MODULE 5

Transducers: Introduction, Electrical Transducer, Resistive Transducer, Resistive position Transducer, Resistance Wire Strain Gauges, Resistance Thermometer, Thermistor, LVDT. Instrumentation Amplifier using Transducer Bridge, Temperature indicators using Thermometer, Analog Weight Scale.
Programmable Logic Controller: Structure, Operation, Relays and Registers.

5.1 Introduction:

A transducer is defined as a device that receives energy from one system and transmits it to another, often in a different form.

Broadly defined, the transducer is a device capable of being actuated by an energizing input from one or more transmission media and in turn generating a related signal to one or more transmission systems. It provides a usable output in response to a specified input measurand, which may be a physical or mechanical quantity, property, or conditions. The energy transmitted by these systems may be electrical, mechanical or acoustical.

The nature of electrical output from the transducer depends on the basic principle involved in the design. The output may be analog, digital or frequency modulated.

Basically, there are two types of transducers, electrical, and mechanical.

5.2 Electrical Transducer

An electrical transducer is a sensing device by which the physical, mechanical or optical quantity to be measured is transformed directly by a suitable mechanism into an electrical voltage/current proportional to the input measurand.

An electrical transducer must have the following parameters:

1. **Linearity:** The relationship between a physical parameter and the resulting electrical signal must be linear.
2. **Sensitivity:** This is defined as the electrical output per unit change in the physical parameter (for example V/°C for a temperature sensor). High sensitivity is generally desirable for a transducer.
3. **Dynamic Range:** The operating range of the transducer should be wide, to permit its use under a wide range of measurement conditions.
4. **Repeatability:** The input/output relationship for a transducer should be predictable over a long period of time. This ensures reliability of operation.
5. **Physical Size:** The Electrical Transducer Definition must have minimal weight & volume, so that its presence in the measurement system does not disturb the existing conditions.

Advantages of Electrical Transducer: The main advantages of electrical transducer (conversion of physical quantity into electrical quantities) are as follows:

1. Electrical amplification and attenuation can be easily done.
2. Mass-inertia effects are minimized.
3. Effects of friction are minimized.
4. The output can be indicated and recorded remotely at a distance from the sensing medium.
5. The output can be modified to meet the requirements of the indicating or controlling units. The signal magnitude can be related in terms of the voltage current. (The analog signal information can be converted in to pulse or frequency information. Since output can be modified, modulated or amplified at will, the output signal can be easily used for recording on any suitable multichannel recording device.)
6. The signal can be conditioned or mixed to obtain any combination with outputs of similar transducers or control signals.
7. The electrical or electronic system can be controlled with a very small power level.
8. The electrical output can be easily used, transmitted and processed for the purpose of measurement.

Electrical transducer can be broadly classified into two major categories,

(i) Active, (ii) Passive.

An **active transducer** generates an electrical signal directly in response to the physical parameter and does not require an external power source for its operation. Active transducers are self-generating devices, which operate under energy conversion principle and generate an equivalent output signal (for example from pressure to charge or temperature to electrical potential).

Typical example of active transducers are piezo electric sensors (for generation of charge corresponding to pressure) and photo voltaic cells (for generation of voltage in response to illumination).

Passive transducer operate under energy controlling principles, which makes it necessary to use an external electrical source with them. They depend upon the change in an electrical parameter (R, L and C).

Typical example are strain gauges (for resistance change in response to pressure), and thermistors (for resistance change corresponding to temperature variations).

Electrical transducer are used mostly to measure non-electrical quantities. For this purpose a detector or sensing element is used, which converts the physical quantity into a displacement. This displacement actuates an electric transducer, which acts as a secondary transducer and give an output that is electrical in nature. This electrical quantity is measured by the standard method used for electrical measurement. The electrical signals may be current, voltage, or frequency; their production is based on R, L and C effects.

A transducer which converts a non-electrical quantity into an analog electrical signal may be considered as consisting of two parts, the sensing element, and the transduction element.

The sensing or detector element is that part of a transducer which responds to a physical phenomenon or to a change in a physical phenomenon.

The transduction element transforms the output of a sensing element to an electrical output. This, in a way, acts as a secondary transducer.

Transducers may be further classified into different categories depending upon the principle employed by their transduction elements to convert physical phenomena into output electrical signals.

The different electrical phenomena employed in the transduction elements of transducers are as follows:

Resistive**,** Photo-emissive**,** Inductive**,** Photo-resistive**,** Capacitive**,** Potentiometric**,** Electro magnetic**,** Thermo-electric**,** Piezo-electric**,** Frequency generating.

5.3 Selecting a Transducer:

The transducer or sensor has to be physically compatible with its intended application. The following should be considered while selecting a transducer.

1. **Operating range:** Chosen to maintain range requirements and good resolution.
2. **Sensitivity:** Chosen to allow sufficient output.
3. **Frequency response and resonant frequency:** Flat over the entire desired range.
4. **Environmental compatibility:** Temperature range, corrosive fluids, pressure, shocks, interaction, size and mounting restrictions.
5. **Minimum sensitivity:** To expected stimulus, other than the measurand.
6. **Accuracy:** Repeatability and calibration errors as well as errors expected due to sensitivity to other stimuli.
7. **Usage and ruggedness:** Ruggedness, both of mechanical and electrical intensities versus size and weight.
8. **Electrical parameters:** Length and type of cable required, signal to noise ratio when combined with amplifiers, and frequency response limitations.

5.4 Resistive Transducer

Resistive Transducer are those in which the resistance changes due to a change in some physical phenomenon. The change in the value of the resistance with a change in the length of the conductor can be used to measure displacement.

Strain gauges work on the principle that the resistance of a conductor or semiconductor changes when strained. This can be used for the measurement of displacement, force and pressure.

The resistivity of materials changes with changes in temperature. This property can be used for the measurement of temperature.

5.3.1 Potentiometer

A resistive potentiometer (pot) consists of a resistance element provided with a sliding contact, called a wiper. The motion of the sliding contact may be translatory or rotational. Some have a combination of both, with resistive elements in the form of a helix, as shown in Fig. 5.1(c). They are known as helipots.

Translatory resistive elements, as shown in Fig. 5.1(a), are linear (straight) devices. Rotational resistive devices are circular and are used for the measurement of angular displacement, as shown in Fig. 5.1(b).

Helical resistive elements are multi turn rotational devices which can be used for the measurement of either translatory or rotational motion. A potentiometer is a passive transducer since it requires an external power source for its operation.

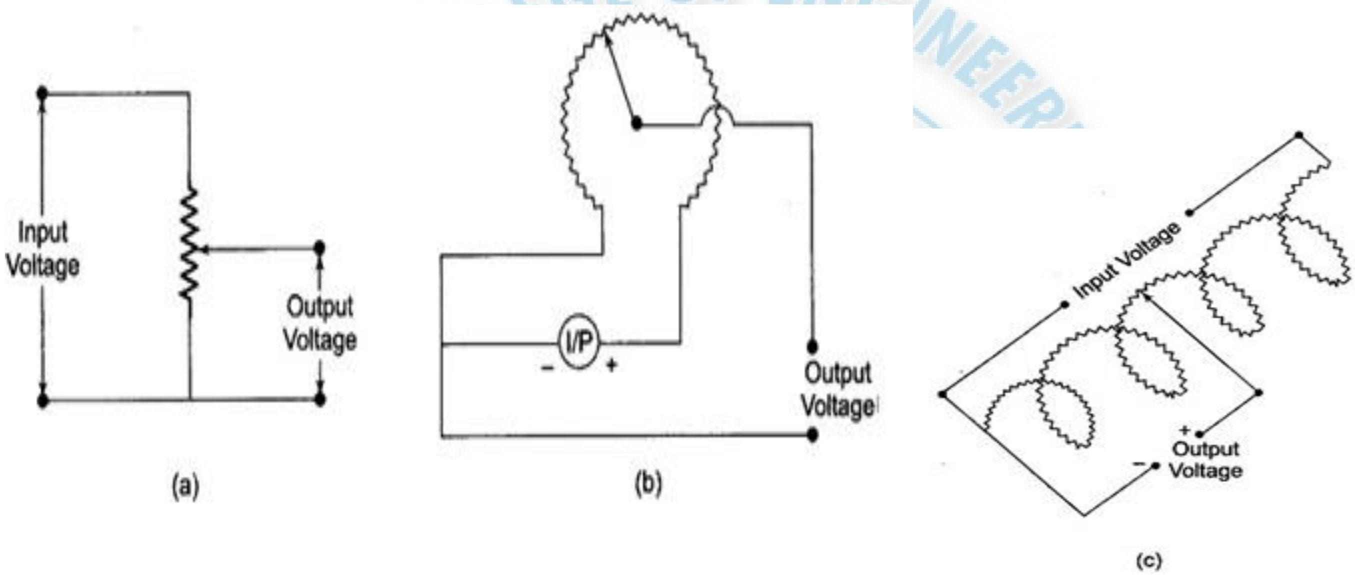

Figure 5.1: (a) Translatory type (b) Rotational type (c) Helipot (Rotational)

Advantage of Potentiometers

1. They are inexpensive.
2. Simple to operate and are very useful for applications where the requirements are not particularly severe.
3. They are useful for the measurement of large amplitudes of displacement.
4. Electrical efficiency is very high, and they provide sufficient output to allow control operations.

Disadvantages of Potentiometers

1. When using a linear potentiometer, a large force is required to move the sliding contacts.
2. The sliding contacts can wear out, become misaligned and generate noise.

5.3.2 Resistance Pressure Transducer

Measurement in the resistive type of transducer is based on the fact that a change in pressure results in a resistance change in the sensing elements. Resistance pressure transducers are of two main types. First, the electromechanical resistance transducer, in which a change of pressure, stress, position, displacement or other mechanical variation is applied to a variable resistor. The other resistance transducer is the strain gauge, where the stress acts directly on the resistance. It is very commonly used for stress and displacement measurement in instrumentation. In the general case of pressure measurement, the sensitive resistance element may take other forms, depending on the mechanical arrangement on which the pressure is caused to act.

Figure 5.2(a) and (b) show two ways by which the pressure acts to influence the sensitive resistance element, i.e. by which pressure varies the resistance element. They are the bellow type, and the diaphragm type.

In each of these cases, the element moved by the pressure change is made to cause a change in resistance. This resistance change can be made part of a bridge circuit and then taken as either ac or dc output signal to determine the pressure indication.

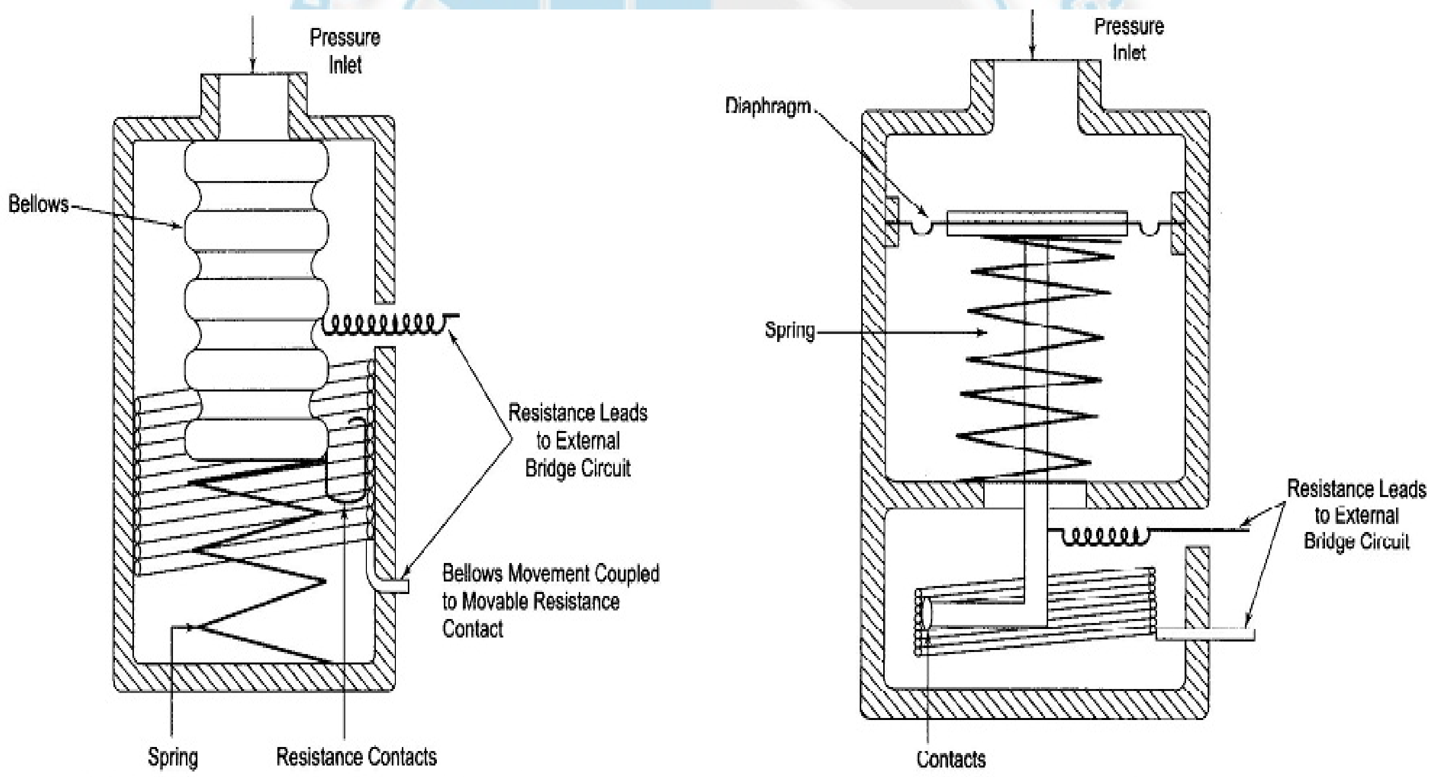

Figure 5.2: (a) Resistance Pressure Transducer (b) Sensitive diaphragm moves the resistance contact.

5.4 Resistive Position Transducer

The principle of the Resistive Position Transducer is that the physical variable under measurement causes a resistance change in the sensing element. (A common requirement in industrial measurement and control work is to be able to sense the position of an object, or the distance it has moved).

One type of displacement transducer uses a resistive element with a sliding contact or wiper linked to the object being monitored or measured. Thus the resistance between the slider and one end of the resistance element depends on the position of the object. Figure 5.3(a) gives the construction of this type of transducer.

Figure 5.3(b) shows a typical method of use. The output voltage depends on the wiper position and is therefore a function of the shaft position. This voltage may be applied to a voltmeter calibrated in cms for visual display.

Considering Fig. 5.3(b), if the circuit is unloaded, the output voltage V_o is a certain fraction of V_t, depending upon the position of the wiper. Therefore,

$$\frac{V_o}{V_t} = \frac{R_2}{R_1 + R_2}$$

When applied to resistive position sensors, this equation shows that output voltage is proportional to R_2, i.e. the position of the wiper of the potentiometer. If the resistance of the transducer is distributed uniformly along the length of travel of the wiper, the resistance is perfectly linear.

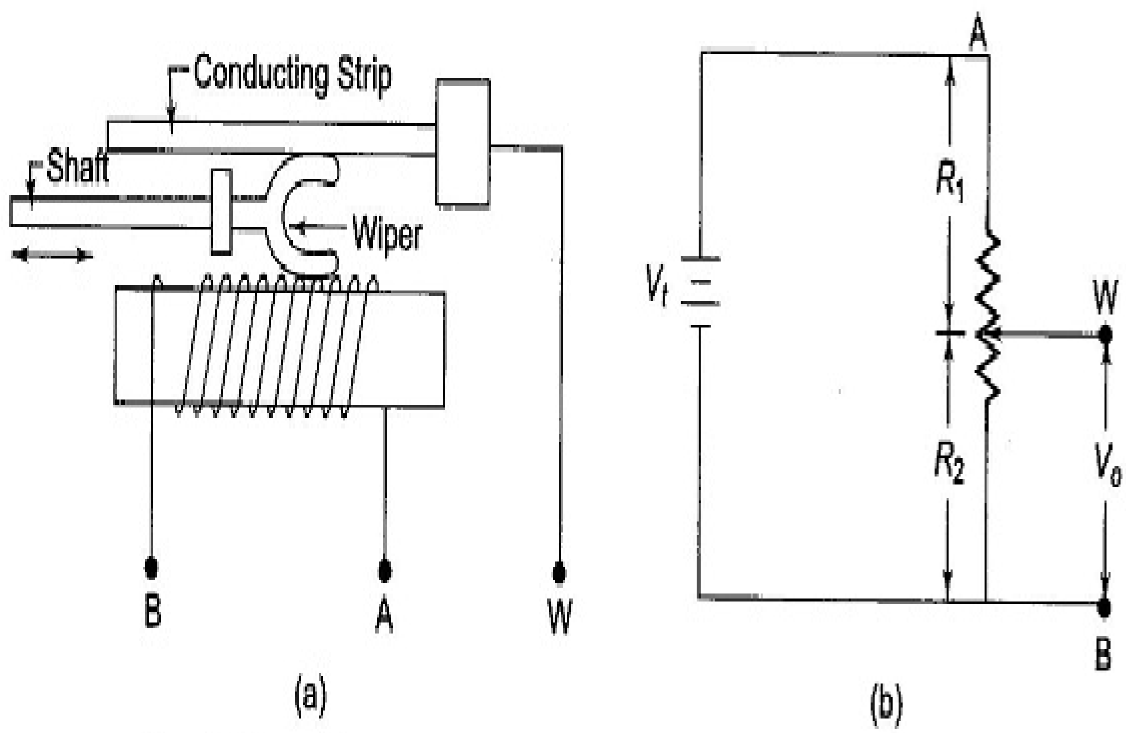

Figure 5.3: (a) Construction of resistance position transducer (b) Typical method

5.5 Strain gauges

The Strain Gauge Factor is an example of a passive transducer that uses the variation in electrical resistance in wires to sense the strain produced by a force on the wires.

Since strain can be measured more easily by using variable resistance transducers, it is a common practice to measure strain instead of stress, to serve as an index of pressure. Such transducers are popularly known as strain gauges.

If a metal conductor is stretched or compressed, its resistance changes on account of the fact that both the length and diameter of the conductor changes. Also, there is a change in the value of the resistivity of the conductor when subjected to strain, a property called the piezo-resistive effect. Therefore, resistance strain gauges are also known as piezo resistive gauges.

Many detectors and transducers, e.g. load cells, torque meters, pressure gauges, temperature sensors, etc. employ Strain Gauge Factor Derivation as secondary transducers.

When a gauge is subjected to a positive stress, its length increases while its area of cross-section decreases. Since the resistance of a conductor is directly proportional to its length and inversely proportional to its area of cross-section, the resistance of the gauge increases with positive strain. The change in resistance value of a conductor under strain is more than for an increase in resistance due to its dimensional changes. This property is called the piezoresistive effect.

The following types of Strain Gauges are the most important.

1. **Wire Strain Gauge**
2. **Foil Strain Gauge**
3. **Semiconductor Strain Gauge**

5.5.1 Resistance Wire Gauge

Resistance wire gauges are used in two basic forms, the unbonded type, and the bonded type.

1. **Unbonded Resistance Wire Strain Gauge:**

An unbonded strain gauge consists of a wire stretched between two points in an insulating medium, such as air. The diameter of the wire used is about 25 µm. The wires are kept under tension so that there is no sag and no free vibration. Unbonded Strain Gauges are usually connected in a bridge circuit. The bridge is balanced with no load applied as shown in Fig. 5.4.

When an external load is applied, the resistance of the Strain Gauge Factor Derivation changes, causing an unbalance of the bridge circuit resulting in an output voltage. This voltage is proportional to the strain. A displacement of the order of 50µm can be detected with these strain gauges.

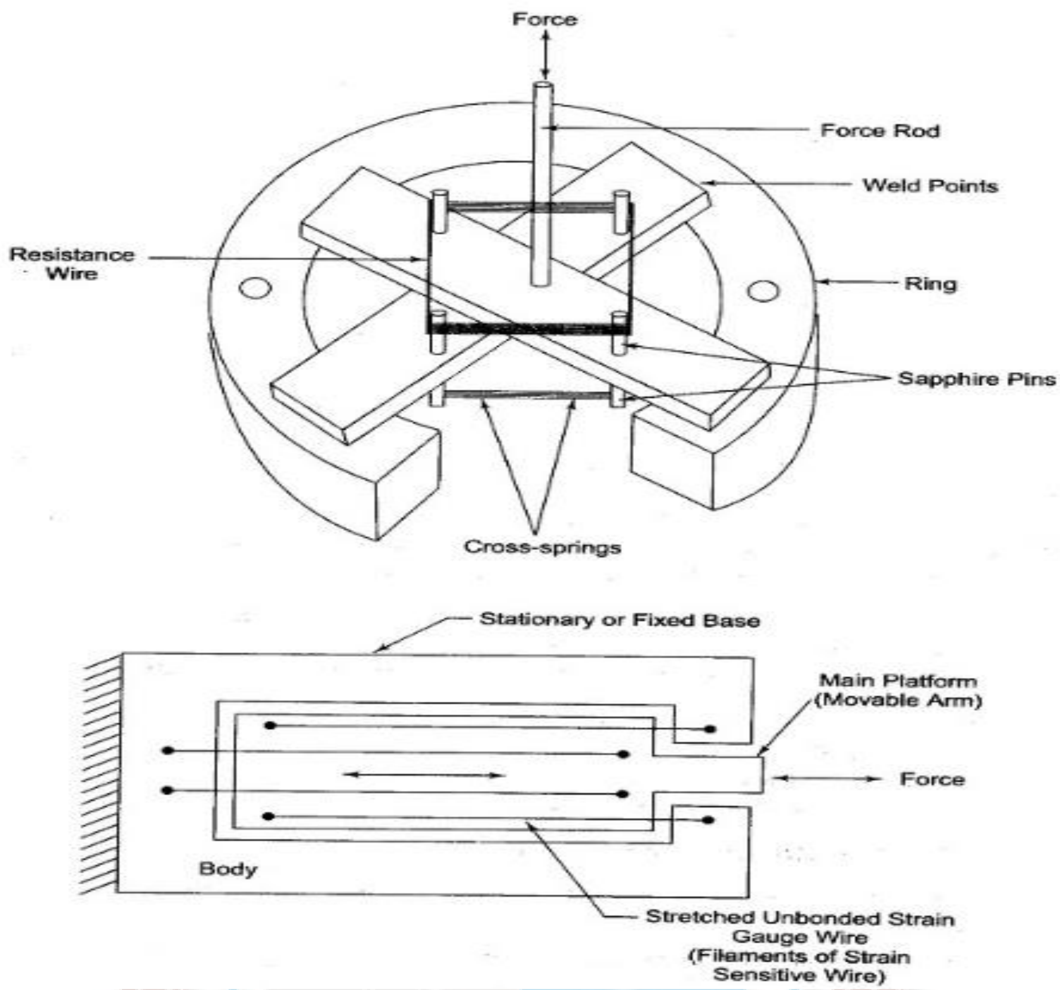

Figure 5.4: Unbonded strain gauge

2. **Bonded Resistance Wire Strain Gauge:**

A metallic bonded Strain Gauge Derivation is shown in Fig. 5.5. A fine wire element about 25 µm (0.025 in.) or less in diameter is looped back and forth on a carrier (base) or mounting plate, which is usually cemented to the member undergoing stress. The grid of fine wire is cemented on a carrier which may be a thin sheet of paper, bakelite, or teflon. The wire is covered on the top with a thin material, so that it is not damaged mechanically. The spreading of the wire permits uniform distribution of stress. The carrier is then bonded or cemented to the member being studied. This permits a good transfer of strain from carrier to wire.

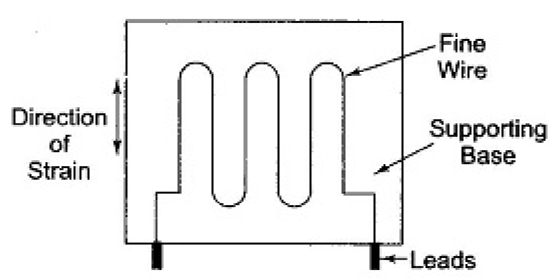

Figure 5.5: Bonded Resistance Wire Strain Gauge

A tensile stress tends to elongate the wire and thereby increase its length and decrease its cross-sectional area. The combined effect is an increase in resistance, as seen from the following equation

$$R = \frac{\rho \times l}{A}$$

where,

ρ = the specific resistance of the material in Ωm.

l = the length of the conductor in m

A = the area of the conductor in m^2

As a result of strain, two physical parameters are of particular interest.

1. The change in gauge resistance.
2. The change in length.

The measurement of the sensitivity of a material to strain is called the gauge factor (GF). It is the ratio of the change in resistance ΔR/R to the change in the length $\Delta l/l$

$$GF\ (K) = \frac{\Delta R/R}{\Delta l/l} \qquad (5.1)$$

where

K= gauge factor

Δ R= the change in the initial resistance in Ω's

R = the initial resistance in Ω (without strain)

Δ l= the change in the length in m

l = the initial length in m (without strain)

Since strain is defined as the change in length divided by the original length,

i.e. $$\sigma = \frac{\Delta l}{l}$$

Eq. (5.1) can be written as

$$K = \frac{\Delta R/R}{\sigma} \qquad (5.2)$$

where σ is the strain in the lateral direction.

The resistance of a conductor of uniform cross-section is

$$R = \rho \frac{\text{length}}{\text{area}}$$

$$R = \rho \frac{l}{\pi r^2}$$

$$r = \frac{d}{2} \quad \therefore \quad r^2 = \frac{d^2}{4}$$

$$R = \rho \frac{l}{\pi d^2/4} = \rho \frac{l}{\pi/4\, d^2} \tag{5.3}$$

where

ρ= specific resistance of the conductor

l = length of conductor

d= diameter of conductor

When the conductor is stressed, due to the strain, the length of the conductor increases by Δl and the simultaneously decreases by Δd in its diameter. Hence the resistance of the conductor can now be written as

$$R_s = \rho \frac{(l + \Delta l)}{\pi/4(d - \Delta d)^2} = \frac{\rho(l + \Delta l)}{\pi/4\,(d^2 - 2d\,\Delta d + \Delta d^2)}$$

Since Δd is small, Δd^2 can be neglected

$$R_s = \frac{\rho\,(l + \Delta l)}{\pi/4\,(d^2 - 2d\,\Delta d)}$$

$$= \frac{\rho\,(l + \Delta l)}{\pi/4 d^2 \left(1 - \frac{2\Delta d}{d}\right)} = \frac{\rho l\,(1 + \Delta l/l)}{\pi/4 d^2 \left(1 - \frac{2\Delta d}{d}\right)} \tag{5.4}$$

Now, Poisson's ratio μ is defined as the ratio of strain in the lateral direction to strain in the axial direction, that is,

$$\mu = \frac{\Delta d/d}{\Delta l/l} \tag{5.5}$$

$$\frac{\Delta d}{d} = \mu \frac{\Delta l}{l} \tag{5.6}$$

Substituting for Δd/d from Eq. (5.6) in Eq. (5.4), we have

$$R_s = \frac{\rho l\,(1 + \Delta l/l)}{(\pi/4)\,d^2\,(1 - 2\,\mu\,\Delta l/l)}$$

Rationalizing, we get

$$R_s = \frac{\rho l\,(1+\Delta l/l)}{(\pi/4)\,d^2\,(1-2\mu\Delta l/l)}\,\frac{(1+2\mu\Delta l/l)}{(1+2\mu\Delta l/l)}$$

$$R_s = \frac{\rho l}{(\pi/4)\,d^2}\left[\frac{(1+\Delta l/l)}{(1-2\mu\Delta l/l)}\,\frac{(1+2\mu\Delta l/l)}{(1+2\mu\Delta l/l)}\right]$$

$$R_s = \frac{\rho l}{(\pi/4)\,d^2}\left[\frac{1+2\mu\Delta l/l+2\Delta l/l+2\mu\,\Delta l/e\,\Delta l/l}{1-4\mu^2\,(\Delta l/l)^2}\right]$$

$$R_s = \frac{\rho l}{(\pi/4)\,d^2}\left[\frac{1+2\mu\Delta l/l+\Delta l/l+2\mu\Delta l^2/l^2}{1-4\mu^2\,\Delta l^2/l^2}\right]$$

Since Δl is small, we can neglect higher powers of Δl.

$$R_s = \frac{\rho l}{(\pi/4)\,d^2}\,[1+2\,\mu\,\Delta l/l+\Delta l/l]$$

$$R_s = \frac{\rho l}{(\pi/4)\,d^2}\,[1+(2\,\mu+1)\,\Delta l/l]$$

$$R_s = \frac{\rho l}{(\pi/4)\,d^2}\,[1+(1+2\,\mu)\,\Delta l/l]$$

$$R_s = \frac{\rho l}{(\pi/4)\,d^2}+\frac{\rho l}{(\pi/4)\,d^2}\,(\Delta l/l)\,(1+2\,\mu)$$

Since from Eq. (5.3),

$$R = \frac{\rho l}{(\pi/4)\,d^2}$$

$$R_s = R + \Delta R \qquad (5.7)$$

$$\Delta R = \frac{\rho l}{(\pi/4)\,d^2}\,(\Delta l/l)\,(1+2\,\mu)$$

The gauge factor will now be

$$K = \frac{\Delta R/R}{\Delta l/l} = \frac{(\Delta l/l)(1+2\mu)}{\Delta l/l}$$

$$= 1 + 2\,\mu$$

$$K = 1 + 2\,\mu \qquad (5.8)$$

5.6 Resistance Thermometer Transducer

The resistance of a conductor changes when its temperature is changed. This property is utilized for the measurement of temperature. The Resistance Thermometer Transducer is an instrument used to measure electrical resistance in terms of temperature, i.e. it uses the change in the electrical resistance of the conductor to determine the temperature.

The main part of a resistance thermometer is its sensing element. The characteristics of the sensing element determines the sensitivity and operating temperature range of the instrument. There are three common types of temperature sensitive resistive elements in use, the wire wound resistance, the thermistor and the PTC semiconductor resistance.

The sensing element may be any material that exhibits a relatively large resistance change with change in temperature. Also, the material used should be stable in its characteristics, i.e. neither its resistance nor its temperature coefficient of resistance should undergo permanent change with use or age.

To maintain the calibration of a resistance thermometer, it is necessary to consider its stability. The need for stability frequently limits the temperature range over which the sensing element may be used. The speed with which a resistive element responds to changes in temperature is important when the measured temperature is subjected to rapid variations. The smaller a given sensing element, the less heat required to raise its temperature, and the faster its response.

Platinum, nickel and copper are the metals most commonly used to measure temperature. The resistivity of platinum tends to increase less rapidly at higher temperatures than for other metals, hence it is a commonly used material for resistance thermometers. The temperature range over which platinum has stability is — 260-1100°C.

Figure 5.6(a) shows an industrial platinum resistance thermometer. The changes in resistance caused by changes in temperature are detected by a Wheatstone bridge, as shown in Fig. 5.6(b). Hence, the temperature sensing element, which may be nickel, copper or platinum contained in a bulb or well, along with the balancing bridge.

The sensing element R_s is made of a material having a high temperature coefficient, and R_1, R_2, and R_5 are made of resistances that are practically constant under normal temperature changes.

When no current flows through the galvanometer, the normal principle of Wheatstone's bridge states the ratio of resistance is

$$\frac{R_1}{R_2} = \frac{R_s}{R_5}$$

In normal practice, the sensing element is away from the indicator, and its leads have a resistance, say R_3**,** R_4**.**Therefore,

$$\frac{R_1}{R_2} = \frac{R_3 + R_s + R_4}{R_5}$$

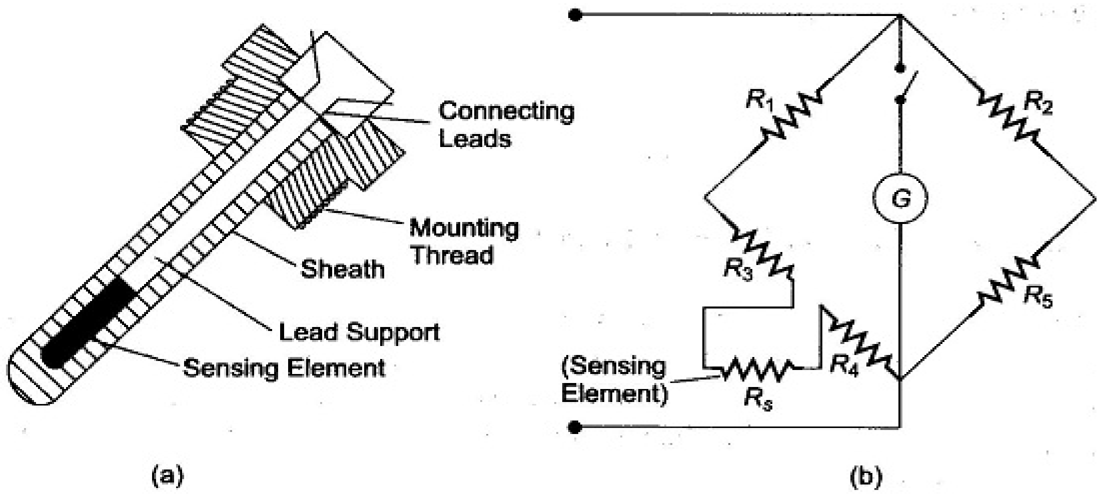

Figure 5.6: (a) Industrial Platinum resistance thermometer (b) Bridge circuit

Now it resistance R_s changes, balance cannot be maintained and the galvanometer shows a deflection, which can be calibrated to give a suitable temperature scale.

Advantages of Resistance Thermometer Transducer

- The measurement of temperature by the electrical resistance method has the following advantages and characteristics.
- The measurement is very accurate.
- It has a lot of flexibility with regard to choice of measuring equipment.
- Indicators, recorders or controllers can also be operated.
- More than one resistance element can be clubbed to the same indicating/ recording instrument.
- The temperature sensitive resistance element can be easily installed and
- The accuracy of the measuring circuit can be easily checked by substituting a standard resistor for the resistive element.
- Resistive elements can be used to measure differential temperature.
- Resistance thermometers have a wide working range without loss of accuracy, and can be used for temperature ranges (-200°C to + 650°C).
- They are best suited for remote indication.
- The resistive element response time is of the order of 2 to lOs
- The limits of error of a resistive element are ± 0.25% of the scale reading.
- The size of the resistive element may be about 6 — 12 mm in diameter and 12 — 75 mm in length.
- Extremely accurate temperature sensing.
- No necessity of temperature compensation.
- Stability of performance over long periods of time.

Limitations of Resistance Thermometer Transducer

- High cost
- Need for bridge circuit and power source
- Possibility of self-heating
- Large bulb size, compared to a thermocouple

5.7 Thermistor

The electrical resistance of most materials changes with temperature. By selecting materials that are very temperature sensitive, devices that are useful in temperature control circuits and for temperature measurements can be made.

Thermistor (THERMally sensitive resISTOR) are non-metallic resistors (semiconductor material), made by sintering mixtures of metallic oxides such as manganese, nickel, cobalt, copper and uranium.

Thermistors have a Negative Temperature Coefficient (NTC), i.e. resistance decreases as temperature rises. Figure 5.7 shows a graph of resistance vs temperature for a thermistor. The resistance at room temperature (25°C) for typical commercial unit's ranges from 100 Ω to 10 Ω. They are suitable for use only up to about 800°C. In some cases, the resistance of thermistors at room temperature may decrease by 5% for each 1°C rise in temperature. This high sensitivity to temperature changes makes the thermistor extremely useful for precision temperature measurements, control and compensation.

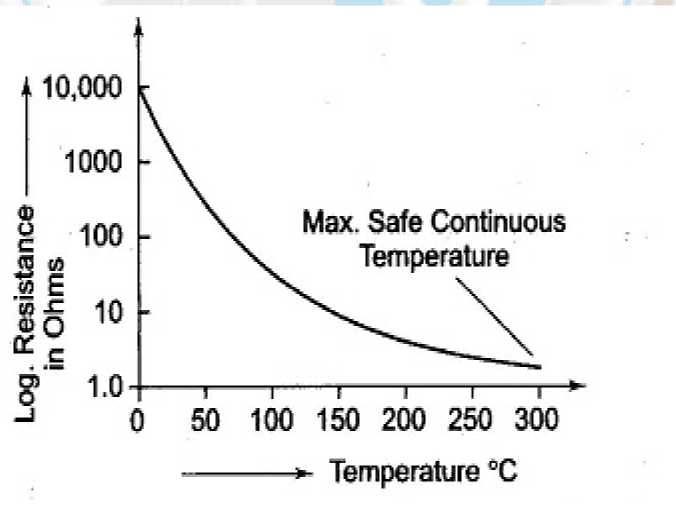

Figure 5.7: Resistance vs temperature graph of a thermistor

The smallest thermistors are made in the form of beads. Some are as small as 0.15 mm (0.006 in.) in diameter. These may come in a glass coating or sealed in the tip of solid glass probes. Glass probes have a diameter of about 2.5 mm and a length which varies from 6-50 mm. The probes are used for measuring the temperature of liquids. The resistance ranges from 300 Ω to 100 Ω. Where greater power dissipations is required, thermistors may be obtained in disc, washer or rod forms.

Disc thermistors about 10 mm in diameter, either self-supporting or mounted on a small plate, are mainly used for temperature control. These thermistors are made by pressing thermistors material under several tons of pressure in a round die to produce flat pieces 1.25 — 25 mm in diameter and 0.25 — 0.75 mm thick, having resistance values of 1 Ω to 1 MΩ. These are sintered and coated with silver on two flat surfaces.

Washer thermistors are made like disc thermistors, except that a hole is formed in the center in order to make them suitable for mounting on a bolt. Rod thermistors are extruded through dies to make long cylindrical units of 1.25, 2.75, and 4.25 mm in diameter and 12.5 — 50 min long. Leads are attached to the end of the rods. Their resistance usually varies from 1 — 50 Ω

The advantage of rod thermistors over other configurations is the ability to produce high resistance units with moderately high power handling capability.

Thermistors can be connected in series/parallel combinations for applications requiring increased power handling capability. High resistance units find application in measurements that employ low lead wires or cables.

Thermistors are chemically stable and can be used in nuclear environments. Their wide range of characteristics also permits them to be used in limiting and regulation circuits, as time delays, for integration of power pulses, and as memory units.

Typical thermistor configurations are as shown in Fig. 5.8(a). Figure 5.8(b) shows a bush type thermistor.

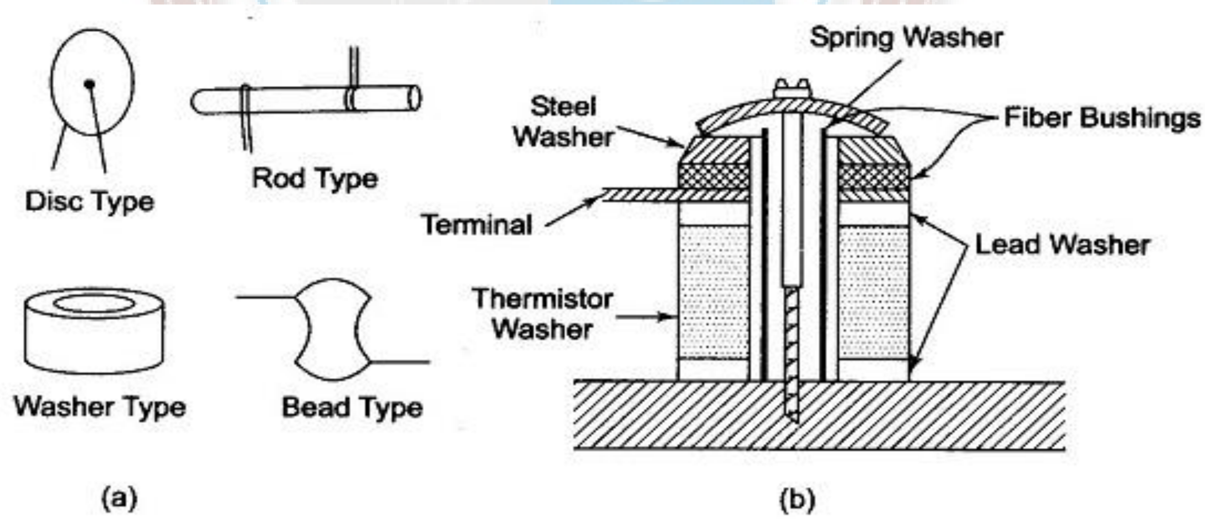

Figure 5.8: (a) Various configurations of thermistor (b) Bush type thermistor

A thermistor in one arm of a Wheatstone bridge provides precise temperature information. Accuracy is limited, in most applications, only by the readout devices. Thermistors are non-linear devices over a temperature range, although now units with better than 0.2% linearity over the 0-100°C temperature range are available. The typical sensitivity of a thermistor is approximately 3 mV/°C at 200°C.

Advantages of Thermistor Circuit

1. Small size and low cost.
2. Fast response over narrow temperature range.
3. Good sensitivity in the NTC region.
4. Cold junction compensation not required due to dependence of resistance on absolute temperature.
5. Contact and lead resistance problems not encountered due to large R_{th} (resistance).

Limitations of Thermistor Circuit

1. Non-linearity in resistance vs temperature characteristics.
2. Unsuitable for wide temperature range.
3. Very low excitation current to avoid self-heating.
4. Need of shielded power lines, filters, etc. due to high resistance.

5.8 Linear Variable Differential Transducer (LVDT)

The differential transformer is a passive inductive transformer. It is also known as a Linear Variable Differential Transducer (LVDT). The basic construction is as shown in Fig. 5.9.

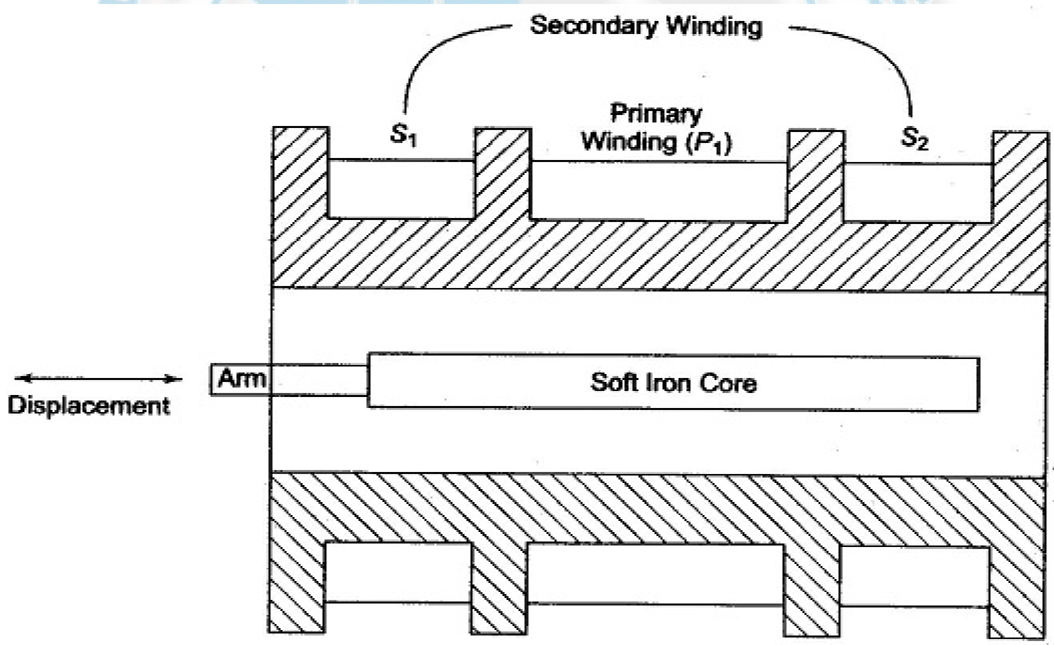

Figure 5.9: Construction of a Linear Variable Differential Transducer

The transformer consists of a single primary winding P_1 and two secondary windings S_1 and S_2 wound on a hollow cylindrical former. The secondary windings have an equal number of turns and are identically placed on either side of the primary windings. The primary winding is connected to an ac source.

A movable soft iron core slides within the hollow former and therefore affects the magnetic coupling between the primary and the two secondaries.

The displacement to be measured is applied to an arm attached to the soft iron core. (In practice, the core is made up of a nickel-iron alloy which is slotted longitudinally to reduce eddy current losses.)

When the core is in its normal (null) position, equal voltages are induced in the two secondary windings. The frequency of the ac applied to the primary winding ranges from 50 Hz to 20 kHz.

The output voltage of the secondary windings S_1 is E_{s1} and that of secondary winding S_2 is E_{s2}.

In order to convert the output from S_1 to S_2 into a single voltage signal, the two secondaries S_1 and S_2 are connected in series opposition, as shown in Fig. 5.10.

Hence the output voltage of the transducer is the difference of the two voltages. Therefore the differential output voltage $E_o=E_{s1}\sim E_{s2}$.

When the core is at its normal position, the flux linking with both secondary windings is equal, and hence equal emfs are induced in them. Hence, at null position $E_{s1} = E_{s2}$. Since the output voltage of the transducer is the difference of the two voltages, the output voltage E_o is zero at null position.

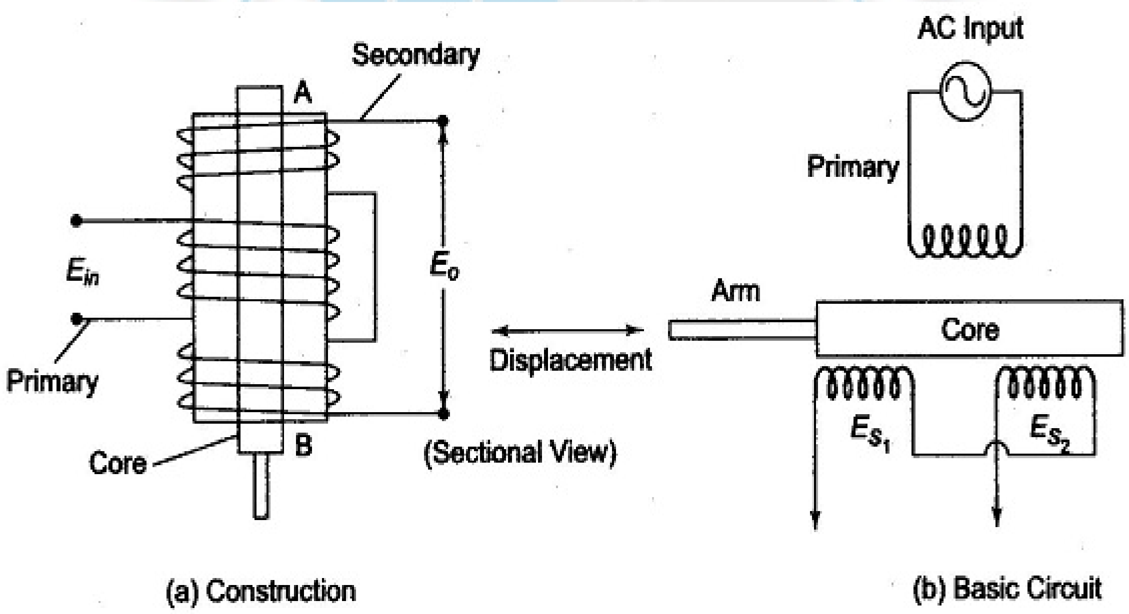

Figure 5.10: Secondary winding connected for differential ouput

Now, if the core is moved to the left of the null position, more flux links with winding S_1 and less with winding S_2. Hence, output voltage E_{s1} of the secondary winding S_1 is greater than E_{s2} . The magnitude of the output voltage of the secondary is then $E_{s1} — E_{s2}$, in phase with E_{s1} (the output voltage of secondary winding S_1). Similarly, if the core is moved to the right of the null position, the flux linking with winding S_2 becomes greater than that linked with winding S_1. This results in E_{s2} becoming larger than E_{s1}. The output voltage in this case is $E_o = E_{s2} — E_{s1}$ and is in phase with E_{s2}.

The amount of voltage change in either secondary winding is proportional to the amount of movement of the core. Hence, we have an indication of the amount of linear motion. By noting which output is increasing or decreasing, the direction of motion can be determined. The output ac voltage inverts as the core passes the centre position. The farther the core moves from the centre, the greater the difference in value between E_{s1} and E_{s2} and consequently the greater the value of E_o. Hence, amplitude is function of distance the core has moved, and the polarity or phase indicates the direction of motion, as shown in Fig. 5.11.

As the core is moved in one direction from the null position, the difference voltage, i.e. the difference of the two secondary voltages increases, while maintaining an in-phase relation with the voltage from the input source. In the other direction from the null position, the difference voltage increases but is 180° out of phase with the voltage from the source.

By comparing the magnitude and phase of the difference output voltage with that of the source, the amount and direction of the movement of the core and hence of the displacement may be determined.

The amount of output voltage may be measured to determine the displacement. The output signal may also be applied to a recorder or to a controller that can restore the moving system to its normal position.

The output voltage of an Linear Variable Differential Transducer is a linear function of the core displacement within a limited range of motion (say 5 mm from the null position).

Figure 5.11(d) shows the variation of the output voltage against displacement for various position of the core. The curve is practically linear for small displacements (up to 5 mm). Beyond this range, the curve starts to deviate.

The diagram in Figs 5.11(a), (b) and (c) shows the core of an Linear Variable Differential Transducer at three different positions.

In Fig. 5.11(b), the core is at 0, which is the central zero or null position. Therefore, $E_{s1} = E_{s2}$, and $E_o = 0$. When the core is moved to the left, as in Fig. 5.11(a) and is at A, E_{s1} is more than E_{s2} and E_o is positive. This movement represents a positive value and therefore the phase angle, is $\Phi = 0°$.

When the core is moved to the right towards B, E_{s2} is greater than E_{s1} and hence E_o is negative. Therefore, S_2 the output voltage is 180° out of phase with the voltage which is obtained when the core is moved to the left. The characteristics are linear from 0-A and 0-B, but after that they become non-linear.

One advantage of a Linear Variable Differential Transducer over, the inductive bridge type is that it produces higher output voltage for small changes in core position. Several commercial models that produce 50 mV/mm to 300 mV/mm are available. 300 mV/mm implies that a 1 mm displacement of the core produces a voltage output of 300 mV.

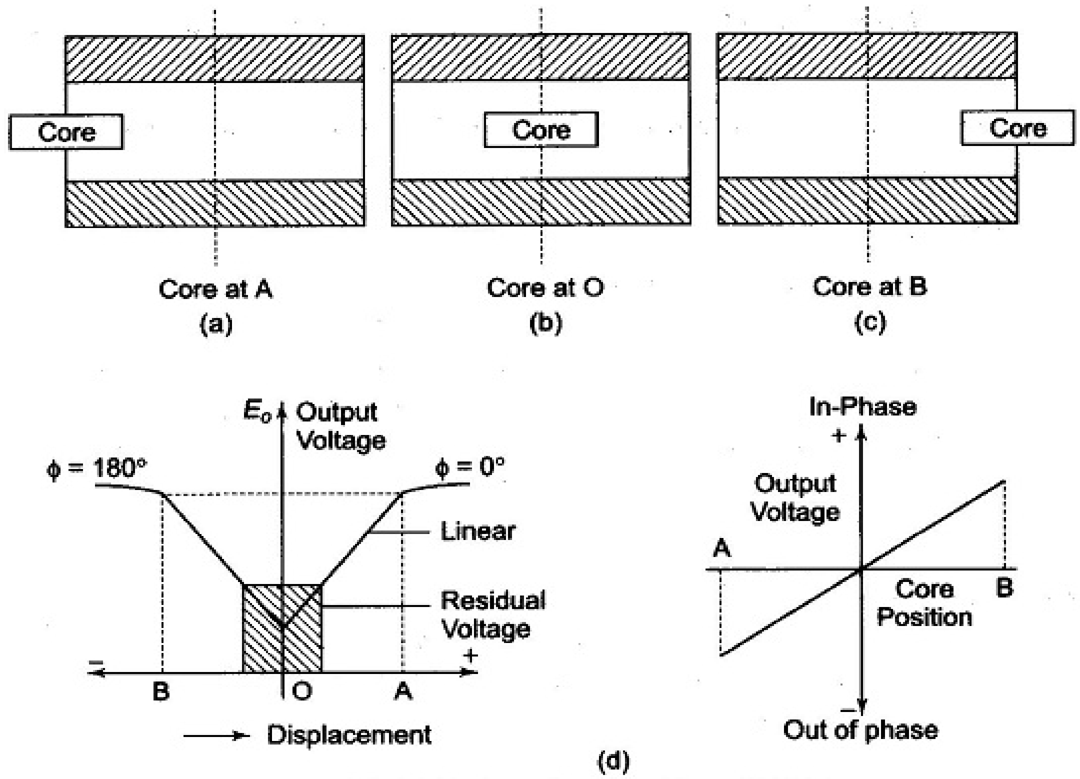

Figure 5.11: (a), (b), (c): Various core position of LVDT
(d) Variations of output voltage vs displacement

Linear Variable Differential Transducer are available with ranges as low as ± 0.05 in. to as high as ± 25 in. and are sensitive enough to be used to measure displacements of well below 0.001 in. They can be obtained for operation at temperatures as low as — 265°C and as high as + 600°C and are also available in radiation resistance designs for nuclear operations.

Advantages of Linear Variable Differential Transducer

1. **Linearity:** The output voltage of this transducer is practically linear for displacements upto 5 mm (a linearity of 0.05% is available in commercial LVDTs).
2. **Infinite resolution:** The change in output voltage is stepless. The effective resolution depends more on the test equipment than on the
3. **High output:** It gives a high output (therefore there is frequently no need for intermediate amplification devices).
4. **High sensitivity:** The transducer possesses a sensitivity as high as 40 V/mm.
5. **Ruggedness:** These transducers can usually tolerate a high degree of vibration and shock.
6. **Less friction:** There are no sliding contacts.
7. **Low hysteresis:** This transducer has a low hysteresis, hence repeatability is excellent under all conditions.
8. **Low power consumption:** Most LVDTs consume less than 1 W of power.

Disadvantages of Linear Variable Differential Transducer

1. Large displacements are required for appreciable differential output.
2. They are sensitive to stray magnetic fields (but shielding is possible).
3. The receiving instrument must be selected to operate on ac signals, or a demodulator network must be used if a dc output is required.
4. The dynamic response is limited mechanically by the mass of the core and electrically by the applied voltage.
5. Temperature also affects the transducer.

5.9 Instrumentation Amplifier Using Transducer Bridge

Figure 5.12 shows a simplified circuit of a Differential Instrumentation Amplifier Transducer Bridge. In this circuit a resistive transducer (whose resistance changes as a function of some physical energy) is connected to one arm of the bridge.

Let R_T be the resistance of the transducer and ΔR the change in resistance of the resistive transducer. Hence the total resistance of the transducer is ($R_T \pm \Delta R$). The condition for bridge balance is $V_b = V_a$, i.e. the bridge is balanced when $V_b = V_a$, or when

$$\frac{R_B(E)}{R_B + R_C} = \frac{R_A(E)}{R_A + R_T}$$

Therefore, $$\frac{R_c}{R_B} = \frac{R_T}{R_A}$$

The bridge is balanced at a desired reference condition, which depends on the specific value of the physical quantity to be measured. Under this condition, resistors R_A, R_B and R_C are so selected that they are equal in value to the transducer resistance R_T. (The value of the physical quantity normally depends on the transducers characteristics, the type of physical quantity to be measured, and the desired applications.)

Initially the bridge is balanced at a desired reference condition. As the physical quantity to be measured changes, the resistance of the transducer also changes, causing the bridge to be unbalanced. Hence, the output voltage of the bridge is a function of the change in the resistance of the transducer. The expression for the output voltage V_0, in terms of the change in resistance of the transducer is calculated as follows.

Let the change in the resistance of the transducer be ΔR. Since R_B and R_C are fixed resistors, the voltage V_b is constant, however, the voltage V_a changes as a function of the change in the transducers resistance.

Therefore, applying the voltage divider rule we have

$$V_a = \frac{R_A(E)}{R_A + (R_T + \Delta R)} \text{ and } V_b = \frac{R_B(E)}{R_B + R_C}$$

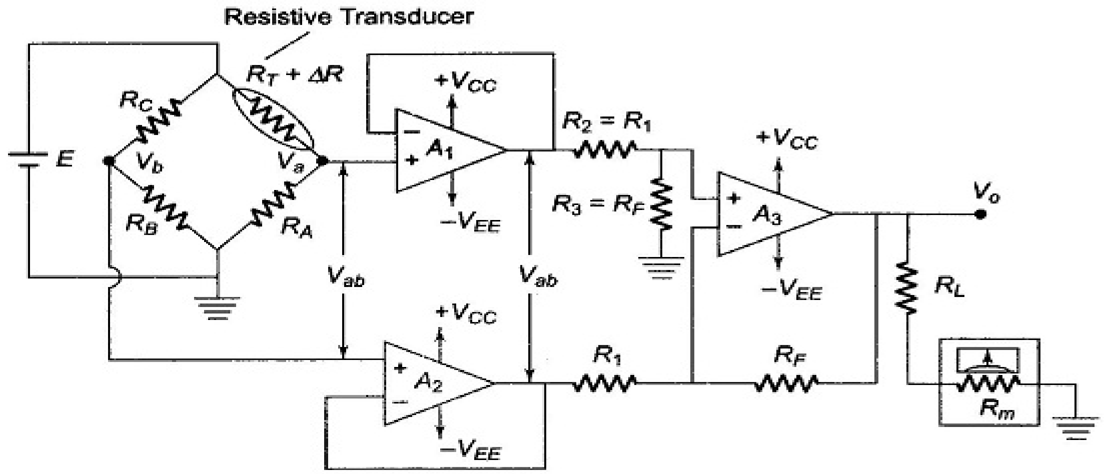

Figure 5.12: Differential instrumentation amplifier using transducer bridge

The output voltage across the bridge terminal is V_{ab}, given by $V_{ab}=V_a-V_b$

Therefore,

$$V_{ab} = \frac{R_A(E)}{R_A + (R_T + \Delta R)} - \frac{R_B(E)}{R_B + R_C}$$

$R_A = R_B = R_C = R_T = R$, then

$$V_{ab} = \frac{R(E)}{2R + \Delta R} - \frac{R(E)}{2R} = E\left(\frac{R}{2R+\Delta R} - \frac{1}{2}\right)$$

$$V_{ab} = E\left(\frac{2R - 2R - \Delta R}{2(2R + \Delta R)}\right) = \frac{-\Delta R(E)}{2(2R + \Delta R)} \tag{5.9}$$

The output voltage V_{ab} of the bridge is applied to the Differential Instrumentation Amplifier Transducer Bridge through the voltage followers to eliminate the loading effect of the bridge circuit. The gain of the basic amplifier is (R_F/R_1) and therefore the output voltage V_o of the circuit is given by

$$V_o = V_{ab}\left(\frac{R_F}{R_1}\right) = \frac{-\Delta R(E)}{2(2R + \Delta R)} \times \frac{R_F}{R_1} \tag{5.10}$$

It can be seen from the Eq. (5.10) that V_o is a function of the change in resistance ΔR of the transducer. Since the change is caused by the change in a physical quantity, a meter connected at the output can be calibrated in terms of the units of the physical quantity.

5.10 Temperature Indicators Using Thermistor

The Thermistor is a relative passive type of temperature resistance transducer. They are basically semiconductors.

In many respects, a thermistor resembles a conventional resistor. It is usually a two-terminal device. It has resistance as its fundamental property. It is generally installed and operated in the manner of an ordinary resistor. But its great difference is that it has a negative temperature coefficient (NTC) or positive temperature coefficient (PTC) type. Most thermistors exhibit an NTC characteristic. An NTC type is one in which its resistance decreases with increase in temperature. The temperature coefficient is expressed in ohms/°C.

Since it is a THERMally sensitive resISTOR, it has a high temperature coefficient of resistance and is therefore well suited for temperature measurement and control.

If in the bridge circuit of Fig. 5.12, the transducer used is a thermistor, the circuit can thus be used as a temperature indicator. The output meter is then calibrated in °C or °F. The bridge is balanced initially at a desired reference condition. As the temperature varies, the resistance of the thermistor also changes, unbalancing the bridge, which in turn produces a meter deflection at the output. By selecting the appropriate gain for the Differential Instrumentation Amplifier Transducer Bridge, the meter can be calibrated to read a desired temperature. In this circuit, the meter movement (deflection) depends on the amount of unbalance in the bridge, which is caused by a change in the value of thermistor resistance ΔR. The change ΔR for the thermistor can be determined as follows.

$$\Delta R = \text{temperature coefficient of resistance} \; [\text{final temperature} - \text{reference tamperature}]$$

If the meter in this circuit is replaced by a relay, and if the output of the Differential Instrumentation Amplifier Transducer Bridge drives the relay that controls the current in the heat-generating circuit, a temperature controller can be formed. A properly designed circuit should energize a relay when the temperature of the thermistor drops below a desired value, causing the heater unit to turn on.

5.11 Analog Weight Scale

Figure 5.12 can be converted into a simple analog weight scale by connecting strain gauges in the bridge circuit. These strain gauges are connected in all the four arms of the bridge, as shown in Fig. 5.13. The strain gauge elements are mounted on a base of the specially made weight platform, on which an external force or weight is placed. One pair of strain gauge elements in opposite arms elongates, (i.e. R_{T1} and R_{T3} both increases in resistance) while the other pair compresses (R_{T2} and R_{T4} both decreases in resistance), and vice-versa.

The bridge is balanced when no external force or weight is applied, i.e. $RT_I = RT_2 = RT_3 = RT_4 = R$, and the output voltage of the weight scale is zero.

Suppose a weight is placed on the scale platform and R_{T1} and R_{T3} increases in resistance. Then R_{T2} and RT_4 decrease in resistance by the same value AR and the bridge is unbalanced, thereby giving an unbalanced output voltage. This unbalanced voltage V_{ab}, is given by

$$V_{ab} = +E\left(\frac{\Delta R}{R}\right)$$

where

E = excitation voltage of the bridge.

$R = R_{T1} = R_{T2} = R_{T3} = R_{T4}$ = unstrained gauge resistance

ΔR = change in gauge resistance.

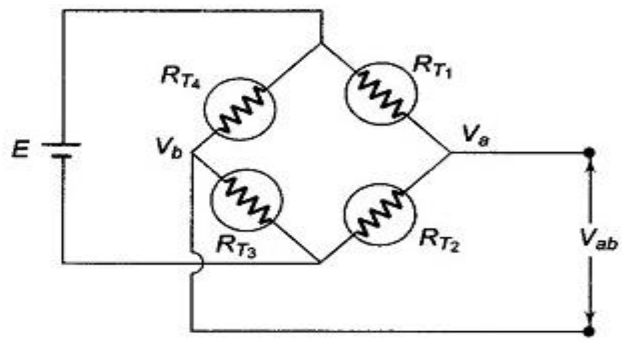

Figure 5.13: Strain gauge bridge for analog weight scale

The Differential Instrumentation Amplifier Transducer Bridge then amplifies the voltage V_{ab}, giving a deflection on the meter movement. As the gain of the amplifier is $(+R_F/R_1)$, the output voltage V_o is given by

$$V_o = E \times \left(\frac{\Delta R}{R}\right) \times \left(\frac{R_F}{R_1}\right)$$

The gain of the amplifier is selected depending on the sensitivity of the strain gauge and on the full scale deflection requirements of the meter. The meter can be then calibrated in grams or kilograms.

For better accuracy and resolution, a micro based digital weight scale may be constructed. However, such a scale is much more complex and expensive then the analog scale.

5.12 Programmable Logic Controller (PLC)

Programmable Logic Controller (PLC) or commonly simply called a Programmable Controller, is a solid state, digital, industrial computer.

It is a device that was invented to replace the necessary sequential relay circuits for machine control. The PLC basically operates by looking at its inputs and depending upon their state, turning on/off its output. The user enters a program, normally through software, that gives the desired results.

PLCs are used in many real world applications such as machining, packaging, material handling, automated assembly, etc. Almost any applications that need some type of electrical control has a need for a PLC.

Let's assume that when a switch turns ON, we want to turn a solenoid ON for 10 seconds and then turn it OFF regardless of how long the switch is ON for. This can be done by a simple external timer. But if the process included 10 or more switches and solenoids, then we would need 10 or more external timers. But if the processes also needed to count how many times the switches individually turned ON, then a lot of external counters would be needed. As can be seen, the bigger the process, the more important is the need of a PLC. The PLC can be simply programmed to count its inputs and turn the solenoids ON for the specified time.

Since the PLC is a computer it should be told what to do. The PLC knows what to do through a program that is developed and then entered into its memory. The PLC however, without a set of instructions, is just a black box, consisting of electronic components only.

A PLC can control devices such as limit switches, push button, proximity or photo-electric sensors, float switches or pressure switches, etc. to provide the incoming control signals into the unit. The incoming control signal is called the INPUT. These control signals or inputs, interact with the instructions specified in the user program, telling the PLC how to react to the incoming signals. The user program also directs the PLC on how to control field devices such as motor starters, pilot lamps and solenoids. A signal going out of the PLC control to a field device is called an OUTPUT.

PLC can also be defined as per National Electrical Manufacturer Association (NEMA) as a digitally operated electronic system, designed for use in industrial environment, which uses a programmable memory for internal storage of user-oriented instructions for implementing specific functions such as logic, sequencing, timing, counting and arithmetic to control, through digital or analog inputs and outputs, various types of machines or processes. Both the PLC Definition and its associated peripherals are designed so that they can be easily integrated into an industrial control system and easily used in all intended functions.

5.12.1 PLC Structure

The PLC Structure mainly consists of a CPU, memory areas, and appropriate circuits to receive input/output data as shown in Fig. 5.14. A PLC can be considered as a box full of hundreds of thousands of separate relays, counters, timers and data storage locations. (These counters, timers, etc. really do not exists physically but rather they are simulated and can be considered software counters, timers, etc.). These internal relays are simulated through bit locations in registers.

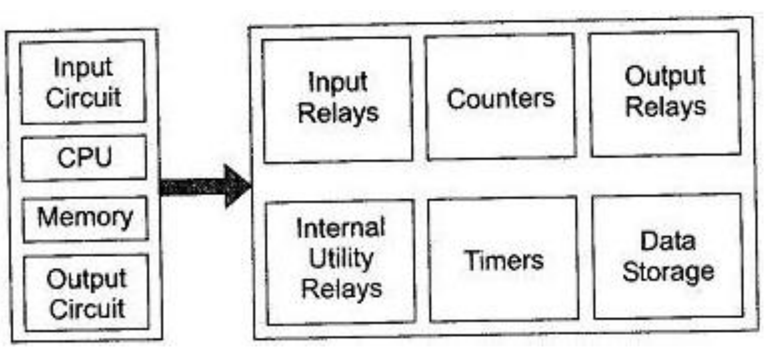

Figure 5.14: PLC structure.

The PLC structure consists of the following:

Input Relays: (Contacts) These are connected to the outside world. They physically exist and receive signals from switches, sensors, etc. Typically they are not relays but are transistors.

Internal Utility Relay: (Contacts) These do not receive signals from the outside world nor do they physically exist. They are simulated relays and are what enables a PLC to eliminate external relays. There are also some special relays that are dedicated to performing only one task. Some are always ON while some are always OFF. Some are ON only once during Power-on and are typically used for initializing data that was stored.

Counters: These again do not physically exist. They are simulated counters and they can be programmed to count pulses. Typically these counters can be up-count, down count or both. Since they are simulated they are limited in their counting speed. Some manufacturers also include high speed counters that are hardware based.

Timers: These also do not physically exist. They come in many Varieties and increments. The most common type is an ON-delay type. Others include OFF-delay and both retentive and non-retentive types. Increments vary from 1 ms — ls.

Output Relays: (Coils) These are connected to the outside world. They exist physically and send ON/OFF signals to solenoid, lamps, etc. They can be transistors, relays or triacs depending upon the type selected.

Data Storage: Typically there are registers assigned simply to store data. They are usually used as temporary storage for math or data. They can also be used to store data in case of a power failure. These registers ensure that there is no loss of contents owing to disconnection of power.

5.12.2 PLC System Operation

A PLC System Operation works by continually scanning a program. This scan cycle can be considered as made up of three important states as shown in Fig. 5.15. In addition there are also more than three states and these are used for checking the system and updating the internal counter and timer values.

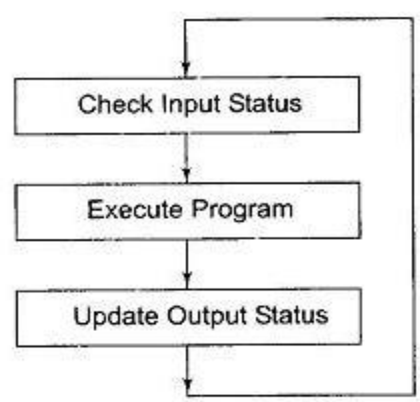

Figure 5.15: PLC operation diagram

The three important states are:

Step 1: Check Input Status: First the PLC takes a look at each input to determine if it is ON or OFF. In other words, it checks and senses whether the sensor connected to the first input is ON, to the second input is ON, to the third input is ON… It records this data into its memory to be used during the next step.

Step 2: Execute Program: The PLC System Operation next executes the program, one instruction at a time. For example, if the program says that if the first input was ON then it should turn ON the first output. Since it already knows which inputs are ON/ OFF from the previous step, it will be able to decide whether the first output should be turned ON based on the state of the first input. It will store the execution results for use later during the third step.

Step 3: Update Output Status: Finally the PLC updates the status of the outputs. It updates the outputs based on which inputs were ON during the first step and the results of executing the program during the second step. Based on example in step 2, it would now turn ON the first output because the first input was ON and the program said to turn ON the first output when this condition is true.

After the third step, the PLC System Operation goes back to step one and repeats the steps continuously.

The time taken to execute the above three steps or one instruction cycle is defined as the scan time.

5.12.3 Relays

The main purpose of a PLC is to replace real world relays. A Relays Definition is basically an electro-magnetic switch. When a voltage is applied to the coil, a magnetic field is generated. This magnetic field attracts the contact of the relay in, causing them to make a connection. These contacts act like a switch and allow current to flow between 2 points thereby closing the circuit.

Let us consider the following example in which we will simply turn ON a bell, whenever the switch is closed. A switch, relay and a bell is connected as shown in Fig. 5.16.

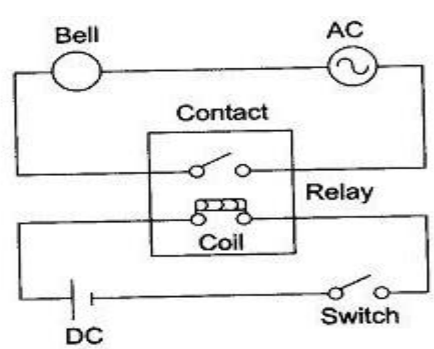

Figure 5.16: Bell circuit diagram

When the switch closes, current is applied to a bell causing it to sound. In Fig.5.16, it is seen that it consists of two separate circuits. One circuit is the dc part and the other circuit is the ac part.

In this case we are using a dc relay to control an ac circuit. When the switch is open, no current flows through the coil of the relay. As soon as the switch is closed, current starts to flow through the coil causing a magnetic field to build up. This magnetic field causes the contacts of the relay to close. Hence, ac current flows through the bell and the sound of the bell can be heard.

Let us now replace the Relays Definition by a PLC. The first process is necessary to create what is called a **ladder diagram**. (A ladder diagram consists of vertical lines called the bus bars and within these vertical lines are placed various horizontal lines consisting of input contacts and output. These horizontal lines are called as rungs.) We have to create a ladder diagram, but a PLC does not understand a schematic diagram. It only recognizes code. Fortunately most PLCs have software which convert ladder diagrams into code.

First step: We have to translate all of the items we are using into symbols the PLC understands. The PLC does not understand terms like switch, relay, bell etc. It prefers input, output, coil, contact, etc. It does not care what actual input or output device actually is. It only cares that it is an input or an output.

The batteries or power supply is replaced by a symbol. This symbol is common to all ladder diagrams. These are called the bus bars. These look like two vertical lines on either side and the input and output are placed within these bars. The left side can be considered as the voltage and the right side as the ground and the current flow from left to right.

The inputs and outputs each are also given a symbol. The input, that is, the switch will be connected by a symbol, shown in Fig. 5.17. This symbol can also be used as the contact of the Relays Definition. Only one output is normally used, e.g. a bell. The output that the bell will be physically connected in the circuit by the symbol is shown in Fig. 5.18. This symbol is used as the coil of a relay.

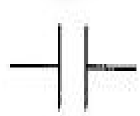

Figure 5.17

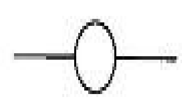

Figure 5.18

The ac supply is an external supply hence it is not put in the ladder diagram. The PLC only knows and cares about which output it has to turn on.

The PLC must know where everything is located. In other words we have to give all the devices an address. The location where the switch is going to be physically connected to the PLC. Each inputs and outputs used have an address. The PLC has a lot of inputs and outputs but the PLC has to figure out which device is connected where.

The final step is to convert the schematic into a logical sequence of events. The program written tells the PLC what to do when certain events take place. The PLC should be told what to do when the operator turns ON the switch. The diagram shown in Fig. 5.19 is the final converted diagram. In Fig. 5.19, the input is called as '0000' and output is called as '0500'.

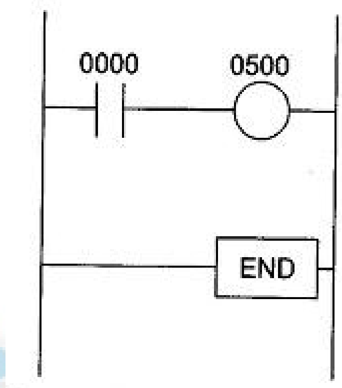

Figure 5.19: Basic ladder diagram

5.12.3 PLC Register

PLC Register – Let us consider a simple example and compare the ladder diagram with its real world external physically connected relay circuit. In Fig. 5.20(a), the coil circuit will be energized when there is a closed loop between the '+' and '—' terminals of the battery. The same circuit can be drawn using ladder diagram. A ladder diagram consists of individual rungs. Each rung must contain one or more inputs and one or more outputs. The first instruction on a rung must always be an input instruction and last instruction on a rung should always be an output coil. The ladder diagram of Fig. 5.20(a) is shown in Fig. 5.20(b).

The PLC Register in use can be explained by using Fig. 5.20(b) and changing SW2 from normally open to normally close as shown in Fig. 5.20(c).

Hence, in Fig. 5.20(c), SW1 will be physically OFF and SW2 will be physically ON initially. Each symbol or instruction has been given an address. This address sets aside a certain storage area in the PLC data files so that the status of the instruction (i.e. true/false) can be stored. Most PLCs uses 16 slots or bit storage locations. In the example given above, two different storage locations or PLC Register are used.

In the tables of two registers 00 and 05 shown in Fig. 5.20(d), we can see that in register 00, bit 00 corresponding to input 0000 was a logic 0 and bit 01 corresponding to input 0001 was a logic 1. Register 05 shows that bit 00 corresponding to output 0500 was a logic 0. The logic 0 or 1 indicate whether an instruction is False or True.

The PLC will only energize an output when all conditions on the rung are TRUE. Hence, in the above example, SW1 must be logic 1 and SW2 must be logic 0, then and only then the output (coil) will be True, that is energized. If any instruction on the rung before the output (coil) is false, then the output (coil) will be false (not energized).

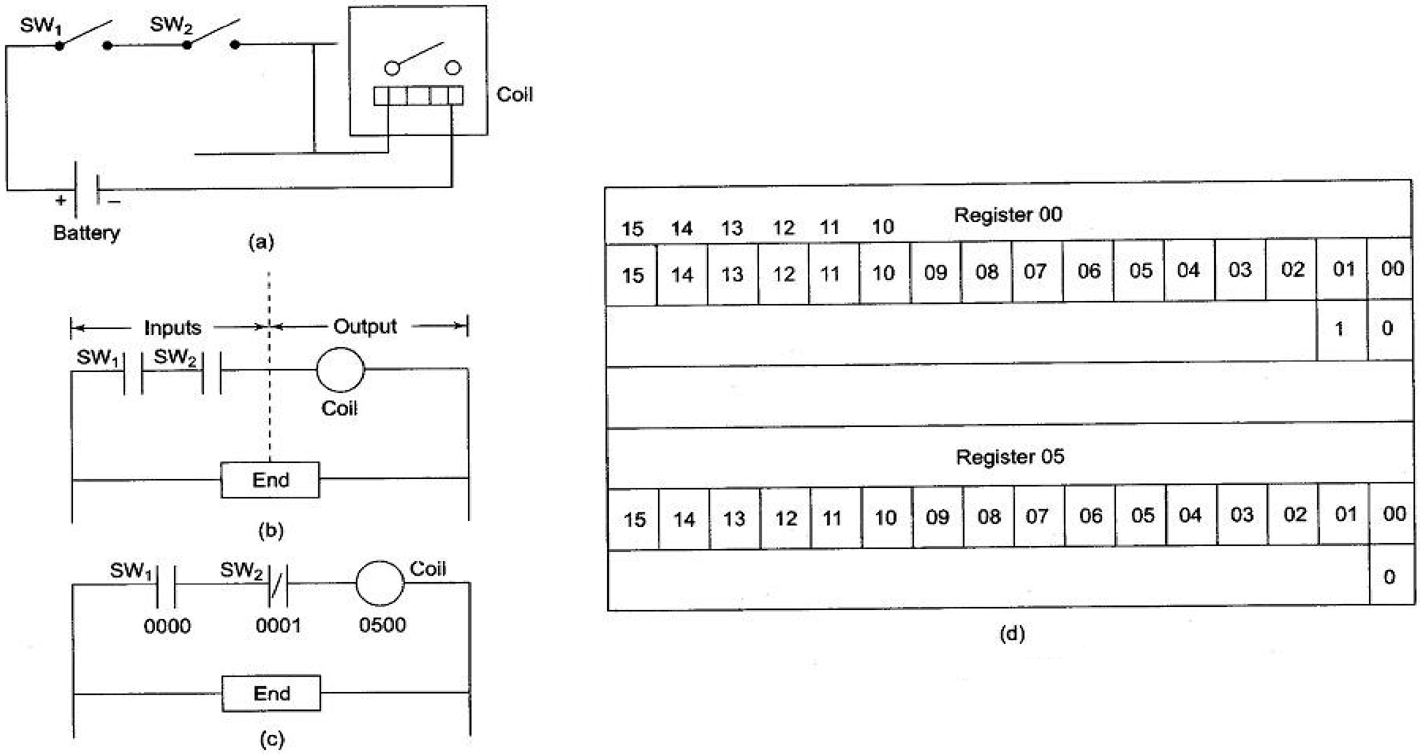
SW1
SW2
Coil
Battery
(a)
Inputs
Output
SW1
SW2
Coil
End
(b)
SW1
SW2
Coil
0000
0001
0500
End
(c)
Register 00
15 14 13 12 11 10 09 08 07 06 05 04 03 02 01 00
1 0
Register 05
15 14 13 12 11 10 09 08 07 06 05 04 03 02 01 00
0
(d)

Figure 5.20