INTRODUCTION

TO

MEASUREMENT

AND

INSTRUMENTATION

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CHAPTER ONE

INTRODUCTION

What Is Measurement?

Measurement is the act of quantitative comparison between a predefined standard and an unknown magnitude. If the result of measurement is to be meaningful, two requirements must be met in the act of measurement:

(i) The standard must be accurately known and internationally accepted

(ii) The apparatus and procedure employed for obtaining the comparison must be provable.

In order to be able to consistently compare quantitatively, certain standards of length, mass, time, temperature and electrical quantities must be known. These standards are internationally accepted and well preserved under controlled environmental conditions at the international Bureau of weights and measurement in service, France.

- Celsius clock has been accepted as the standard of time measurement
- Kelvin temperature scale for temperature
- Standard meter is defined in terms of the wavelength of the orange-red light of Kr^{86} lamp. (1,650, 763.73 wavelength of Kr^{86} = 1m).
- The kilogram is defined in terms of platinum iridium mass.

FUNDAMENTAL METHODS OF MEASUREMENTS

There are 2 basic methods of measurement.

(I) Direct comparison with the primary or secondary standard and

(ii) Indirect comparison with a standard, through a calibrated system.

CALIBRATION

Calibration is the act of determining the uncertainty associated with measurement and, if possible, reducing that uncertainty. Calibration process consists of 3 parts namely

1. Verifying that the current measurement capability of the measuring device is within specification.

2. Adjusting the device to reduce its measurement uncertainty.

3. Verifying the measurement capability of the device to ensure that it is operating within specification or to check if the measurement uncertainty has been reduced.

Benefits of Calibration

- Reduced measurement uncertainty
- Ensure measurement certainty
- Increase production yield
- Consistently meeting quality requirements

The calibration of all instruments is important, for it affords the opportunity to check the instrument against known standard and subsequently reduce the error in the measurement. Calibration procedure involves the comparison of a particular instrument with either

1. Primary standard;
2. A secondary standard with higher accuracy than the instrument;
3. A known input source.

Calibration must be done periodically so as to maintain measurement accuracy. The ability of a measurement to accurately measure a physical quantity changes with a number of factors namely: Time in service, temperature, humidity, environmental exposure and abuse (all these can affect accuracy). Calibration decreases measurement uncertainty by comparing the measurement with a known standard.

Measurable physical quantities can be classified into two categories namely

(i) Fundamental quantities
(ii) Derived quantities

Fundamental quantities are units that cannot be derived e.g. Mass, Distance, Time, Current, Luminous intensity, Amount of substance, Plane angle and Solid angle. Derived quantities are obtained from fundamental quantities. E.g. Velocity, Force, Energy, Power.

Units can also have prefix such as

Name	***Symbol***	***Multiplier***
Pico	p	10^{-12}
Nano	n	10^{-9}
Micro	μ	10^{-6}
Milli	m	10^{-3}
Kilo	K	10^{3}
Mega	M	10^{6}
Giga	G	10^{9}
Tera	T	10^{12}

Why Do We Measure?

Measurements are essential for evaluating the performance of a system, or studying its response to a particular input function, or studying some basic law of nature

A very basic function of all engineering branches is design of systems consisting of several elements which are expected to function in a particular fashion. The measurement is required to test the functioning of components, which constitute the system, and finally the function of the system itself.

Inaccuracy of Measurement and Its Analysis: Errors

The objective of each measurement is to describe some physical property of an object quantitatively: Length, temperature, pressure, force etc. Every measurement of such a quantity has a certain amount of uncertainty. This may be explained by considering a common experiment of measuring the diameter of a disc or a rod using:

- 3 Instruments: square caliper, micrometer screw abbemestroscope
- 3 similar instruments
- Only a single instrument is used to measure the diameter of the disc three times.

From these three groups of measurements one may likely get different values of the diameter. Thus one finds that even repeated measurements on the same instrument may give different values of the physical quantity. Therefore it can be concluded that all measured values are inaccurate to some degree due to the fact that there are variations in the values obtained from the same measurement (Error).

It is in fact impossible to find the true value, although it is safe to assume that the true value exists. The aim is, therefore, to find the most probable value of the measurement and assign the uncertainty to it. The task is to determine how uncertain a measurement may be and device a consistent way of specifying the uncertainty in an analytical form (Error analysis).

TYPES OF ERRORS

- Errors can be grouped into two broad groups, namely, determinate and indeterminate errors.
- DETERMINATE: These are errors that arise from actual mistake, either on the part of the analyst (observer) or from faulty instrument. They are not susceptible to mathematical treatment. They are further classified into constant and systematic errors.

- **CONSTANT ERRORS:** These errors are the same in magnitude for all measurement.

- **SYSTEMATIC ERRORS:** These errors vary from one measurement to another. They are due to biases in the measuring procedure and variability intrinsic in the phenomena being measured.

Some examples of determinate errors are given below:

- **INSTRUMENTAL ERRORS:** These include those due to apparatus, instruments and reagents, for example insufficient sensitivity of balance, use of non-calibrated weight and presence of impurities in reagents.

- **OPERATIVE ERROR:** This is due to inexperience in carelessness of the analysts for example leaving funnel on top of burette during titration. Failure to apply temperature corrections in volumetric analysis.

- **PERSONAL ERROR:** Due to inability to make observations accurately, for example inability to judge colour change correctly during titration.

- **METHODICAL ERRORS:** These originate from chemical in physicochemical properties of the analytical system. Changing methods and conditions under which the measurement is carried out can eliminate them.

- **INDETERMINATE ERRORS:** These are caused by variability inherent in the process of making measurements. They are numerous, small and likely to combine in linear fashion and are subject to the law of probability analysis. Indeterminate errors originate in the limited ability of the analyst to control or make corrections for external conditions such as weather, or his inability to recognize the appearance of factors that will result in errors.

CHAPTER TWO

MEASUREMENT OF CIRCUIT PARAMETERS

Introduction

The basic electrical circuit parameters are resistance, inductance, and capacitance (impedance in general). Direct-current Wheatstone bridge shown in figure 1, can be used to measure Resistance. Other bridge circuits (modification of Wheatstone bridge) such as Maxwell Inductance Bridge, Maxwel-Wien Bridge, Anderson Bridge, Hay's Bridge, De Sauty Bridge and Schering Bridge can be used to measure other circuit parameters.

DIRECT-CURRENT WHEATSTONE BRIDGE

Direct-current Wheatstone bridge is a circuit that consists of four resistances connected together and to a common input and output. With this arrangement it is easy to measure an unknown resistance in the bridge circuit in terms of other resistances. Figure 2.1 shows a direct-current Wheatstone bridge.

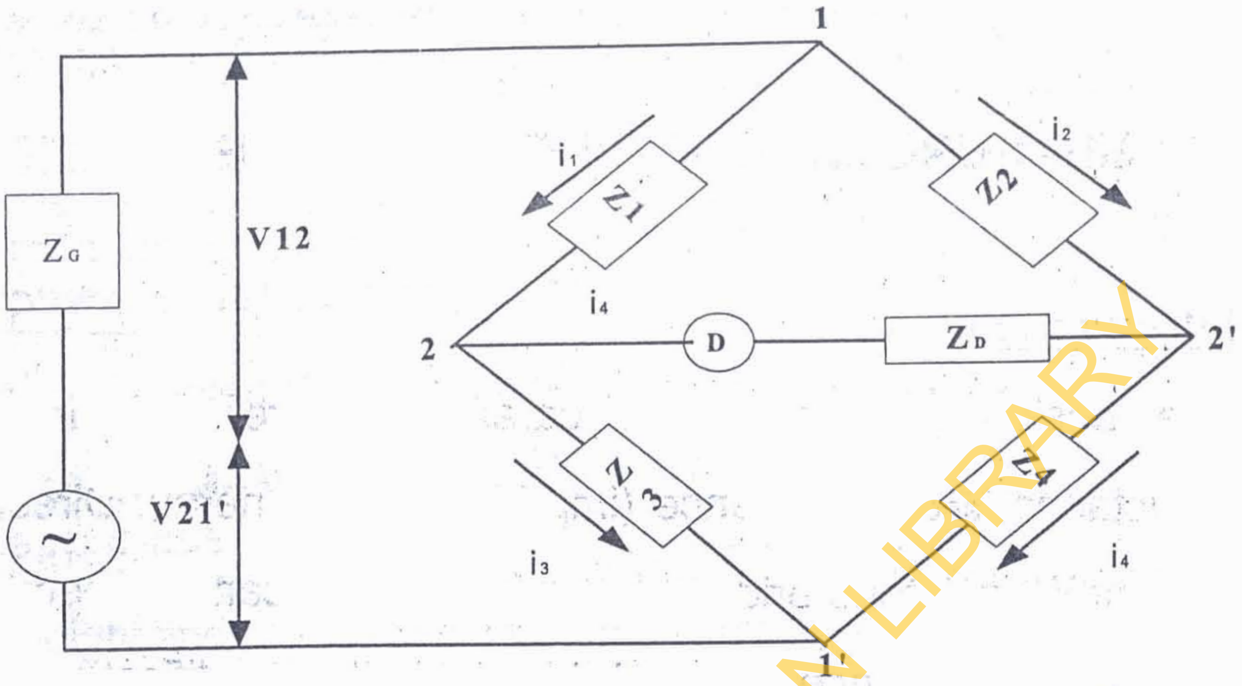


Figure 2.1: The basic AC Bridge (Wheatstone bridge)

From figure 2.1

$V'_{12} \quad = \quad V_{12}^{1}$ i.e. $Z_1 I_1 = Z_2 I_2$

1.1

$V_{21}^{1} \quad = \quad V_{2}^{1}1^{1}$ i.e. $Z_3 I_3 = Z_4 I_4$

1.2

and also at balance

$I_D = 0$, $I_1 = I_3$, and $I_2 = I_4$

dividing 1.1 by 1.2 gives 1.3

$Z_1/Z_3 = Z_2/Z_4$ or $Z_1Z_4 = Z_2Z_3$

1.3

In general, the four bridge impedances could be complex variable

$$Z_1Z_4e^{j(ö_1+ö_4)} = Z_2Z_3e^{j(ö_2+ö_3)} \qquad 1.4$$

If we equate magnitude and phase angles of the impedances, then

$Z_1Z_4 = Z_2Z_3$

and

$ö_1 + ö_4 = ö_2 + ö_3$

1.5

the condition of balance is that

$Z_1Z_4 = Z_2Z_3$ or $Z1/Z_3 = Z_2/Z_4$

where $Z_1 = R_1$, $Z_2 = R_2$, $Z_4 = R_3$, $= Z_4 = R_4$

and V_G = dc supply, Z_G = impedance components of the power supply.

- A similar four-arm bridge as shown in Figure 1 with some modifications can also measure Inductances and Capacitances. In these arrangements V_G will be alternating current power supply while **D** will be Vibration galvanometer instead of ordinary Galvanometer.
- To measure inductance, Maxwell's Inductance Bridge will be discussed.
- To measure capacitance, Schering Bridge will be discussed.

MAXWELL'S INDUCTANCE BRIDGE

This bridge circuit is used for medium inductances and can be arranged to yield results of considerable precision. The bridge circuit is shown in figure 2.2.

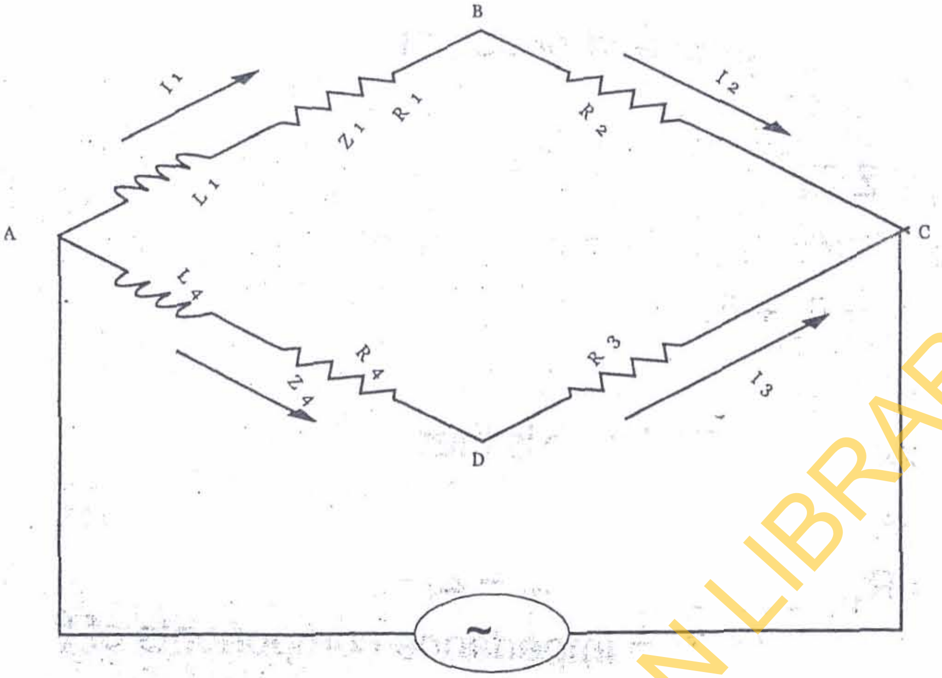


Figure 2.2: Maxwell's Inductance Bridge

From figure 2.2:

$$Z_1 = R_1 + JX_1 = R1 + JwL_1$$

1.1

$$Z_4 = R_4 + JX_4 = R_4 + JwL_4 \qquad 1.2$$

R_2 and R_3 are known pure resistances

If a coil of unknown impedance Z_1 is placed in one arm, then its positive phase angle ö can be compensated for in either of the following two ways:

(i) Known impedance with equal positive phase angle may be used in the adjacent arm (i.e. $\varphi_1 = \varphi_2 =$ or $\varphi_1 = \varphi_4$). This type of network is known, as Maxwell's bridge.

(ii) Impedance with an equal negative phase angle (i.e. capacitance) may be used in opposite arm (so that $\varphi_1 + \varphi_3 = \varphi$). Such a network is known as Maxwell-Wien or Maxwell's L/C Bridge.

From figure 2.2, the bridge is balanced by varying L_4 and one of the resistances R_2 or R_3 or alternatively, R_2 and R_3 are kept constant by connecting an additional resistance in that arm can vary the resistance of one of the other two arms. This is shown in figure 2.3.

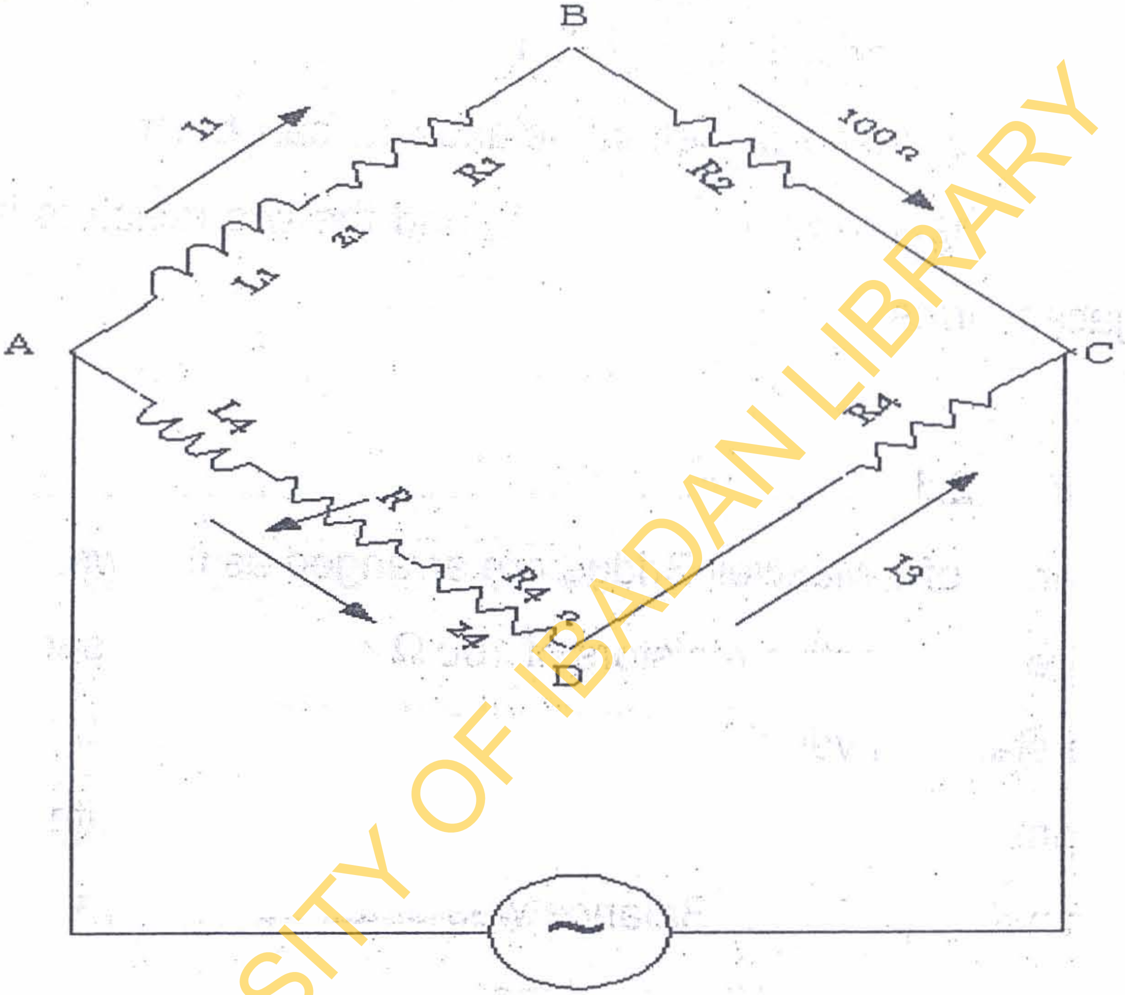


Figure 2.3: Balancing of Maxwell's Inductance Bridge

The balance condition is

$$Z_1 Z_3 = Z_2 Z_4 \qquad 1.3$$

$$\text{Therefore, } (R_1 + jwL_1) R_3 = (R_4 + jwL_4) R2 \qquad 1.4$$

Equating the real and imaginary parts on both sides, we get.

$R_2 R_3 = R_2 R_4$ or $R_1 / R_4 = R_2 / R_3$ 1.5

and

$wL_1 R_3 = wL_4 R_2$ or $L_1 = L_4 R_2 / R_3$ 1.6

and by induction, $L_1 = L_4 R_1 / R_4$ 1.7

Hence, the unknown self-inductance L_1 can be measured in terms of the known inductance L_4 and the two resistors in the adjacent arms.

Example 2.1

The arms of a Maxwell Bridge are arranged as follows: AB and BC are non-reactive resistors of 100 Ω and 200 Ω respectively, DA a standard variable reactor L_1 of resistance 32.7Ω and CD comprises of a standard variable resistor R in series with a coil of unknown impedance. Balance was obtained with $L_1 = 47.8$mH and R = 2.45Ω. Find the resistance and inductance of the coil.

Solution

The circuit diagram for the example 2.1 is given in figure 2.4.

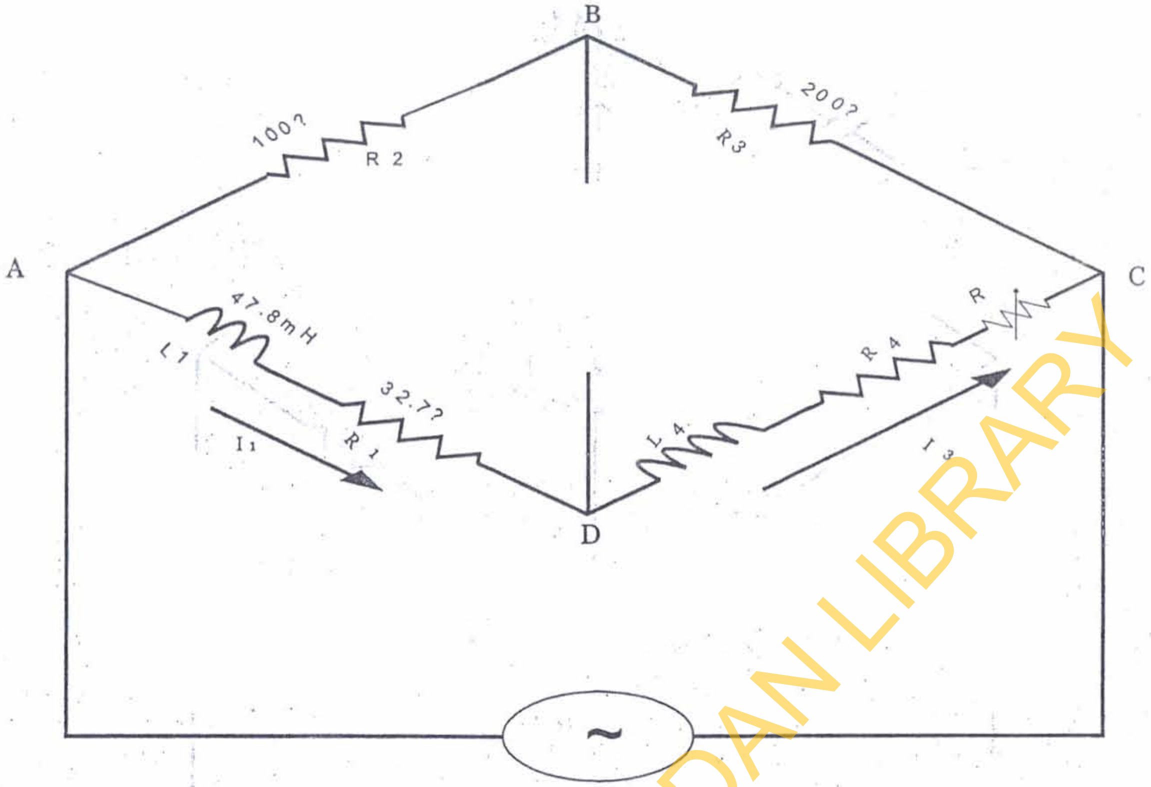


Figure 2.4: The circuit Diagram for Example 2.1

Since the product of the reactance of opposite arms are equal, then

$$R2\ (R4+R) = R3\ (R1)$$

$$100(1.36+R4) = 200(32.7)$$

$$R4 = 65.4\ 2.45$$

$$R4 = 62.95\Omega$$

Then from equation 1.6

$$L_1 = L_4\ R_2\ /R_3$$

$$L_1\ R_3 = L_4\ R_2$$

$$L_4 = L_1 R_3 / R_2$$

$$L_4 = 47.8 * 200/100$$

$$L_4 = 95.6\text{mH}$$

Maxwell-Wien Bridge *(Maxwell's L/C Bridge).*

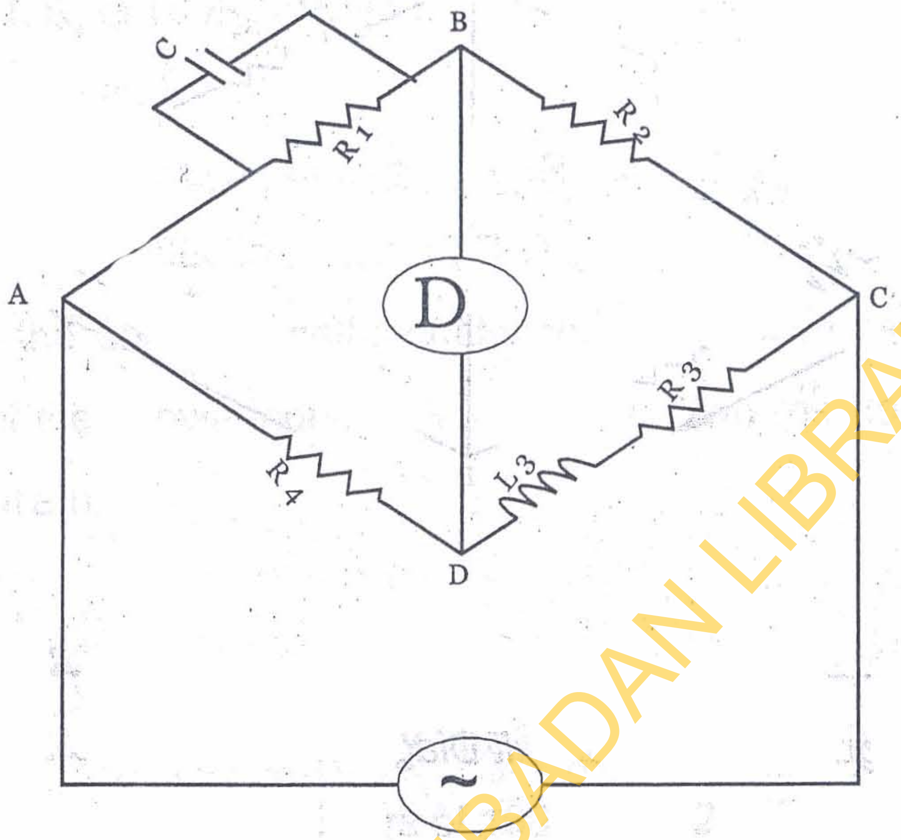


Figure 2.5: Maxwell-Wien Bridge

As mentioned earlier under Maxwell's bridge, the positive phase angle of inductive impedance may be compensated by the negative phase angle of capacitive impedance put in the opposite arm. This is shown in figure 2.5.

Impedance of arm 1 is given as:

$$\frac{1}{Z_1}=\frac{1}{R_1}+\frac{1}{\sqrt{X_c}}=\frac{1}{R}+\frac{j}{X_c}=\frac{1}{R_1}+jwc$$

$$=\frac{1+jwCR_1}{R_1}$$

$$\therefore Z_1 = \frac{R_1}{1 + jwCR_1},\ Z_2 = R_2$$

$$Z_3 = R_3 + jwL_3,\ Z_4 = R_4$$

Balance condition is $Z_1 Z_3 = Z_2 Z_4$

$$\therefore \frac{R_1(R_3 + jwL_3)}{1 + jwCR_1} = R_2 R_4$$

$$R_1 R_3 + jwL_3 R_1 = R_2 R_4 + jwCR_1 R_2 R_4$$

Separating the real and imaginary parts, we have

$$\therefore R_3 = \frac{R_2 R_4}{R_1} \text{ and } L_3 = CR_2 R_4$$

Example 2.2: The arms of an ac Maxwell-Wien bridge are arranged as follows: AB is a non-active resistance of 1,000Ù, in parallel with a capacitor of capacitance 0.5ìF, B.C is a non-inductive resistance of 600Ù, CD is inductive impedance (unknown) and DA is a non-inductive resistance of 400Ù. If balance is obtained under these conditions, find the value of the resistance and the inductance of the branch CD.

Solution

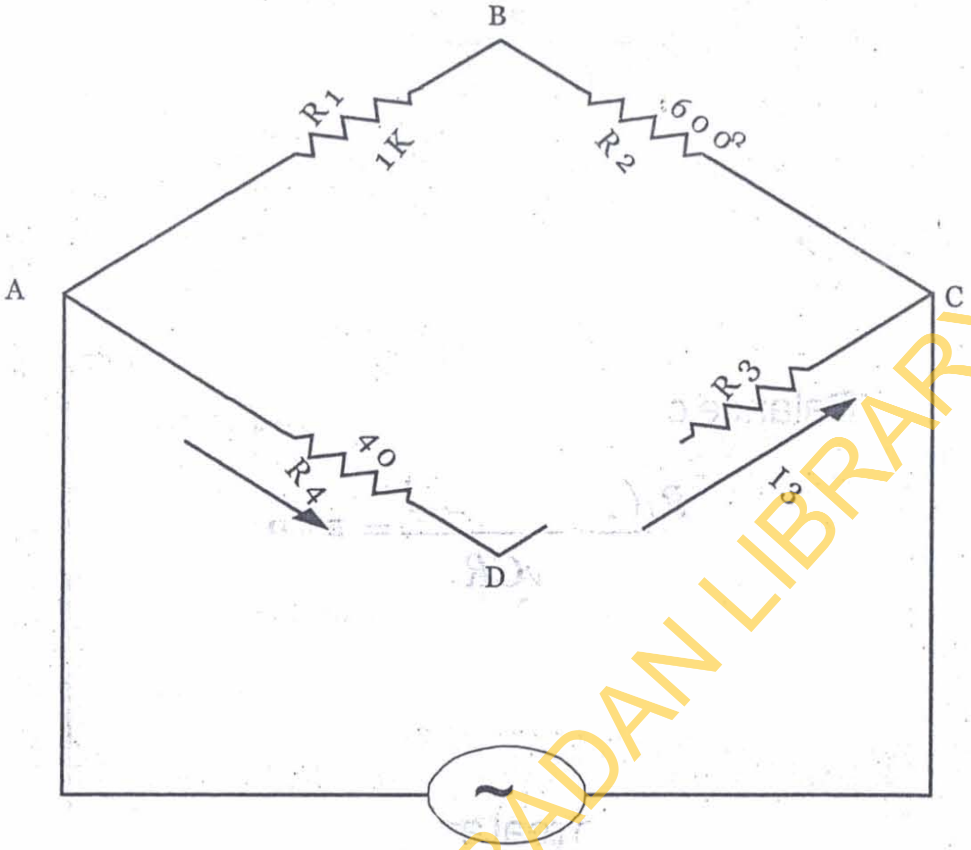


Figure 2.6: The Circuit Diagram for Example 2.2

$R_1 R_3 = R_2 R_4$

$$\therefore R_3 = \frac{R_2 R_4}{R_1}$$

$$R_3 = \frac{600 \ x \ 400}{1000} = 240\Omega$$

Also $L3 = CR_2 R_4$

$= 0.5 X 10^{-6} X 400 X 600$

$= 12 X 10^{-2}$

$L3 = 0.12H$

Schering Bridge

Schering Bridge can be used for the measurement of capacitance, the circuit arrangement is shown in figure 2.7.

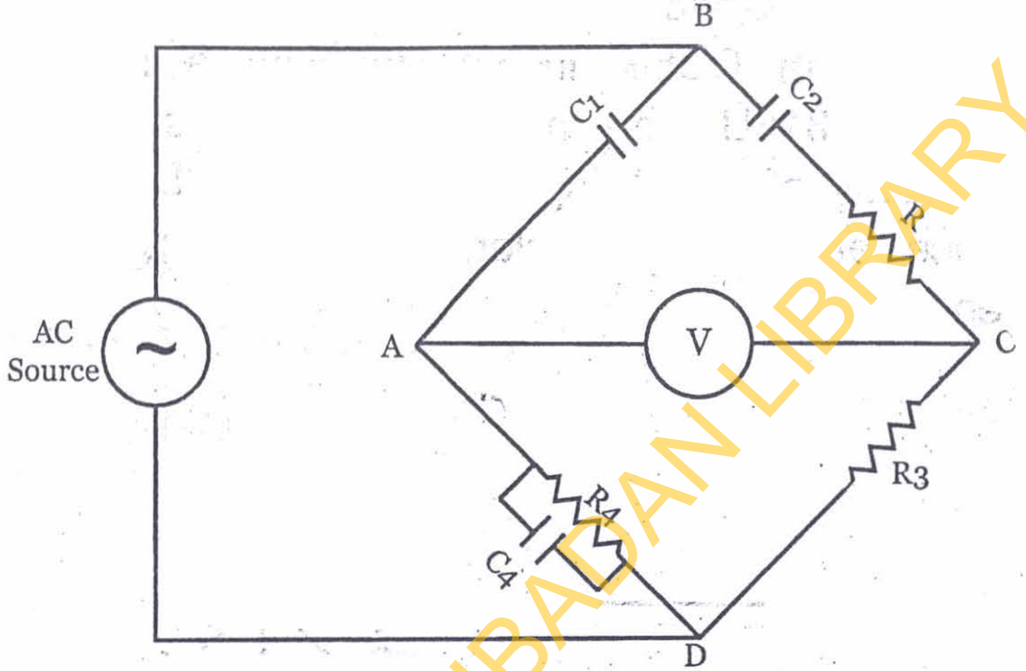


Figure 2.7: Diagram of Schering Bridge

Where, C1, C4 - loss-free standard capacitor

C_2 - unknown capacitor

R - Resistance in series with C_2

R_3, R_4 - pure resistance.

From the diagram in figure 2.7, the impedance of the arms are given as:

$$Z_1 = \frac{-J}{wC_1}; Z_2 = \frac{R - j}{wC_2}; Z_3 = R_3;$$

$$Z_4 = \frac{1}{(1/R_4) + JwC_4} = \frac{R_4}{1 + jwC_4R_4}$$

Condition for balance: $Z_1Z_3 = Z_2Z_4$

Separating the real and imaginaries we have

$$C_2 = C_1 (R_4/R_3) \text{ and } R = R_3 (C_4/C_1)$$

Example 2.3: Testing of a Bakelite sample by Schering Bridge, having a standard capacitor of 106pF balance was obtained with a capacitance of 0.35ìF in parallel with a non-inductive resistance of 318U, the non-inductive resistance in the remaining arm of the bridge being 130Ù. Determine the capacitance and the equivalent series resistance of the specimen.

Solution

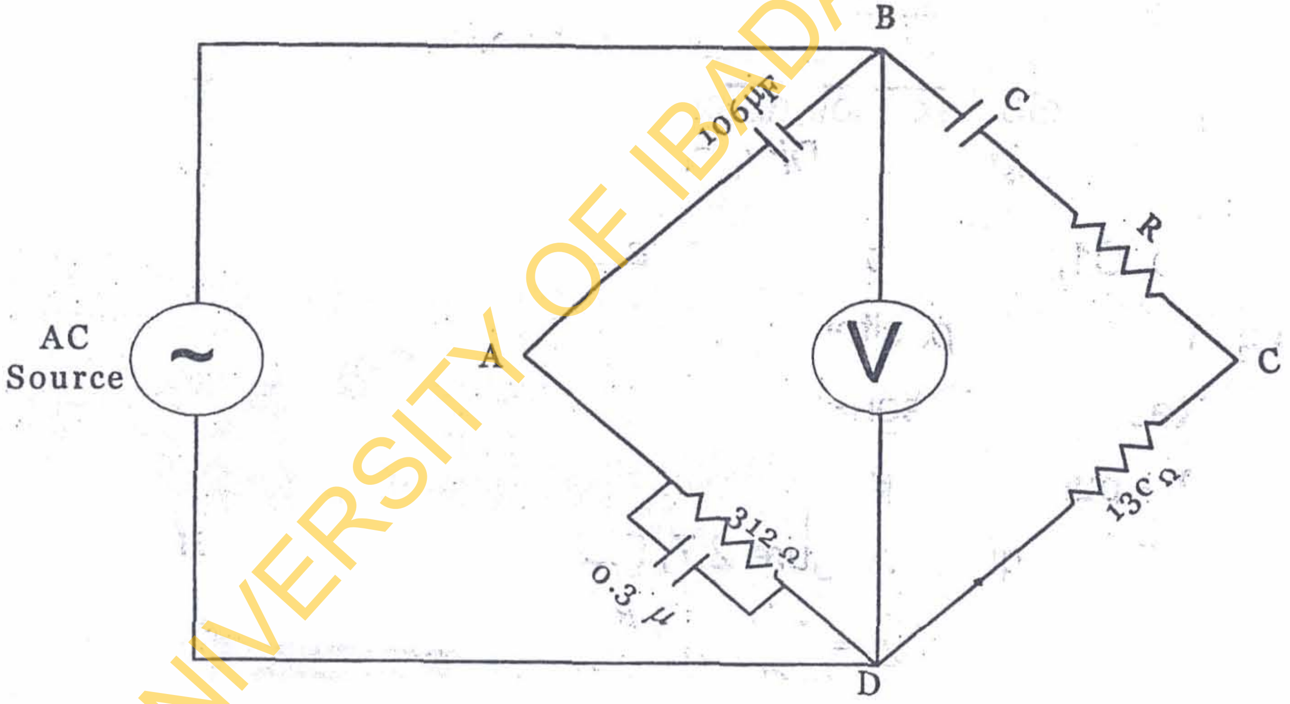


Figure 2.8: The Circuit Diagram for Example 2.3

$C_1 = 106\mu F$, $C4 = 0.35\mu F$, $R4 = 318\Omega$, $R_3 = 130\Omega$

$R = ?$

$C_2 = ?$

$C_2 = C_1 (R_4/R_3)$

$C_2 = 106 \times 318/130 = 259.3\mu F$

$R = R_3 (C4/C_1)$

$R = 130.\ 0.35/106 \times 10^{-6}$

$R = 0.429M\Omega$

CHARPTER THREE

ELECTRICAL INSTRUMENTS AND MEASUREMENT

Electrical instruments are devices that are used to measure electrical quantities such as current, Voltage resistance, impedance, power, frequency, etc. Electrical instruments may be classified into

(i) Absolute instruments
(ii) Secondary instruments

Absolute instruments are those, which give the value of the constants of the instrument and their deflection only. For example, a Tangent galvanometer, which gives the value of current, in terms of the tangent of deflection produced by the current, the radius and number of turns of the coil.

Secondary instruments are those, which the value of electrical quantity to be measured can be determined from the deflection of the instruments accurately, only when they have been pre-calibrated by comparison with am absolute instrument.

Electrical instruments may also be classified as (i) indicating instrument, (ii) recording instrument, and (iii) controlling instrument.

Indicating instruments: are those, which indicate the instantaneous Value of the electrical quantity being measured. (Ammeters, Voltmeters, watt meters)

- **Recording instruments**: are those which instead of indicating by means of a pointer and a scale the instantaneous value of electrical quantity, gives a record of the variation of such a quantity over a selected period of time. The moving system of the instrument carries an inked pen that rests on a chart so that the deflection of the pen is printed on the charts. The part traced out by the pen presents a continuous record of the variations in the defection of the instrument and hence a recording of the measurement. Examples include X-Y plotter, recording VOM, strip-chart recorder etc.

- **Integrating instruments** are those, which measure and register by a set of dials and pointers either the total quantity (in amp-hour) or the total amount of electrical energy (in watt-hour) KwH supplied to a circuit in a given time. The summation gives the product of time and electrical quantity, but does not give the direct indication as to the rate at which the quantity of energy is being supplied. Examples are Ampere-hour and Watt-hour meters.

ESSENTIALS OF INDICATING INSTRUMENTS

Indicating instruments are those, which indicate the value of the quantity that is being measured at the time at which it is measured. Instruments of this type consist of a pointer, which move over a calibrated scale and that is attached to a moving system. This is shown in figure 3.1. The moving system is subjected to three types of torque, namely:

(a) Deflecting torque (b) Controlling or Restoring torque

(c) Damping torque.

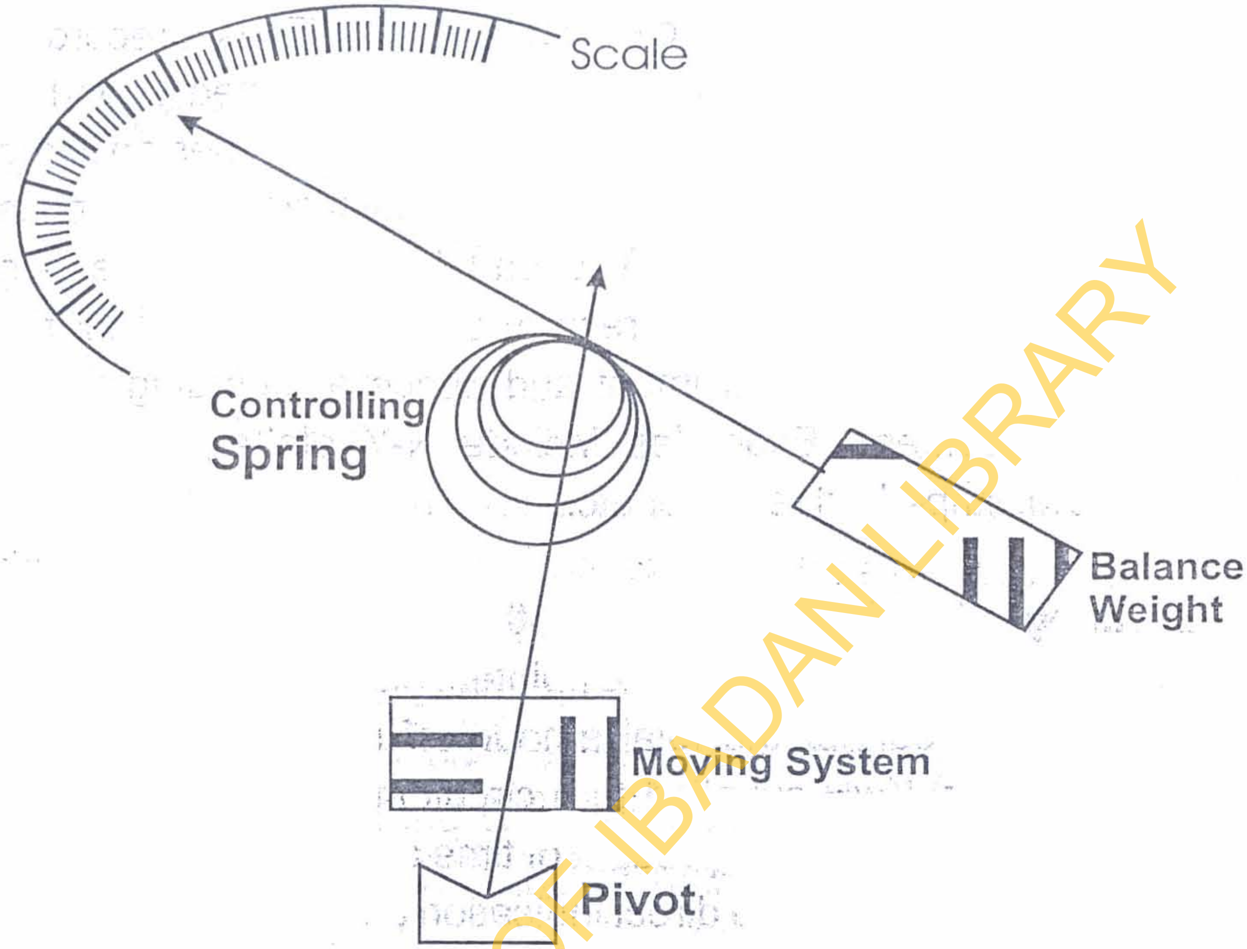


Figure 3.1: Basic Diagram of Indicating Instrument (spring controlled)

a. **Deflecting torque: (T_d):** This is the force that deflects the pointer from its rest (zero position) that is, when not being used for measurement. Using magnetic, electrostatic, thermal inductive, electrodynamics effects, can produce the Deflecting torque.

B. **Controlling Torque (T_c):** The deflection of the moving system would be indefinite if there were no controlling or restoring torque. This torque opposes the deflecting torque and increases with the deflecting torque. The pointer is brought to rest at a position where the two opposing tongues are equal. Without such torque the pointer would swing to the maximum deflection and will not return back to the zero point after the measurement. The controlling torque can be obtained either by a spring or by gravity control.

Spring control:

For spring control: e.g. moving coil, permanent magnet type Indicating instrument.

$T_d \propto I$ (i)

$T_c \propto \theta$ (ii)

$T_c = T_d$ (iii) at equilibrium

Therefore, $\theta \propto I$

Where θ and I represent the displacement of the pointer from rest and the current flowing in the instrument respectively.

Since the deflection θ is directly proportional to current I, the spring control instruments have a uniform scale (equally spaced scales) over the whole of their range as shown in figure 3.2.

To ensure that the controlling torque is proportional to the angle of deflection, the

Spring must have a fairly large number of turns so that angular deformation per unit length on full-scale deflection will be small.

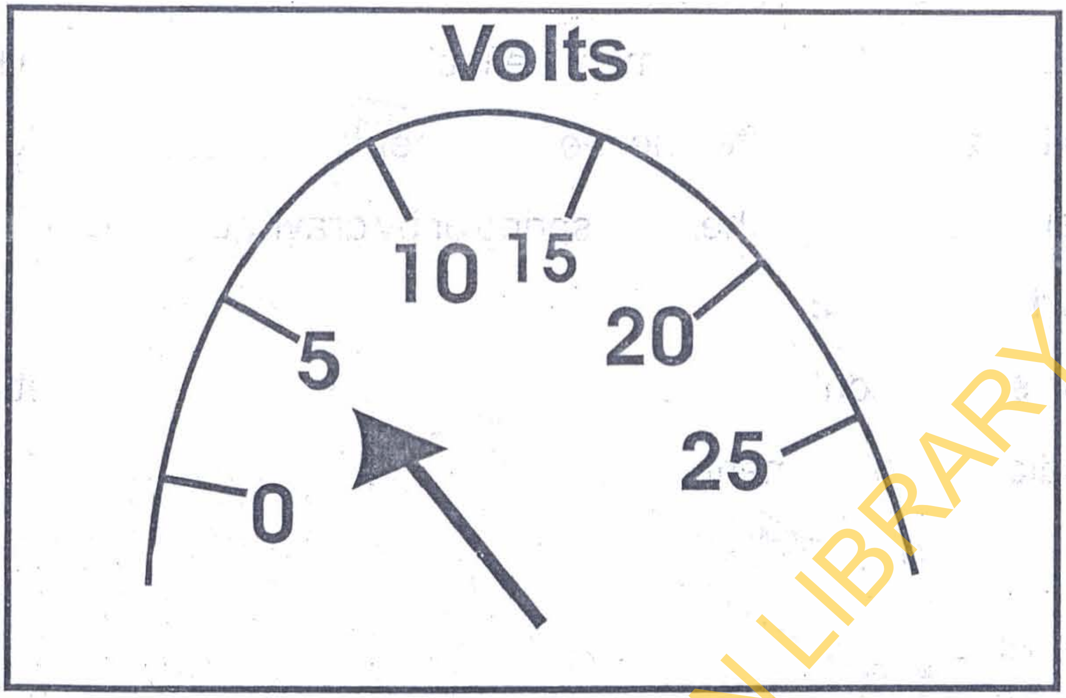


Figure 3.2: Scale of Spring Controlled Indicating Instrument

Gravity control:

Gravity control is achieved by attaching a small adjustable weight to some part of the moving system such that the two exert torques in opposite directions. This is shown in figure 3.3.

From the diagram:

$T_c \propto \sin\theta$ (i)

$T_d \propto I$ (ii)

at equilibrium $T_d = T_c$

Therefore $I \propto \sin\theta$

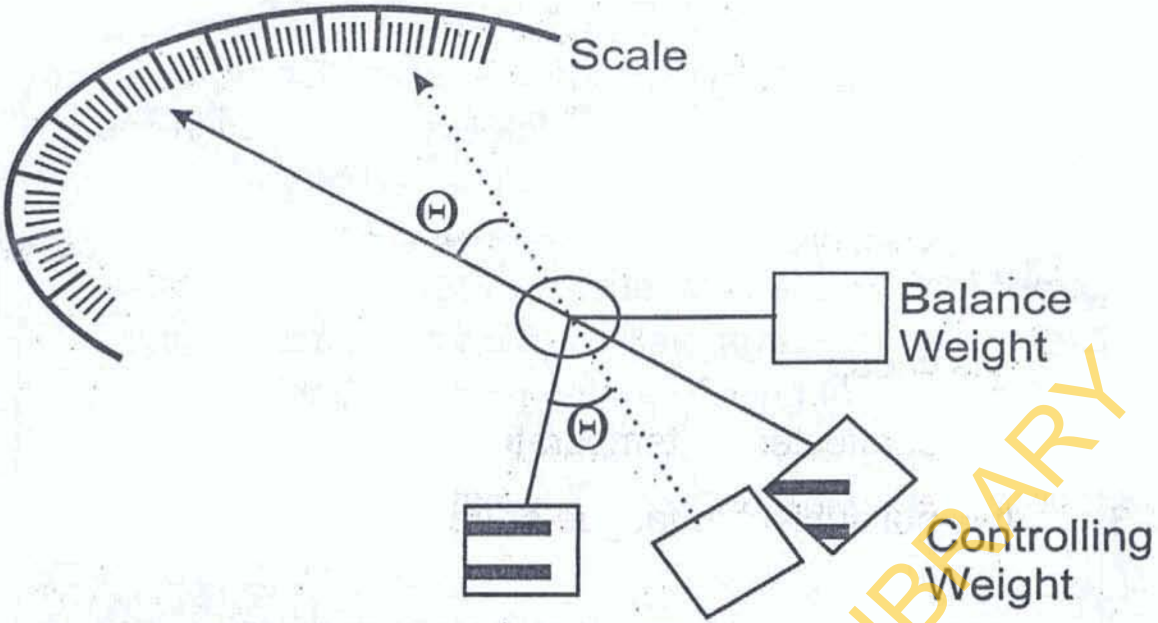


Figure 3.3: Basic Diagram of Indicating Instrument (gravity controlled)

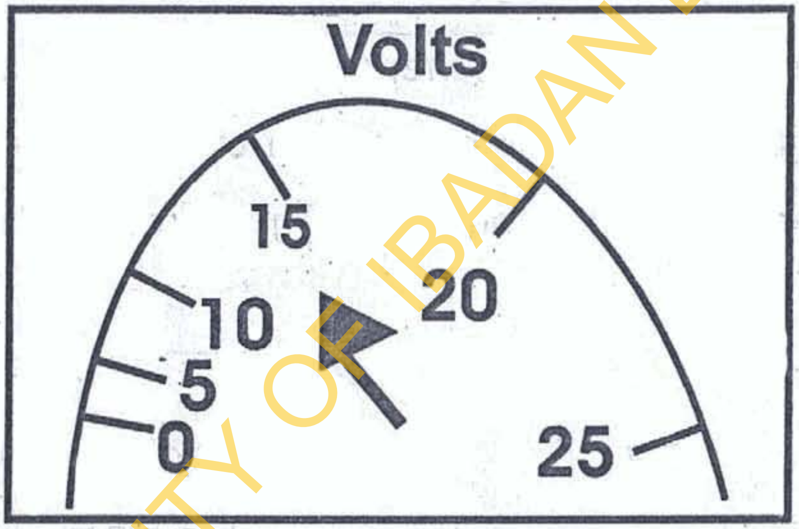


Figure 3.4: Scale Of Gravity Controlled Indicating Instrument

Disadvantage

1.It gives cramped (uneven) scale as shown in figure 3.4

2. The instrument has to be kept vertical when in use.

Advantages

1. It is cheap
2. It is unaffected by temperature
3. It is not subject to fatigue or deterioration with time

Example 3.1: The torque of an ammeter varies as the square of the current through it. If a current of 10A produces a deflection of 90^0, what deflection will occur for a current of 3A when the instrument is (1) spring controlled (ii) gravity control?

Solution

For spring control	*For gravity control*
$T_c \propto \theta$	$T_c \propto \sin\theta$
$\theta \propto I^2$	$\sin\theta \propto I^2$
$90^0 \propto 10^2$	$\sin 90^0 \propto 10^2$
and	$\sin\theta \propto 3^2$
$\theta \propto 3^2$	$\sin\theta\ 3^2/10^2$
$\theta = 90^0 \times 3^2/10^2$	$\theta\ \sin^{-1} 32/10^2$
$\theta = 8.10^0$	$\theta = 5.13^0$

(c.) **Damping Torque:** A damping force is one which acts on the moving system of the instrument only when it is moving and always opposes its motion. Damping Torque is known as stabilizing force that is necessary to bring the pointer to rest quickly; otherwise (due to inertial of the moving system) the pointer will oscillate about its final deflection position for some time before coming to rest in a steady position. Air friction, eddy currents and fluid friction can produce damping force. These are shown in figures 3.5-

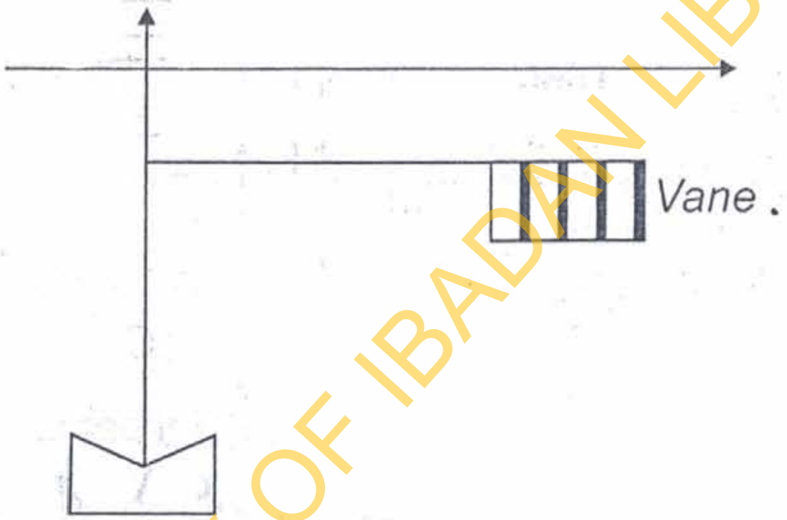


Figure 3.5: Damping Torque produced by air friction

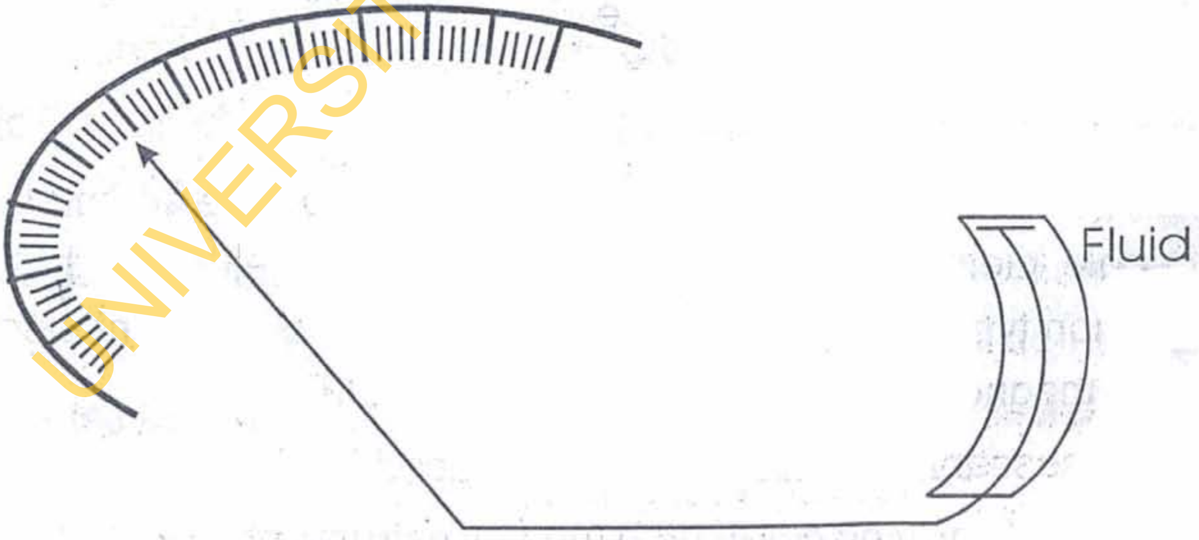


Figure 3.6: Air or Fluid Friction

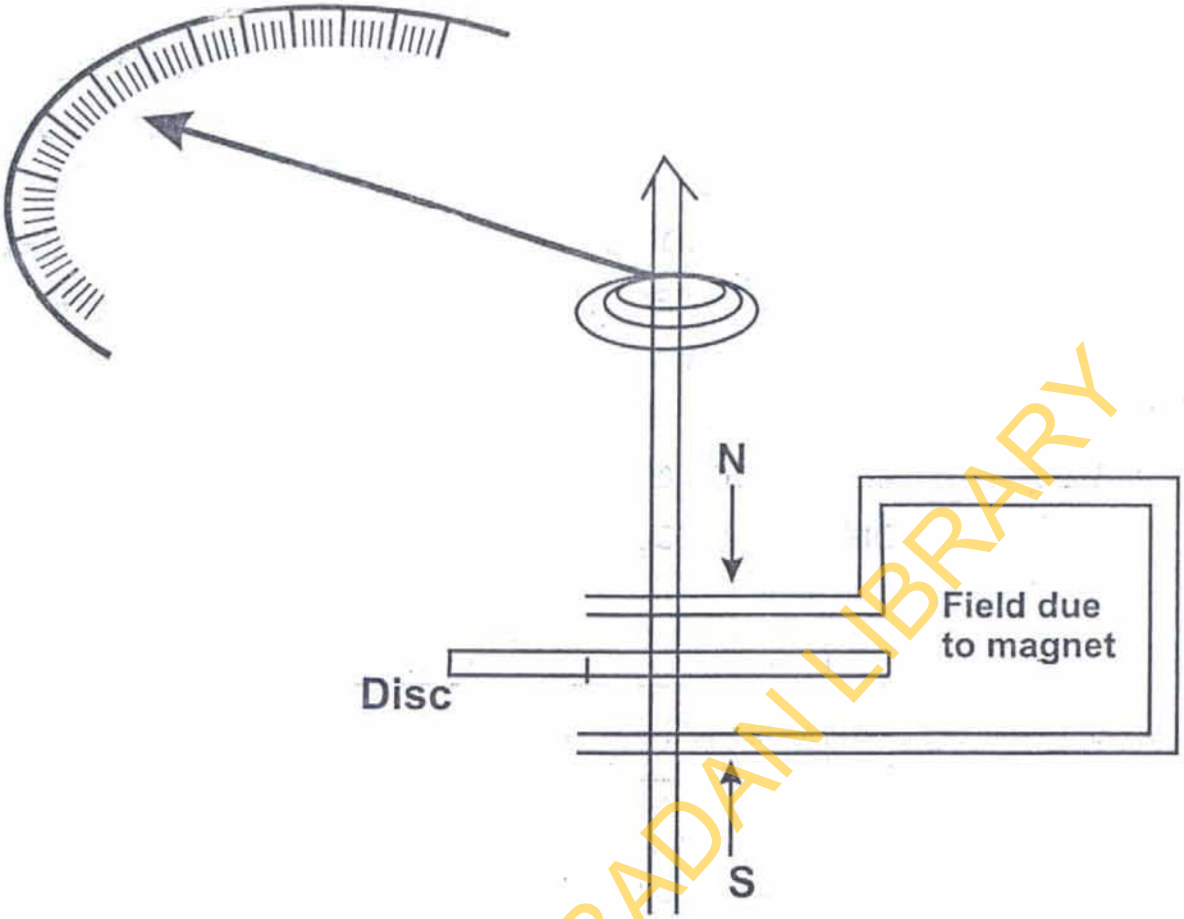


Figure 3.7: Damping By Eddy Currents

Moving Iron Instruments (Ammeters or Voltmeters)

There are two basic type of moving iron instruments

(i) The attraction type
(ii) The repulsion type

The operation of the attraction type depends on the attraction of a single piece of soft iron into a magnetic field and that of repulsion type depends on the repulsion of two adjacent pieces of iron magnetized by the same magnetic field.

The necessary magnetic field is produced by the ampere-turns of a current carrying coil in both type of instrument.

Attraction Type M. I. Instruments

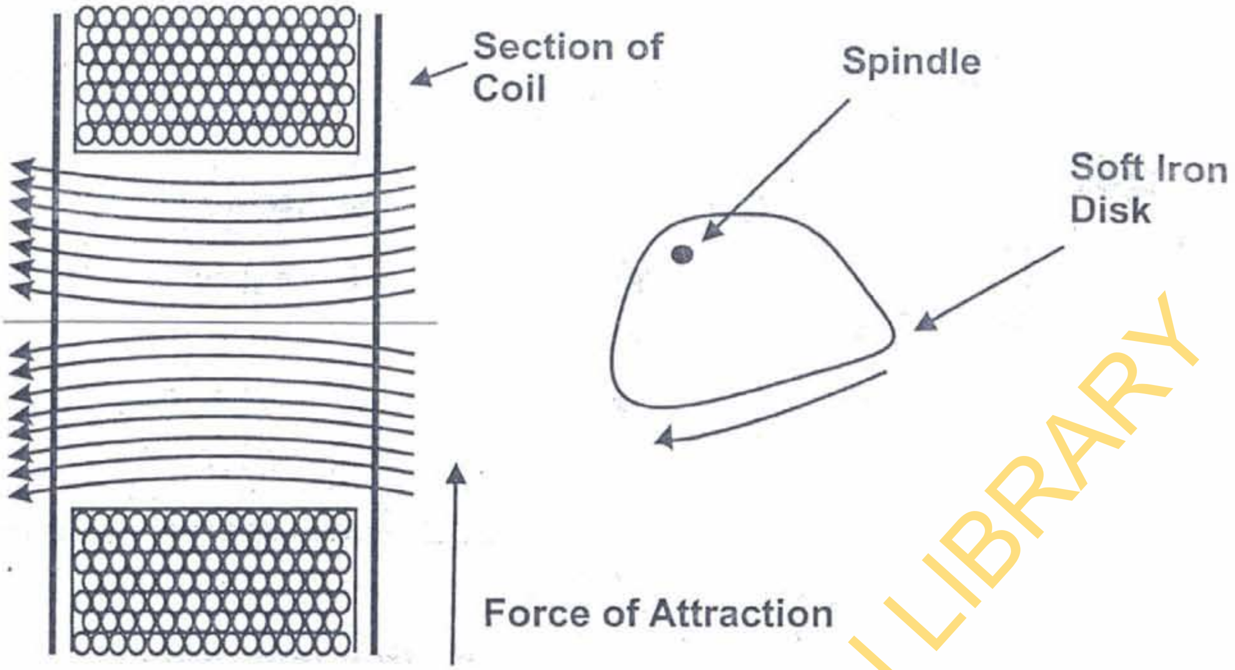


Figure 3.8: Attraction Type Moving Iron Instrument

It is a known fact that if a piece of an unmagnified soft-iron is brought up near either of the two ender of a current carrying coil, it would be attracted into the coil in the same way as it would be attracted by the pole of a bar magnet. “Hence,” it an oval shaped soft-iron disc is pivoted on a spindle between bearings near the coil as shown in the diagram of figure 3.8; the iron disc will swing into the coil when there is current passing through the coil.

If a pointer is fixed to the spindle-carrying disc, then the passage of current through the coil will cause the pointer to deflect. Moving-iron instruments can be used to measure dc and ac because the soft iron disc would be attracted inside irrespective of the direction of the current flowing through the coil.

Repulsion Type Moving Iron Instrument

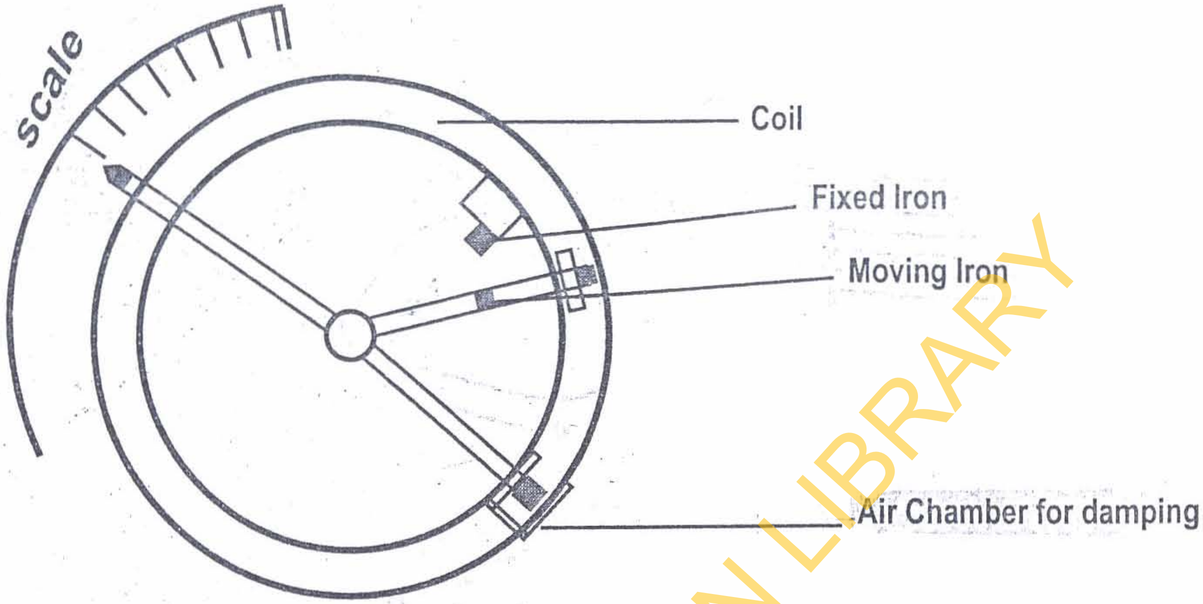


Figure 3.9: Repulsion Type Moving Iron Instrument

Working Principle of Repulsion M. I. Instrument

It consists of a fixed coil inside which are placed two soft-iron rods/bars A and B parallel to one another and along the axis of the coil. Bar A is fixed and the other bar B, which is movable, carries a pointer that moves over a calibrated scale. When the current to be measured is passed through the fixed coil, it sets up its own magnetic field which magnetizes each of the rods similarly, and causes the bars to repel each other with the result that the pointer is deflected against the controlling torque of spring or gravity.

The force of repulsion is approximately proportional to the square of the current passing through the coil.

i.e. $\theta \alpha I^2$

- The scales of such instruments are uneven if rods /bars are used and uniform if suitably shaped pieces of iron sheets are used.
- Damping of the instrument is either gravity-controlled or spring control.
- Damping is by pneumatic, eddy current damping cannot be employed because the presence of a permanent magnet required for such a purpose would affect the deflection and hence the readings of the instruments.
- Since the polarity of both rods reverses simultaneously, the instrument can be used for ac and dc circuit measurements i.e. un-polarized class of instrument.
- These instruments are liable to errors due to (i) hysteretic (ii) stray magnetic field (iii) changes in resistance of the coil due to temperature changes.

Advantages

They are cheap and robust. They give reliable service and can be used both on ac and dc circuit. They do not have high degree of precision because of hysteresis.

Extension of the Measuring Range of Indicating Instruments by Shunts and Multipliers:

For Ammeter: - The measuring range of the indicating instruments when used as an ammeter can be extended by using a suitable shunt resistance Rs across (parallel) its terminals as shown in figure 3.10. With dc measurement, there is no problem in extension of range but for ac measurement the time constants of the instrument coil and shunt must be the same. That is:

If Ls, Rs, L and R are inductances and resistances of the shunt and the ammeter.

Therefore, ratio $L/R = Ls/Rs$

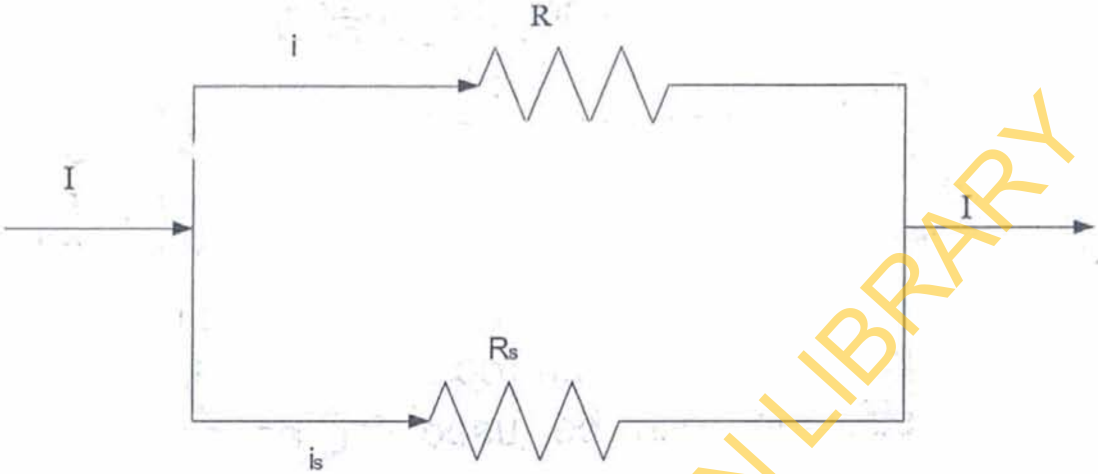


Figure 3.10: Extension of an Ammeter Measuring Range by a Shunt Resistor

The ratio of maximum current (with shunt) to the full-scale deflection current (without shunt) is known as multiplying factor of the shunt.

From figure 3.10:

$$\begin{aligned} iR &= IsRs \\ Is &= I - i \\ iR &= (I-i)\,Rs \\ iR &= IRs - iRs \\ i(R+Rs) &= IRs \\ I/i &= (R+Rs)/Rs \\ I/i &= R/Rs + 1 \end{aligned}$$

Multiplying factor $N = 1 + R/Rs$

It can be seen that the lower the value of Rs the greater the multiplying power N and hence the extension of the measuring range.

For Voltmeter: The measuring range of an indicating instrument, when used as a voltmeter can be extended by adding a high non-inductive resistance R in series with the moving iron instrument as shown below in figure 3.11.

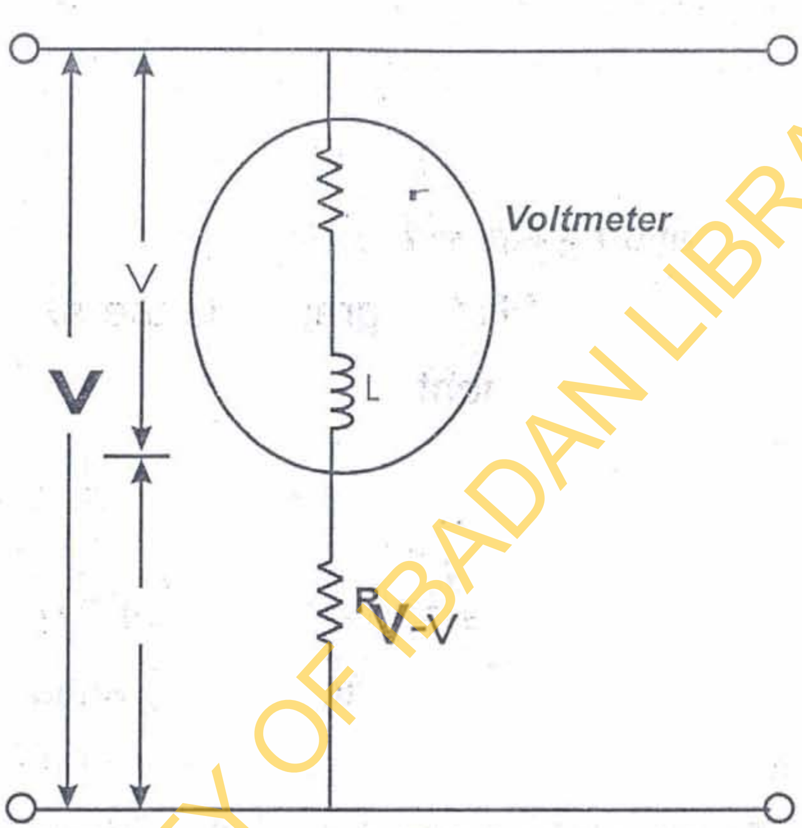


Figure 3.11: Extension of a Voltmeter Measuring Range Using Multiplier Resistance

Suppose the range of the instrument is to be extended from **v** to **V**. Then from figure 12 above, (**V-v**) volts must be dropped across R.

Let **I** be the full-scale deflection current of the instrument.

$IR = V - v$ (I)

$R = (V-v)/I = V/I - Ir/I$ (ii)

$R = V/I - r$ (iii)

Voltage magnification = V/v

From (i)

IR = V-r (iv)

Dividing equation (iv) by **v**

IR/v = V/v - 1 (v)

IR/Ir = V/v -1

V/v = R/r + 1 (vi)

Voltage magnification = **R/r + 1**

The greater the value of R the greater is the extension in the voltage range of the instrument.

Example 3.2

A moving coil ammeter has a fixed shunt of 0.02Ù with a coil circuit resistance of R=1KÙ and needs a potential difference of 0.5v across it for full deflection.

(1) To what total current does this correspond?

(2) Calculate the value of shunt to give a full-scale deflection when the total current is 10A and 75A

Solution

1. Im = V/R

Im = 0.5/1000 = 0.0005A

Is = V/Rs

Is = 0.5/0.02 = 25A

Total current = 25.0005A

2. (i) When total current = 10A, Is = (10 - 0.0005) = 9.9995A

$$R_s = \frac{I_m R_m}{I_s} = \frac{0.0005 \quad x\ 1000}{9.9995} = 0.05\ \Omega$$

(Ii) When total current = 75A, Is = (75 - 0.0005) = 74.9995A

$$R_s = \frac{I_m R_m}{I_s} = \frac{0.0005 \quad x\ 1000}{74.9995} = 0.00667\ \Omega$$

Moving Coil Instruments

There are two types of this instrument namely:

(i) Permanent - magnet type (dc measurement only)

(ii) The dynamometer type (ac and dc measurements)

Permanent Magnet Moving-Coil Instruments (PMMC)

The operation of a PMMC type instrument is based upon the principle of current carrying conductor that is placed in a magnetic field; the conductor is acted upon by a force, which tends to move it to one side and out of the field depending on the magnitude of the current passing through the conductor.

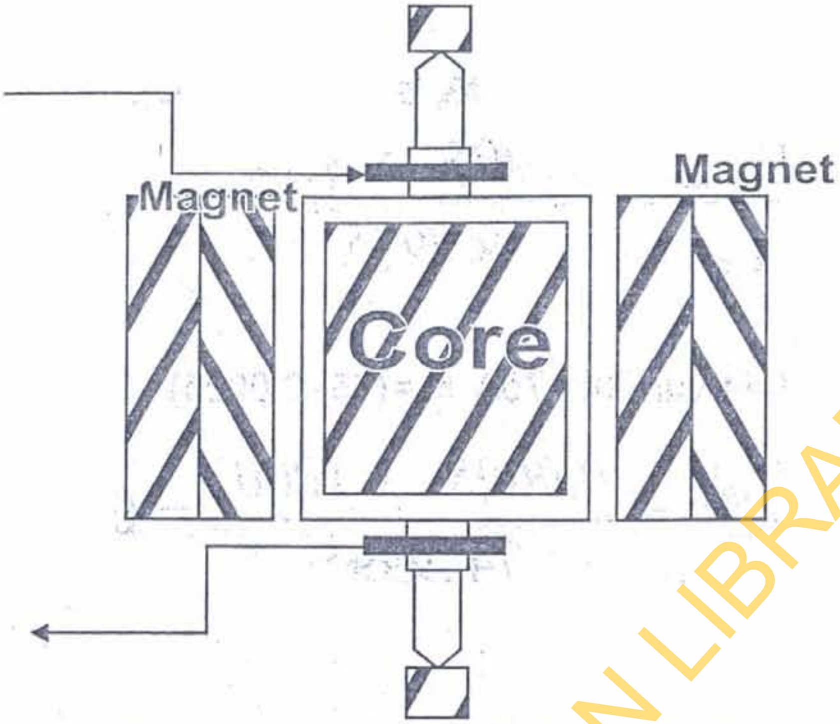


Figure 3.12: Diagram of PMMC Instrument

PMMC instrument consists of a permanent magnet and a rectangular coil of many turns wound on a light aluminum or copper former inside which is an iron core as shown in figure 3.12. This is placed in between the poles of a U-shaped permanent magnet. Surrounding the core is a rectangular coil of many turns wound on a light aluminum or copper frame, which is supported by delicate bearings and to which is, attached a light pointer that will show the deflection with respect to the current flowing in the instrument.

Control of the coil movements is actualized by two phosphor-bronze hair springs, one above and one below, through which current moves in and out of the coil. The two springs are spiraled in opposite directions in order to neutralize the effects of temperature change. The instrument has a uniform scale.

For this type of instrument, if flux density B is constant, then T_d is proportional to the current passing through the coil i.e. $T_d \alpha I$
PMMC instrument is spring controlled so that T_c á deflection è.
At the final deflected position, $Td = T_c$

$$\theta \alpha I$$

Advantages

(I) They have low power consumption
(ii) Uniform scale and can be extended over an angle of 270^0
.(iii) They possess high torque/weight ratio
(iv) They have no hysteresis loss
(v) The range can be extended by shunts & multiplier resistance to cover a wide range of currents & voltages.
(vi) They have very effective and efficient eddy current damping.
(vii) They are not much affected by stray magnetic fields.

Disadvantages

(i) Costlier as compared to moving iron instrument
(ii) Some errors set in due to ageing of control springs and permanent magnets.

Dynamometer Type Instruments

A Dynamometer is a moving coil instrument in which the operating field is produced not by a permanent magnet but by another fixed coil (electromagnet), that is capable of producing magnetic field when current flows through the coil. It can be used as ammeter, voltmeter, and usually as wattmeter.

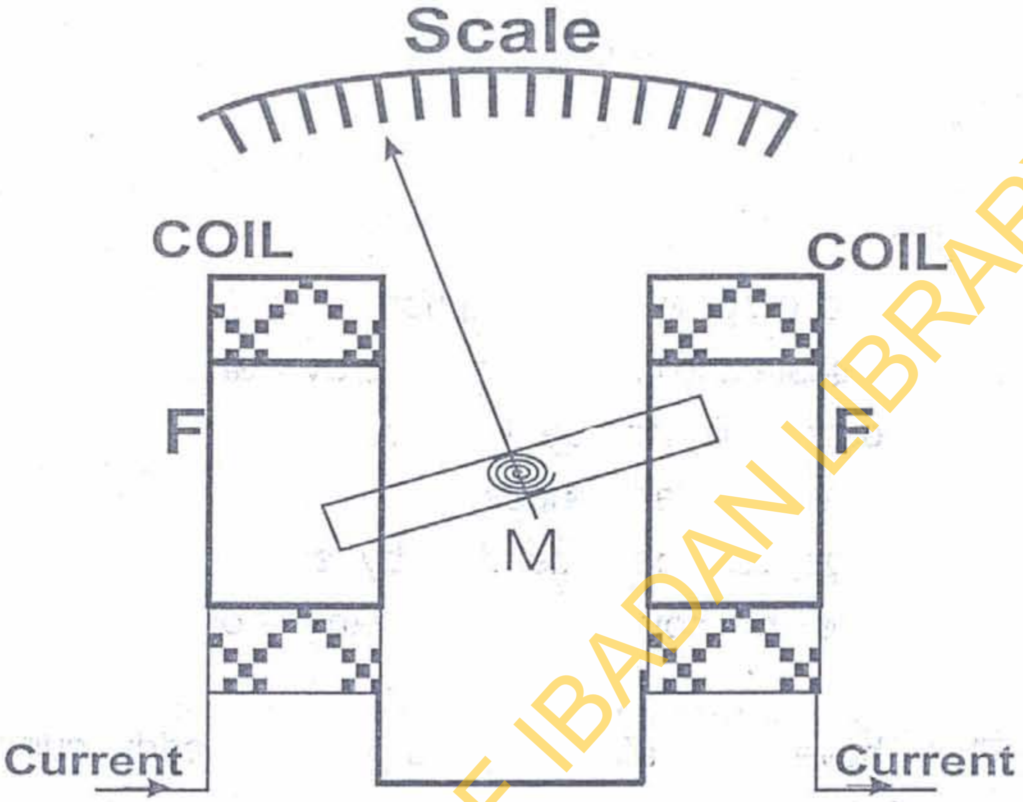


Figure 3.13: Block Diagram of a Dynamometer

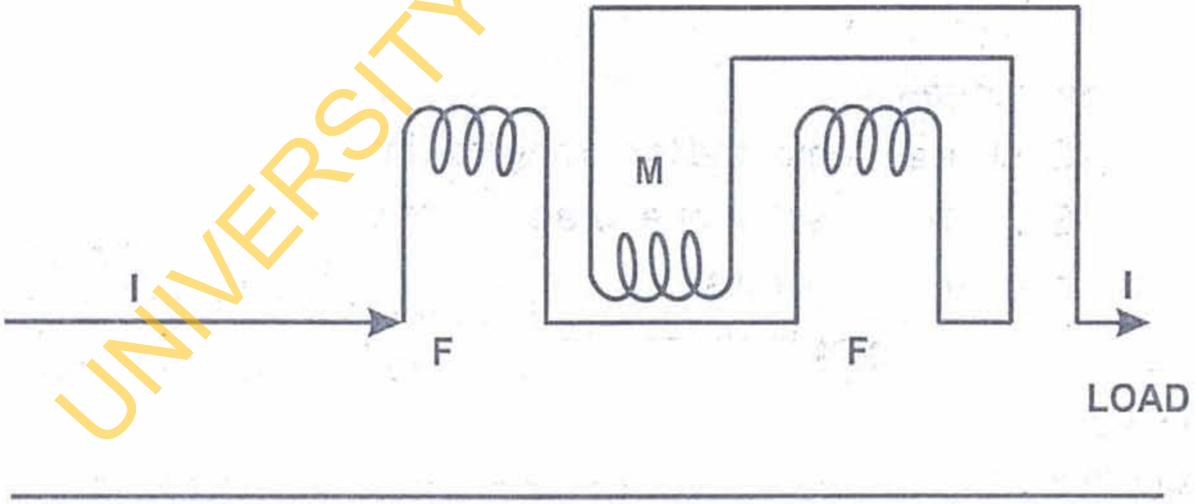


Figure 3.14: Electrical Connection of the Fixed and the Moving Coils

The fixed coil is usually arranged in two sections F and F placed parallel to each other. The moving coil is placed in-between the two fixed coils and it is spring controlled with a pointer attached to it as shown in figure 3.13. Figure 3.14 shows the electrical connection of the fixed and the moving coils of a dynamometer instrument.

For this type of instrument the deflecting torque is proportional to the product of the currents following in the fixed and the moving coils. Since the instrument is spring-controlled, the restoring or control torque is proportional to the angular deflection è.

$T_d \; I_1 I_2,\qquad T_c \; \theta$

At equilibrium $Td = T_c$

Therefore, è $I_1 I_2$

When the instrument is used as an ammeter the same current is passing through both the fixed and the moving coils. The connection in figure 3.14 is used for measuring small current. For large current a shunt is used to limit the current flowing through the moving coil, this is shown in figure 3.15.

When used as voltmeter the fixed and moving coils are joined in series along with a high multiplier resistance R and connected as shown in figure 3.16.

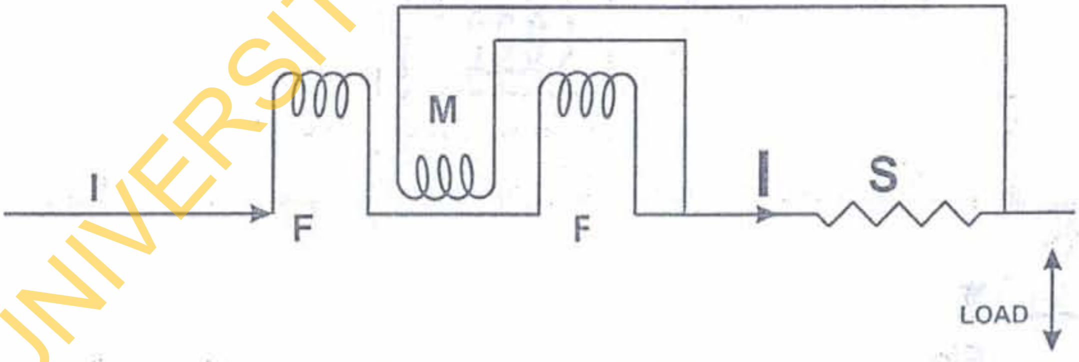


Figure 3.15: Dynamometer Used as Ammeter for Measuring Large Current

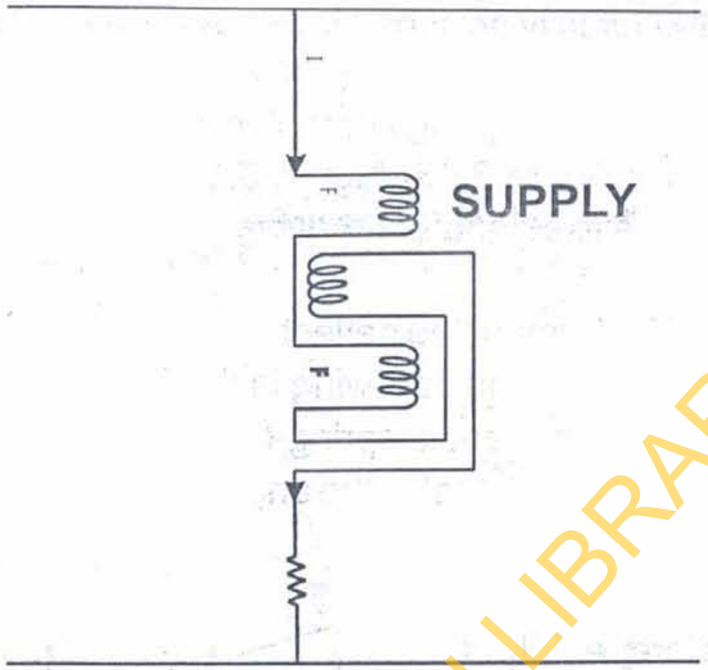


Figure 3.16: Dynamometer Used as Voltmeter for Measuring Large Voltage.

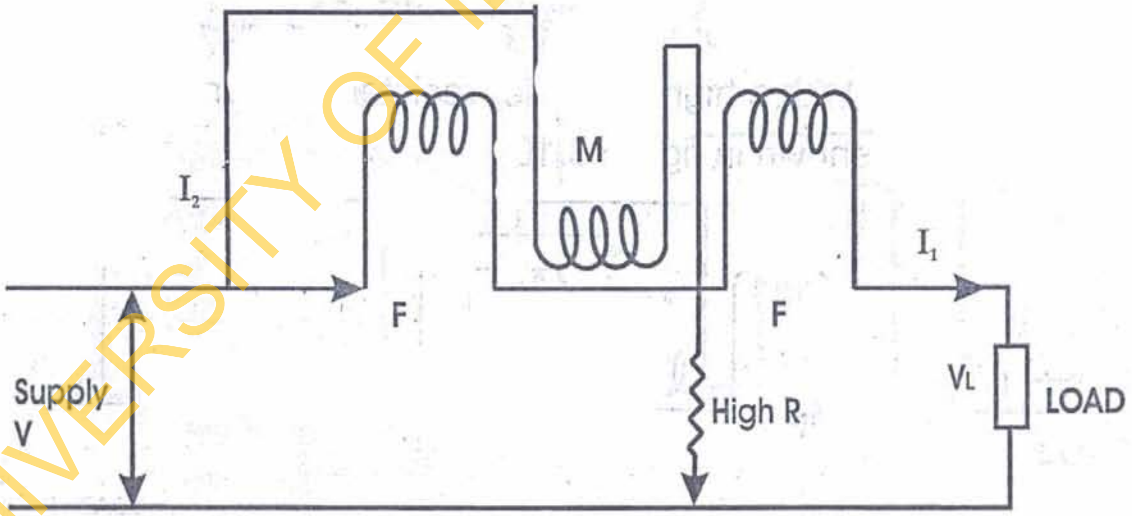


Figure 3.17: Dynamometer Used as Wattmeter for Measuring Power.

When Used as Wattmeter

When the dynamometer is used as wattmeter, the fixed and the moving coils are arranged as shown in figure 3.17. In this arrangement, torque is proportional to power.

Since Td $I_1 I_2$ for other arrangements (figures 3.14-3.16)

But for this arrangement (figure 3.17), current I_2 causes a voltage drop V_L that is equal to the load voltage across the resistor R.

Hence Td $I_1 V_L$? Td Power (drawn by the load)

Therefore, è á Power

Advantage/Disadvantage

(i) Such instruments are free from hysteresis and eddy-current error (because there is no iron core in the moving coil).

(ii) Since (torque/weight) ratio is small, such, instrument has low sensitivity.

Cathode Ray Oscilloscope (CRO)

It is generally referred to as oscilloscope or scope and it is a basic tool that can be used as voltmeter, ammeter and wattmeter. The block diagram of an oscilloscope is shown in figure 3.18. The scope provides a two-dimensional visual display of the signal wave shape on a screen. An oscilloscope can display and also measure many electrical quantities like dc or ac voltage, time, phase relationships, frequency and a wide range of waveform characteristics like rise-time, fall time. It can also be used to measure non-electrical quantities like pressure, temperature, flow rate, speed, displacement, level by using appropriate transducers to first convert them into an equivalent voltage, and thereafter fed into the scope.

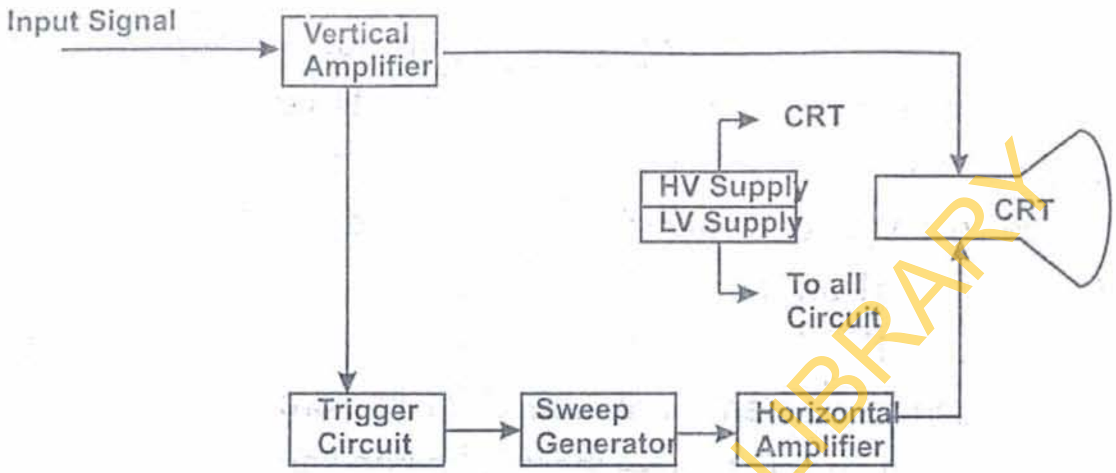


Figure 3.18: The Functional Block Diagram of Oscilloscope.

The components of oscilloscope are described below.

(1) Cathode ray tube CRT: It displays the quantity being measured on a luminescent screen.

(2) Vertical amplifier: It amplifies the signal waveform to be viewed.

(3) Sweep generator: produces saw tooth voltage waveform used for horizontal deflection of the electron beam.

(4) Horizontal amplifier: It is fed with a saw tooth voltage, which is then applied, to the X-plates of the CRT.

(5) Trigger circuit: producers trigger pulses to start horizontal sweep.

CATHODE RAY TUBE

Cathode Ray Tube is an electron tube, or evacuated glass container, having at one end a device called an electron gun that projects a beam of electrons against a luminescent screen at the opposite end of the tube. A bright spot of light appears wherever the electrons strike on the screen. Cathode ray tubes are used as picture tubes in television receivers and as visual display screens in radar equipment, computer visual display unit (VDU), and oscilloscopes.

Electrons are emitted from a heated cathode (negative electrode), in the electron gun. A series of grids having a positive potential with respect to the cathode accelerate the electrons as they pass. The electrons then pass through a series of doughnut-shaped anodes that focus the stream of electrons so that they strike the luminescent screen as a fine point. Between the electron gun and the screen are either two sets of electric deflecting plates or two sets of magnetic deflecting coils depending on the size of the tube. Electric deflecting plates are used in small CRTs, whereas magnetic deflecting coils are used in large CRTs in which a large deflection is required, such as in television tubes.

In CRTs containing electric deflecting plates, a horizontal pair of plates controls the up-and-down motion of the electron beam, and a vertical pair controls the left-to-right motion of the beam. Both plates in each pair can be charged. If the charges on the two plates are equal, the beam will strike the center of the

The instruction copies the content of memory location $02000 to data register D0. i.e. [02000] $\longrightarrow$ D0

2. **MOVEA**: The instruction Moves data from the effective address of source operand to an address register. The assembler syntax is:

MOVEA.S (EA), An

Op-code operand size source address address register

MOVEA instruction can be used to load an address into an address register from memory or for loading an immediate data into address register. . The

EA is calculated using the addressing mode specified in the instruction. For example, consider the instruction ***MOVEA.W #$2000, A5***

This instruction moves the immediate 16bits word 2000_{16} into the low 16-bit of A5 Address register. It signs extend 2000_{16} to 32-bit i.e. 00002000_{16}

i.e. $2000_{16} \longrightarrow$ [A5] and then signed extended to:

[A5] = 00002000_{16}.

Consider the instruction **MOVEA.L $04(A5,D2.W), A2**

Assume: [A5] = 00024580_{16}, [D2] = 0045_{16} and [$0245C9_{16}$] = 89764512_{16}

Then, EA = 04+00024580+0045 = $000245C9_{16}$

After the execution of the above instruction, 89764512_{16} is copied into data register A2.

[A2] = 89765412_{16}

MOVEA can use all available (14) addressing modes.

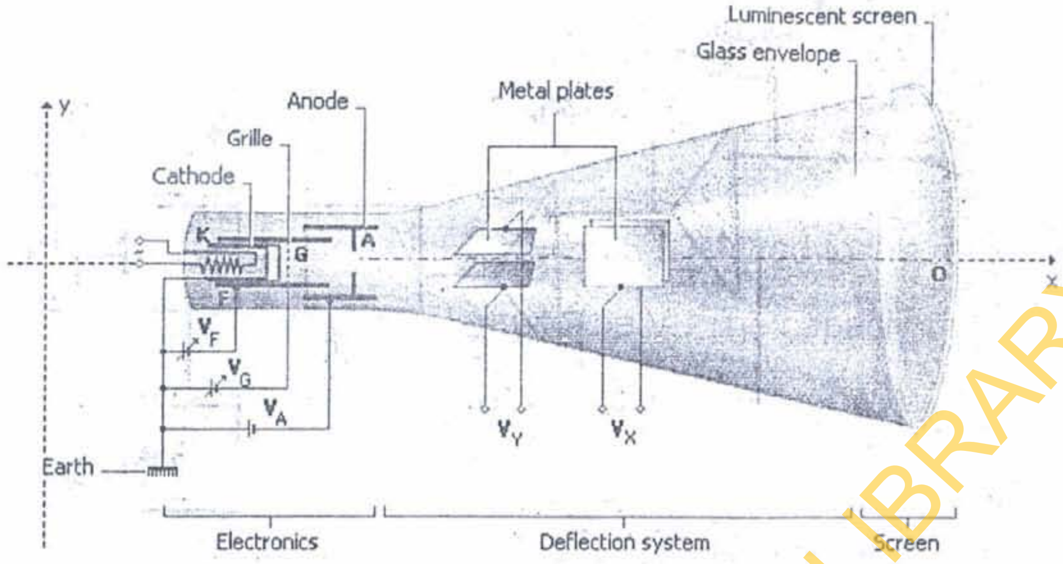


Figure 3.19: Detailed Diagram of CRT Showing Major Components

Electron Gun: This is a device that projects a beam of electrons against a luminescent screen at the opposite end of the tube.

Cathode: Electrons are emitted from a heated cathode, or negative electrode, in the electron gun.

Anode they are used to accelerate the electron towards the Luminescent screen

X-Plates: They are used to divert the electron beam up or down (Vertical)

Y-Plates: They are used to divert the electron beam right or left (Horizontal)

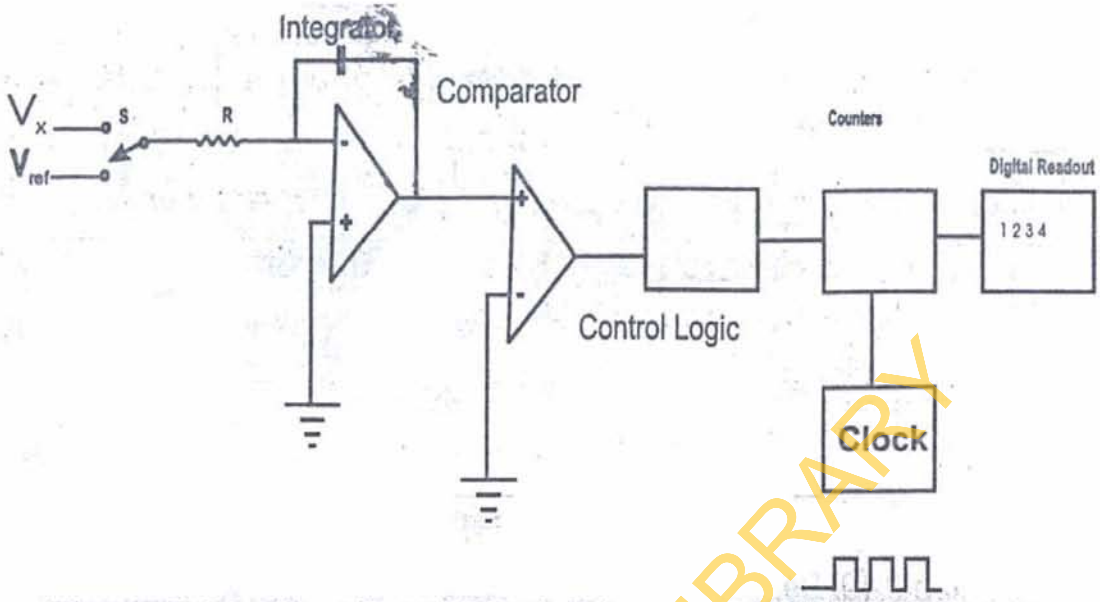


Figure 3.20: Functional Block Diagram of Digital Voltmeter

Digital Voltmeter displays measurements of dc and ac voltages as discrete numerals instead of pointer deflection on a continuous scale as in analog indicating instruments.

The operation of DVM is based on dual-slope analog to digital conversion method. It consists of five blocks: an Op-amp used as an integrator, a level comparator, a basic clock (for generating pulses), a set of decimal counters and a block of logic circuitry as shown in figure 3.20.

The unknown voltage V_x to be measured is applied through switch S to the integrator for a known period of time T. This period is determined by counting the clock frequency using the decimal counters. During time T, capacitor C is charged at a rate proportional to the measured voltage V_x.

At the end of time interval T, switch S is shifted to the reference voltage V_{ref} of opposite polarity to the V_x. The capacitor's charge being to decrease with time and results in a downward linear ramp voltage. During the second period a known voltage (V_{ref}) is observed for an unknown time (t). This unknown time t is determined by counting timing pulses from the clock until the voltage across the capacitor reaches the basic reference value. The count after time t, which is proportional to the input voltage V_x, is displayed as the measured voltage on the digital readout. By using appropriate signal conditioning, current, resistances and ac voltage can be measured by the same instrument (DVM).

CHAPTER FOUR

TRANSDUCERS

A transducer is a device or combination of devices whose response to a mechanical or electrical, chemical or physical stimulus is an output signal functionally related to the magnitude and sense of the (direction) stimulus.

Transducers usually contain two principal elements. Primary element or sensor and a secondary element that is responsible for the generation of the output signal. The name transducer and sensor are often interchanged for one another.

Transducer's stimuli generally fall into one of the following six groups.

(i) **Physico-mechanical**: force, weight, displacement (linear/angular), velocity (rectilinear or angular), acceleration, pressure, flow rate, viscosity, moisture content, vibration, level, hardness, thickness, density, colour, opacity, turbidity, particle concentration.

(ii) **Electrical**: voltage, current, frequency, phase angle, power, inductance, and capacitance.

(iii) **Magnetic**: Field strength (H), Hysteresis, induction

(iv) **Thermal**: Thermal conductivity, Temperature.

(v) **Radiation**: X-ray, Uv, radiation frequency, visible light, nuclear radiation.

(vi) **Chemical**: Concentration, composition, pH.

Terms Used In Transducer Specification.

1. **Accuracy**: is the closeness to which the output value approaches the true value of the stimulus.
2. **Sensitivity**: is the ratio of change in the output signal to the change in input signal. For example, if a 1^0 change in input angle of an angular displacement transducer results in a 2v change in output signal, it is said to have 2v/degree sensitivity.
3. **Range/Span:** Range/Span of a Transducer is the difference between the maximum and minimum values of the input stimulus to which the output signal responds. Range ability is a measure of the ratio of maximum input stimulus value to minimum input stimulus value.

$$\text{Range ability} = \frac{\text{Max input stimulus value}}{\text{Min input stimulus value}}$$

4. **Linearity Error**: If the sensitivity of a transducer over its entire range is precisely constant, it may be considered linear. However no practical device can be perfectly linear. Therefore, linearity error is the ratio of the change in the sensitivity of a transducer to the range of the transducer.
5. **Resolution**: A small change in the input stimulus to which the output will respond. It is expressed as the % of the input range. Thus a rectilinear displacement transducer with a range of 100cm of a resolution of 0.1% will be

incapable of sensing changes in input displacement can sense an infinitesimal change in stimulus. It is said to have an into an infinite resolutions

6. **Precision**: is a measure of the degree of repeatability of successive measurement of the same input stimulus.

TEMPERATURE TRANSDUCERS

Temperature is a common and widely measured physical parameter. Measured temperature values are used for monitoring and control of some important processes. There are various transducers for measuring temperature namely, thermistor, thermocouple, optical pyrometer, resistance thermometer detector (RTD), semiconductor temperature sensor IC, etc. They provide a wide choice to suit a variety of applications, such as temperature measurement, temperature control, over temperature protection, over-current protection, liquid level detection, etc.

THERMISTOR

Thermistor or thermal resistors are semiconductor devices whose use as transducers is due to the fact that their resistance changes markedly when their temperature changes. They can be used for measurement of temperature. They are usually in rod, disc and bead shapes. It is a sensitive, low-cost temperature sensor, which is available in a broad range of resistance values. It covers a limited temperature range, but it is quick to respond to temperature alterations and gives a large resistance change in value with temperature (e.g. 4% per 1^0c). It can be employed to detect small changes in temperature. The resistance change it exhibits is non-linear.

There are 2 types of thermistor namely, negative temperature co-efficient (NTC) and positive temperature co-efficient (PTC).

N.T.C Thermistor: Their resistance decreases with the increase in temperature. The changes in the resistance are not linearly related to the changes in the temperature. They are used for measuring temperature changes after taking into consideration the non-linearity factor of the thermistor and proper calibration.

P.T.C Thermistor: Their resistances increase sharply above a certain temperature. They are used mainly to prevent damage in circuit, which might experience a large temperature rise. For example, it is used in power supply units for over-heating protection. Figure 4.1 shows a temperature-controlled switch that will on at a certain temperature determined by the resistance change of the thermistor Rt.

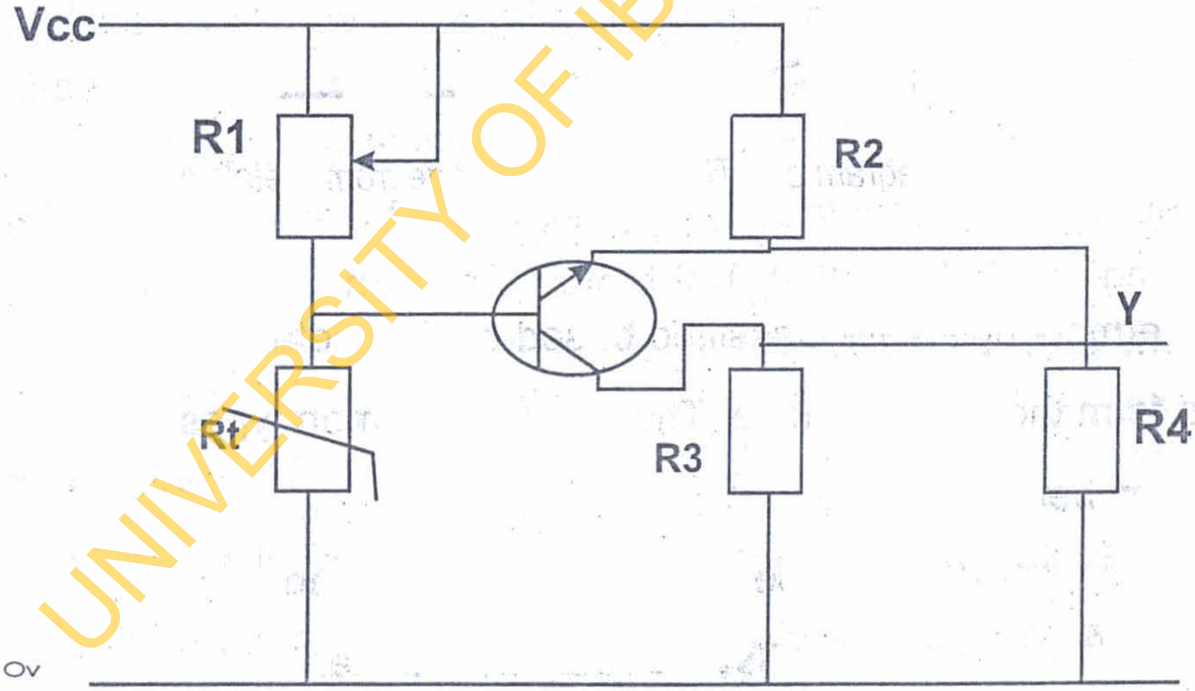


Figure 4.1: Temperature-controlled Switch Circuit.

THERMOCOUPLE:

This is a simple, inexpensive sensor, which measures temperature over a wide range. A thermocouple can measure up to 2000°C. It produces a very low voltage (mill volts), which increases non-linearly with temperature. Welding two dissimilar metals together can construct thermocouple. When the welded joint is heated, a voltage difference will appear between the two terminals. The magnitude of the voltage depends on the material of each of the two wires. As shown in figure 4.2, metals A and B are welded together to form a thermocouple.

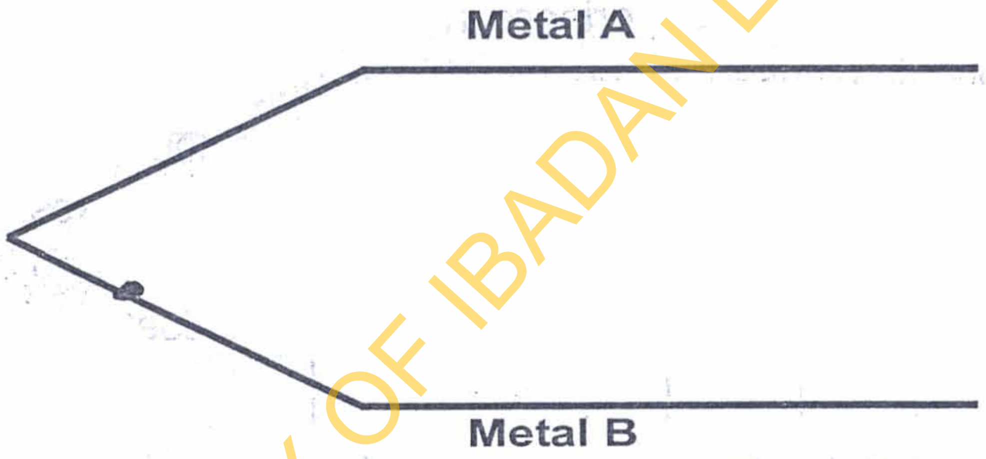


Figure 4.2: Diagram of a Thermocouple Made from Metals A and B

Thermocouples are classified based on the metals combined to form the thermocouple. The various common types are given below namely,

Type E Chromel-Constantan

Type J Iron-Constantan

Type K Chromel-Alumel
Type T Copper-Constantan

The comparison of the magnitude of the temperatures and the voltages for the various thermocouple types are given below.

Temperature range: Type K > Type E > Type J > Type T
Voltage magnitude: Type E > Type J > Type T > Type K

There are standard calibration tables relating the output voltage to the measured temperature for each thermocouple type.

RESISTIVE TEMPERATURE SENSORS (RTD)

This type of sensor covers a wide range of temperature. It is of low cost and also referred to as RTD. It is made of pure metals and the resistance of the metal changes with temperature. It is based on the fact that the resistance of pure metals changes with temperature, in a highly predictable and repeatable manner. RTD makes use of this change in resistance, to measure temperature. Current is required to flow through the sensor, which will in turn produce a stable reading whose change with temperature is more linear than that of thermocouple and thermistor.

The change is, however, small and relatively slow. Since the change in magnitude is small, temperature alteration can be detected by using a Wheatstone bridge as shown in figure 4.3.

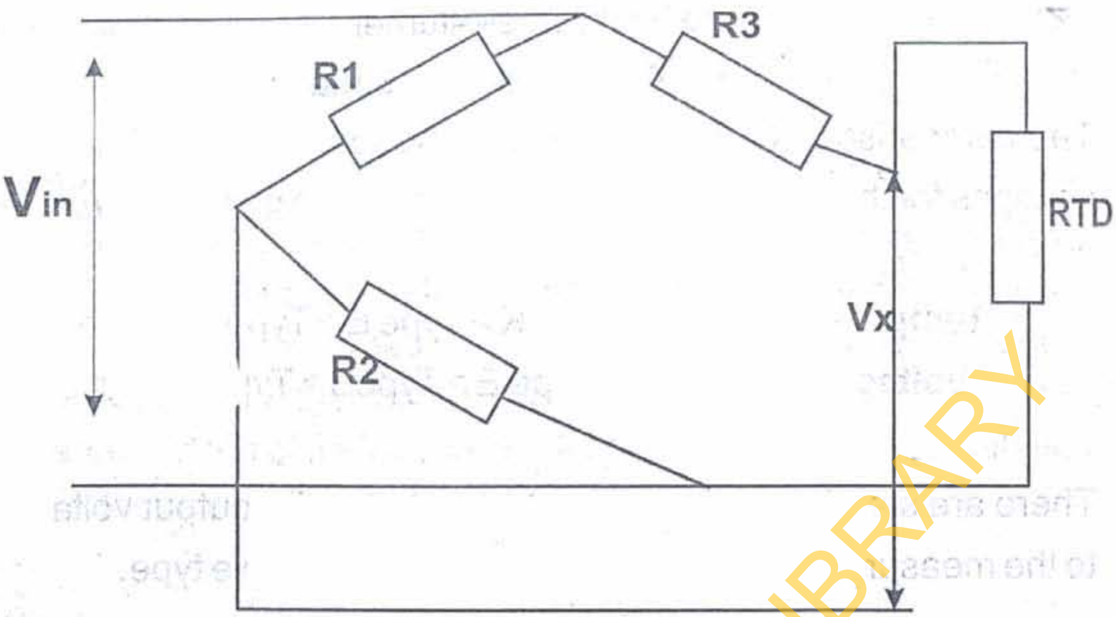


Figure 4.3: Temperature Measurement Using RTD in a Wheatstone bridge.

The output of the bridge V_x is given as:

$$V_x = V_{in}\left(\frac{RTD}{R_3 + RTD} - \frac{R_2}{R_1 + R_2}\right)$$

From the above equation the resistance value of the RTD can be calculated at an unknown temperature. The equation relating the resistances of a pure metal at two different temperatures is given below as:

$$R_1 = R_0\,[1 + \alpha\ (T_1 - T_0)]$$

Where $T_1 \alpha T_0$ are two Temperatures [To = 0°c or 25°c]

α -Temperature co-efficient of resistance for the metal

R_0 -resistance at T_0

LINEAR SEMICONDUCTOR TEMPERATURE SENSORS

These inexpensive semiconductor sensors produce a voltage that is linearly proportional to temperature. It has a limited temperature range and, like most temperature sensors, suffers from self-heating. To get accurate readings and to prevent damage to the sensor, a moderate current should be applied.

An example of such sensor is National Semiconductor LM335 precision temperature sensor with temperature range -40 to + 100°C. Other variants are:

LM135 with temperature range -55 to 150°C.

LM335 with temperature range -40 to + 150°C

Each of these sensors produces an output voltage, which changes by 10mV/°C in temperature and has a current range of 0.4mA to 5mA. A linear semiconductor temperature sensor may be connected as shown in figure 4.4. Vo will change by 10mV for each 1/°C change in the temperature.

DISPLACEMENT TRANSDUCERS

These are sensors that are used for measuring distance, position and presence of an object. Examples of these are *Capacitance Transducer*, *Linear Variable Differential Transformer* (LVDT) Transducer, *Encoders*, *Linear Variable Differential Inductance* (LVDI) Transducer, Synchro and Resolvers, Potentiometers, Limit Switches, Photoelectric Position Sensor, and Magnetic Proximity Detector.

Limit Switch: are used in refrigerator door, car door, seat belt, to detect the position of the doors whether closed or open and usage of the seat belt by car occupants. They are of the single pole single throw switch (ON/OFF) type.

Photoelectric Position Sensor: This is used to detect the presence of an object. It consists of a light source and a light detector. When the object passes in between the light source and light detector, the light path from the source to the detector is broken, thereby signifying presence of an object.

The light source could be LED, small bulb, sun or daylight, while the detector could by photodiode, phototransistor or photo resistor. Figure 4.5 shows an object passing in between the light source (LED) and the light detector. When the object is blocking the light source, the transistor **Tr1** will not conduct and hence Vo will be high. With this, the presence of the object can be determined by reading Vo or powering of an LED by Vo. Vo may also be connected to other electronic components such as counter IC to count the number of objects that have passed.

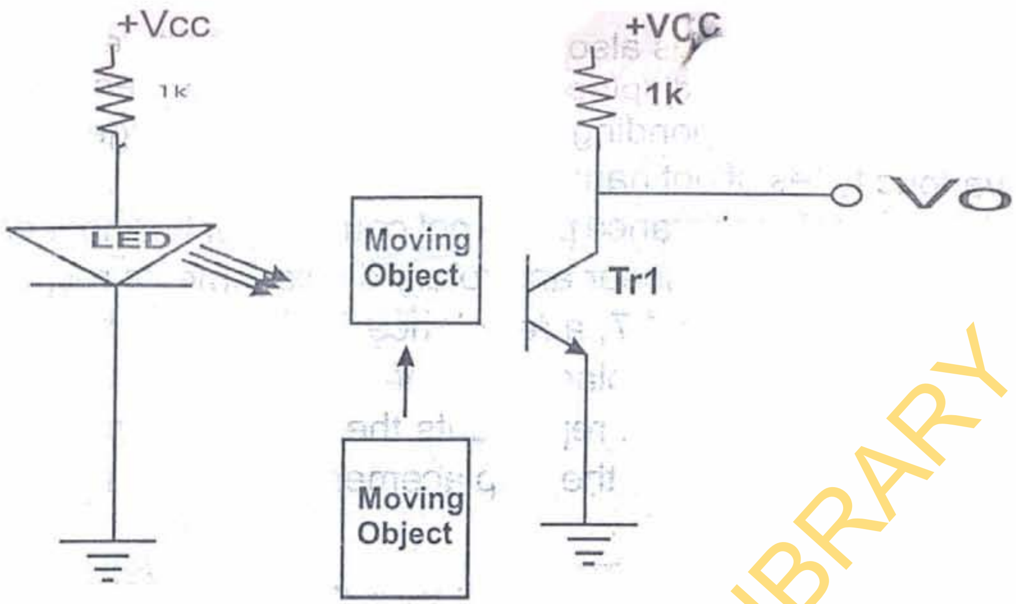


Figure 4.5: Arrangement of Light Source and Detector to Sense Presence of an Object

Light Intensity: The light detectors, photodiode, phototransistor and photo resistor can also be used to measure light intensity. This is shown in figure 4.6 using a light dependent resistor (LDR) to measure the intensity of the ambient light. The more the light intensity, the lower the resistance of the LDR and hence, Vo reduces.

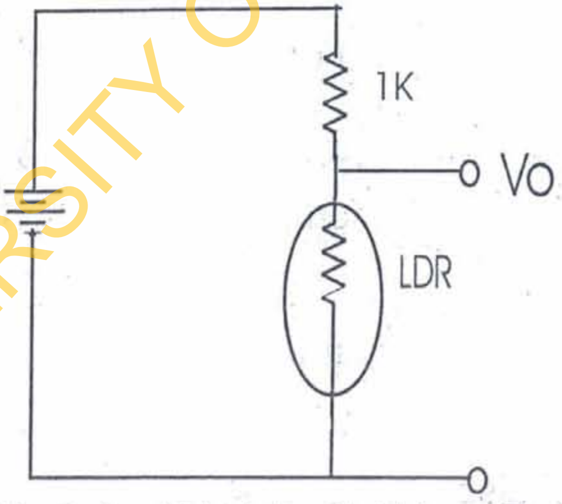


Figure 4.6: Measuring Light Intensity Using a Photo Resistor (LDR)

Potentiometer: It is also known as '**Pot**', constitutes one of the simplest forms of displacement sensor. A movement on the pot will give a corresponding proportional output voltage. There are various types of pot namely, wire wound pot, conductive plastic pot, magneto resistance pot. A pot could either be linear or rotary pot for measuring linear and rotary displacements respectively. As shown in figure 4.7, a resistance Rp is uniformly distributed over the range of displacement of interest and a fixed voltage applied across it. If X represents the displacement (relative to the full scale value of the displacement), the output Vo is given by $V_0 = V_R X$

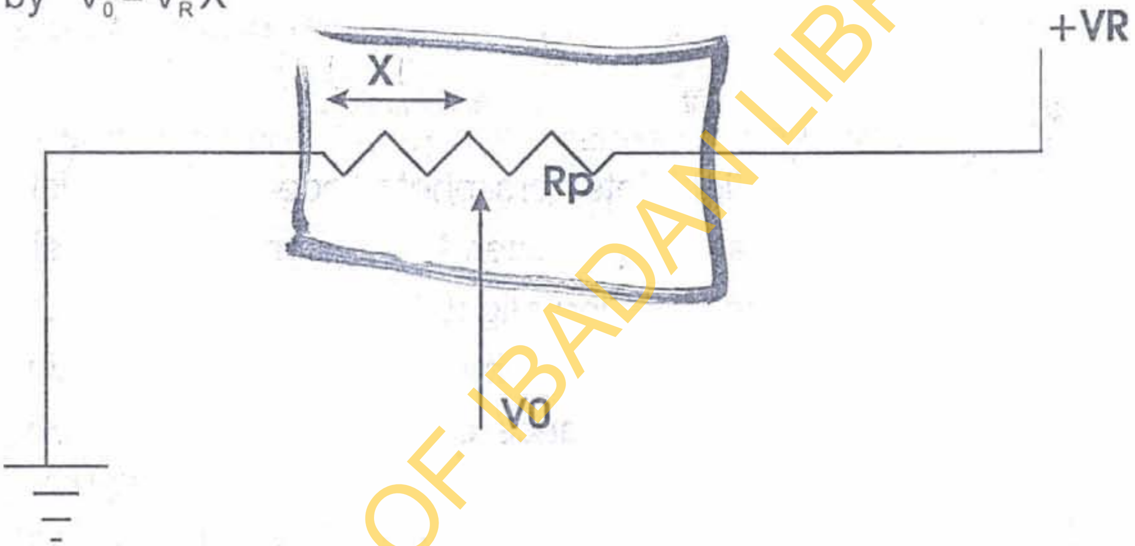


Figure 4.7: Linear Potentiometer as a Position Sensor

With the arrangement of figure 4.7, the voltage Vo is directly proportional to the displacement X and Vo cannot be higher than V_R.

Figure 4.8 shows the diagram of the rotary potentiometer. It works on the same principle used by the linear pot except that it measures angular displacement.

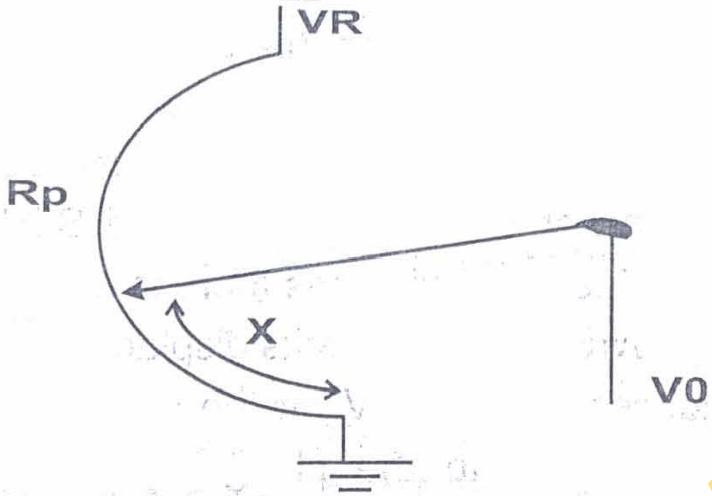
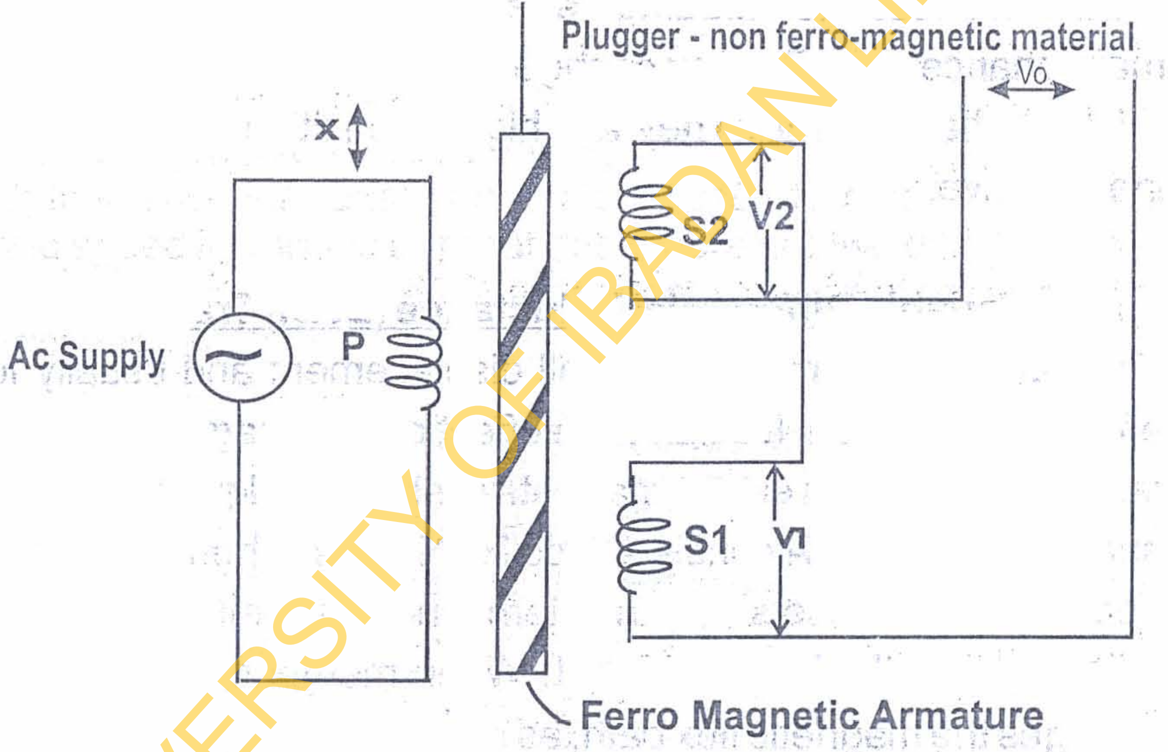


Figure 4.8: Diagram of Rotary Potentiometer Showing the Displacement X

Linear Variable Differential Transformer (LVDT)



P -Primary winding

S_1 and S_2 are two secondary windings symmetrically placed with respect to P.

$V_0 = V_2 - V_1$

Figure 4.9: Diagram of LVDT Transducer

LVDT is a sensor that can measure displacement in the range of 1mm to 1m. The diagram of LVDT is shown in figure 4.9. It consists of a primary winding P placed symmetrically at the mid point of two secondary windings S_1 and S_2. In between this primary and secondary windings there is a metal core attached to a plunger. When this plunger is displaced form its rest, the P winding induces a voltage V_0 at the secondary output that is directly proportional to the plunger displacement X. V_0 is adjusted to be zero when the plunger is at origin.

LVDT are rugged and can be used in any environment, they are insensitiveness to loading effect, last longer, and are maintenance free. For any change in the displacement, there is a linear change in V_0. They are highly sensitive and relatively inexpensive.

Linear Variable Differential Inductance (LVDI) Transducer

They are used to measure small displacement and usually for proximity detection. It utilizes the effect of ferromagnetic core on flux produced by an electromagnet. As shown in figure 4.10, an E shaped member ***AA*** consists of coil of N turns, when ac power is applied, the coil sets up an alternating magnetic flux, which follows the path shown with dot. When member ***B*** is moved it changes the magnetic flux path, as a result, the current in the coil changes, the ammeter A reading indicates this. The closer member B is to the coil the more the flux and the current in the coil. Member ***B*** can therefore be attached to the body whose proximity is to be determined, and usually member ***B*** is metal.

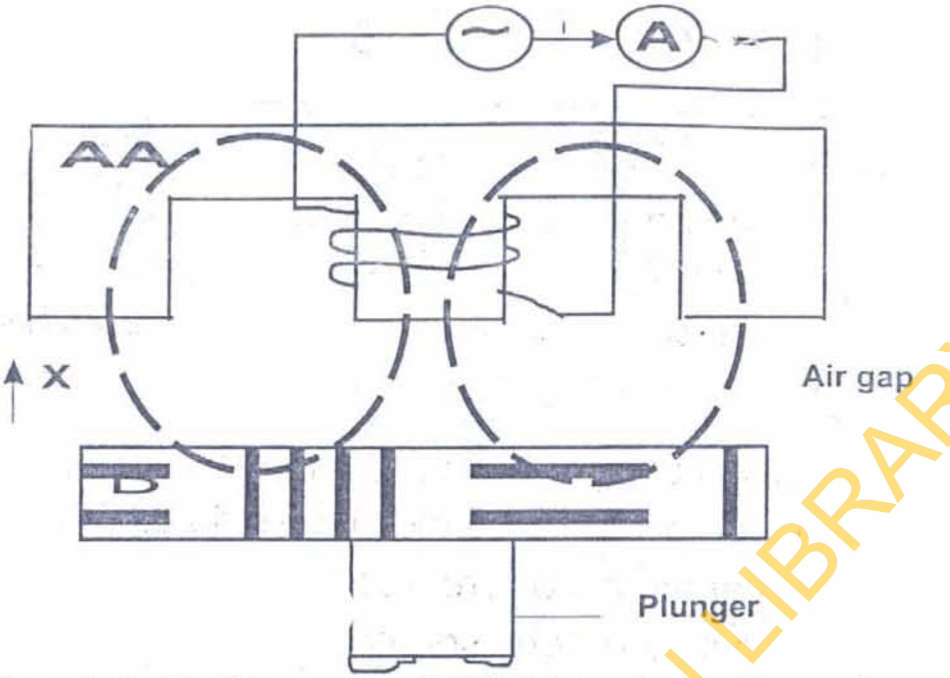


Figure 4.10: Diagram of LVDI Proximity Transducer

ENCODERS (Optical Encoders)

Optical encoder sensors are widely used to measure position and speed in various applications. There are two different types of optical encoder namely Incremental encoder and Absolute encoder.

INCREMENTAL ENCODER: Is divided into linear encoder and rotary encoder. A linear encoder consists of a strip with equally spaced slots or holes through which light can be transmitted. A light source and a light sensitive device can be placed on either sides of the strip, a few millimeters apart. When the strip is moved, light passes from the light source to the light detector or the light sensitive device only through the slot. Conduction through the light sensitive device will be sensed by the interface circuit, which will count the number of time the photosensitive device is turned on and off, thus obtaining a count proportional to the displacement and the speed of the object can be measured by dividing the displacement by the time taken to cover the distance.

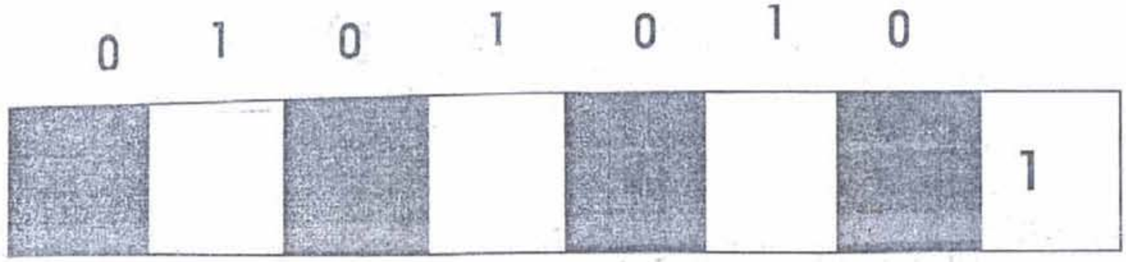


Figure 4.11: Reflective surface Linear Encoders Disk For Measuring Linear Speed

Rather than using slots or holes, equally spaced light reflective surface can be placed on one side of the strip as shown in figure 4.11. The un-shaded portions represent reflective surfaces. With this arrangement, the light source and the light sensor are placed on the same side. The sensor will be turned ON and OFF as the reflective lines are moved.

Linear encoders are suitable for detecting motion along a straight line while rotary encoders are used for angular measurement of displacement and speed.

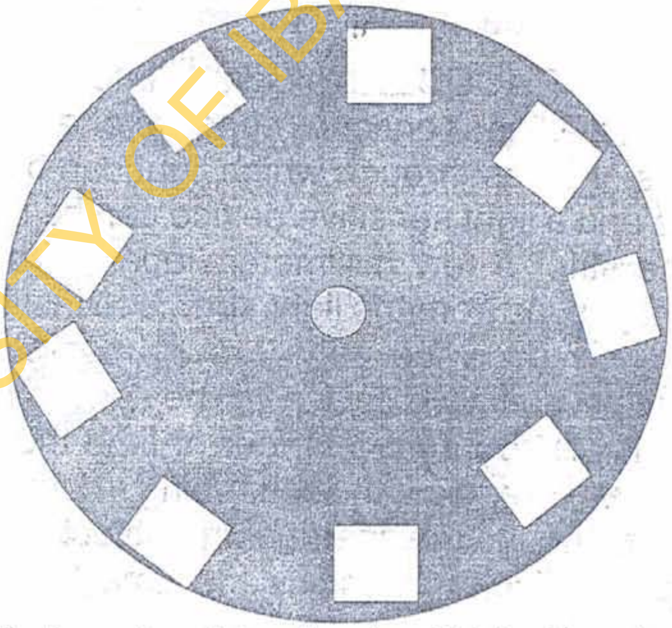


Figure 4.12: Reflective surface Rotary Encoders Disk For Measuring Angular Speed

Rotary encoders are based also on the same principle used for linear encoder except that rotary encoder is in a form of reflective disk rather than a reflective strip as shown in figure 4.12

ABSOLUTE ENCODERS: These encoders are coded to represent every position by a unique code (binary, Gray, excess 3, BCD, etc). They provide the absolute position being measured. Let us consider, a three channel absolute encoder shown in figure 4.13.

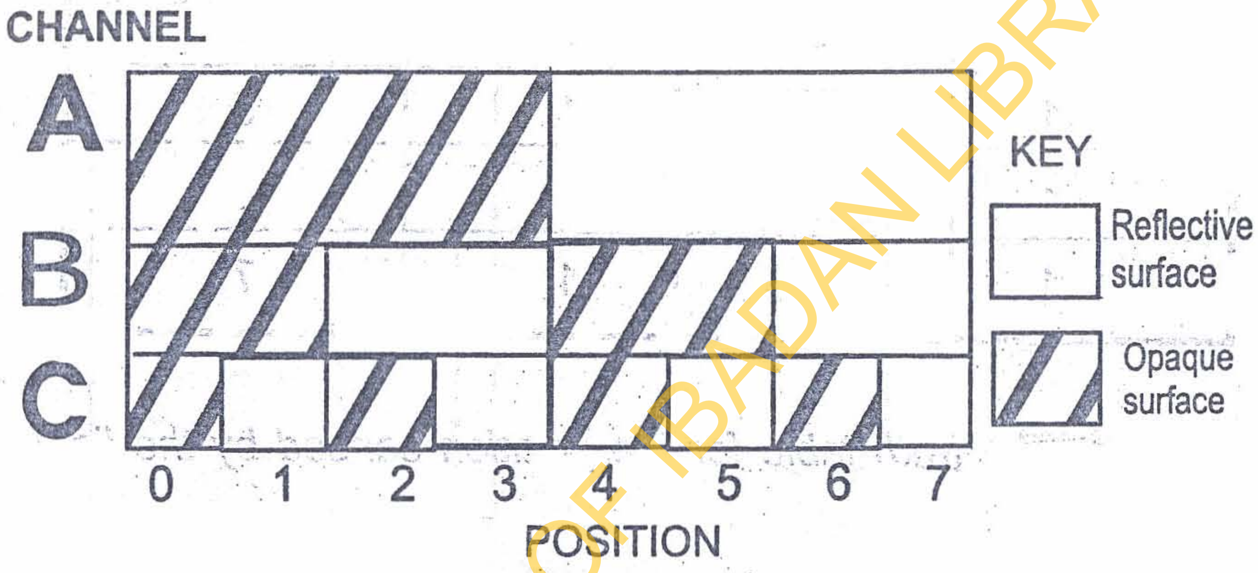


Figure 4.13: A Three Channel Reflective Surface Absolute Encoder

Where the reflective and opaque surfaces are made on three horizontal lines, this gives eight different positions; each is read as a three bit binary number, where a reflective area permits conduction of light, thereby causing a photosensitive device to turn on. Three different light detectors A, B and C are used to detect light from the three channels. The truth table for the position sensed by the light detectors is given in table 4.1.

Channel C	Channel B	Channel A	Position Sensed
0	0	0	0
0	0	1	1
0	1	0	2
0	1	1	3
1	0	0	4
1	0	1	5
1	1	0	6
1	1	1	7

Table 4.1: The truth table for the position sensed by the light detectors

The advantages of absolute encoders are:

(i) Ability to give the exact position of an object in one reading.

(ii) Accurate reading can still be obtained after turning the power to the encoder OFF and ON again.

(iii) It provides digital output (all encoders can do this).

CAPACITIVE DISPLACEMENT TRANSDUCER

A capacitor consists of two conducting plates separated by insulator, which may be air or dielectrics material. When a voltage is applied to the metal plates of capacitor, equal and opposite electrical charges appear on the plates. The ratio of the charge to voltage is the capacitance C i.e. $q/v = C$.

Capacitance variation can be achieved by changing either the area or the separating distance between the plates.

Capacitance Variation Caused By Plate Separation

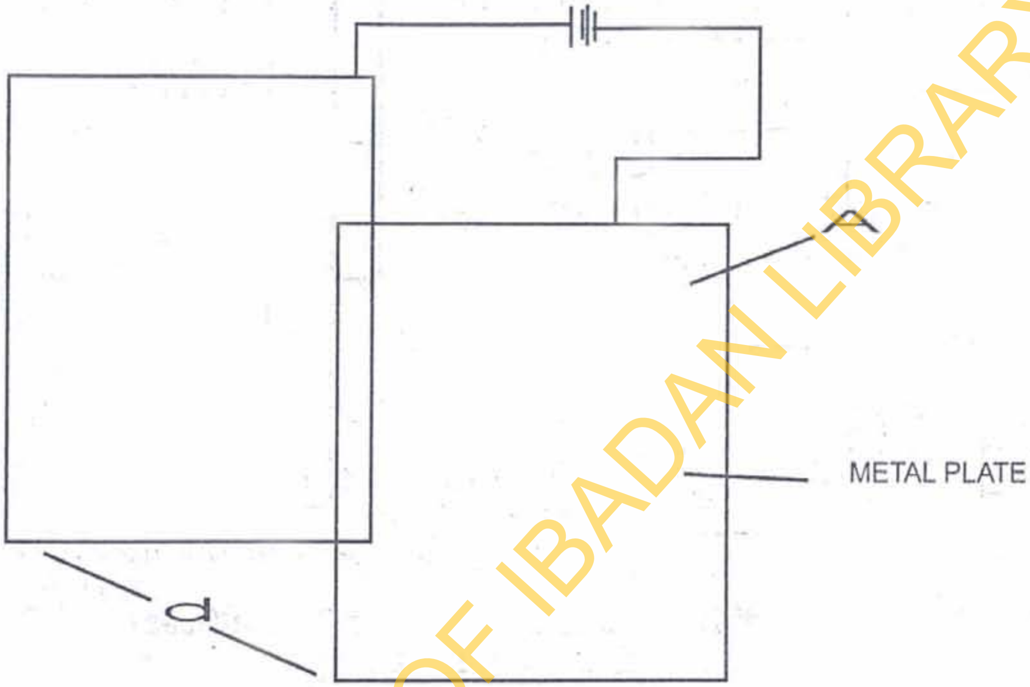


Figure 4.14: Diagram Of Capacitance Plates With Power Supply Connected.

The capacitance C between two facing plates as shown in figure 4.14 is given as:

$$C = \varepsilon_0 A/d$$

Where ε_0 -permittivity of free air ($\varepsilon_0 = 8.854\text{pFm}^{-1}$)

d - the plate separation

A - the area of the plates

From this equation of capacitance C, the area A and permitivity of free air are constant. If the plate separation d is varied, there will be change in the capacitance of the plates; hence variation of the plate separation d can be obtained by measuring the changes in the capacitance of the plates.

Capacitance Variation Caused By Area

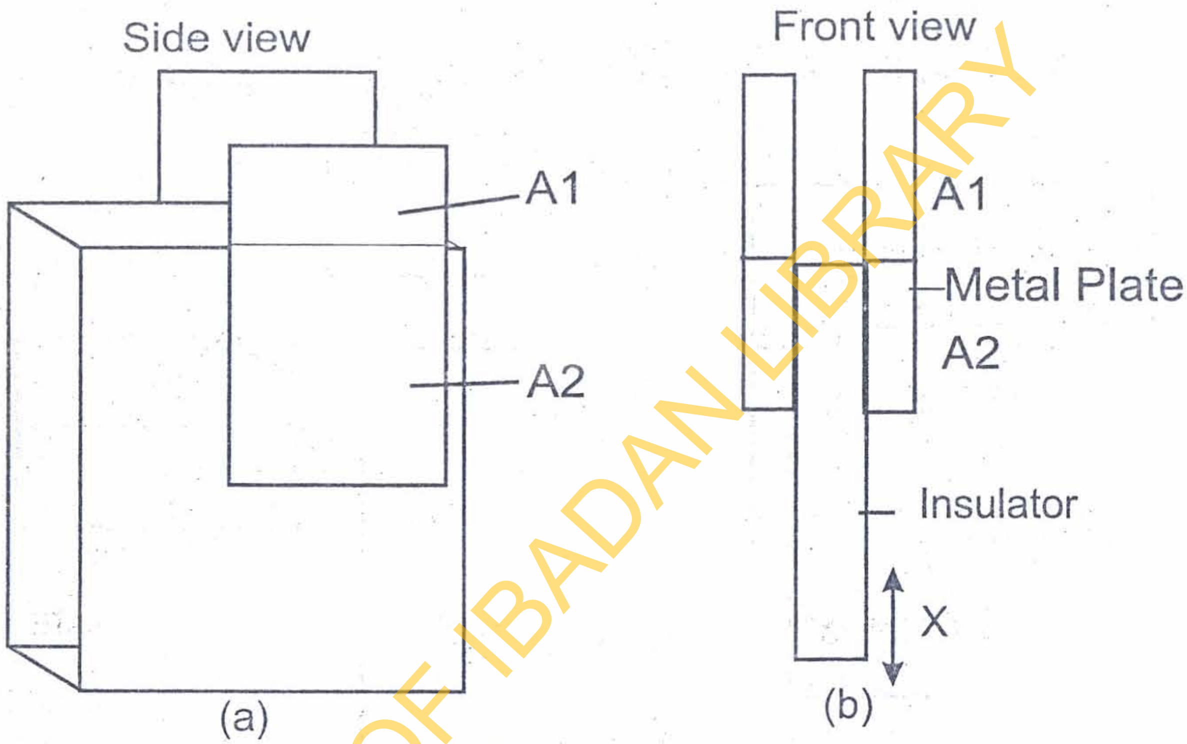


Figure 4.15: Variation of Capacitance By Varying the Surface Areas of The Plates.

Another way to vary the capacitance is to introduce an insulator between the plates as shown in figure 4.15a. If we assume that the insulators thickness is the same as the plate separation d, then, if the insulator is varied by displacement X as shown in figure 4.15b, and then Areas A_1 and A_2 will also vary and will cause a proportional change in the overall value of the capacitance. The object whose displacement is to be measured is attached to the end of the insulator. The equation of the capacitance will change to:

$$C = \varepsilon_0 A_1/d + \varepsilon_0 \varepsilon_r A_2/d$$

Where ε_r - Relative permeability of the insulator

MEASUREMENT OF FLUID FLOW

Measurement of flow rate is also very important to the industries involved in the production and distribution of gas, water, fuel, chemical and etc. there are many transducers used for these purposes, they are usually called flow meters. Some of them are *Venturi tube flow meter, Orifice flow meter, Pitot tube flow meter, electromagnetic flow meter, ultrasonic flow meter, Coriolis flow meter and Vortex flow meter*. Each of these flow meters has various advantages and they are used for various types of fluids depending on the properties of the fluid.

Fluid comprises of gases, liquids, mixture of solids and liquid and a fluid can be compressible or non-compressible.

There are three types of measurement that flow meters can provide, namely.

Flow velocity: The velocity with which a fluid is moving, measured in m/s.

Volumetric flow rate: The volume of fluid moving along a pipe in unit time, measured in m^3/s.

Mass flow rate: The mass of fluid moving along a pipe in unit time, measured in Kg/s.

The Venturi Tube Flow Meter

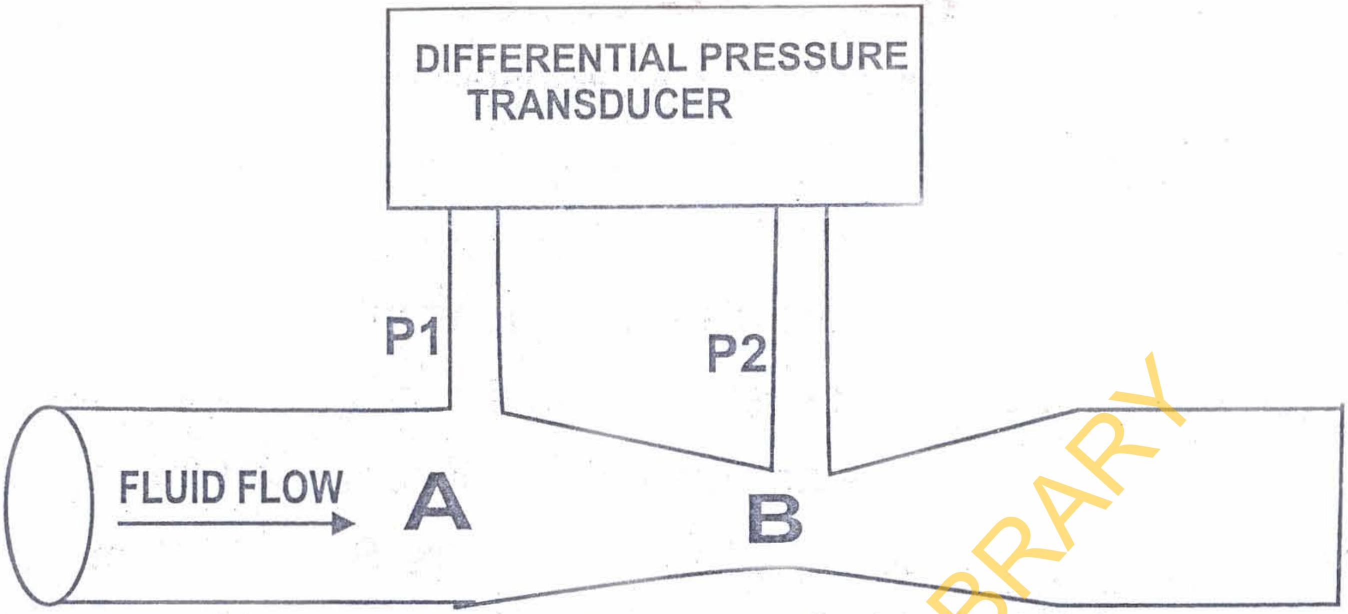


Figure 4.16: The Diagram of a Venturi Tube

The Venturi tube can be used to measure volumetric rate of flow of a flowing fluid in a pipe. The Venturi tube is inserted in between the pipe and as the fluid is flowing through the Venturi tube there is a change in the pressure of the fluid at the constricted throat of the Venturi tube. As shown in figure 4.16, the diameter of point B is smaller than that of point A, hence when the fluid is passing through point B it move faster than at point A. This increase in speed causes a decrease in the pressure of the fluid. The pressure change is measured by the differential pressure transducer connected to the Venturi tube at the pressure points P1 and P2 through pipes.

The volumetric flow rate Q of a Venturi tube is given as

Q = Constant of the Venturi tube X v (Pressure difference between points A and B)

Turbine Flow Meter

Turbine flow meter is one of the flow meters widely used in water and fuel distribution industries. The block diagram of a Turbine flow meter is shown in figure 4.17.

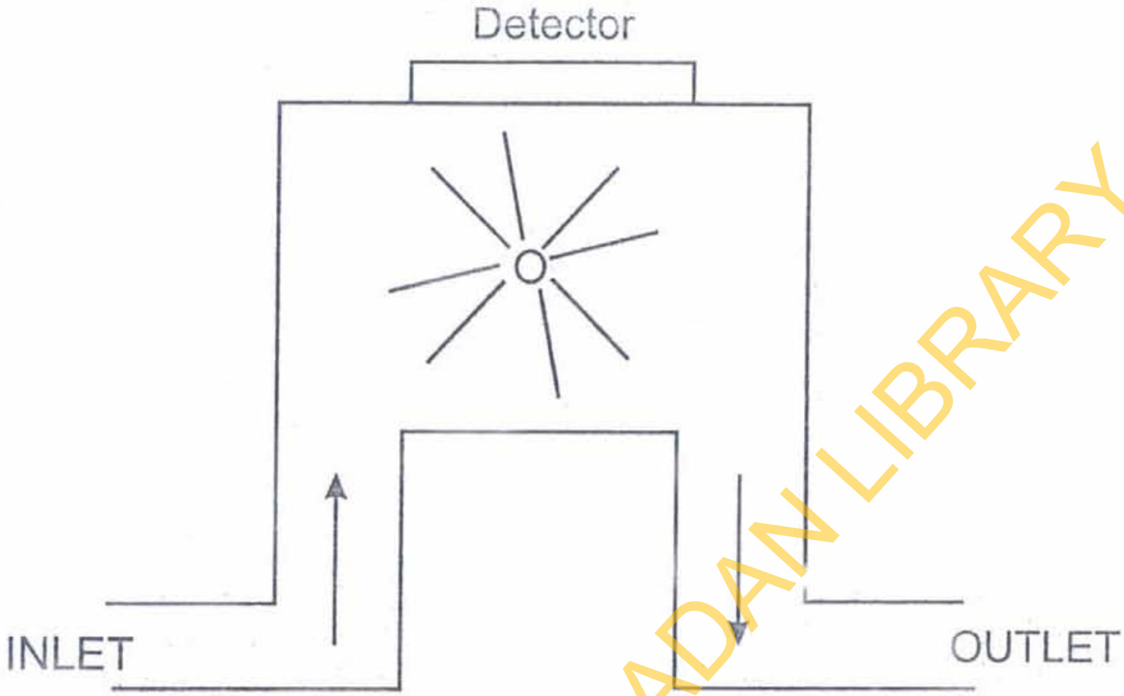


Figure 4.17: Turbine Flow Meter

The flow of liquid causes the rotor to spin at an angular velocity, which is proportional to the velocity of the liquid. The angular velocity of the rotor is detected from outside the tube by electromagnetic detector (dc generator) to provide an electrical signal proportional to the flow rate or mechanical counters as being used in the old fuel dispensing pumps at filling stations

DATA LOGGING SYSTEM

Data logging system is a system that accepts data from real life processes using appropriate transducers. Transducer receives stimulus from the process and produce output signal functionally related to the magnitude and sense of the stimulus.

The stimulus can be in any form for example pressure, flow rate, color, particle concentration, vibrations, moisture content, opacity, turbidity, temperature and sounds signal obtained from experiments or surveys and that can used as basis for making analysis, calculations, control or drawing conclusions.

DESIGN OF DATA LOGGING SYSTEM

A data acquisition system consists of many components that are integrated together namely:

i. Acquisition of electrical signals equivalent to the stimuli using transducers
ii. Condition the electrical signals to make it readable by an analog to digital converter (ADC) circuit.
iii. Convert the signal into a digital format acceptable by a computer
iv. Process, analyze, store, and display the acquired data with the help of software.

Figures 4.18 and 4.19 show the basic block diagram and the architecture of typical data logging system. The multiplexer (MUX) in figure 4.19 is to select one out of n transducers. The analog signal-conditioning block is to perform scaling, amplification, linearization of the transducer signal. The personal computer is doing the job of controlling the whole system by sending the address of the next sensor to acquire physical parameter, and all other processes that follows the acquisition such as signal conditioning, conversion to digital form, storage, printing and for control purposes.

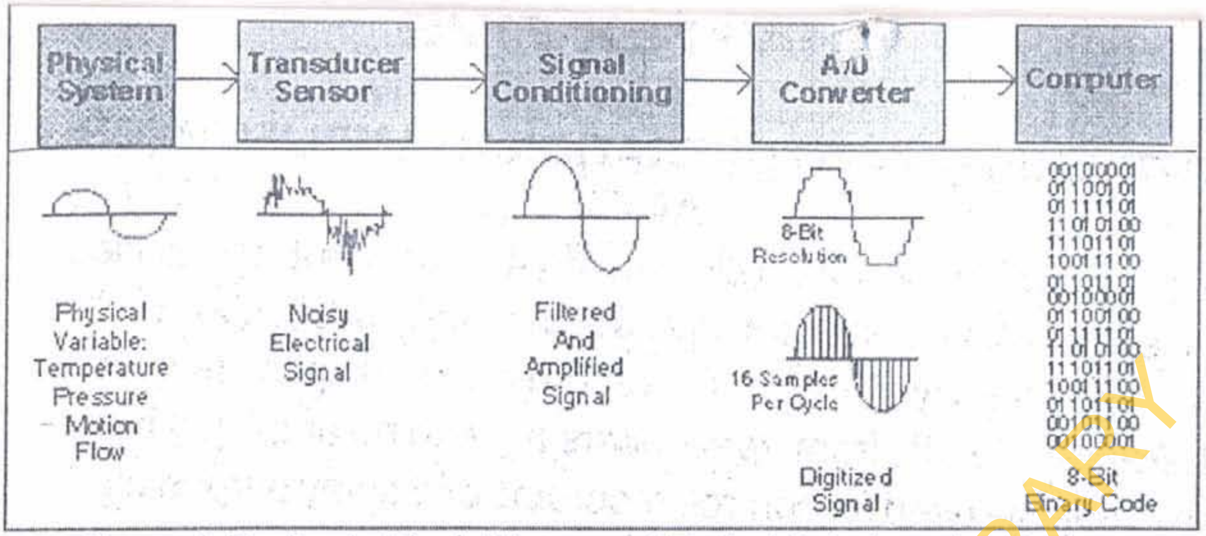


Figure 4.18: Basic Block Diagram of Typical Data Logging System.

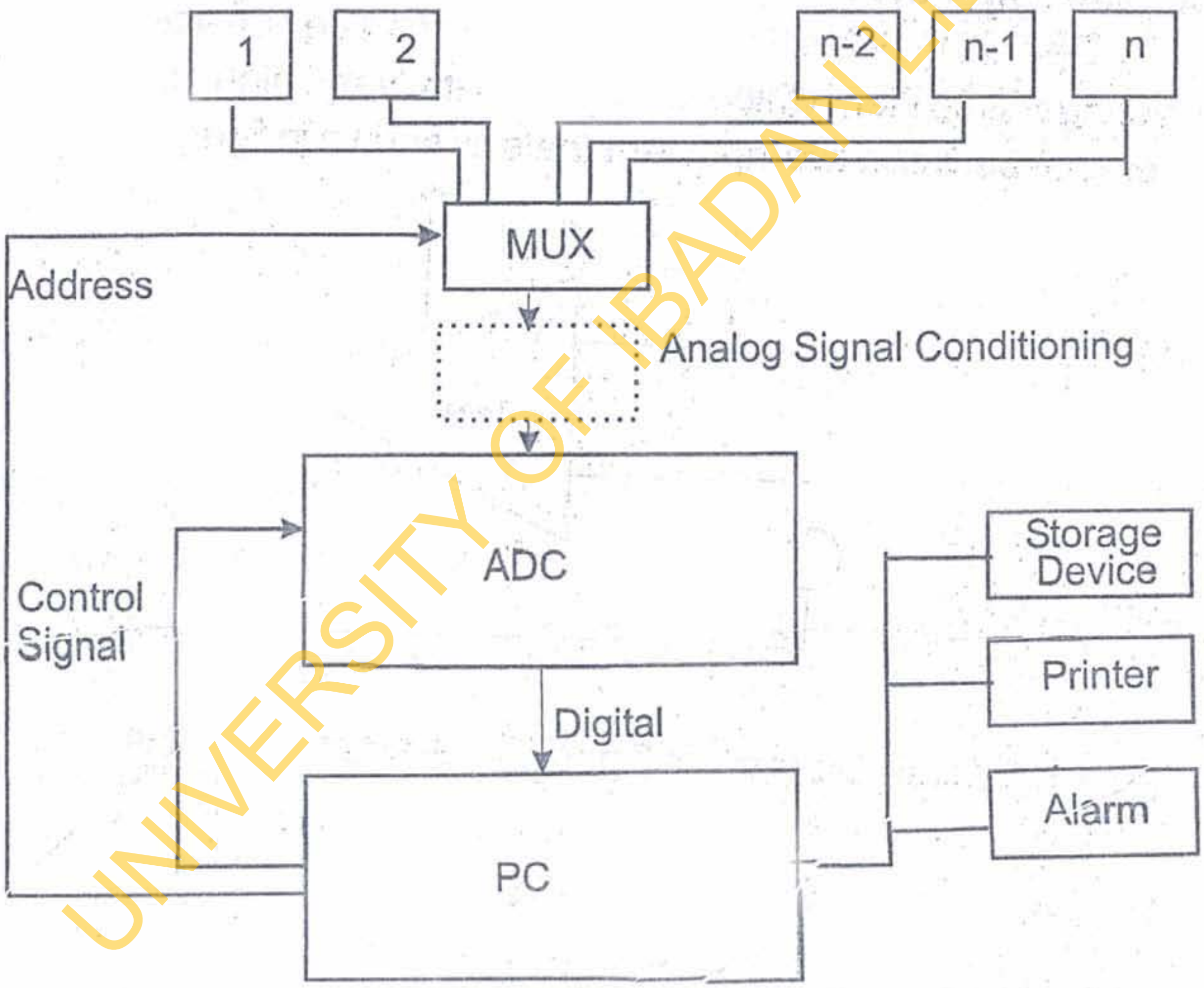


Figure 4.19: Architecture of Typical Data Logging System

CHAPTER FIVE

INTRODUCTION TO OPERATIONAL-AMPLIFIER (OP-AMP)

The need for signals amplifiers in most instrumentation is clear, since the output signal from transducers are usually too small to be used directly for control, recording or display purposes. Therefore, signals from transducers have to be amplified before they could be used for control, recording or display purposes.

OP-AMP CIRCUITS

Operational-Amplifier at its simplest can be considered as a voltage amplifier, which amplifies with very high gain the difference between two input terminals as shown in figure 5.1.

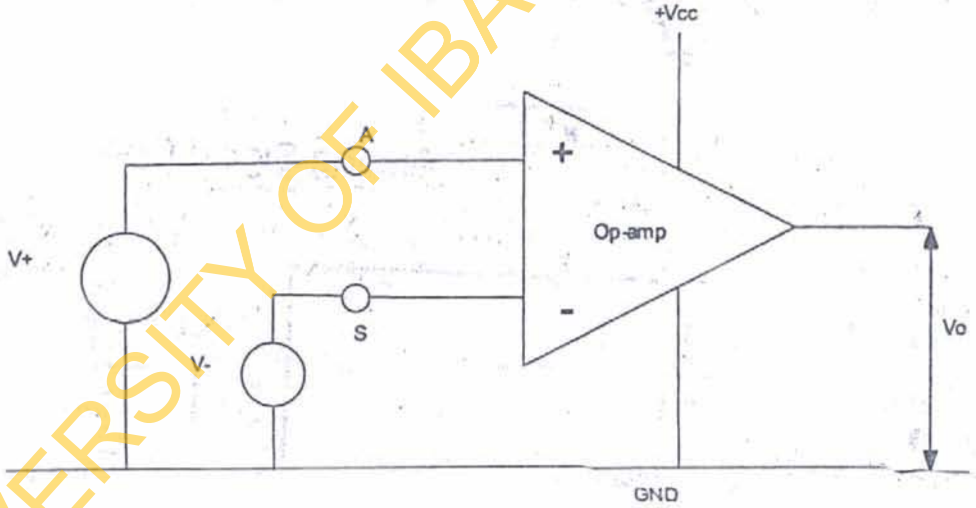


Figure 5.1: Basic Diagram of Operational-Amplifier Circuit.

V_0 = A_v (V+) (V-)
A_v = Differential voltage gain
A = Non-inverting input (V+)
B = Inverting input (V-)

It has a voltage gain ranging from 150 to 20000. This gain depends on the operating conditions of the Op-Amp and the components used to connect the Op-Amp. For example, the output V_0 is limited by the power supply to the Op-Amp.

CHARACTERISTICS OF OP-AMP

i. Infinite gain

ii. Infinite input resistance (The Op-Amp behaves as if it does not draw any current)

iii. Zero output resistance (you can draw as much current as possible from the output)

Due to characteristic (iii), Op-Amp can be use as a Buffer i.e. it can deliver large current without taking current from the transducer (it is assumed that the current the Op-Amp takes up is zero).

Because the gains of Op-Amps are not very stable, Op-Amps are always connected using feedback so that one can replace the Op-Amp with another of different make and voltage gain. The use of negative feed back in Op-Amp circuit is to eliminate the large practical variation in voltage gain of Op-Amps and partly due to other imperfections. Negative feedback is used to reduce the gain to useful and predictable value.

Negative Feedback

Negative feedback is the feeding back of a percentage of the output signal to the input of an operational amplifier. There are three configurations of negative feedback, namely:

1. Single ended feedback connection, which could be inverting or non-inverting
2. Differential Op-Amps connection
3. Instrumentation Op-Amp, which is a variation of the differential Op-Amps.

Single Ended Non-Inverting Amplifier

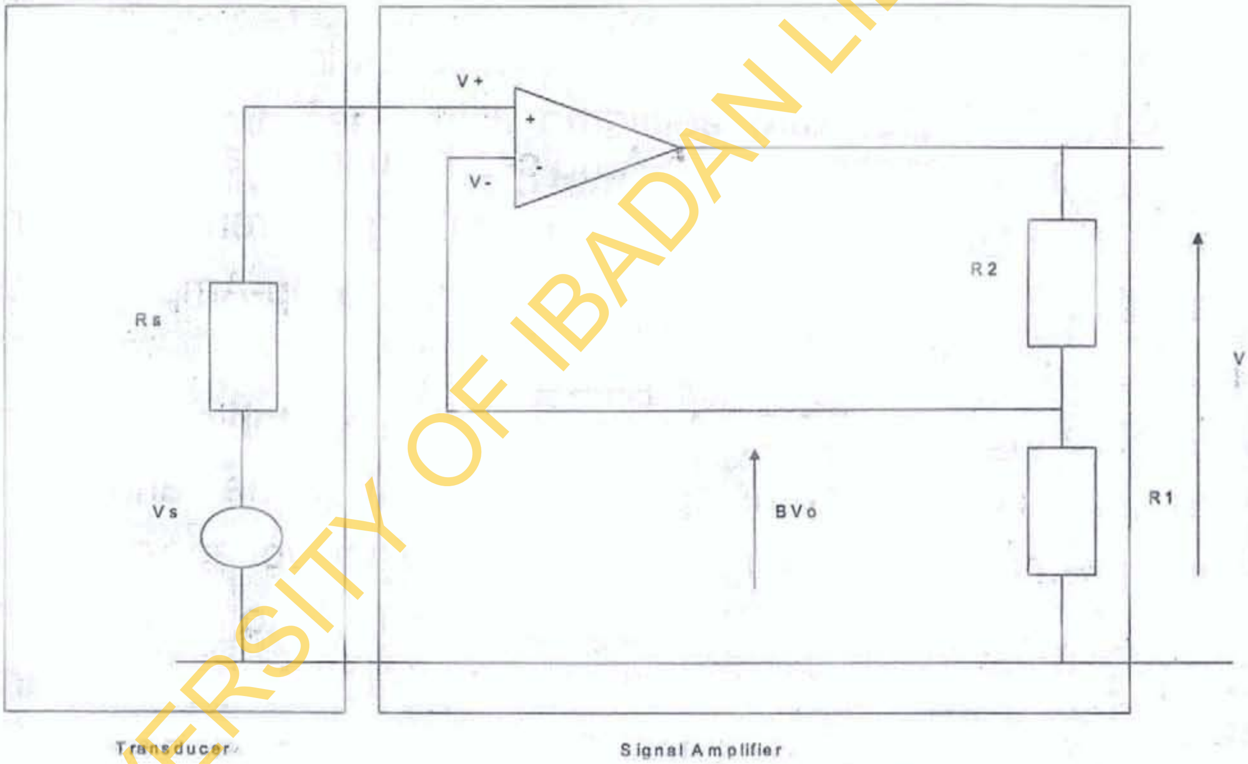


Figure 5.2: Diagram of Single Ended Non-Inverting Amplifier

When one side of the transducer output voltage is connected to the common line of the amplifier voltage, the GND supply, so that there is only a signal source of voltage. This is known as Single Ended Amplifier and we have 2 types namely, Non-inverting and Inverting Single Ended Amplifier.

Let us consider figure 5.2:

Due to infinite input resistance, V+ = Vs and

$$\beta = \frac{R_1}{R_2 + R_1}$$

$$V- = V_0 \frac{R_1}{R_2 + R_1}$$

$$V_0 = A_V(V+ - V-)$$

$$\frac{V_0}{V_s} = \text{Gain} = \frac{output}{input} = \frac{V_0}{V_s}$$

$$V_0 = A_V V_s A_V \beta V_0$$

$$V_0 = (1 + A_V \beta) = A_V V_s$$

$$\frac{V_0}{V_s} = G_V = \frac{A_V}{(1 + A_V \beta)} \quad \beta$$

$$G_V = \frac{A_V}{(1 + A_V \beta)} \text{ (feedback gain)}$$

To understand the effect of negative feedback on closed loop gain Gv, considered what happen if the Op-amp gain Av changes dramatically suppose because of failure, the Op-amp is change and while the old one had a typical gain of 200,000 and the new one has a gain of 20,000. Suppose also that the feedback fraction,

$$\beta = 1/100$$

If the connection is in feedback, the change in the gain will not have any considerable effect on the operation of the circuit (or the output)

With Av = 200000, we have

$$Gv = \frac{A_V}{(1+\beta A_V)} = \frac{20,000}{1+ {}^{1}\!/_{100x200000}} = \frac{200,000}{201} = 99.95$$

With Av = 20000, we have

$$Gv = \frac{A_V}{(1+\beta A_V)} = \frac{20,000}{1+ {}^{1}\!/_{100x200000}} = \frac{200,000}{201} = 99.50$$

The percentage change in gain is 0.45%, which is negligible, compared to what we are going to have in non-feedback configuration. (Where one might have to change all the resistors and the whole configuration in addition to the Op-Amp changed because of a fault with it). Feedback configuration is important because one might not get the exact Op-Amp that is faulty, you might get one with another gain (A_v). Hence feedback configuration is much more desirable.

A ten-fold change in the Op-Amplifier gain results only in 0.45% change in the closed-loop gain, Gv and it can also be shown that Gv is inversely proportional to β .

i.e. $Gv \alpha {}^{1}\!/_{\beta}$

Proof:

$$\text{From, } Gv = \frac{A_V}{(1+\beta A_V)}$$

$$Gv = \frac{1}{\left(\frac{1}{A_V}+\beta\right)}$$

It can be seen from the above equation that Gv is inversely proportional to the feedback fraction â, if differential gain Av is very large and â is not also very small. It therefore implies that the Op-Amp gain Av has little or no effect on feedback Op-amp configuration, it only depends on the feedback fraction a.

Single Ended Inverting Amplifier

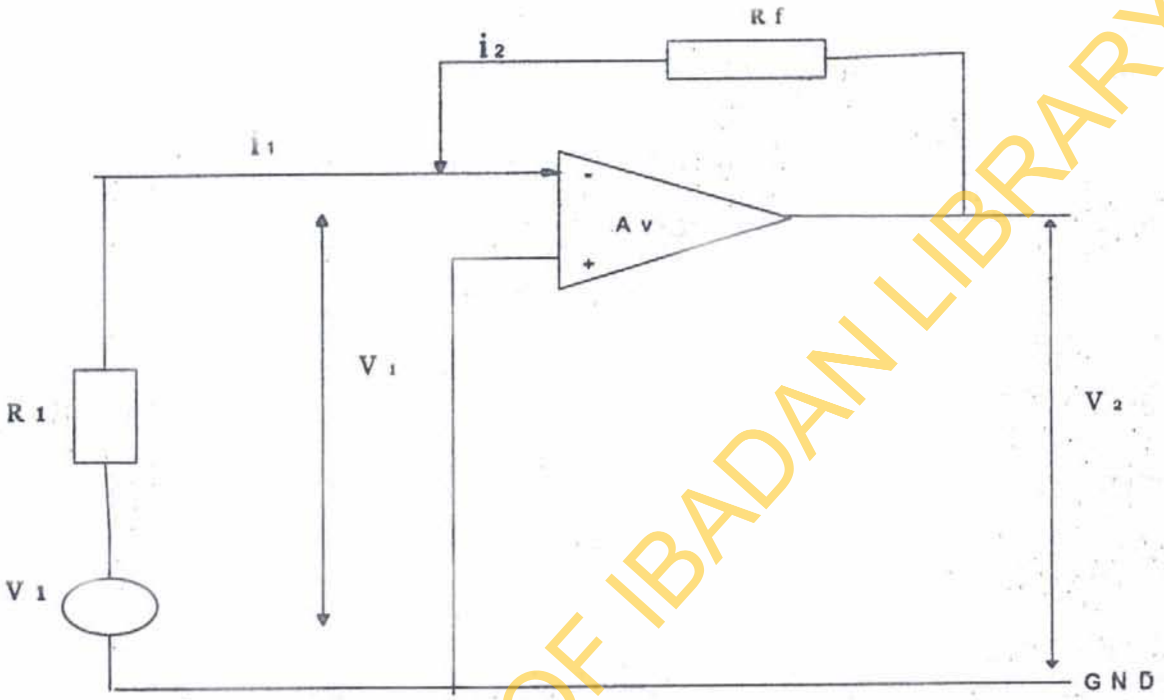


Figure 5.3: Diagram of Single Ended Inverting Amplifier

From the diagram of figure 5.3, if we assume infinite op-amp gain, then we have

$V_- = V_+$

Since, the non-inverting input of the op-amp is connected to the ground,

then $V_+ = 0$, hence V_- is at ground potential.

$i_1 + i_2 = 0$ (due to infinite input resistance of ideal op-amp)

$i_1 = V_1/R1$ and $i_2 = V_2/Rf$

$$V_1/R1 + V_2/Rf = 0$$

Re-arranging this equation to give feedback gain G_V

$$G_V = V_2/V_1 = -Rf/R1$$

The feedback gain is independent of the op-amp gain Av and it is equal to the negative ratio of the feedback resistance Rf to the transducer resistance R1.

DIFFERENTIAL AMPLIFIER

There may be time when the signal to be amplified is the difference between two signals, two halves of a Bridge circuit or output of two transducers such as differential pressure transducer mentioned in chapter four. Differential amplifier will produce an output, which is an amplified version of the difference between two input signal voltages. The diagram of a differential op-amp is shown in figure 5.4. The gain G_V is given as $G_V = -Rf/R1$

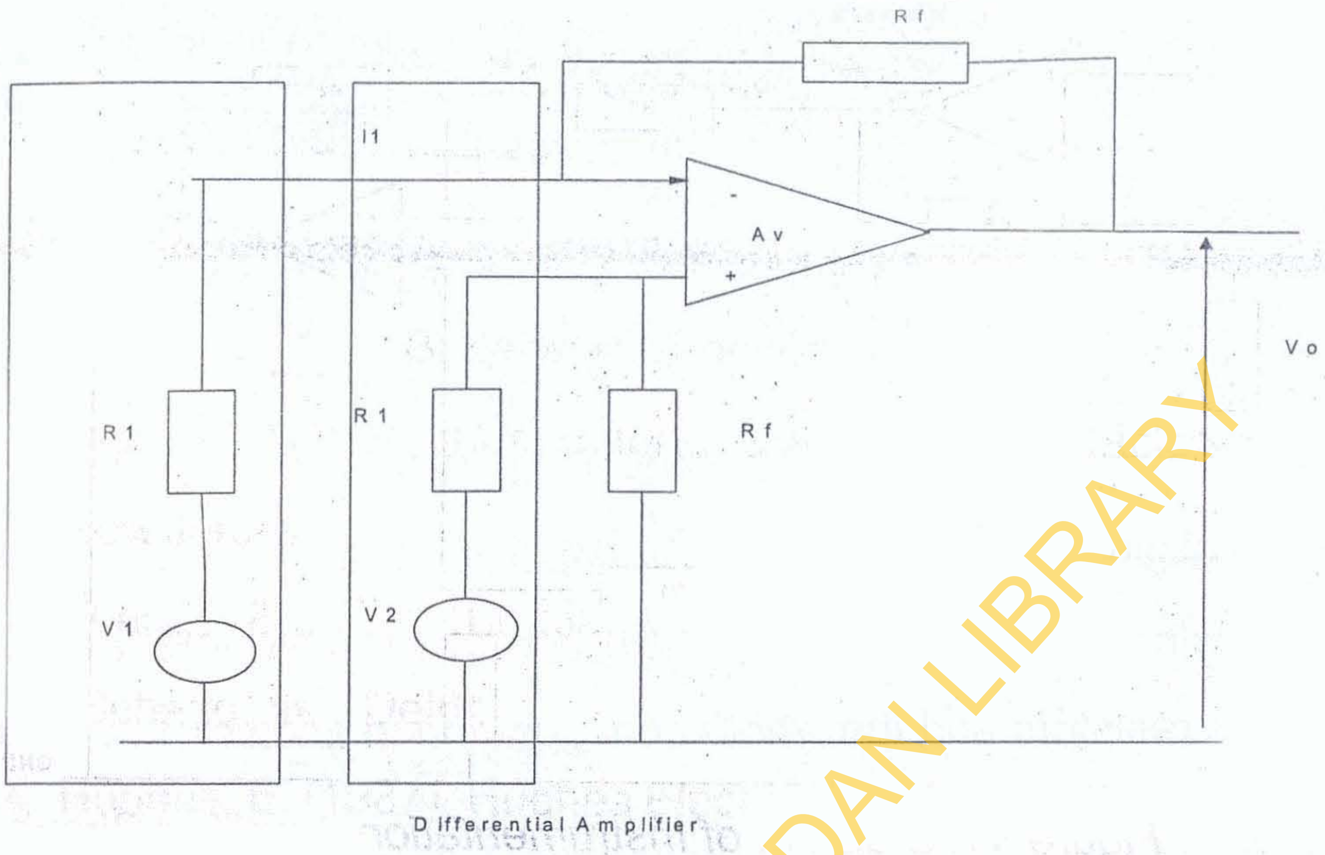


Figure 5.4: Diagram of Differential Amplifier Circuit

INSTRUMENTATION AMPLIFIER

It is a differential amplifier with two pre-amplifier op-amp circuits included. The pre-amplifier op-amp prevents loading of the transducer by the differential amplifier by providing buffering condition. This configuration is widely used in instruments to prevent the instrument from drawing power from the transducer or the test point. An example of instrumentation amplifier is LH 0036 instrumentation amplifier. The circuit diagram of an instrumentation operational amplifier is shown in figure 41.

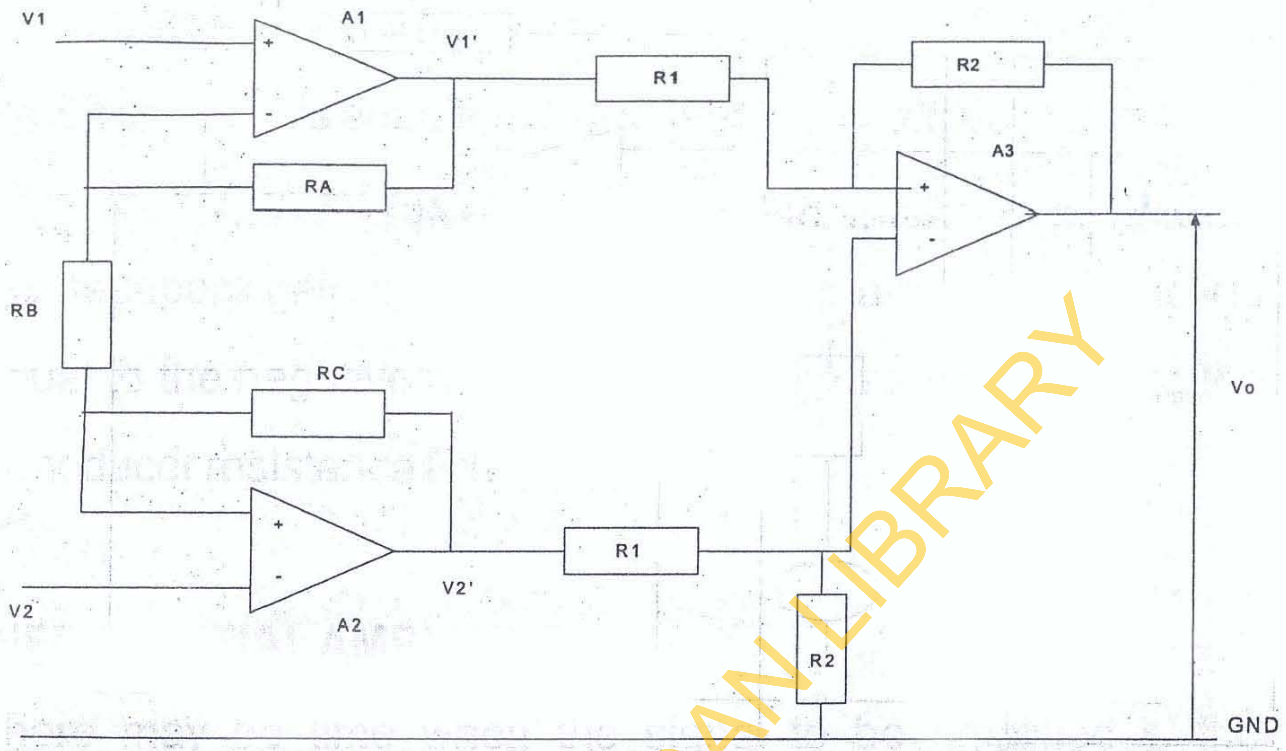


Figure 41: Diagram of Instrumentation Amplifier Circuit

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