BENHA UNIVERSITY
FACULTY OF ENGINEERING (SHOUBRA)
ELECTRONICS AND COMMUNICATIONS ENGINEERING

ECE 444
Industrial Electronics

(2022 - 2023) 1st term

Lecture 4: Analog Signal Conditioning.

Dr. Ahmed Samir
https://bu.edu.eg/staff/ahmedsaied

Outlines:

- Analog Signal Conditioning.
- Analog Signal Conditioning Categories.
- Voltage Divider Circuit.
- Wheatstone Bridge Circuit.
- Design Guideline.

Analog Signal Conditioning (S/C):

- Signal conditioning refers to operation performed on signals to convert them to a form that is suitable to interface with other elements in the process-control loop.
- A sensor <u>measures</u> a variable by converting information about that variable into a dependent signal.
- We often describe the effect of the signal conditioning by the term transfer function.
- Signal conditioning Categories:
    1) Signal Level and bias changes.
    2) Linearization.
    3) Conversion.
    4) Filtering.
    5) Impedance Matching.

1-Signal level and bias changes:

- One of the most common types of signal conditioning involves adjusting the level (magnitude) and bias (zero value) of some voltage representing a process variable.

- For example, some sensor output voltage may vary from 0.2 to 0.6 V equipment to which this sensor output must be connected perhaps requires a voltage that varies from 0 to 5 V for the same variation of the process:

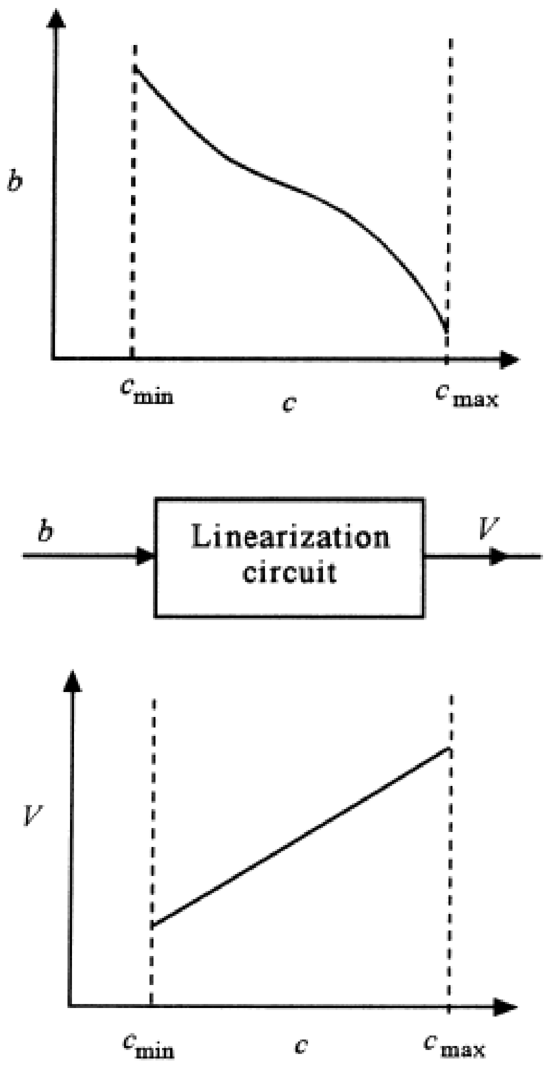
  - subtracting 0.2 → a zero shift, or a bias adjustment (0 to 0.4)
  - multiply the voltage by 12.5 → amplification (0 to 5)

2. Linearization:

- The designer has a little choice of the characteristics of a sensor (Often has a nonlinear T.F.).

- A linearization circuit is difficult to design and has a narrow range.

- Now software based linearization techniques are used.



3. Conversion:

- To convert one type of electrical variation into another (e.g. ΔR to ΔV or ΔI)

- For signal transmission (4-20 mA current loop) (V to I and I to V)

- For digital interface, The use of computers in process control requires conversion of analog data into a digital format by integrated circuit devices called analog-to-digital converters (ADCs). An analog signal conversion is usually required to adjust the analog signal to match the input requirement of the ADC

  e.g. Sensor output 20 – 90 mV

  ADC range 0 - 5 V

4. Filtering:

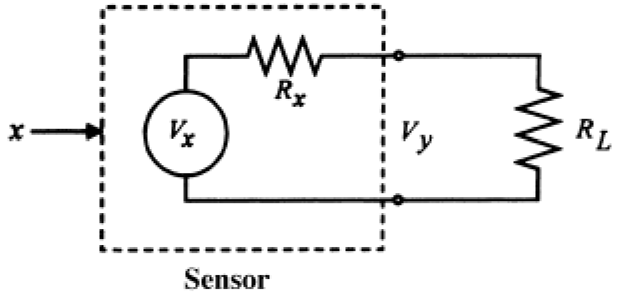
- Often, spurious signals of considerable strength are present in the industrial environment, such as the 60-Hz line frequency signals.

- Motor start transients may also cause pulses and other unwanted signals in the process-control loop.

- In many cases, it is necessary to use high-pass, low-pass, Band-pass, band-reject or notch filters to eliminate unwanted signals from the loop.

5. Impedance Matching:

- Impedance matching is an important element of signal conditioning when transducer internal impedance or line impedance can cause errors in measurement of a dynamic variable.
- Loading introduces uncertainty in the amplitude of a voltage as it is passed through the measurement process. (Loading Effect).



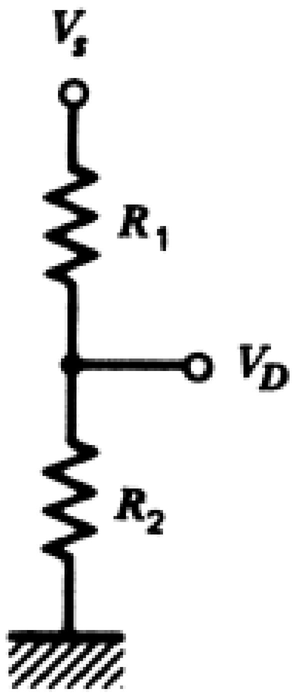
$$V_y = V_x\left(1 - \frac{R_x}{R_L + R_x}\right)$$

- If loading is ignored, serious errors can occur in expected outputs of circuits and gains of amplifiers.

Passive circuit:

Voltage Divider Circuit:

- The simple voltage divider can often be used to convert resistance variation into voltage variation.
- $V_D = V_s R_2 /(R_1 + R_2)$
- R_1 or R_2 may be a sensor
- Notes:
  - Nonlinearity of the equation
  - Loading effect
  - R1 & R2 power rating



Voltage Divider Circuit:

EXAMPLE 2 The divider of Figure 4 has $R_1 = 10.0\ \text{k}\Omega$ and $V_s = 5.00$ V. Suppose R_2 is a sensor whose resistance varies from 4.00 to 12.0 kΩ as some dynamic variable varies over a range. Then find **(a)** the minimum and maximum of V_D, **(b)** the range of output impedance, and **(c)** the range of power dissipated by R_2.

Solution

a. The solution is given by Equation (2). For $R_2 = 4\ \text{k}\Omega$, we have

$$V_D = \frac{(5\ \text{V})(4\ \text{k}\Omega)}{10\ \text{k}\Omega + 4\ \text{k}\Omega} = 1.43\ \text{V}$$

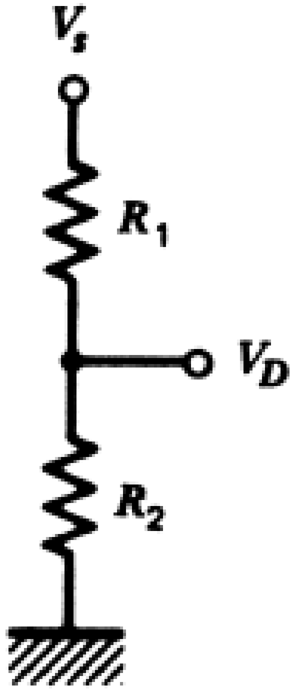
For $R_2 = 12\ \text{k}\Omega$, the voltage is

$$V_D = \frac{(5\ \text{V})(12\ \text{k}\Omega)}{10\ \text{k}\Omega + 12\ \text{k}\Omega} = 2.73\ \text{V}$$

b. Thus, the voltage varies from 1.43 to 2.73 V.

c. The range of output impedance is found from the parallel combination of R_1 and R_2 for the minimum and maximum of R_2. Simple parallel resistance computation shows that this will be from 2.86 to 5.45 kΩ.

d. The power dissipated by the sensor can be determined most easily from V^2/R_2, as the voltage across R_2 has been calculated. The power dissipated varies from 0.51 to 0.62 mW.



Wheatstone Bridge Circuit:

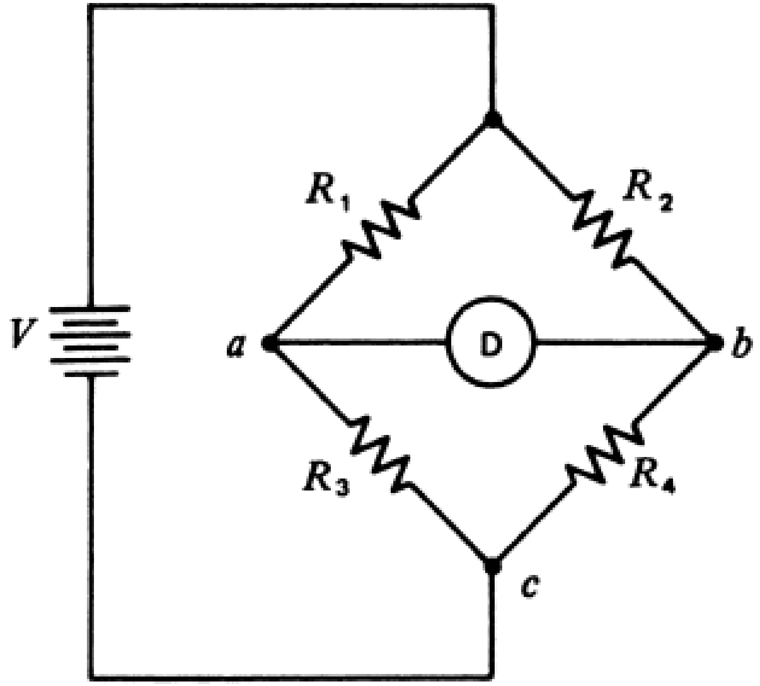
- To convert impedance variations into voltage variations.
- One of the advantages of the bridge for this task is that it can be designed so the voltage produced varies around zero.
- To measure impedance precisely.

- $\Delta V = V_a - V_b$ (voltage offset)

$$=V_s \frac{(R_3R_2 - R_1R_4)}{(R_1+R_3)(R_2+R_4)}$$

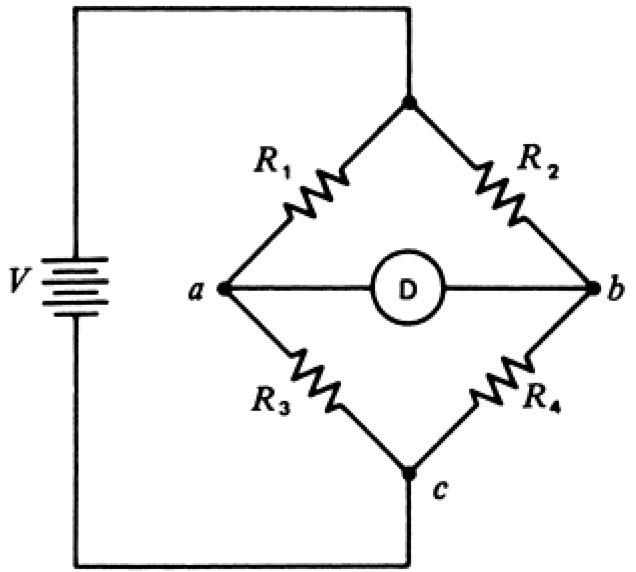
- Null condition:

$$R_3R_2 = R_1R_4$$



Using Galvanometer to detect the offset:

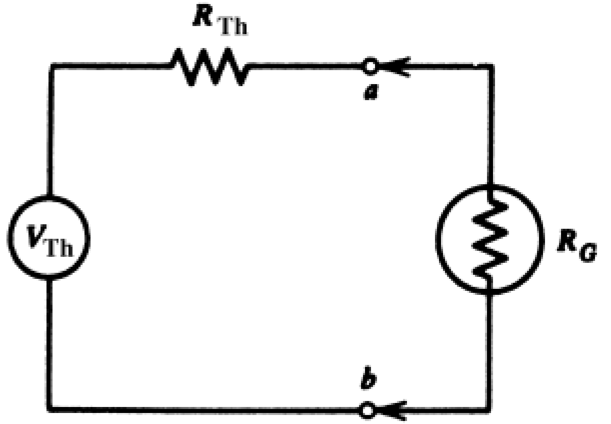
- In some cases, a highly sensitive galvanometer with a relatively low impedance may be used
- When a galvanometer is used for a null detector, it is convenient to use the Thévenin equivalent circuit of the bridge



$$V_{Th} = V\frac{R_3R_2 - R_1R_4}{(R_1 + R_3)(R_2 + R_4)}$$

$$R_{Th} = \frac{R_1R_3}{R_1 + R_3} + \frac{R_2R_4}{R_2 + R_4}$$

$$I_G = \frac{V_{Th}}{R_{Th} + R_G}$$



Using Galvanometer to detect the offset:

EXAMPLE 5 A bridge circuit has resistance of $R_1 = R_2 = R_3 = 2.00\ \text{k}\Omega$ and $R_4 = 2.05\ \text{k}\Omega$ and a 5.00-V supply. If a galvanometer with a 50.0-Ω internal resistance is used for a detector, find the offset current.

Solution

From Equation (9), the offset voltage is V_{Th}.

$$V_{Th} = 5\ \text{V}\frac{(2\ \text{k}\Omega)(2\ \text{k}\Omega) - (2\ \text{k}\Omega)(2.05\ \text{k}\Omega)}{(2\ \text{k}\Omega + 2\ \text{k}\Omega)(2\ \text{k}\Omega + 2.05\ \text{k}\Omega)}$$

$$V_{Th} = \mathbf{-30.9\ mV}$$

We next find the bridge Thévenin resistance from Equation (10):

$$R_{Th} = \frac{(2\ \text{k}\Omega)(2\ \text{k}\Omega)}{(2\ \text{k}\Omega + 2\ \text{k}\Omega)} + \frac{(2\ \text{k}\Omega)(2.05\ \text{k}\Omega)}{(2\ \text{k}\Omega + 2.05\ \text{k}\Omega)}$$

$$R_{Th} = \mathbf{2.01\ k\Omega}$$

Finally, the current is given by Equation (11):

$$I_G = \frac{-30.9\ \text{mV}}{2.01\ \text{k}\Omega + 0.05\ \text{k}\Omega}$$

$$I_G = \mathbf{-15.0\ \mu A}$$

Bridge resolution

- It is the resistance change in one arm of the bridge that causes an offset voltage (offset current) that is equal the resolution of the detector.

- Gives a limit to min. measurable resistance change.

- Seen as overall accuracy of the instrument

Bridge resolution

EXAMPLE 6

A bridge circuit has $R_1 = R_2 = R_3 = R_4 = 120.0\text{-}\Omega$ resistances and a 10.0-V supply. Clearly, the bridge is nulled, as Equation (8) shows. Suppose a $3\frac{1}{2}$-digit DVM on a 200-mV scale will be used for the null detector. Find the resistance resolution for measurements of R_4.

Solution

On a 200-mV scale, the DVM measures from 000.0 to 199.9 mV, so the smallest measurable change is 0.1 mV, or 100 μV. So, we need to find out how much R_4 has changed from 120 Ω to create this much off null voltage.

We simply use Equation (6), with R_4 changed to some unknown value so that 100 μV results:

$$100\ \mu\text{V} = \frac{(120\ \Omega)(10\ \text{V})}{120\ \Omega + 120\ \Omega} - \frac{R_4(10\ \text{V})}{120\ \Omega + R_4}$$

This equation is a bit of an algebraic challenge to solve, but eventually we find

$$R_4 = 119.9952\ \Omega$$

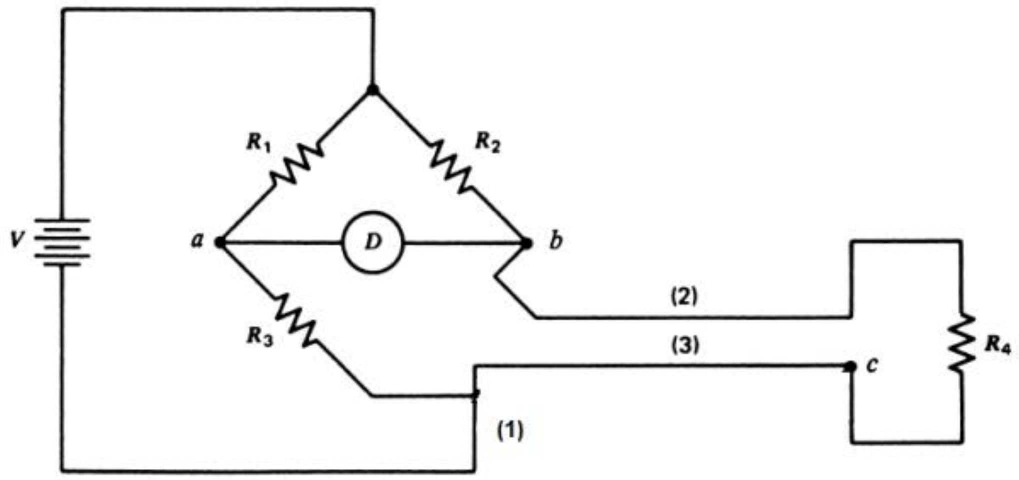
So the smallest change in resistance that can be measured is

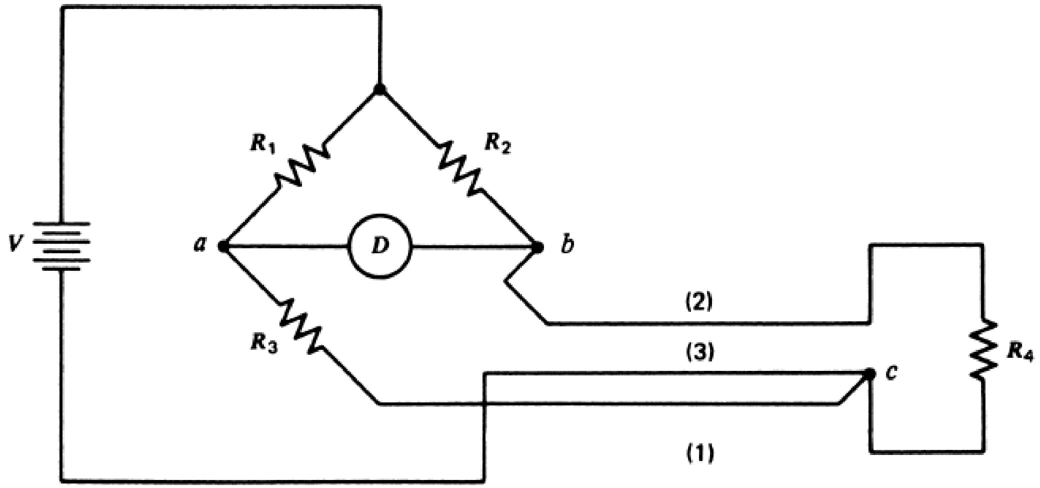
$$\Delta R_4 = 120\ \Omega - 119.9952\ \Omega = 0.0048\ \Omega$$

A bridge offset of $+100\ \mu$V is caused by a reduction of R_4. It follows that a bridge offset of $-100\ \mu$V would be caused by an increase of R_4.

Bridge Compensation:

- A Problem: In many process-control applications, a bridge circuit may be located at considerable distance from the sensor whose resistance changes are to be measured. The resistance of the wires (2) & (3) must be considered to minimize the error in measurement
- For remote sensor applications, this compensation system is used to avoid errors from lead resistance.



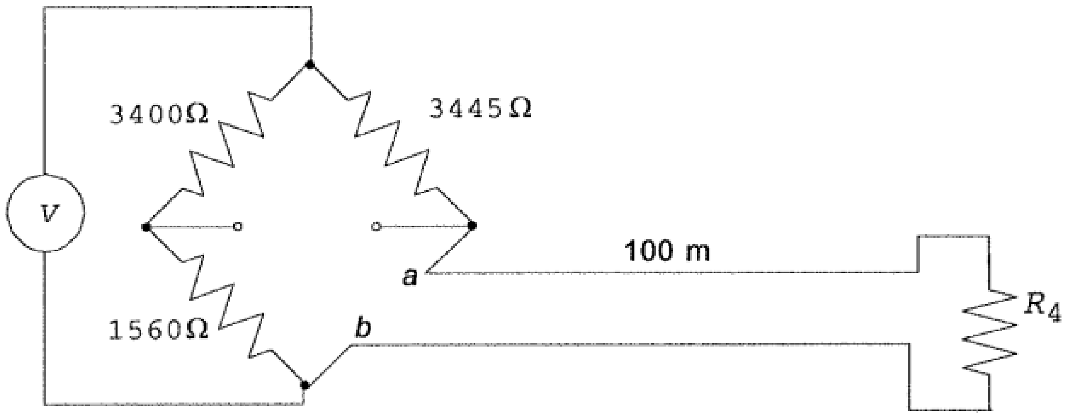


Bridge Compensation:

9 A bridge circuit is used with a sensor located 100 m away. The bridge is not lead compensated, and the cable to the sensor has a resistance of 0.45 Ω/ft. The bridge nulls with $R_1 = 3400\ \Omega$, $R_2 = 3445\ \Omega$, and $R_3 = 1560\ \Omega$. What is the sensor resistance?

Solution

A diagram will help you understand this problem. The circuit is,



If you use the null equation to find R_4, it will give the resistance from *a* to *b* in the schematic, which includes the two 100 m lead resistances. Thus these must be subtracted to find the actual sensor resistance.

$$R_{ab} = (3445\ \Omega)(1560\ \Omega)/(3400\ \Omega) = 1580.6\ \Omega$$

but the lead resistance is,

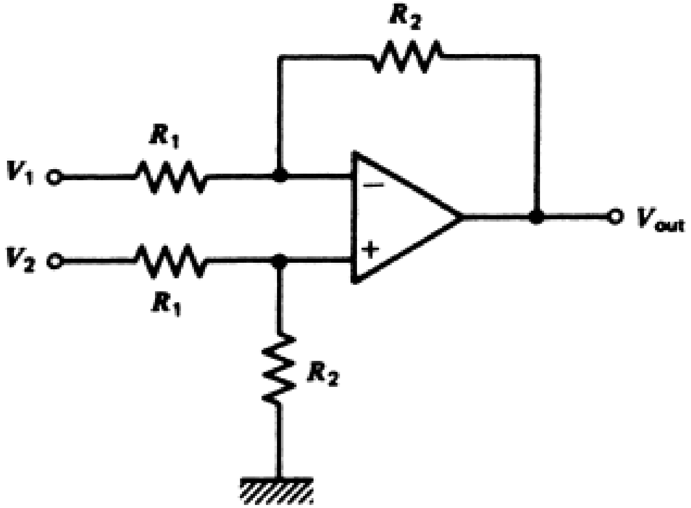
$$R_{lead} = 2(100\ \text{m})(0.3048\ \text{m/ft})(0.45\ \Omega/\text{ft}) = 295.3\ \Omega$$

So the actual sensor resistance is,

$$R_4 = 1580.6\ \Omega - 295.3\ \Omega = 1285.3\ \Omega$$

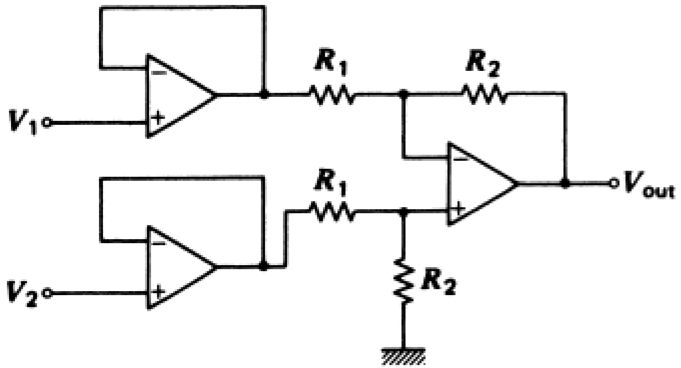
OPERATIONAL AMPLIFIERS:

Differential Amplifier



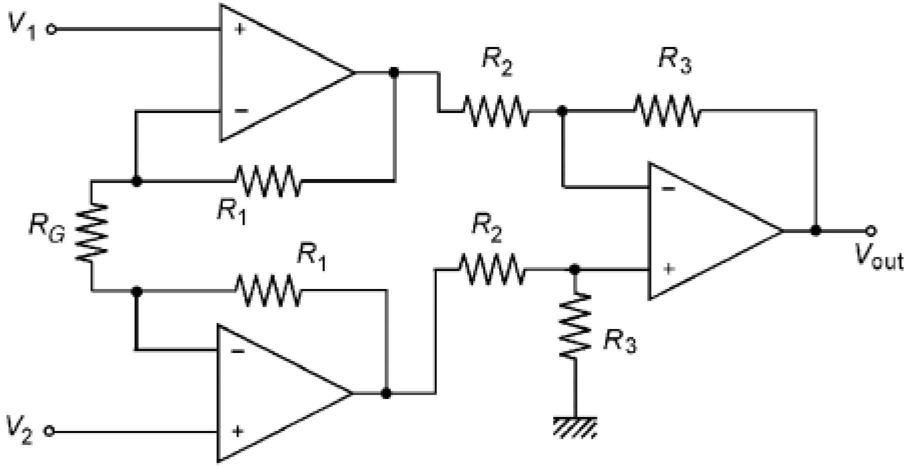
$$V_{out} = \frac{R_2}{R_1}(V_2 - V_1)$$

Instrumentation Amplifier



$$V_{out} = \frac{R_2}{R_1}(V_2 - V_1)$$

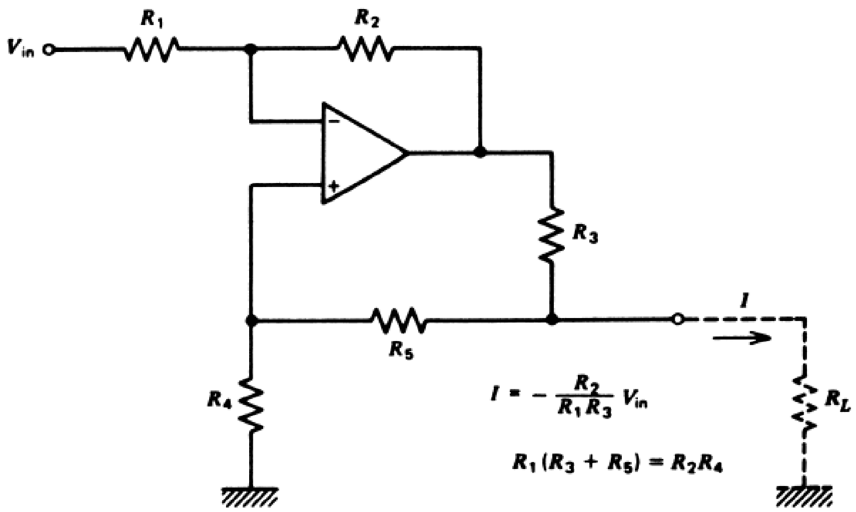
Instrumentation Amplifier



$$V_{out} = \left(1 + \frac{2R_1}{R_G}\right)\left(\frac{R_3}{R_2}\right)(V_2 - V_1)$$

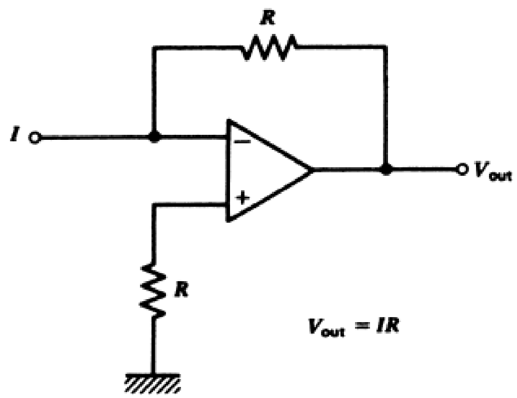
OPERATIONAL AMPLIFIERS:

Voltage-to-Current Converter



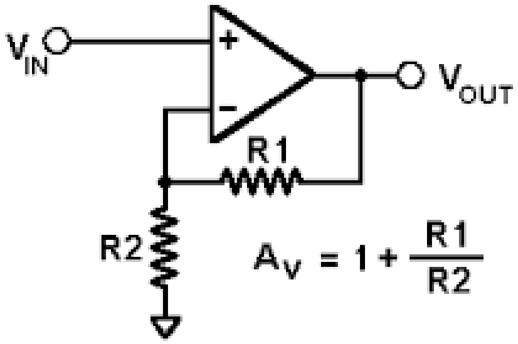
$$I = -\frac{R_2}{R_1 R_3} V_{in}$$

Current-to-Voltage Converter

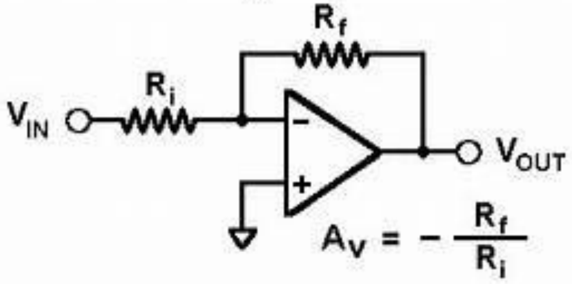


$$V_{out} = -IR$$

Non-Inverting Amplifier



Inverting Amplifier



OPERATIONAL AMPLIFIERS:

EXAMPLE 20 A sensor outputs a range of 20.0 to 250 mV as a variable varies over its range. Develop signal conditioning so that this becomes 0 to 5 V. The circuit must have very high input impedance.

Solution

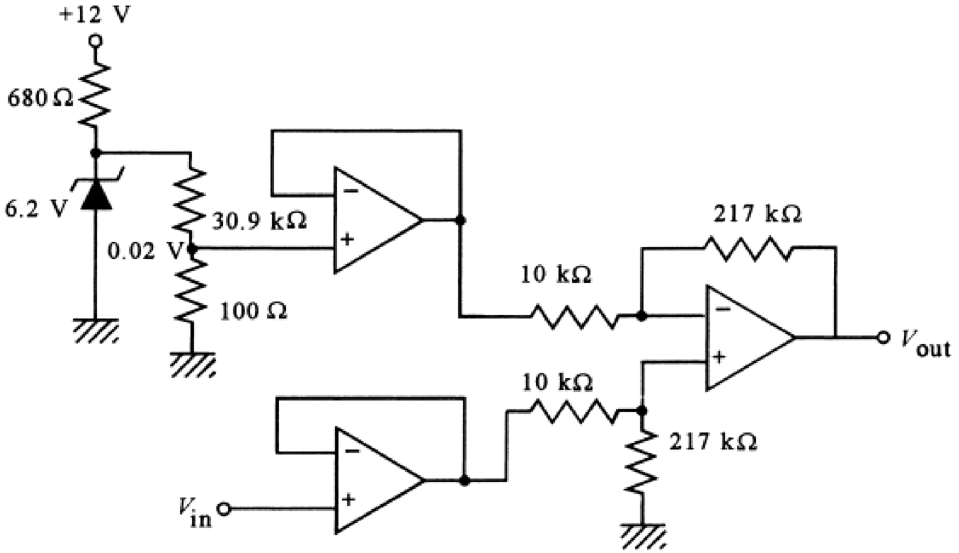
$$V_{out} = mV_{in} + V_0$$

$$0 = m(0.02) + V_0$$
$$5 = m(0.25) + V_0$$

We get $m = 21.7$ and $V_0 = -0.434$ V using standard algebra. The equation is

$$V_{out} = 21.7\,V_{in} - 0.434$$

$$V_{out} = 21.7\,(V_{in} - 0.02)$$



OPERATIONAL AMPLIFIERS:

EXAMPLE 24 A sensor outputs a voltage ranging from −2.4 to −1.1 V. For interface to an analog-to-digital converter, this needs to be 0 to 2.5 V. Develop the required signal conditioning.

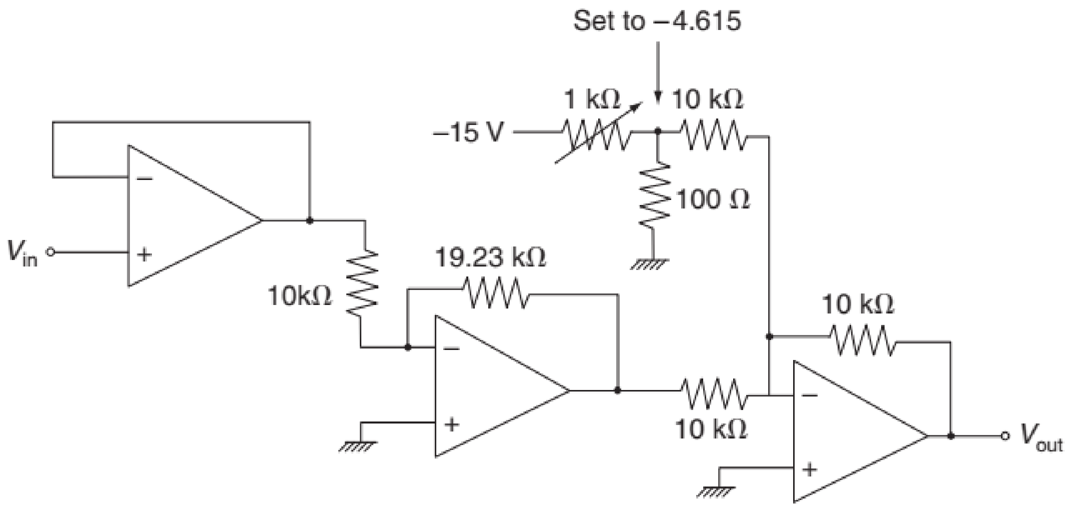
Solution

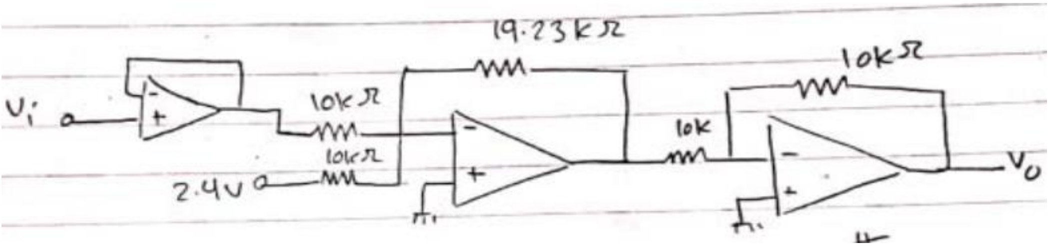
$$V_{out} = mV_{in} + V_0$$

$$0 = -2.4m + V_0$$
$$2.5 = -1.1m + V_0$$

The transfer function equation is thus

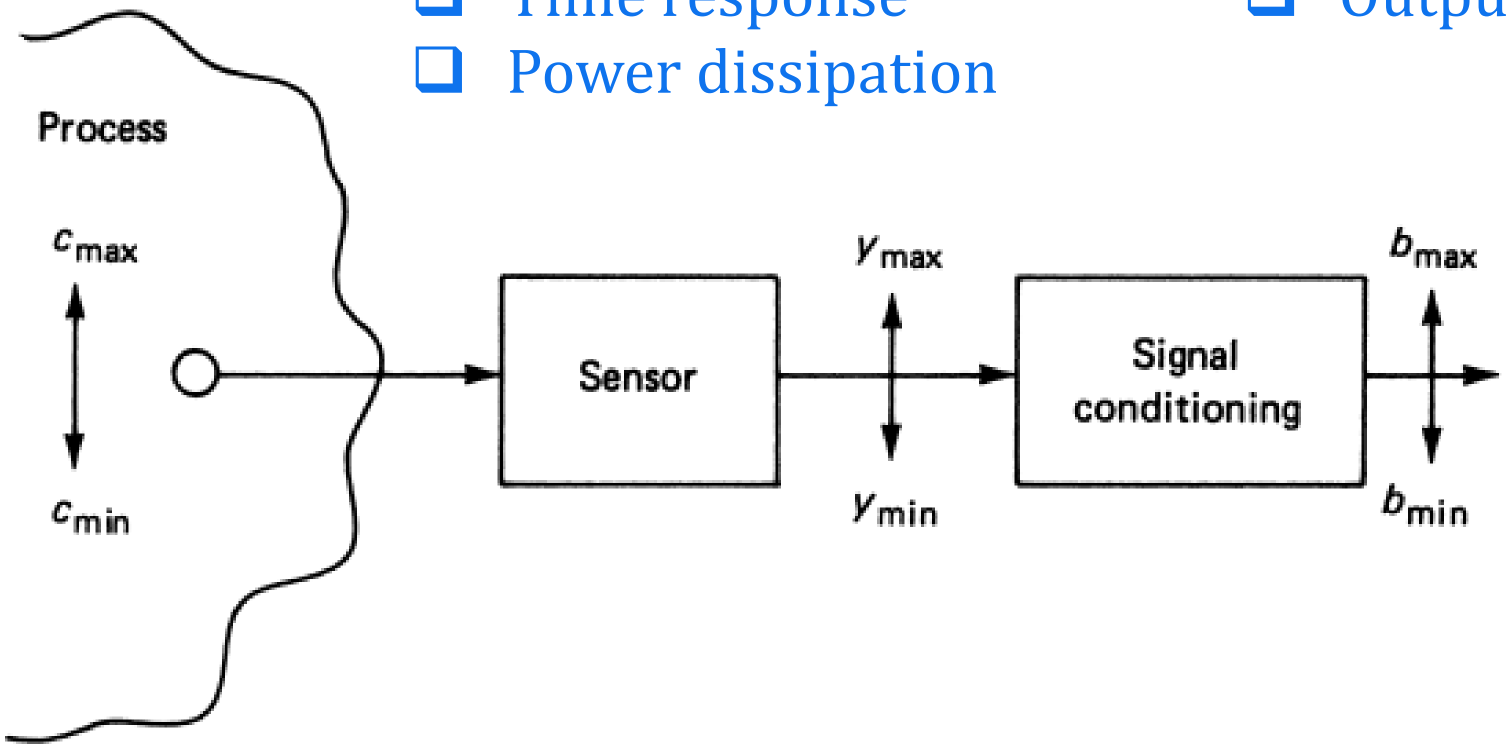
$$V_{out} = 1.923\,V_{in} + 4.615 \qquad V_{out} = 1.923(V_{in} + 2.4)$$





Design Guidelines:

- Measurement Objective:
  - Parameter
  - Range
  - Accuracy
  - Linearity
  - Noise
- Select a Sensor:
  - Parameter
  - Range
  - Transfer function
  - Time response
  - Power dissipation
- Signal Conditioning:
  - Parameter
  - Range
  - Input Impedance
  - Output Impedance



Design Guidelines:

EXAMPLE 25 Temperature is to be measured in the range of 250°C to 450°C with an accuracy of ±2°C. The sensor is a resistance that varies linearly from 280 Ω to 1060 Ω for this temperature range. Power dissipated in the sensor must be kept below 5 mW. Develop analog signal conditioning that provides a voltage varying linearly from −5 to +5 V for this temperature range. The load is a high-impedance recorder.

Solution

Following the guidelines, let us first identify all the elements of the problem.

Measured Variable Parameter: Temperature

Range: 250° to 450°C

Accuracy: ±2°C

Noise: unspecified

Sensor Signal

Parameter: resistance

Transfer function: linear

Time response: unspecified

Range: 280 Ω to 1060 Ω, linear

Power: maximum 5 mW dissipated in sensor

Signal Conditioning

Parameter: voltage, linear

Range: −5 to +5 V

Input impedance: keep power in sensor below 5 mW

Output impedance: no problem, high-impedance recorder

Design Guidelines:

Solu:

$P = I^2 R \qquad 5\times10^{-3} = I^2 (280) \Rightarrow I = 4.2\,mA$

$\qquad\qquad\qquad = I^2 (1660) \Rightarrow I = 2.17\,mA$

1) The design must always keep the Sensor Current below 2mA

let we make it $I_{max} = 1mA$

$\Delta R : 280 \rightarrow 1660\ \Omega$

$\Delta V : -5 \rightarrow 5\ V$ } → linear relation

$V_{out} = m R_s + V$

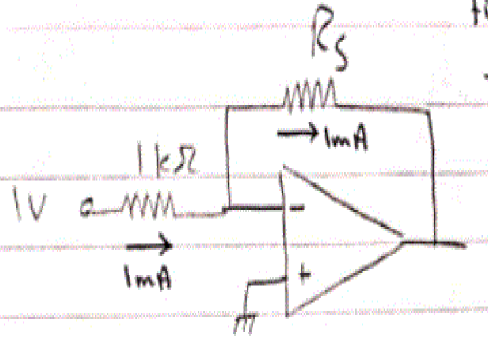
$-5 = m(280) + V$ (I)

$5 = m(1660) + V$ (II)

} ⇒ $m = 0.0128$, $V = -8.58$

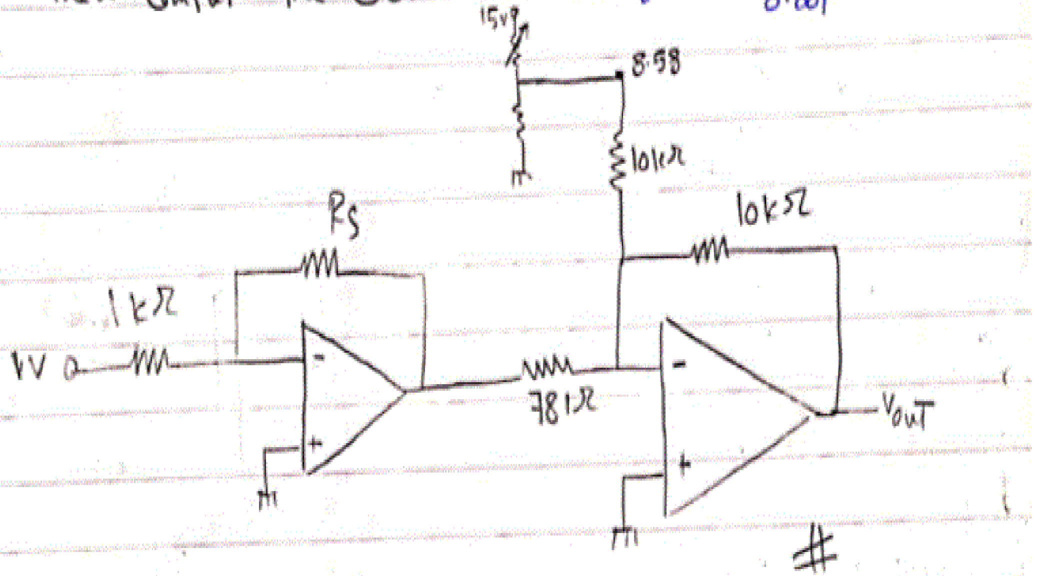
$\therefore V_{out} = 0.0128 R_s - 8.58$

first use Rs Sensor with op.amp and Take Care of Current $I_{max} = 1mA$



$V_o = -0.001 R_s$

Then Complete The Ct.: The remain gain: $\frac{0.0128}{0.001} = 12.8$



END OF LECTURE

BEST WISHES