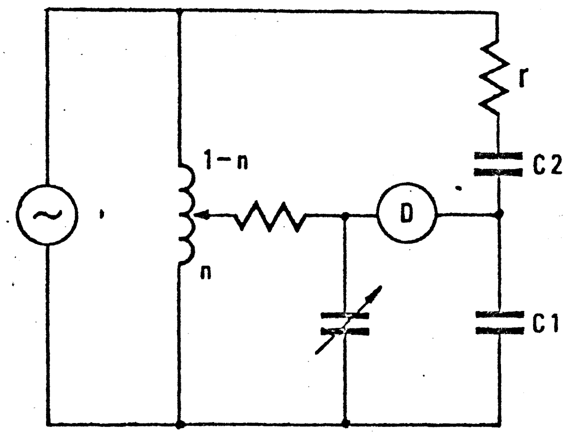

Fig.8

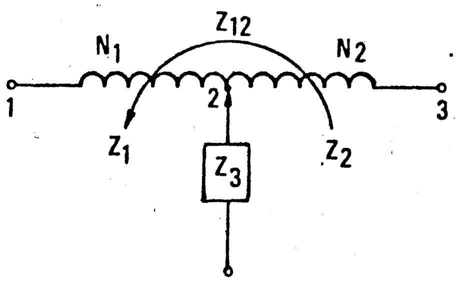

Fig. 9a

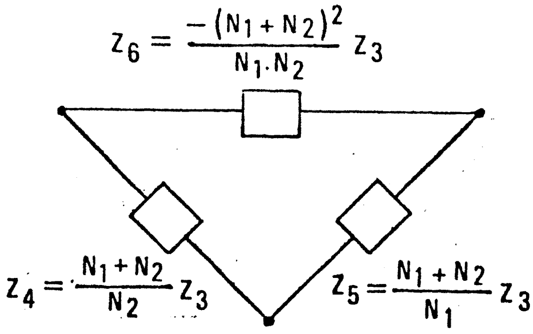

Fig. 9b

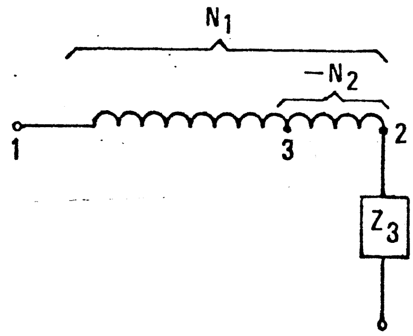

Fig. 10

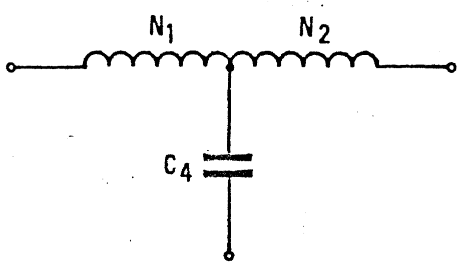

Fig. 11a

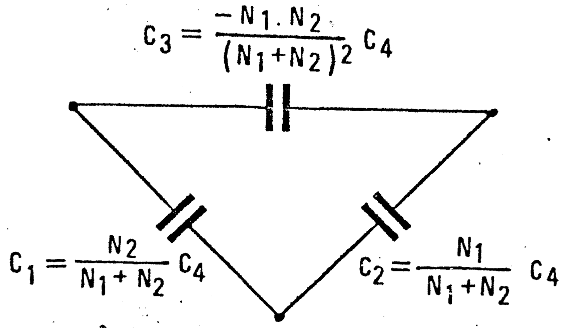

Fig. 11b

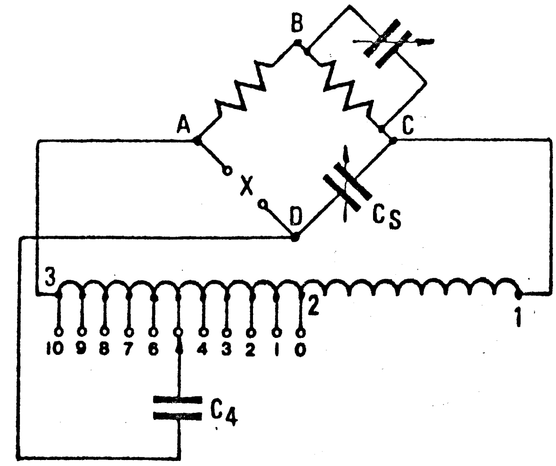

Fig.12

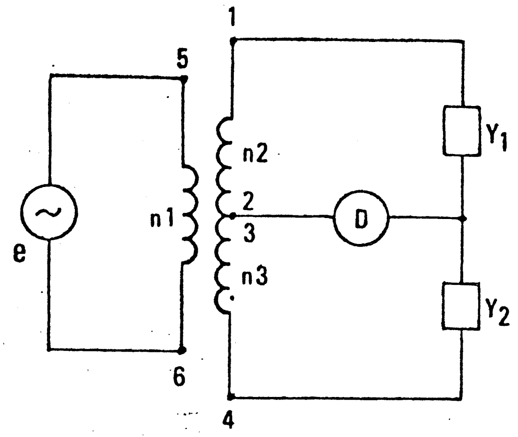

Fig.13

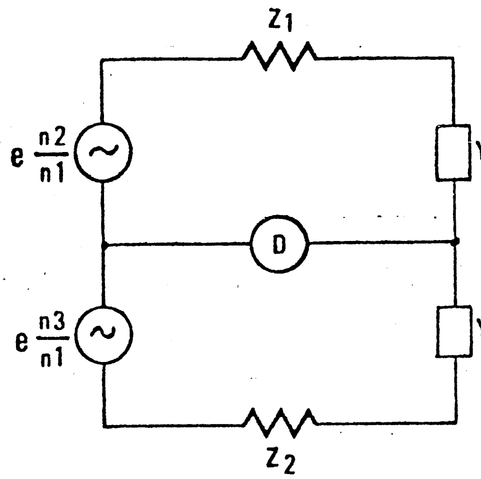

Fig.14

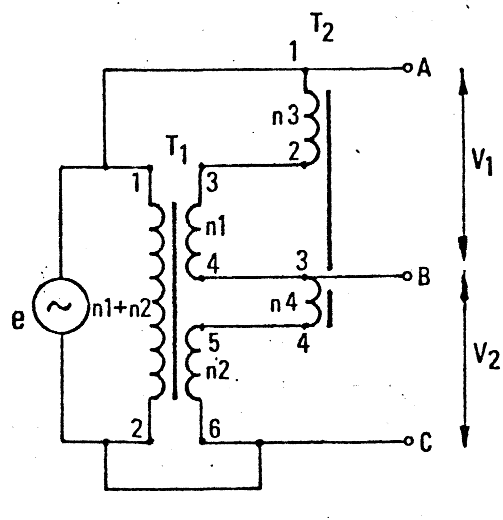

Fig.15

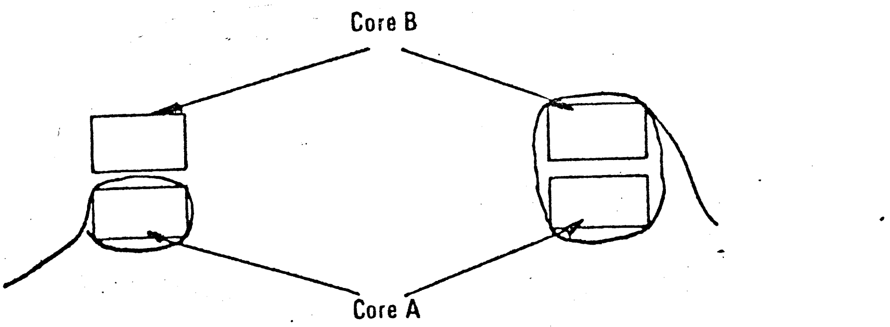

Fig.16

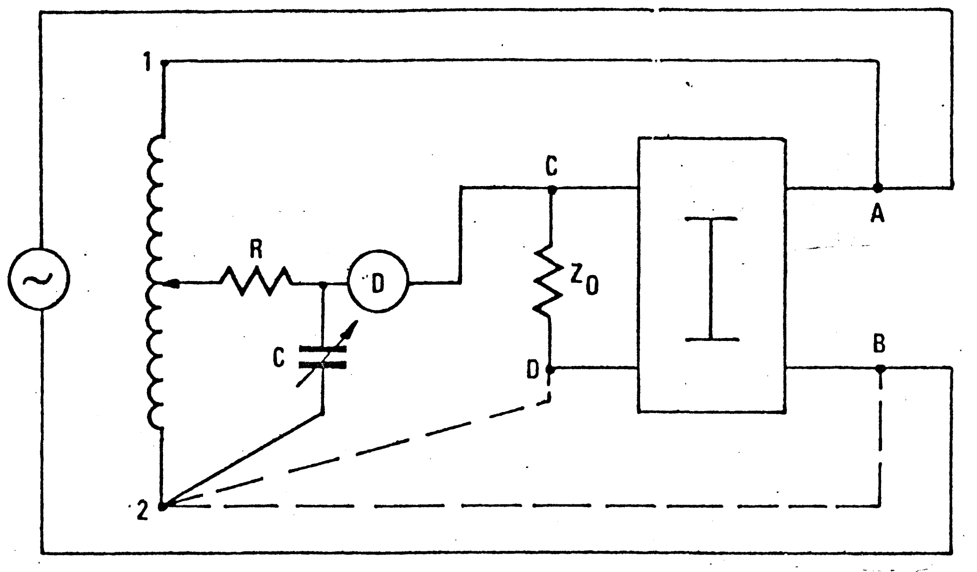

Fig.17

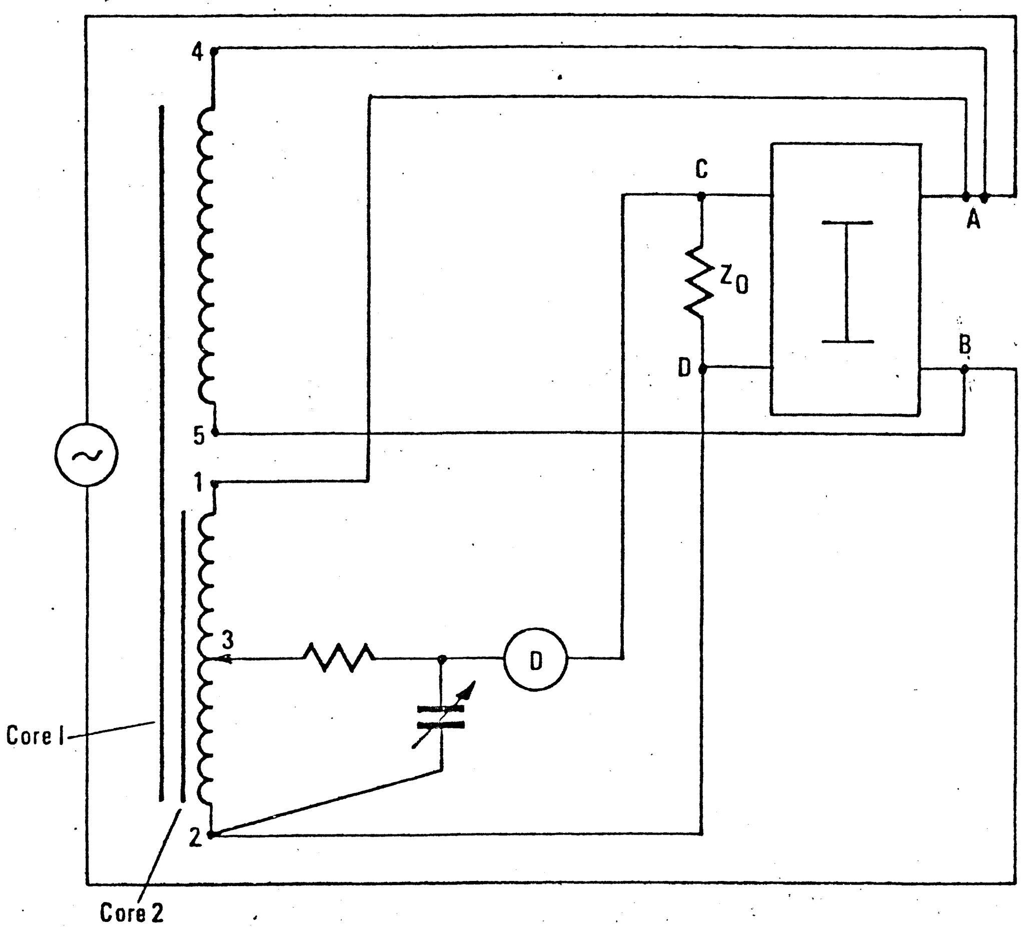

Fig.18

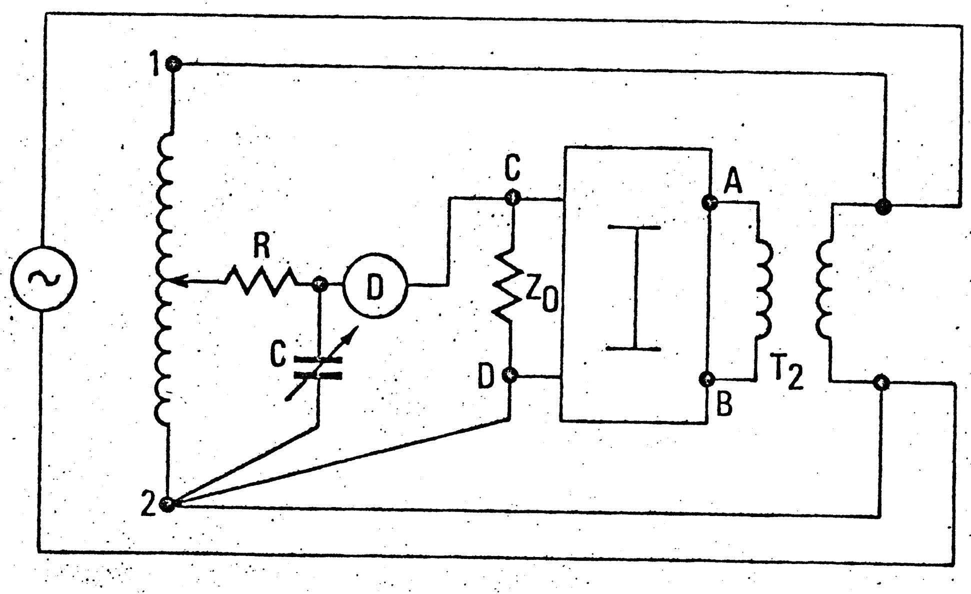

Fig. 19

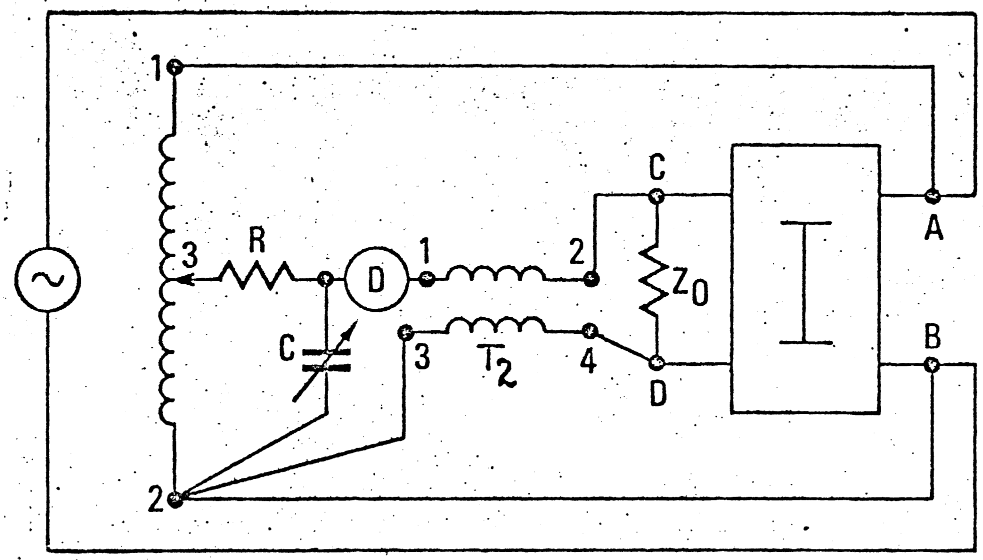

Fig. 20

CALIBRATION OF INDUCTIVE VOLTAGE DIVIDER USING F9200