

الجمهورية الجزائرية الديمقراطية الشعبية
The People's Democratic Republic of Algeria
العالي والبحث العلمي وزارة التعليم
Ministry of Higher Education and Scientific Research
جامعة عمارثليجي – الأغواط
University Amar Telidji of Laghouat

Faculty : Technology
Department: Electrotechnics
Domain : Sciences et Technologies
Field : Electrotechnics / Electromechanics
Specialty: Electrotechnics / Electromechanics
Course Handout (Lectures)
Intended for students of: License Level 3rd Year

Sensors and Measurement Chains

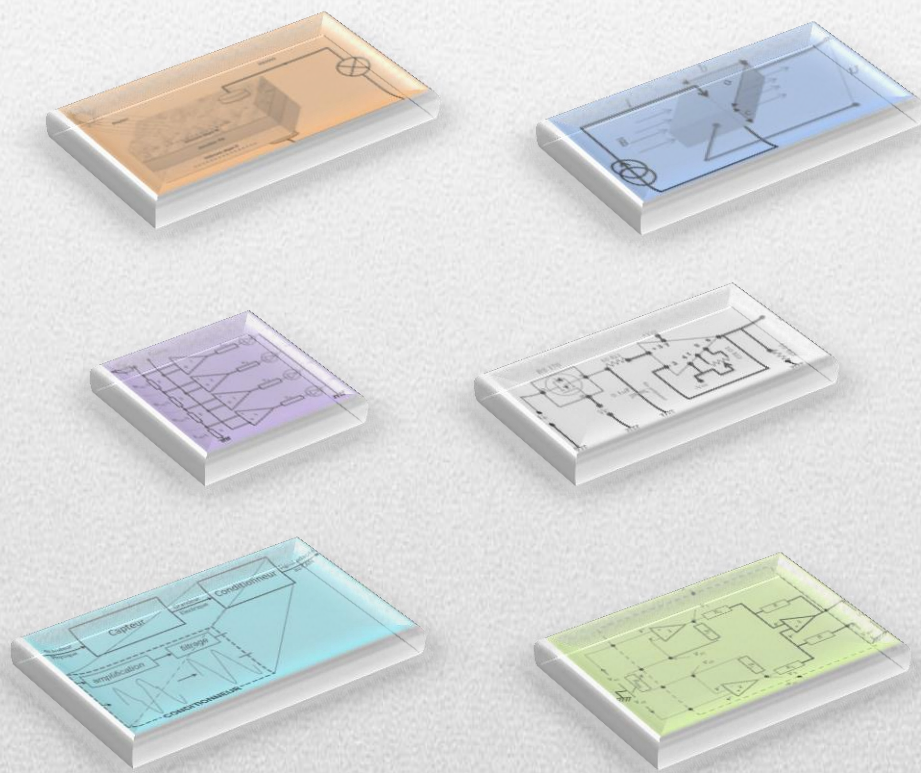
Presented by: OMRANE MOHAMMED

Grade: MCA

Email : m.omrane@lagh-univ.dz

Academic year : 2024/2025

Sensors and Measurement Chains



Omrane Mohammed

TABLE OF CONTENTS

Table of Contents	I
List of Figures.....	VII
Foreword XI	
Objectives of the Teaching.....	i
CHAPTER 1.	1
Principles and Applications of Operational Amplifiers and Associated Assemblies 1	
Summary of Chapter 1.....	1
1.1 Introduction	2
1.2 Voltage Generator and Current Generator.....	2
1.3 Voltage Calculation	2
1.3.1 Voltage Divider.....	2
1.3.2 Wheatstone Bridge	3
1.3.3 Millman's Theorem	4
1.3.4 Law of Superposition.....	5
1.4 Amplification:.....	5
1.4.1 Operational Amplifiers	6
1.4.2 Use of Feedback	6
1.5 Positive Feedback (or Saturation) Fixtures	8
1.5.1 Comparator Amplifier.....	8
1.6 Linear-Mode (negative feedback)	11
1.6.1 Follower Buffer.....	11
1.6.2 Inverter and Non-Inverter Amplifier.....	11
1.6.3 An inverting Amplifier.....	12
1.6.4 Non-inverting Amplifier.....	12

1.6.5	Non-inverting Voltage Summing Amplifier.....	13
1.6.6	Voltage Inverter Summing Amplifier	14
1.6.7	Summing Amplifier With OFFSET.....	14
1.6.8	Cascading of Amplifiers.....	15
1.7	Instrumentation Amplifier	15
1.7.1	Two OP-AMP Instrumentation Amplifier	15
1.7.2	Thee OP-AMP Instrumentation Amplifier Mounting	16
1.8	Useful Amplifier Assemblies.....	18
1.8.1	Linearization Circuit.....	18
1.8.2	Current-Voltage Converters.....	19
1.8.3	Voltage-to-Current Generator Conversion.....	21
CHAPTER 2.		23
Physical Phenomena Present in Sensors		23
Summary of Chapter 2.....		23
2.1	Introduction	24
2.2	Thermoelectric Effect.....	24
2.3	Conduction Effect.....	25
2.4	Pyroelectric.....	25
2.5	Piezoelectric Effect.....	25
2.6	Hall Effect	26
2.7	Photovoltaic Effect	27
2.8	Capacitance Effect.....	27
2.9	Inductance Effect	28
CHAPTER 3.		29
Characteristics of the Sensors.....		29
Summary of chapter 3.....		29

3.1	Definition of a Sensor.....	30
3.1.1	Introducing a Sensor	30
3.1.2	Transmitter.....	31
3.1.3	Transmitter Sensor	31
3.1.4	Detector	31
3.2	Characteristics of a Sensor's Quantities	31
3.2.1	Measure.....	31
3.2.2	Measurement.....	31
3.2.3	Measurand	31
3.2.4	Calibration	32
3.2.5	Measurement range	32
3.2.6	Resolution.....	32
3.2.7	Sensitivity.....	33
3.2.8	Precision	33
3.2.9	Linearity	34
3.2.10	Hysteresis.....	35
3.2.11	Speed.....	36
3.3	Criteria for Choosing a Sensor.....	37
3.3.1	Operating Area	37
3.3.1.1	Nominal Domain	37
3.3.1.2	Domain of Non-Deterioration.....	37
3.3.1.3	Non-Destruction Domain.....	37
3.3.2	Destruction Domain	37
3.4	Sensor Performance	38
3.4.1	Static Sensor Performance.....	38
3.4.2	The Absolute Error:.....	39

3.4.3	The relative error:	39
3.4.4	Average Value	39
3.4.5	The systematic error:	40
3.4.6	Variance:	40
3.4.7	Standard Deviation:	40
3.4.8	Decomposition of The Accuracy Error	43
3.4.9	Determining the Linearity Error	43
3.4.10	Determination of Hysteresis Error	45
3.4.10.1	The Hysteresis Error:	45
3.4.10.2	Determining the Linearity Error of a Hysteresis Cycle..	45
3.4.11	Resolution Error	47
3.4.12	Offset of a Sensor	48
3.5	Sensor Classification	49
3.6	Passive Sensors	49
3.7	Active Sensors	49
3.7.1	Ranking According to Their Exit Signals	50
3.7.1.1	Logic or Digital Sensors:	50
3.7.1.2	Analog Sensors	50
3.7.1.3	Digital Sensors:	50
3.8	Classification According to the Entry Size	51
3.8.1	Temperature Sensors:	51
3.8.2	Pressure Sensors:	51
3.8.3	Position and Motion Sensors:	51
3.8.4	Light and Image Sensors:	52
3.8.5	Force and Torque Sensors:	52
3.8.6	Proximity and Distance Sensors:	52

CHAPTER 4.	53
Measurement Chain and Packaging Circuit of a Sensor	53
Summary of chapter 4.....	53
4.1 Definition	54
4.2 Synoptic Diagram of an Industrial Regulation Chain	54
4.3 Conditioner	56
4.3.1 Role of a Conditioner.....	57
4.3.1.1 Amplification:	57
4.3.1.2 Filtration	58
4.4 Conversion of Current to Voltage:.....	67
4.5 Scaling	68
4.6 Digitizing a Signal.....	69
4.7 Analog-to-Digital Converter (ADC)	69
4.7.1 Converter Symbol:.....	70
4.7.2 Quantum of an ADC	70
4.7.3 Transfer Feature	71
4.7.4 Full-scale Excursion of a ADC.....	72
4.7.5 Solving an ADC.....	73
4.7.5.1 Bit Resolution of an ADC.....	73
4.7.5.2 Resolution as a Percentage of an ADC	73
4.8 Sampling:	73
4.8.1 Sampling Time	73
4.8.2 Sampling Frequency	73
4.8.3 Sampler / Blocker	75
4.8.4 Symbol and Construction of a Sampler/Blocker	76
4.9 Quantization:.....	77

4.10	Signal Coding	78
4.11	ADC Architecture	82
4.11.1	Introducing a Parallel CAN (FLASH)	83
4.11.2	Successive Approximation CAN	85
4.11.2.1	How a Successive Approximation ADC Works	86
4.11.3	Operation.....	86
4.12	Analog-Digital DAC Converter (DAC).....	88
4.12.1	DAC Symbol:.....	88
4.12.2	Quantum of a DAC	89
4.12.3	Transfer Characteristic of an DAC	89
4.12.4	Full-scale Excursion of ADC.....	89
4.12.5	The Resolution of a ADC	90
4.13	Reconstruction of an Analog Signal.....	90
4.13.1	DAC Architecture	90
4.14	DAC With Weighted Resistors	91
4.14.1	General Operation.....	92
4.14.2	Simplified Example	92
4.15	DAC to R-2R.	93
	General Conclusion	96
	Bibliography	98

LIST OF FIGURES

Figure 1 Diagramming of a voltage generator (a) and current generator (b).....	2
Figure 2 (a) Voltage divider without the introduction of the measuring device, (b) Voltage divider with the introduction of the measuring device.	3
Figure 3 Simple Wheatstone bridge.....	4
Figure 4 Example Millman Theorem	4
Figure 5 Symbolization of the Op-Amp	6
Figure 6 Input voltages and output voltages of Op-Amp.	6
Figure 7 Feedback Transfer Function	7
Figure 8 Using the OP-AMP in a Comparator Setup	8
Figure 9 Input voltages and output voltage for variable signals	9
Figure 10 Positive feedback editing.....	9
Figure 11 Hysteresis curve (Schmitt trigger)	10
Figure 12 Op-Amp Voltage Buffer	11
Figure 13 Negative Feedback Circuit	11
Figure 14 Inverter circuit	12
Figure 15 Non-inverter mounting	12
Figure 16 Non-inverting summing mounting	13
Figure 17 Voltage inverter summing circuit	14
Figure 18 Summer Mounting with Offset	14
Figure 19 Cascading of Op-amp.....	15
Figure 20 Cascaded 2 Op-Amps.....	16
Figure 21 Instrumentation amplifier.....	17
Figure 22 Divider Bridge.....	18
Figure 23 Linearization circuit.....	19

Figure 24 Current-to-voltage conversion using a resistor.....	20
Figure 25 Current-to-voltage converter	20
Figure 26 Voltage to Current Generator Conversion (Howland Source).....	21
Figure 27 Seebeck effect thermoelectricity	24
Figure 28 Principle of the Peltier Effect	24
Figure 29 Generation of loads due to temperature variation or variation in light intensity	25
Figure 30 Principle of direct piezoelectricity	26
Figure 31 Principle of the Hall Effect.....	26
Figure 32 Principle of the photovoltaic effect	27
Figure 33 Application of the capacitive effect.....	28
Figure 34 Use of the inductive effect for measuring the rotational speed.....	28
Figure 35 Presentation of a sensor	30
Figure 36 Measuring Range of a Sensor.....	32
Figure 37 Linear Feature of a Pressure Sensor.....	35
Figure 38 Hysteresis cycle of a pressure sensor	35
Figure 39 Response time.....	36
Figure 40 Steps for calculating errors.....	39
Figure 41 Probability density as a function of standard deviation.....	41
Figure 42 Measurement curve and estimation of linearity error.....	44
Figure 43 Determination of hysteresis error	45
Figure 44 Determination of the average curve of a hysteresis cycle	46
Figure 45 Average hysteresis cycle of a sensor and the best fit line	46
Figure 46 Illustration of a potentiometer measuring from an angle.....	48
Figure 47 Overview of Offset of a Sensor	49
Figure 48 Different curves (A-linear curve, B-nonlinear curve)	50

Figure 49: Transfer function of different sensor classes.....	51
Figure 50 Blocks of a Chain of Measure.....	55
Figure 51 Processing chain	56
Figure 52 Sensor signal conditioning.....	57
Figure 53 Amplifier mounting with OP-Amp.....	58
Figure 54 Amplification of a sinusoidal signal	58
Figure 55 Example of a noisy signal.....	59
Figure 56 Different types of filters	59
Figure 57 Diagram of a low-pass filter with passive components.....	60
Figure 58 Representative diagram of a low-pass filter operating at two different frequency levels.....	61
Figure 59 Diagram of a low-pass filter with active components	61
Figure 60 Passive high-pass filter.....	62
Figure 61 Representative diagram of a high-pass filter operating at two different frequency levels.....	63
Figure 62 Active high-pass filter (with OP-amp).....	63
Figure 63 Band-pass Filter Circuit Diagram.....	64
Figure 64 Passive global band-pass filter	65
Figure 65 Active Band-pass Filter.....	66
Figure 66 Voltage Current Converter.....	67
Figure 67 Standardized analog-to-digital converter symbol	70
Figure 68 Diagramming the Outputs of a 4-Bit ADC Converter.....	70
Figure 69 Transfer characteristic of a 4-bit ADC, $V_{ref}=5V$	72
Figure 70 Sampling an analog signal.....	74
Figure 71 Scrambled signal.....	75
Figure 72 Signal from the output of the low-pass filter (36dB/octave, $f_c=10Hz$)	75

Figure 73 Symbolization of the sampler-blocker.....	76
Figure 74 Example of a blocker sampler by an AOMP.....	76
Figure 75 Signal sampled with blocker.....	77
Figure 76 3-bit quantized signal.....	78
Figure 77 Quantized signal $q=2.5V$ and encoded in $n= 3$ bits and sampled at a time $T_e=10$ ms.....	79
Figure 78 Sampled signal for $T_e=10$ ms.....	81
Figure 79 Encoding on a 1-bit ($T_e=10$ ms)	81
Figure 80 2-bit encoding ($T_e=10$ ms)	81
Figure 81 3-bit encoding ($T_e=10$ ms)	81
Figure 82 4-bit encoding ($T_e=10$ ms)	81
Figure 83 8-bit encoding ($T_e =10$ ms).....	82
Figure 84 Types of converters.....	82
Figure 85 Diagram of a 2-bit ADC.....	84
Figure 86 Transcoder logic circuit	85
Figure 87 Transcoder logic circuit using NAND universal gates	85
Figure 88 Structure of an ADC with successive approximations.....	86
Figure 89 Standardized symbol for the digital-to-analogue converter	88
Figure 90 Diagramming the inputs and outputs of a 4-bit DAC converter	88
Figure 91 Transfer Characteristic of a 3-bit DAC	89
Figure 92 Chain of restitution	90
Figure 93 5-bit weighted resistor DAC.....	92
Figure 94 4-bit $R/2R$ resistor DAC.....	94
Figure 95 Equivalent diagram of the $R-2R$ mount for all bits are grounded	94

FOREWORD

The modern world is governed by measurement and control. From simple electrical devices to complex industrial systems, the accuracy and reliability of sensors and packaging circuits are at the heart of technological innovation. It is in this context that this course material is positioned as a companion for students in bachelor's or master's degree in electrotechnics and electromechanics, students interested in familiarizing themselves with the concepts of sensors and electronic packaging circuits.

This document, organized into several sections, begins with the basics of electrical circuits, offering a necessary reminder for those who want to strengthen their knowledge. Helpful reminders like voltage dividers, Wheatstone bridges, and the fundamentals of electricity, are dedicated. An introduction to amplification is presented, with a particular focus on Op-Amps and their different layouts. Every type of component is explored in detail, from inverter amplifiers to cascade components to instrumentation amplifiers.

We then illustrate some physical phenomena present in the sensors. Whether it's the Hall Effect, the piezoelectric effect, or the photovoltaic effect, each effect is explored to show how it translates into practical measurement solutions. The metrology sensor characteristics section provides a view of a sensor's characteristic parameters such as resolution, accuracy, and hysteresis, allowing students to select and evaluate a sensor for a typical application.

This course material also covers the measurement chain and the conditioning circuit, providing useful knowledge about conditioners, voltage digitization, and analog-to-digital conversion.

We hope that this teaching assistance will help our students to better understand and benefit from better support, in order to gain solid knowledge and a better understanding of the measurement chain.

Author

Omrane Mohammed

OBJECTIVES OF THE TEACHING

By the end of this unit, the student will be able to:

1. Understand the elements that make up a measurement chain.
2. Know how sensors work by applying the basics.
3. Evaluate the metrological characteristics of the sensors and evaluate them according to their use.

CHAPTER 1.

PRINCIPLES AND APPLICATIONS OF OPERATIONAL AMPLIFIERS AND ASSOCIATED ASSEMBLIES

SUMMARY OF CHAPTER 1

This chapter is dedicated to operational amplifiers (OP Amps) and their applications in electronic circuits. It begins with an introduction to their critical role in amplification and signal processing. Several voltage calculation methods are explored, such as voltage dividers, Wheatstone bridges and Millman's theorem.

Signal amplification is addressed through the use of operational amplifiers, emphasizing the importance of feedback. The chapter also explores positive feedback configurations, commonly used in comparators, and negative feedback in applications such as inverting and non-inverting amplifiers. The operation of instrumentation amplifiers, used for precise measurements, is also explained.

Finally, practical applications of amplifiers are presented, such as linearization circuits and current-to-voltage converters.

1.1 INTRODUCTION

In this section, we introduce some important concepts for examining sensors, especially operational amplifiers that play an important role in most stages of packaging and digitization.

1.2 VOLTAGE GENERATOR AND CURRENT GENERATOR

The transducer can be powered either by a voltage generator, which produces a constant voltage when the load varies, or by a current generator, which produces a constant current when the voltage varies.

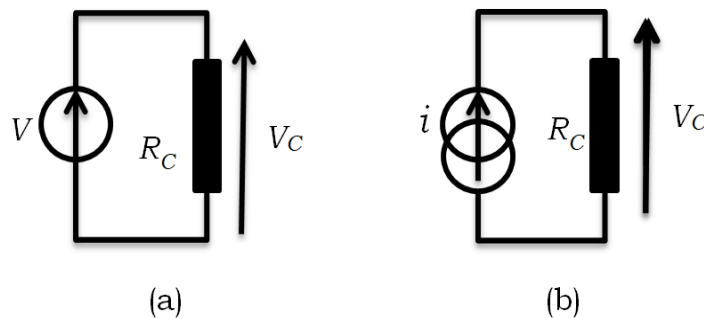


Figure 1 Diagramming of a voltage generator (a) and current generator (b)

As far as the voltage generator is concerned, it can be seen that ($V = V_C$, Figure 1), which means that the voltage across the sensor will remain unchanged. On the other hand, when using a current generator $V_C = R_C i$, the voltage across the sensor varies with the variation in the resistance R_C of the sensor. However, to implement this solution, it is essential to have a whole device to transform a voltage generator into current generator.

1.3 VOLTAGE CALCULATION

The voltage divider and the Wheatstone bridge are the main most commonly used in electrical systems.

1.3.1 VOLTAGE DIVIDER

It is a simple electrical circuit often used to reduce a voltage, using two impedances in series. One of the first solutions proposed is the division of the voltage.

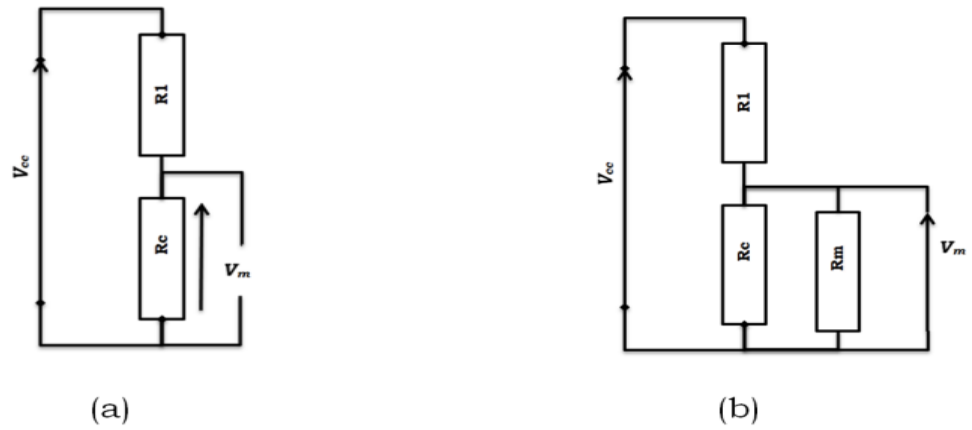


Figure 2 (a) Voltage divider without the introduction of the measuring device, (b) Voltage divider with the introduction of the measuring device.

Case (a):

$$V_m = \frac{R_c}{R_1 + R_c} V_{cc}$$

Case (b):

$$\begin{aligned} V_m &= \frac{R_c // R_m}{R_1 + R_c // R_m} V_{cc} = \frac{\frac{R_m \cdot R_c}{R_m + R_c}}{R_1 + \frac{R_m \cdot R_c}{R_m + R_c}} V_{cc} = \frac{R_m \cdot R_c}{R_1(R_m + R_c) + R_m \cdot R_c} V_{cc} \\ &= \frac{R_m \cdot R_c}{R_1 R_m + R_1 R_c + R_m \cdot R_c} V_{cc} = \frac{R_c}{R_1 + R_c + \frac{R_1 R_c}{R_m}} V_{cc} \end{aligned}$$

Looking at the two results, it can be seen that the installation of the measuring device has an impact on the measured value. Due to its importance in relation to the resistance value of the sensor, it is possible to introduce measurement errors.

1.3.2 WHEATSTONE BRIDGE

A Wheatstone bridge is used for measurements of very small variations in electrical resistance. This technique is commonly used for sensors measuring deformations, as it can detect relative deformations of a few millimeters accurately.

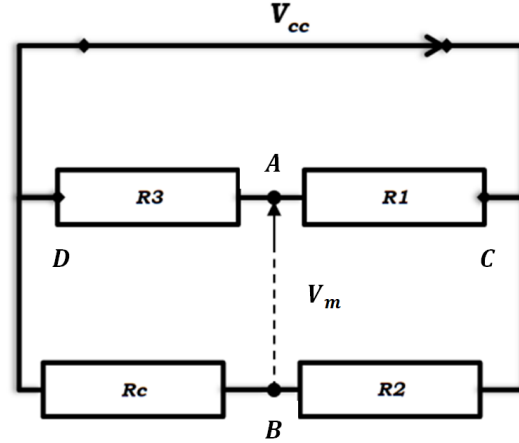


Figure 3 Simple Wheatstone bridge

Calculation of the measured voltage V_m :

$$V_m = V_A - V_B$$

Now we can calculate V_A and V_B by the method of voltage dividers

$$V_A = \frac{R_3}{R_1 + R_3} V_{cc} \text{ and } V_B = \frac{R_c}{R_2 + R_c} V_{cc} \text{ therefore:}$$

$$V_m = \frac{R_3}{R_1 + R_3} V_{cc} - \frac{R_c}{R_2 + R_c} V_{cc} = \left(\frac{R_3}{R_1 + R_3} - \frac{R_c}{R_2 + R_c} \right) V_{cc}$$

$$V_m = \left(\frac{R_3}{R_1 + R_3} - \frac{R_c}{R_2 + R_c} \right) V_{cc}.$$

In equilibrium, $V_m = 0$ this gives:

$$\left(\frac{R_3}{R_1 + R_3} - \frac{R_c}{R_2 + R_c} \right) = 0, \frac{R_3}{R_1 + R_3} = \frac{R_c}{R_2 + R_c} \text{ or}$$

Finally: we see the equilibrium condition of the bridge

$$R_3(R_2 + R_c) = R_c(R_1 + R_3)$$

$$R_3 R_2 + R_3 R_c = R_c R_1 + R_c R_3$$

$$R_3 R_2 = R_c R_1.$$

1.3.3 MILLMAN'S THEOREM

Millman's theorem honors the Ukrainian electronics engineer is a particular form of the law of knots expressed in potential.

$$V_m = \frac{\sum_{i=1}^m \left(\frac{\mp V_i}{Z_i} \right) + \sum_{i=1}^n (\mp I_i)}{\sum_{i=1}^m \left(\frac{1}{Z_i} \right)}$$

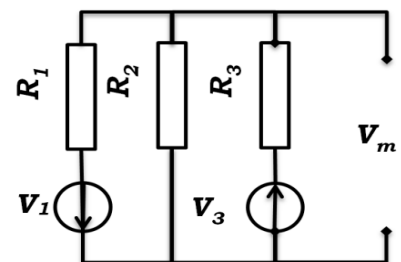


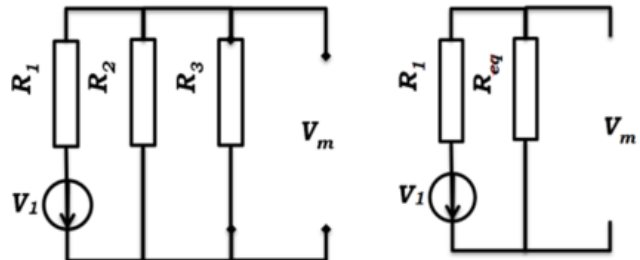
Figure 4 Example Millman Theorem

Exemple 1:

$$\begin{aligned}
 V_m &= \frac{\sum_{i=1}^3 \frac{\bar{V}_i}{Z_i}}{\sum_{i=1}^3 \frac{1}{Z_i}} = \frac{\frac{-V_1}{R_1} + \frac{0}{R_2} + \frac{V_3}{R_3}}{\frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3}} = \frac{\frac{-V_1}{R_1} + \frac{V_3}{R_3}}{\frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3}} = \\
 &= \frac{\frac{-R_2 R_3 V_1 + R_1 V_3}{R_1 R_2 R_3}}{\frac{R_2 R_3 + R_1 R_3 + R_1 R_2}{R_1 R_2 R_3}} = \frac{-R_2 R_3 V_1 + R_1 V_3}{R_2 R_3 + R_1 R_3 + R_1 R_2} \\
 &= \frac{-R_2 R_3 V_1 + R_1 R_2 V_3}{R_2 R_3 + R_1 R_3 + R_1 R_2}; V_1 = 5V; V_3 = 12V; R_1 = 3\Omega; R_2 = 10\Omega; R_3 = 8\Omega \\
 &= \frac{-10 * 8 * 5 + 3 * 10 * 12}{30 + 24 + 80} = -0.298 V \approx -0.3 V
 \end{aligned}$$

1.3.4 LAW OF SUPERPOSITION

When there are several generators in a linear network. In a branch of this network, the current intensity is equivalent to the algebraic sum of the currents created by each generator. The internal resistor replaces other generators, making them more efficient.


Exemple 2:

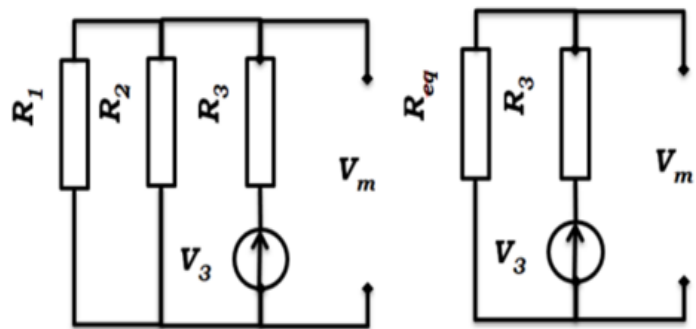
$$\begin{aligned}
 V_{m1} &= \frac{R_{eq} \cdot V_1}{R_1 + R_{eq}} = \frac{\frac{R_2 R_3}{R_2 + R_3} \cdot V_1}{R_1 + \frac{R_2 R_3}{R_2 + R_3}} = \\
 \frac{\frac{80}{18} \cdot (-5)}{3 + \frac{80}{18}} &= -2.985V
 \end{aligned}$$

$$\bullet V_{m2} = \frac{R_{eq} \cdot V_3}{R_3 + R_{eq}} =$$

$$\frac{\frac{R_1 R_2}{R_1 + R_2} \cdot V_3}{R_3 + \frac{R_1 R_2}{R_1 + R_2}} =$$

$$\frac{\frac{3 \cdot 10}{10 + 3} \cdot (12)}{8 + \frac{30}{13}} = 2.686V,$$

$$\text{which gives according to the law of superposition. } V_m = V_{m1} + V_{m2} = -2.985 + 2.686 = -0.299 V \approx -0.3 V.$$


1.4 AMPLIFICATION:

Has the role of increasing the amplitude of the signal to compensate for losses or to make the signal easier to measure. The most used element in instrumentation is the operational amplifier.

1.4.1 OPERATIONAL AMPLIFIERS

An operational amplifier is an integrated electronic circuit designed to perform mathematical operations by amplifying an electric potential difference between its two inputs. Its use is widespread in sensor signal conditioning circuits.

Symbol:

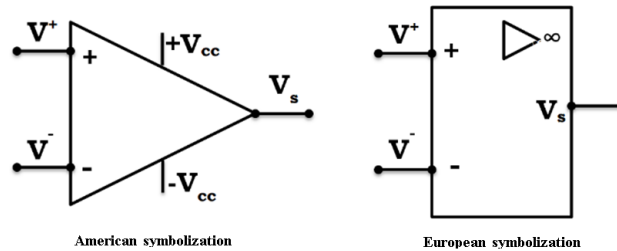


Figure 5 Symbolization of the Op-Amp

The equation of voltages and inputs and outputs

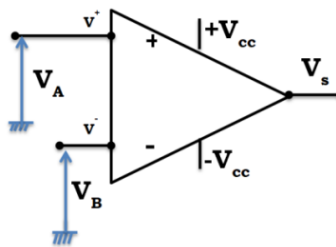


Figure 6 Input voltages and output voltages of Op-Amp.

$$V_s = A \cdot V_E = A(V_A - V_B)$$

Or the gain of the OP-AMP: $A \rightarrow \infty$; $V_s = \begin{cases} +\infty & \text{si } V_A > V_B \\ -\infty & \text{si } V_A < V_B \end{cases}$

In practice $V_A = V_B$ there is no such thing, and the output V_s voltage cannot be infinite.

$$V_s = \begin{cases} +V_{cc} & \text{si } V_A > V_B \\ -V_{cc} & \text{si } V_A < V_B \end{cases}$$

In the following, we admit that the op-amp is perfect $V_A - V_B = \varepsilon = 0$, unless otherwise stated.

1.4.2 Use OF FEEDBACK

The transfer functions when using feedback.

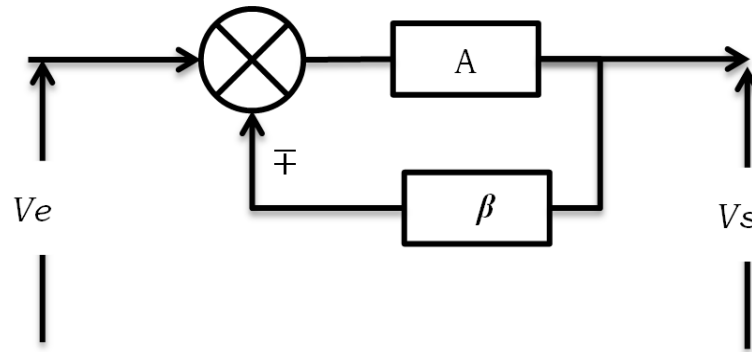


Figure 7 Feedback Transfer Function

$$V_s = A(V_e \mp \beta V_s) \text{ Hence } V_s = \frac{A.V_e}{1 \mp A.\beta}$$

- When the counter-reaction is negative:

$$V_s = \frac{A.V_e}{1 - A.\beta} = \frac{V_e}{\frac{1}{A} - \beta}$$

$$\text{Practically: } \begin{cases} A.\beta > 0 \\ \beta > 1 \text{ and } A.\beta \gg 1 \\ \frac{1}{A} \rightarrow \infty \end{cases}$$

We can therefore adopt the following approximation:

$$V_s \approx \frac{V_e}{\beta} = \frac{1}{\beta} V_e$$

$\frac{1}{\beta}$: is the closed-loop gain. The circuit is said to be linear.

- In the event that the feedback is positive:

$$V_s = \frac{A.V_e}{1 - A.\beta}, \text{ practically } A.\beta \gg 1.$$

A non-linear circuit is one that allows V_s oscillations between $+V_{cc}$ and $-V_{cc}$. In this situation, the output is not directly proportional to its input.

* Things to remember:

- If the output is looped on the negative input, it is called a linear assembly.
- If the output is looped on the positive input, it is called a non-linear assembly.

1.5 POSITIVE FEEDBACK (OR SATURATION) FIXTURES

Comparison mode fixtures (positive feedback or no feedback). In this case, the circuit's output corresponds to the maximum or minimum value the Op-Amp can supply.

1.5.1 COMPARATOR AMPLIFIER

The circuit of the (Figure 8) called the voltage comparator, let's calculate the output voltage.

$$V_A = \frac{R_3}{R_3 + R_c} V, V_B = \frac{R_2}{R_1 + R_2} V$$

$$\text{This gives } V_A - V_B = \left(\frac{R_3}{R_3 + R_c} - \frac{R_2}{R_1 + R_2} \right) V$$

$$V_s = +V_{cc} \text{ si } V_A > V_B \rightarrow \frac{R_3}{R_3 + R_c} > \frac{R_2}{R_1 + R_2}$$

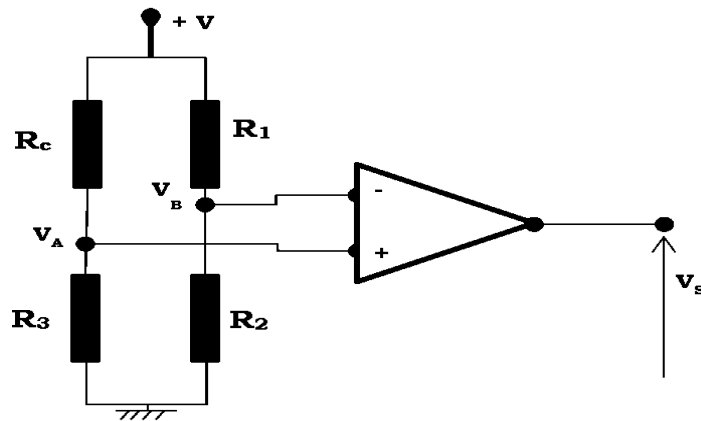


Figure 8 Using the OP-AMP in a Comparator Setup

$$V_s = +V_{cc} \text{ for } R_3 R_1 > R_2 R_c$$

$$V_s = -V_{cc} \text{ for } R_3 R_1 < R_2 R_c$$

Example 3: -

- A comparator circuit between two variables voltages.

If we inject the two variable voltages V_A and V_B , in such a way that V_A will be injected at the negative input and V_B the positive input.

$$\begin{pmatrix} V_A = 4 + 3\sin\frac{2\pi}{5}t \\ V_B = 4.5 + 2\sin\frac{\pi}{5}t \end{pmatrix}$$

The supply voltage of the Op Amp is $V_{cc} = \pm 10V$.

The input voltages and the output voltage are represented by the (Figure 9).

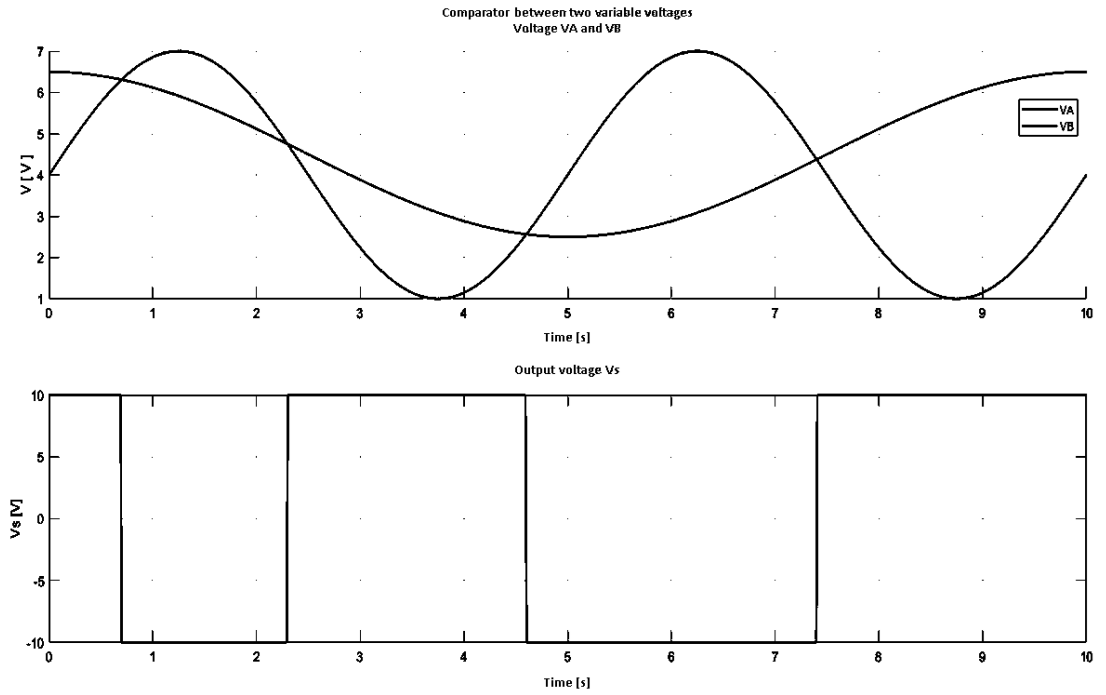


Figure 9 Input voltages and output voltage for variable signals

- Hysteresis Voltage Comparator – Schmitt Trigger

Let the assembly represented by the (Figure 10).

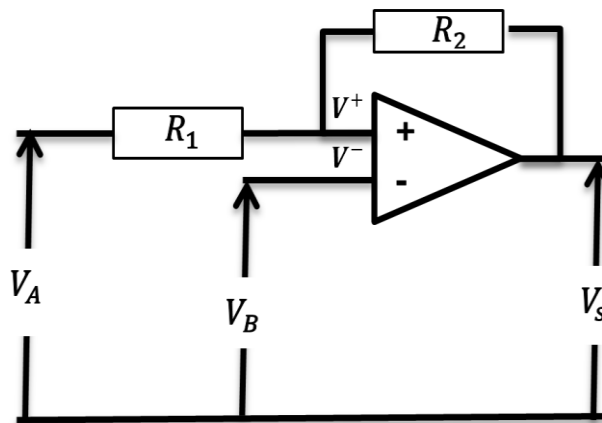


Figure 10 Positive feedback editing

The feedback is positive, the editing is therefore non-linear:

Under these conditions, the output voltage can only take two values

$$V_s = \pm V_{cc}$$

Indeed, in this case, we can write the following equations:

$$\left\{ \begin{array}{l} V^+ = \frac{\frac{V_A}{R_1} + \frac{V_s}{R_2}}{\frac{1}{R_1} + \frac{1}{R_2}} = \frac{R_2 V_A + R_1 V_s}{R_1 + R_2} = \frac{R_2}{R_1 + R_2} V_A + \frac{R_1}{R_1 + R_2} V_s \\ \text{and} \\ V^- = V_B \end{array} \right.$$

If we increase the voltage V_B by an extremely negative value. In the beginning, you get $V_s = +V_{cc}$. When the potential at point B exceeds that of A , the output voltage becomes $-V_{cc}$.

Consequently, there is a threshold voltage such that:

$$v_{1_{seuil}} = \frac{R_2}{R_1 + R_2} V_A + \frac{R_1}{R_1 + R_2} V_{cc}$$

If we take $V_A = V_{Ref}$ as the reference voltage

$$v_{1_{seuil}} = \frac{R_2}{R_1 + R_2} V_{Ref} + \frac{R_1}{R_1 + R_2} V_{cc}$$

We then decrease V_B from a positive value. Initially, we have $V_s = -V_{cc}$

As before, we have a system switch for another threshold $v_{2_{seuil}}$ that differs $v_{1_{seuil}}$ from such as:

$$v_{2_{seuil}} = \frac{R_2}{R_1 + R_2} V_{Ref} - \frac{R_1}{R_1 + R_2} V_{cc}$$

Since the values of the two tipping voltages are different, the system is said to have ***hysteresis***.

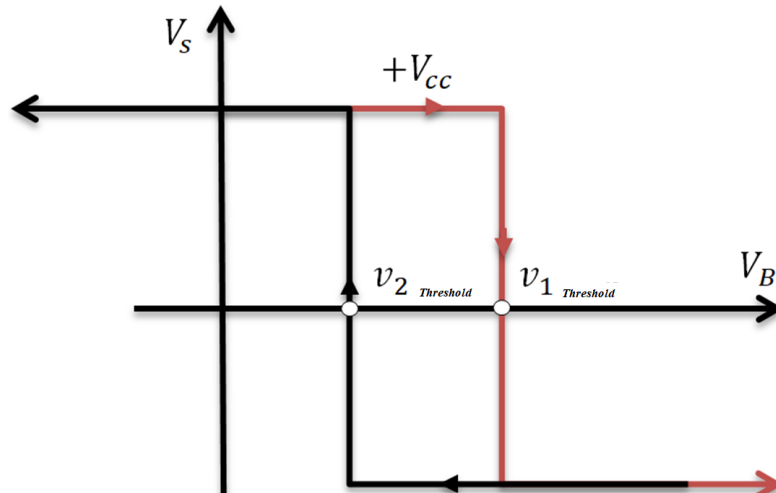


Figure 11 Hysteresis curve (Schmitt trigger)

This circuit is called a Schmitt trigger and is used especially if the signal from a sensor is scrambled.

1.6 LINEAR-MODE (NEGATIVE FEEDBACK)

1.6.1 FOLLOWER BUFFER

The called Op-Amp Voltage Buffer is the simplest circuit. In this case, the output is looped back to the negative input. The role of this assembly is to adapt the impedance between stages.

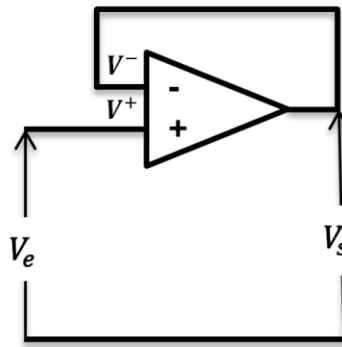


Figure 12 Op-Amp Voltage Buffer

The equation for this setup is as follows:

$$V_s = V_e$$

1.6.2 INVERTER AND NON-INVERTER AMPLIFIER

Under these conditions, we consider:

$$V^+ = V^- \text{ therefore } V^+ - V^- = \varepsilon$$

Let the circuit represented by the (Figure 13):

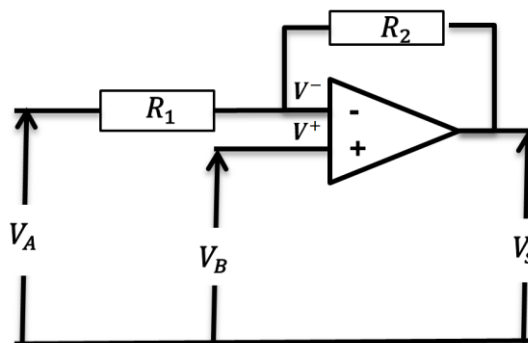


Figure 13 Negative Feedback Circuit

We can write the following two equations:

$$\left\{ \begin{aligned} V^- &= \frac{\frac{V_A}{R_1} + \frac{V_s}{R_2}}{\frac{1}{R_1} + \frac{1}{R_2}} = \frac{R_2 V_A + R_1 V_s}{R_1 + R_2} = \frac{R_2}{R_1 + R_2} V_A + \frac{R_1}{R_1 + R_2} V_s \\ &\text{and} \\ V^+ &= V_B \end{aligned} \right.$$

Where from: $V_s = \frac{R_1 + R_2}{R_1} V_B - \frac{R_2}{R_1} V_A = (1 + \frac{R_2}{R_1}) V_B - \frac{R_2}{R_1} V_A$

Negative feedback leads to a decrease in output voltage due to the difference in inputs. It is conceivable that the voltage will stabilize at a precise, equilibrium value. In addition, the transfer function is linear.

1.6.3 AN INVERTING AMPLIFIER

Using the same circuit as above, if we connect the (+) input to the ground, $V_B = 0$, the output equation will be:

$$V_s = -\frac{R_2}{R_1} V_A$$

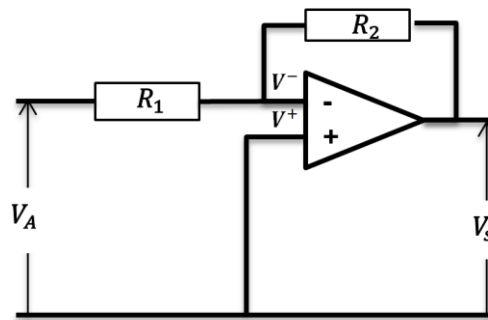


Figure 14 Inverter circuit

1.6.4 NON-INVERTING AMPLIFIER

If we now connect the input "A" to the ground $V_A = 0$. The input signal is injected through the "B" input.

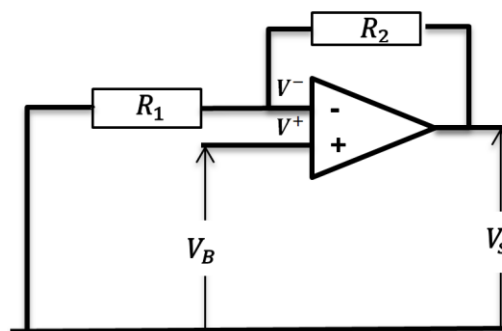


Figure 15 Non-inverter mounting

The equation can therefore be rewritten as follows:

$$V_s = (1 + \frac{R_2}{R_1})V_B$$

The gain is positive and always greater than unity, unlike the non-inverting circuit, which allows a gain (in value absolute value) of less than 1, (i.e. attenuation).

1.6.5 NON-INVERTING VOLTAGE SUMMING AMPLIFIER

The system is linear, $V^+ = V^-$

$$V^- = \frac{\frac{V_s}{R_2}}{\frac{1}{R_1} + \frac{1}{R_2}} = \frac{\frac{V_s}{R_2}}{\frac{R_1 + R_2}{R_1 R_2}} = V_s \frac{R_1}{R_1 + R_2}$$

et

$$V^+ = \frac{\frac{V_A}{R_3} + \frac{V_B}{R_4}}{\frac{1}{R_3} + \frac{1}{R_4}} = \frac{R_4 V_A + R_3 V_B}{R_3 + R_4}$$

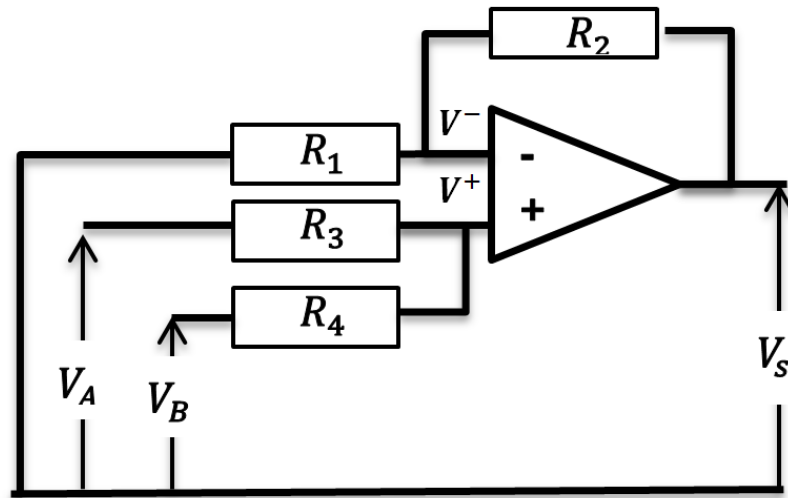


Figure 16 Non-inverting summing mounting

$$V_s \frac{R_1}{R_1 + R_2} = \frac{R_4 V_A + R_3 V_B}{R_3 + R_4}$$

Where from:

$$V_s = R_4 \frac{(R_1 + R_2)}{R_1(R_3 + R_4)} V_A + R_3 \frac{(R_1 + R_2)}{R_1(R_3 + R_4)} V_B$$

This circuit allows you to increase the amplitude of both signals depending on choice of resistors. At the same time, it's possible to sum the two input signals. For example, in the case of, $R_1 = R_2 = R_3 = R_4$, the output voltage is : $V_s = V_A + V_B$.

1.6.6 VOLTAGE INVERTER SUMMING AMPLIFIER

In this arrangement the inputs V_A and V_B are connected to the negative input of the Op-Amp.

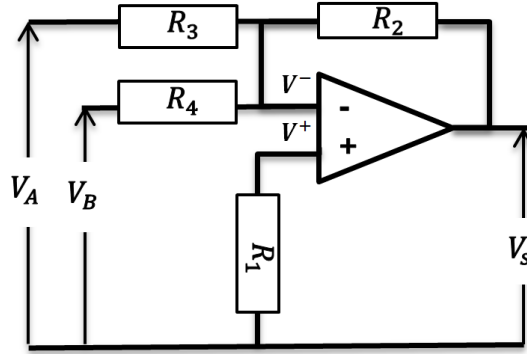


Figure 17 Voltage inverter summing circuit

$$V^- = \frac{\frac{V_s}{R_2} + \frac{V_A}{R_3} + \frac{V_B}{R_4}}{\frac{1}{R_2} + \frac{1}{R_3} + \frac{1}{R_4}} = V^+ = 0$$

$$\frac{V_s}{R_2} + \frac{V_A}{R_3} + \frac{V_B}{R_4} = 0$$

$$V_s = -\frac{R_2}{R_3} V_A - \frac{R_2}{R_4} V_B$$

We can see that this assembly is the inverted sum of V_A and V_B with the respective gains R_2/R_3 and R_2/R_4 .

1.6.7 SUMMING AMPLIFIER WITH OFFSET

We use the same formula found for the inverter summer case, however, we notice that $V_A = V_0$ (offset voltage) which can vary between $+V_{cc}$ and $-V_{cc}$ and $V_B = V_e$.

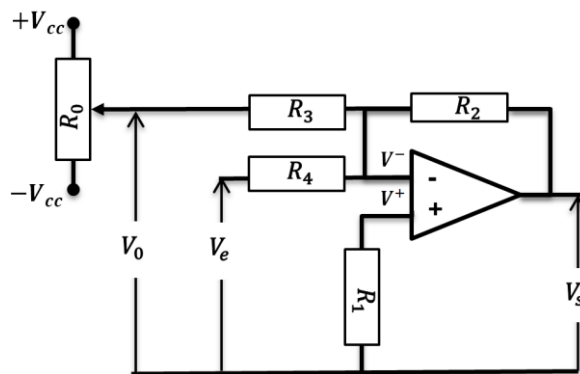


Figure 18 Summer Mounting with Offset

$$V_s = -\left(\frac{R_2}{R_4}V_e + \frac{R_2}{R_3}V_0\right)$$

$$\text{If } R_1 = R_2 = R_3 = R_4, V_s = -(V_e + V_0)$$

To achieve good amplification accuracy or for weak input signals, it is essential to adjust the offset.

1.6.8 CASCADING OF AMPLIFIERS

In op-amp circuits, cascade circuits are used, which are the most common form of cascade circuits. Cascaded circuits are calculated in parts, for example for the following figure is made up of one of two circuits, the first is a follower the second is a non-inverting circuit.

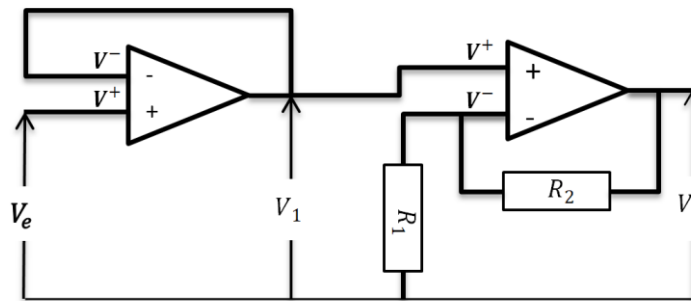


Figure 19 Cascading of Op-amp

Using the results found previously:

- For follower buffer: $V_1 = V_e$.
- For non-inverter mounting: $V_s = \left(1 + \frac{R_2}{R_1}\right)V_1$

The final equation is: $V_s = \left(1 + \frac{R_2}{R_1}\right)V_e$

1.7 INSTRUMENTATION AMPLIFIER

An instrumentation amplifier is a device for detecting small signals used in noisy environments to reduce noise generated by amplification and improve open-loop gain. These are differential amplifiers that have the advantage of having very high input impedance. Compare with the differential amplifier circuit.

1.7.1 TWO OP-AMP INSTRUMENTATION AMPLIFIER

This arrangement consists of two non-inverting assemblies.

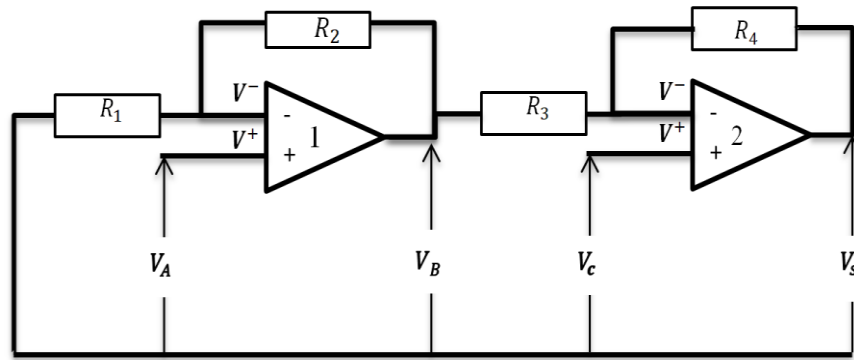


Figure 20 Cascaded 2 Op-Amps

From the first cut (amp 1), you can write:

$$V_B = \left(1 + \frac{R_2}{R_1}\right)V_A$$

On the other hand, for the second edit (Amp 2), it's a linear setup.

$$\begin{aligned} V^- &= V^+ \\ \text{And } \left\{ \begin{aligned} V^- &= \frac{\frac{V_S + V_B}{\frac{R_4}{R_3} + 1}}{\frac{1}{R_3} + \frac{1}{R_4}} = \frac{R_3 V_S + R_4 V_B}{R_3 + R_4} \\ V^+ &= V_C \end{aligned} \right\} \end{aligned}$$

$$V_C = \frac{R_3 V_S + R_4 V_B}{R_3 + R_4}, \text{ which gives } V_S = V_C \frac{(R_3 + R_4)}{R_3} - \frac{R_4}{R_3} V_B$$

$$\text{Finally, } V_S = V_C \frac{(R_3 + R_4)}{R_3} - \frac{R_4}{R_3} \left(1 + \frac{R_2}{R_1}\right)V_A$$

If we make the following constraint to simplify: $\frac{R_2}{R_1} = \frac{R_3}{R_4}$

$$V_S = V_C \left(1 + \frac{R_4}{R_3}\right) - \left(1 + \frac{R_4}{R_3}\right)V_A$$

And finally:

$$V_S = \left(1 + \frac{R_4}{R_3}\right)(V_C - V_A)$$

It is a differential assembly that makes the difference between the two inputs V_C and V_A .

1.7.2 THEE OP-AMP INSTRUMENTATION AMPLIFIER MOUNTING

Showing the assembly of the following figure:

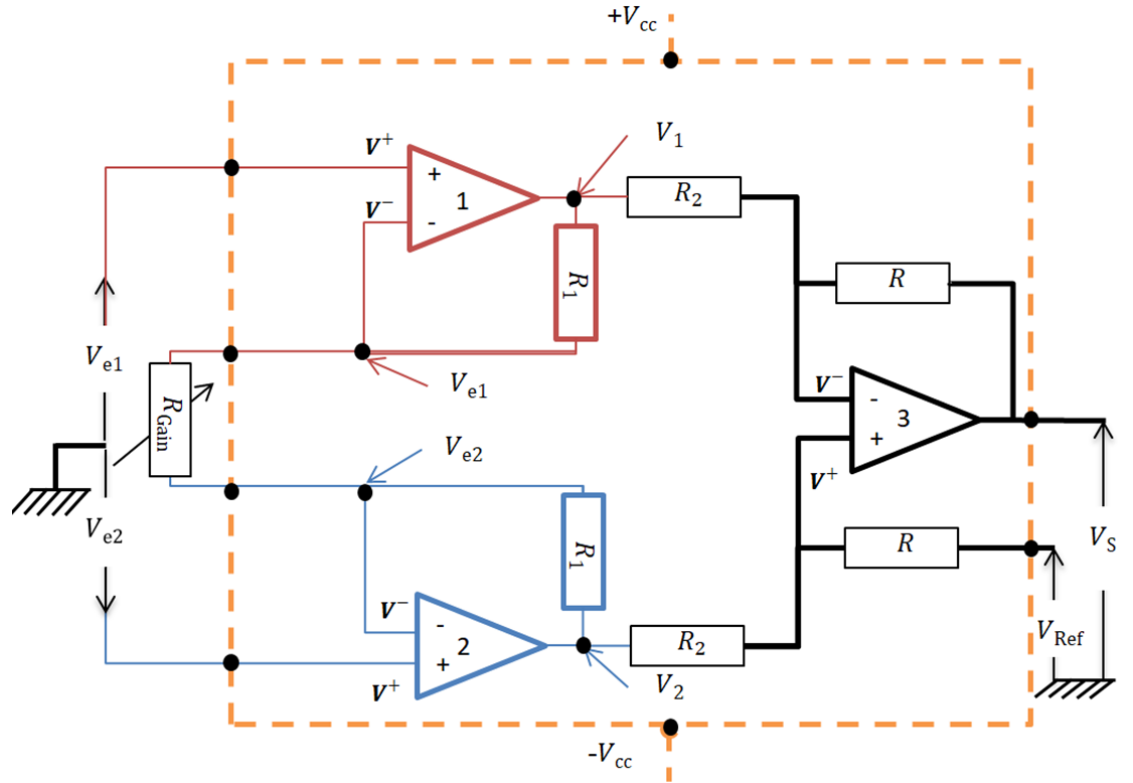


Figure 21 Instrumentation amplifier

Equations:

- For Amplifier (1)

$$\left\{ \begin{array}{l} V^- = \frac{\frac{V_1}{R_1} + \frac{V_{e2}}{R_{Gain}}}{\frac{1}{R_1} + \frac{1}{R_{Gain}}} = \frac{R_{Gain}V_1 + R_1V_{e2}}{R_1 + R_{Gain}} \\ V^+ = V_{e1} \\ V^- = V^+ \end{array} \right\}$$

This gives:

$$\frac{R_{Gain}V_1 + R_1V_{e2}}{R_1 + R_{Gain}} = V_{e1}$$

We derive the value of: V_1

$$V_1 = V_{e1} \left(\frac{R_1 + R_{Gain}}{R_{Gain}} \right) - \frac{R_1}{R_{Gain}} V_{e2}$$

- With Amplifier (2)

Given the symmetry of the setup, we deduce directly the equation of V_2

$$V_2 = V_{e2} \left(\frac{R_1 + R_{Gain}}{R_{Gain}} \right) - \frac{R_1}{R_{Gain}} V_{e1}$$

- About the amp (3)

$$\left\{ \begin{array}{l} V^- = \frac{\frac{V_1}{R_2} + \frac{V_s}{R}}{\frac{1}{R_2} + \frac{1}{R}} = \frac{RV_1 + R_2V_s}{R_2 + R} \\ V^+ = \frac{\frac{V_2}{R_2} + \frac{V_{Ref}}{R}}{\frac{1}{R_2} + \frac{1}{R}} = \frac{RV_2 + R_2V_{Ref}}{R_2 + R} \\ V^- = V^+ \end{array} \right.$$

We write:

$$\frac{RV_1 + R_2V_s}{R_2 + R} = \frac{RV_2 + R_2V_{Ref}}{R_2 + R}$$

We draw : V_s

$$V_s = \frac{R}{R_2}(V_2 - V_1) + V_{Ref}$$

Let's replace with the values and already found V_1V_2

$$\begin{aligned} V_s &= \frac{R}{R_2}(V_2 - V_1) + V_{Ref} \\ &= (V_{e2} - V_{e1}) \left(\frac{2R_1 + R_{Gain}}{R_{Gain}} \right) \\ V_s &= \frac{R}{R_2} \left(1 + \frac{2R_1}{R_{Gain}} \right) (V_{e2} - V_{e1}) + V_{Ref}. \end{aligned}$$

1.8 USEFUL AMPLIFIER ASSEMBLIES

In this part, we will introduce some useful amplifier setups that are commonly used in sensor measurement chains.

1.8.1 LINEARIZATION CIRCUIT

Let's calculate the output voltage of a divider bridge V_{AB} :

$$\begin{aligned} V_{AB} &= V_A - V_B \\ V_A &= \frac{R_1 + \Delta R}{2R_1 + \Delta R} V_{cc} \text{ and } V_B = \frac{1}{2} V_{cc} \text{ (voltage divider circuit).} \\ V_{AB} &= \frac{R_1 + \Delta R}{2R_1 + \Delta R} V_{cc} - \frac{1}{2} V_{cc} \\ V_{AB} &= \frac{2R_1 + 2\Delta R}{2(2R_1 + \Delta R)} V_{cc} - \frac{(2R_1 + \Delta R)}{2(2R_1 + \Delta R)} V_{cc} \\ V_{AB} &= \frac{2R_1 + 2\Delta R - 2R_1 - \Delta R}{2(2R_1 + \Delta R)} V_{cc} \\ V_{AB} &= \frac{\Delta R}{4R_1 + 2\Delta R} V_{cc} \end{aligned}$$

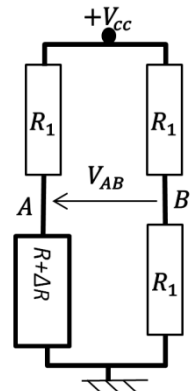


Figure 22 Divider Bridge

The voltage V_{AB} in function ΔR is not linear.

Let us now calculate this voltage if this voltage is observed by an operational amp (see V_{AB} Figure 23).

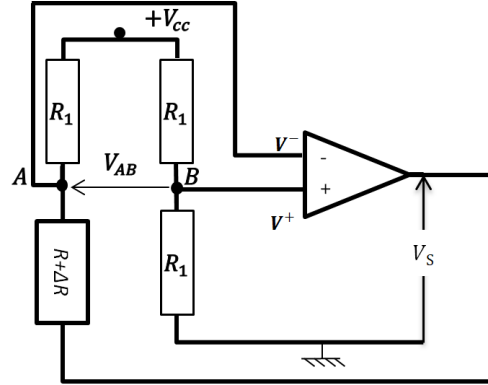


Figure 23 Linearization circuit

The assembly is linear $V^- = V^+$ (against negative reaction)

Calculation of $V^+ = V_B$: the voltage $V^+ = \frac{1}{2} V_{cc}$ (voltage divider).

Calculation of $V^- = V_A = \frac{\frac{V_{cc} + V_s}{\frac{1}{R_1} + \frac{1}{R + \Delta R}}}{\frac{1}{R_1} + \frac{1}{R + \Delta R}}$

$$V^- = V_A = \frac{(R + \Delta R)V_{cc} + R_1 V_s}{R + \Delta R + R_1}$$

$$V_s = +\frac{R_1}{2R_1} V_{cc} - \frac{1}{2R_1} V_{cc}(R + \Delta R) =$$

Finally:

$$V_s = \frac{R_1 - (R - \Delta R)}{2R_1} V_{cc}$$

It is clear that the function has become linear by integrating an Op-Amp $V_s = f(\Delta R)$.

Note: Simply add an inverter circuit to eliminate the negative sign.

1.8.2 CURRENT-VOLTAGE CONVERTERS

To convert a current signal to a voltage signal for more convenient analysis.

In some circumstances, such as conditioning a current source sensor like AD-590 or a photodiode, it is necessary to convert a current into a voltage.

The simplest method is used by inserting a resistor R into the circuit: the voltage across the resistor changes depending on the current flowing through it. This is suitable if the current generator is ideal. In fact, this is not always the case. In practice, current generators always have an internal resistance (Figure 24). The example shows that the voltage measured across the conversion resistor R is $V_m = \frac{R \cdot R_m}{R + R_m} I_m$ and not $R \cdot I_m$. Part of the current flows through R (resistance of the measuring device). In other words; the current I_m does not flow completely through R .

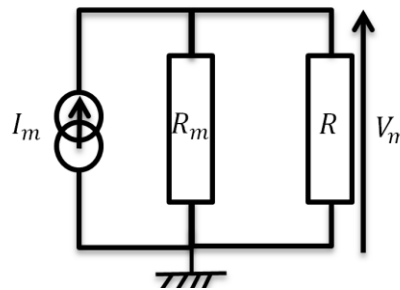


Figure 24 Current-to-voltage conversion using a resistor

To solve this problem, the current-voltage converter circuit consisting of an Op-Amp and resistor R a feedback (Figure 25).

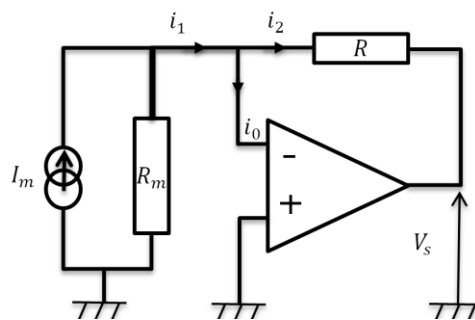


Figure 25 Current-to-voltage converter

In the majority of cases $R_m \gg$ to the resistance the inverting input.

We write $i_1 \approx i_2 = I_m$

Where from:

$$V_s = -RI_m$$

The voltage is an image of the current I_m ; we have a current converter in a voltage.

1.8.3 VOLTAGE-TO-CURRENT GENERATOR CONVERSION

A current voltage converter can be made with an operational amplifier as shown in the Figure 26.

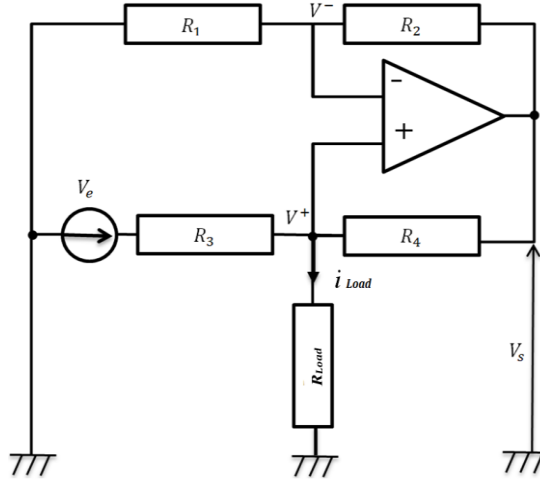


Figure 26 Voltage to Current Generator Conversion (Howland Source)

Let's calculate the current i_{Load}

$$i_{Load} = \frac{V^+}{R_{Load}}$$

The assembly is linear, therefore $V^- = V^+$,

$$V^- = \frac{\frac{V_s}{R_2}}{\frac{1}{R_1} + \frac{1}{R_2}} = \frac{R_1 V_s}{R_1 + R_2} = V^+ \text{ and } V_s = \frac{R_1 + R_2}{R_1} V^+.$$

Moreover; $V^+ = \frac{\frac{V_e}{R_3} + \frac{V_s}{R_4}}{\frac{1}{R_{Load}} + \frac{1}{R_3} + \frac{1}{R_4}}$ and we replace by its value we find:

$$V^+ = \frac{\frac{V_e}{R_3} + \frac{1}{R_4} \left(\frac{R_1 + R_2}{R_1} \right) V^+}{\left(\frac{1}{R_{Load}} + \frac{1}{R_3} + \frac{1}{R_4} \right)}$$

$$V^+ = \frac{V_e}{\left[\left(1 + \frac{R_3}{R_{Load}} + \frac{R_3}{R_4} \right) - \frac{R_3}{R_4} \left(\frac{R_1 + R_2}{R_1} \right) \right]}$$

The load current is then:

$$i_{Load} = \frac{V_e}{R_{Charge} \left[\left(1 + \frac{R_3}{R_{Load}} + \frac{R_3}{R_4} \right) - \frac{R_3}{R_4} \left(\frac{R_1 + R_2}{R_1} \right) \right]}$$

$$i_{Load} = \frac{V_e}{\left[\left(R_{Load} + R_3 + \frac{R_3}{R_4} R_{Load} \right) - \frac{R_3}{R_4} R_{Load} \left(\frac{R_1 + R_2}{R_1} \right) \right]}$$

$$i_{Load} = \frac{V_e}{R_3 + R_{Load} \left(1 + \frac{R_3}{R_4} - \frac{R_3}{R_4} \left(\frac{R_1 + R_2}{R_1} \right) \right)}$$

For the current to be independent of the load, it is necessary that:

$$R_{Load} \left(1 + \frac{R_3}{R_4} - \frac{R_3}{R_4} \left(\frac{R_1 + R_2}{R_1} \right) \right) = 0$$

Let $R_{Load} = 0, V_s = 0$. ,

$$\text{Or: } 1 + \frac{R_3}{R_4} - \frac{R_3}{R_4} \left(\frac{R_1 + R_2}{R_1} \right) = 0$$

$$\frac{R_3 + R_4}{R_4} = \frac{R_3}{R_4} \left(\frac{R_1 + R_2}{R_1} \right)$$

$$R_1 R_3 + R_1 R_4 = R_1 R_3 + R_2 R_3$$

$$R_1 R_4 = R_2 R_3$$

Finally, the current: $i_{Load} = \frac{V_e}{R_3}$

The simplest special case if:

$$R_1 = R_2 = R_3 = R_4 = R$$

$$V_s = 2V^+ \text{ and } V^+ = \frac{R_{Load}}{R} V_e, V_s = 2 \frac{R_{Load}}{R} V_e \text{ and } i_{Load} = \frac{V_e}{R}$$

The circuit therefore behaves in the same way as a perfect current source, no matter what its value; the resistor R_{Load} will always be traversed by the same current i_{Load} . In the event of an equality of the four resistances, we obtain $i_{Load} = \frac{V_e}{R}$. This arrangement is called the Howland Current Source.

CHAPTER 2.

PHYSICAL PHENOMENA PRESENT IN SENSORS

SUMMARY OF CHAPTER 2

This chapter examines the physical phenomena used in different types of sensor. It covers the thermoelectric effect, where a temperature difference generates a voltage, the pyroelectric effect, which relies on heat-induced changes in certain materials, and the piezoelectric effect, which generates an electrical charge in response to mechanical pressure.

The chapter also covers the Hall Effect, used in magnetic field sensors, and the photovoltaic effect, which converts light into electricity. Other phenomena such as conduction, capacitance and inductance effects are explored, each of which is fundamental to the detection of different physical parameters.

These phenomena are the key to understanding how sensors measure changes in physical environments, which is essential for developing efficient and accurate sensors.

2.1 INTRODUCTION

Many physical phenomena can be used in sensors, to measure quantities such as temperature, pressure, distance, speed, acceleration, brightness, etc.

Here are some of the most common phenomena used in sensors:

2.2 THERMOELECTRIC EFFECT

This effect is used in thermocouples to measure temperature by producing a voltage proportional to the temperature difference between the two ends of the thermocouple.

A circuit formed by two conductors of different chemical nature or two semiconductors whose junctions are at temperatures T_1 and T_2 is the seat of an electromotive force.

$e = f(T_1, T_2)$. This phenomenon is called **the Seebeck effect**.

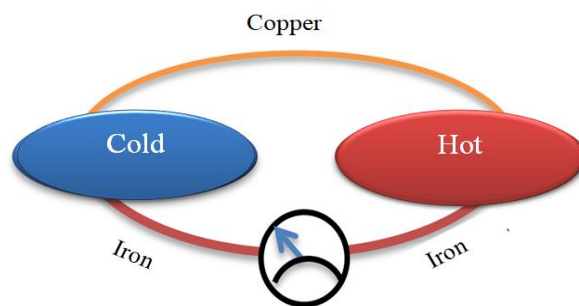


Figure 27 Seebeck effect thermoelectricity

The opposite principle, known as **the Peltier effect**, allows mini-refrigerators or electronic modules, for example, to generate cold from an electrical voltage.

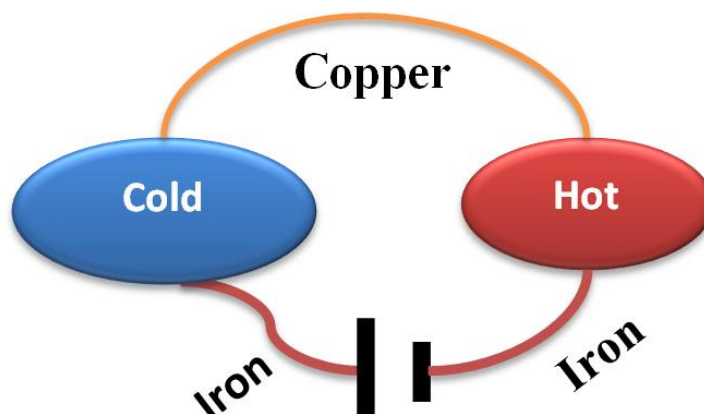


Figure 28 Principle of the Peltier Effect

The Peltier effect occurs when two types of conductors are subjected to a direct voltage. The direction of heat travel depends on the direction of current flow through the conductors, which ensures the reversibility of the system.

2.3 CONDUCTION EFFECT

It is typically used in thermal resistance temperature sensors to measure temperature by measuring the electrical resistance of the temperature-sensitive material.

Conduction occurs when heat flows pass from one body to another, through contact. Convection is when a moving body takes with it the heat it contains. This mode of transfer involves a displacement of matter in the medium.

2.4 PYROELECTRIC

Pyro-electricity is a physical phenomenon that occurs in certain crystalline materials when they are subjected to temperature variations. These materials, called pyro-electrics, generate an electrical charge when heated or cooled (Figure 29). This phenomenon is due to an imbalance in the distribution of electric charges inside the crystal.

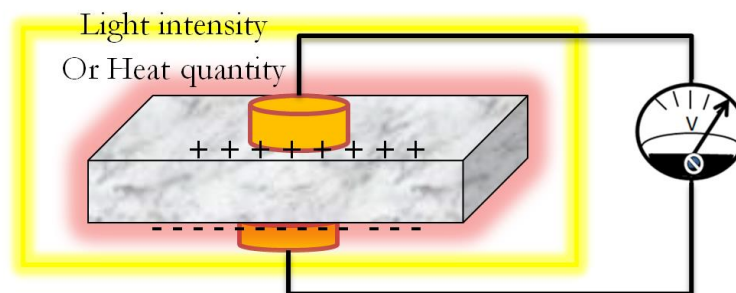


Figure 29 Generation of loads due to temperature variation or variation in light intensity

Applications of pyroelectricity include heat sensors, motion detectors, and energy conversion devices. The pyroelectric materials are often used in devices such as infrared sensors and thermal monitoring devices.

2.5 PIEZOELECTRIC EFFECT

Pressure and displacement sensors use the piezoelectric effect (piezo: squeeze) to produce a voltage proportional to the deformation of the piezoelectric material.

The conversion of mechanical energy (deformation) into electrical energy is known as the direct piezoelectric effect, and conversely, if an electric field is applied, a mechanical vibration is obtained.

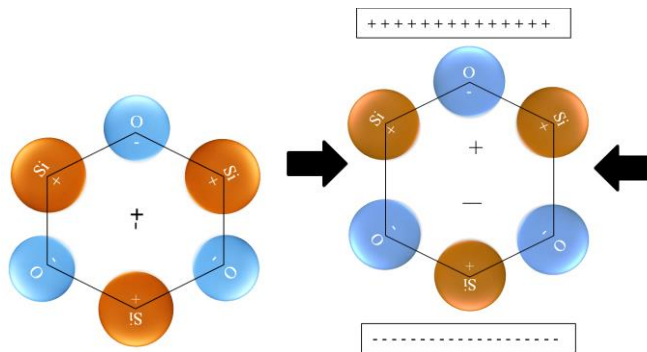


Figure 30 Principle of direct piezoelectricity

Among the most widely used piezoelectric materials at the moment is quartz (SiO_2).

2.6 HALL EFFECT

Generally, position sensors use this effect: it consists of measuring the magnetic field by producing proportional voltage to the strength of the field.

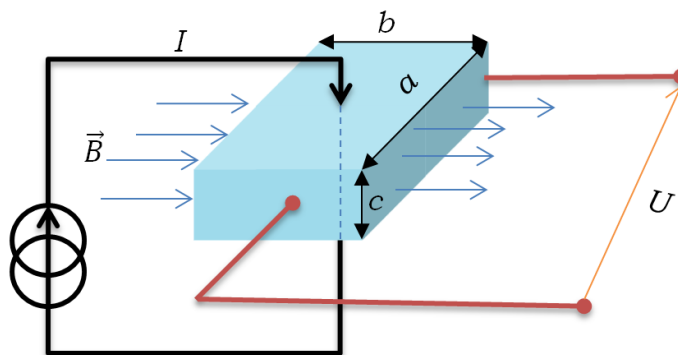


Figure 31 Principle of the Hall Effect

A semiconductor bar subjected to a uniform magnetic field B is traversed by an electric current of intensity I , and is the seat of an electromotive force U on two of its faces.

$$U = \left(\frac{1}{n \cdot e} \right) \frac{I \cdot B}{b}$$

n : Number of electrons per unit volume.

e : Charge of the electron.

$K_H = \frac{1}{n \cdot e}$ Represents Hall's constant.

Note that the voltage is inversely proportional to the number of electrons per unit volume, if a large number of charge carriers are present, the Hall voltage becomes lower. This is why semiconductors are used in Hall effect applications.

2.7 PHOTOVOLTAIC EFFECT

The effect is used in photoresistors and photodiodes to measure brightness by producing a voltage proportional to the intensity of the incident light (Figure 32).

The photovoltaic effect refers to the ability of certain materials, particularly semiconductors, to directly convert the various components of sunlight (and not its heat) into electricity.

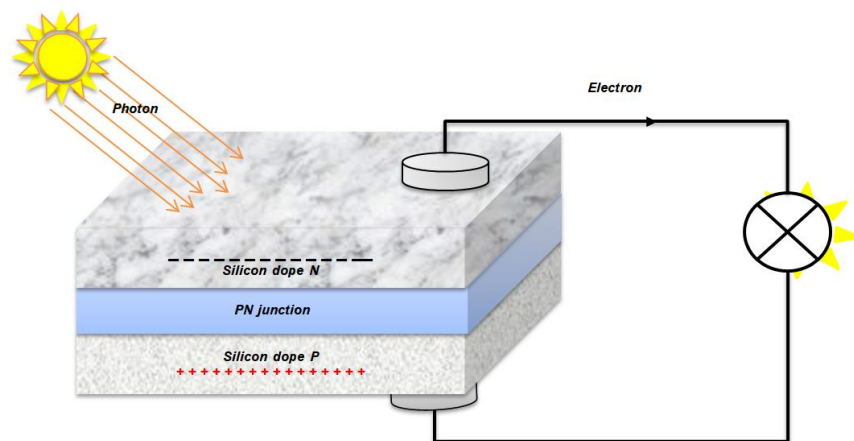


Figure 32 Principle of the photovoltaic effect

This phenomenon is used in photoelectric sensors such as photodiodes and phototransistors.

2.8 CAPACITANCE EFFECT

Capacitor displacement sensors used this effect to measure position by measuring the capacitance of the system.

This relates to the ability of a substance subject to a potential difference to store electrical charges.

The capacity depends mainly on the type of insulation and the geometry of the two conductors. This phenomenon can be used to measure the level of a liquid.

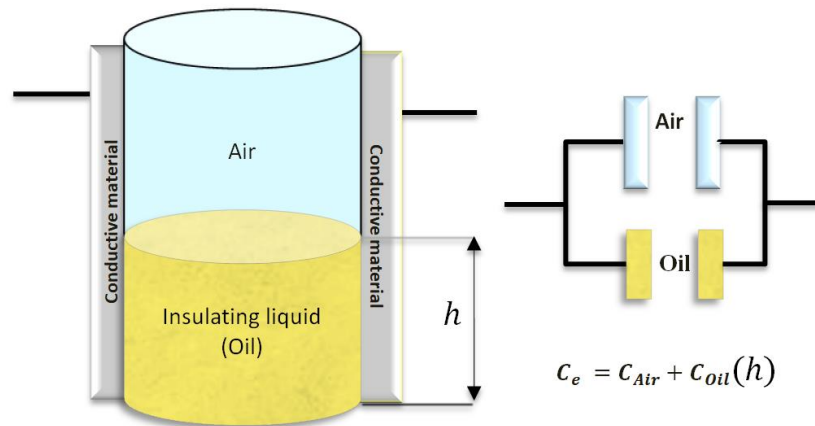


Figure 33 Application of the capacitive effect

Two conductors form the system, while the insulation is made of two insulators, namely air and oil. This is equivalent to two capacitors in parallel. The level varies depending on the height of the oil in the tank.

2.9 INDUCTANCE EFFECT

The effect is used in induction speed sensors to measure speed by measuring changes in the system's inductance.

Variable inductance and variable reluctance sensors generally produce an electrical signal proportional to the displacement of a conductive or magnetically permeable object (usually a steel rod) with respect to a coil (Figure 34).

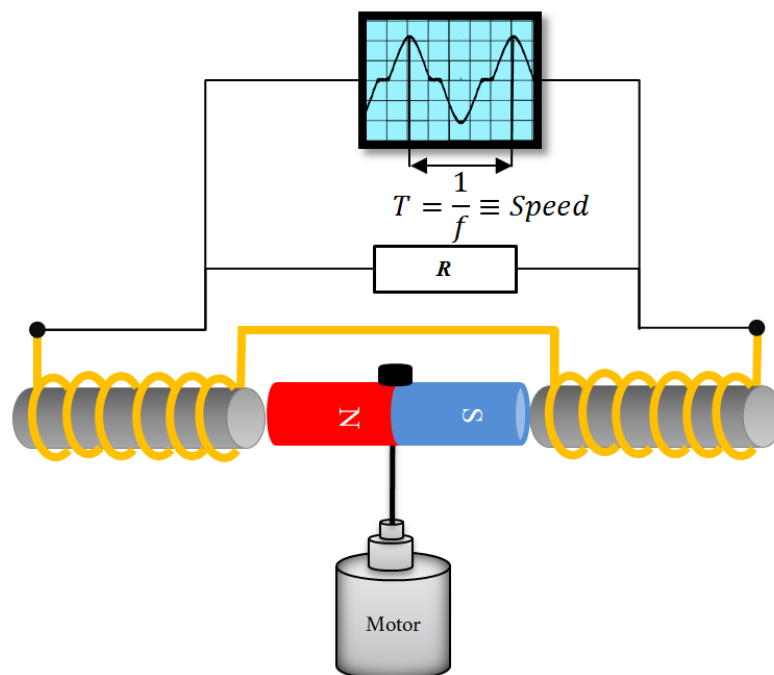


Figure 34 Use of the inductive effect for measuring the rotational speed

CHAPTER 3.

CHARACTERISTICS OF THE SENSORS

SUMMARY OF CHAPTER 3

This chapter is dedicated to sensor characteristics and operation. It begins by defining what a sensor is, and distinguishes between different types of sensor, such as transmitters and detectors. It focuses on the different quantities associated with a sensor, such as measurement, measurement range, resolution and sensitivity. These properties are essential for assessing a sensor's performance under specific conditions.

The chapter also covers criteria such as accuracy, linearity, hysteresis and response speed, which influence measurement quality. Errors such as systematic errors and resolution errors are detailed, along with their impact on overall sensor performance.

Finally, sensors are classified according to the type of output signal (analog or digital) and the quantities they measure, such as temperature, pressure or distance. Passive and active sensors are explained, highlighting their differences and specific applications.

3.1 DEFINITION OF A SENSOR

Generally speaking, the international vocabulary of metrology considers the sensor to be an element of a measurement system that is directly subject to the action of the phenomenon, the body or the substance bearing the quantity to be measured.

3.1.1 INTRODUCING A SENSOR

A sensor is a device that detects and measures physical quantities such as temperature, pressure, light, etc. It converts these quantities into usable electrical or electronic signals.

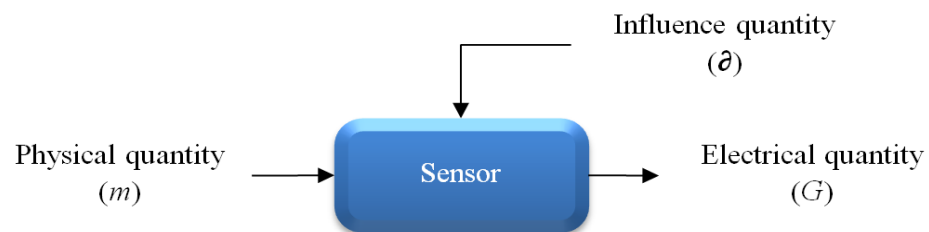


Figure 35 Presentation of a sensor

The measurand is used to designate the physical quantity to be measured. The electrical quantity can be a current or a voltage, or even an impedance variation.

The sensor can be thought of as a black box that converts a measurement (m) into voltage or electric current. However, the output of a sensor is not only based on the measurand, but also on the influence quantity (∂). The characteristics of the sensor are modified due to the interaction of physical quantities. Therefore, we can write:

$$G = f(m, \partial)$$

There are many different types of sensors, each designed to measure a particular range of physical quantities, such as pressure, distance, velocity, acceleration, etc.

3.1.2 TRANSMITTER

A transmitter is a device that receives electrical signals produced by a sensor and transforms them into a suitable form for transmission over a network or to another part of the system.

3.1.3 TRANSMITTER SENSOR

This is the composition of the two devices (sensor + transmitter); it picks up the specific physical quantity and then converts it into an electrical signal, and then transmits this signal to other devices or systems for processing, display or recording. It is used to monitor and measure physical parameters in various environments and transmit this information for use in control, monitoring, or automation systems.

3.1.4 DETECTOR

A detector is a sensor that specializes in detecting the presence or absence of specific substances, so its output signal is a logic signal from a sensor is a comparator.

3.2 CHARACTERISTICS OF A SENSOR'S QUANTITIES

A quantity called measurable if we know how to define an arithmetic relationship (sum, ratio between two values, etc.) of this quantity.

3.2.1 MEASURE

Physical measurement involves comparing the value of a quantity to another constant quantity of the same kind that will serve as a reference.

3.2.2 MEASUREMENT

Includes; all operations whose purpose is to measure a value of a quantity.

3.2.3 MEASURAND

It is the physical quantity to be measured (force, speed, displacement, etc.). This is the entry size.

It is important to choose a sensor that can measure the appropriate physical quantity for a given application to ensure that the measured data is reliable and accurate. The measurement range, sensitivity, accuracy, speed, and offset of the sensor are all important factors to consider ensuring optimal sensor operation for a given application.

3.2.4 CALIBRATION

Calibration is a measurement that ensures the same measurement result for a sensor. It verifies that the measurement produced complies with the standards. If this is not the case, it is possible to readjust the sensor setting.

3.2.5 MEASUREMENT RANGE

In English «*span of a nominal interval*», the MR (Measurement Range) is the interval of values in which the sensor is able to detect or measure a signal in a precise way.

Exemple 1: -

Consider a temperature sensor with a variable measuring range between (-20°C to 100°C). In this case, the measuring range of the sensor is (EM=100°C - (-20°C) = 120°C). This means that the sensor is designed to provide accurate measurements within that specific temperature range, but beyond this range, the accuracy of the measurements may decrease.

Exemple 2: -

For a nominal range of indications from -40 °C to +50 °C,

$$MR = /m_{max} - m_{min}/ = /50 - (-40)/ = 90^{\circ}C$$

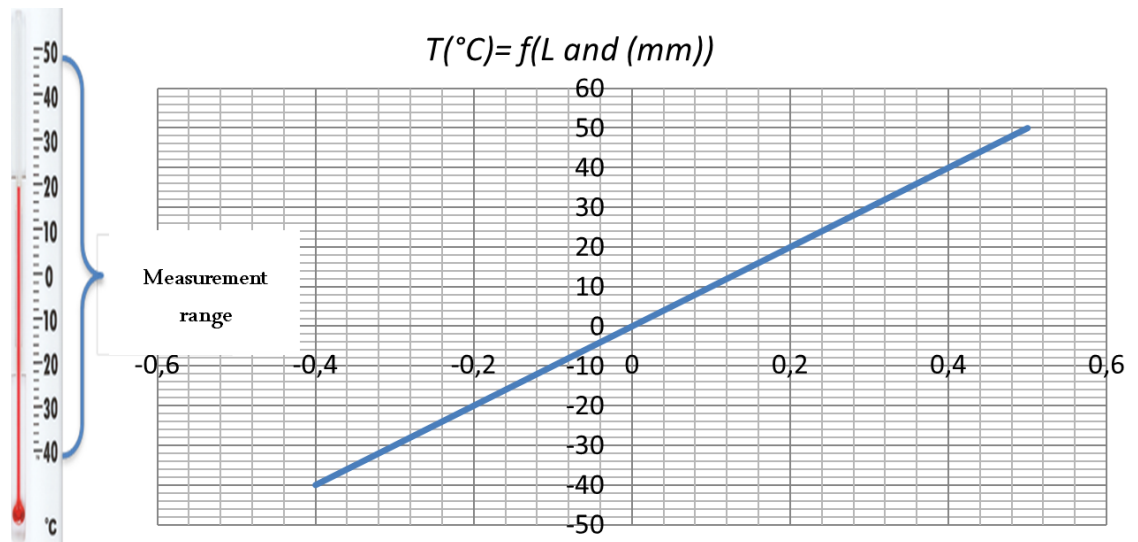


Figure 36 Measuring Range of a Sensor

3.2.6 RESOLUTION

This is the smallest difference in measurement that the sensor is able to detect. The resolution is usually expressed in units of the measured quantity.

Exemple 3: -

Consider a temperature sensor with a resolution of 0.1°C. This means that the sensor is able to detect temperature variations as small as 0.1°C. If the temperature rises from 25.0°C to 25.1°C, the sensor will be able to detect this difference. Higher resolution allows for more accurate measurement.

3.2.7 SENSITIVITY

It is the response of the sensor to a variation in the physical quantity measured. The higher the sensitivity, the more sensitive the sensor is to small changes in the measured quantity.

It is often defined as the ratio of the variation in the output of the sensor to the corresponding variation in the input quantity.

$$S = \frac{\Delta \text{Output variables}}{\Delta \text{Input size}}$$

High sensitivity means that small variations in the input quantity will produce significant changes in the sensor output.

A lower sensitivity indicates that the sensor is less responsive to small variations.

Exemple 4: -

A pressure sensor has sensitivity of 0.5 V/bar, this means that the output of the sensor will vary by 0.5 volts for each variation of one bar in the measured pressure.

3.2.8 PRECISION

This refers to the sensor's ability to measure the physical quantity with a high degree of accuracy error. The higher the precision, the lower is the measurement error. It is generally expressed as a percentage or in units of the measured quantity.

It is given by the relation:

$$\text{Precision} = \left(1 - \frac{\text{Error}}{\text{Calibration}}\right) * 100. \%$$

The error represents the difference between the sensor measurement and the true value.

The true value is a theoretical notion of a measured quantity, while the calibration value is the specific value used to adjust and verify the accuracy of a measuring instrument.

Exemple 5: -

A temperature sensor gives 30.7°C when the true temperature is 30°C, so the error is 0.7°C, the accuracy would be:

$$Précision = \left(1 - \frac{0.7}{30}\right) * 100. \% = 97.6\%$$

3.2.9 LINEARITY

This quantity represents the sensor's ability to provide proportional values to the physical quantity measured. The more linear the sensor, the closer the measured values are to a regression line.

Linearity can be expressed by the equation:

$$Output = A * Input + B$$

Where **A** is the slope of the output characteristic with respect to the input variable and **B** is the y-intercept.

Non-linearity can occur when the relationship between the output and the input variable is not perfectly linear. This may be due to imperfections in the design or variations in the properties of the material used for the sensor.

Exemple 6: -

The data from a pressure sensor is grouped in the following table:

Table 0-1 Pressure sensor readings

Pressure (Bars)	0	1	2	2,5	3	3,5	4	4,5	5
Output (Volts)	0,18	0,35	0,51	0,58	0,68	0,76	0,84	0,93	1,02

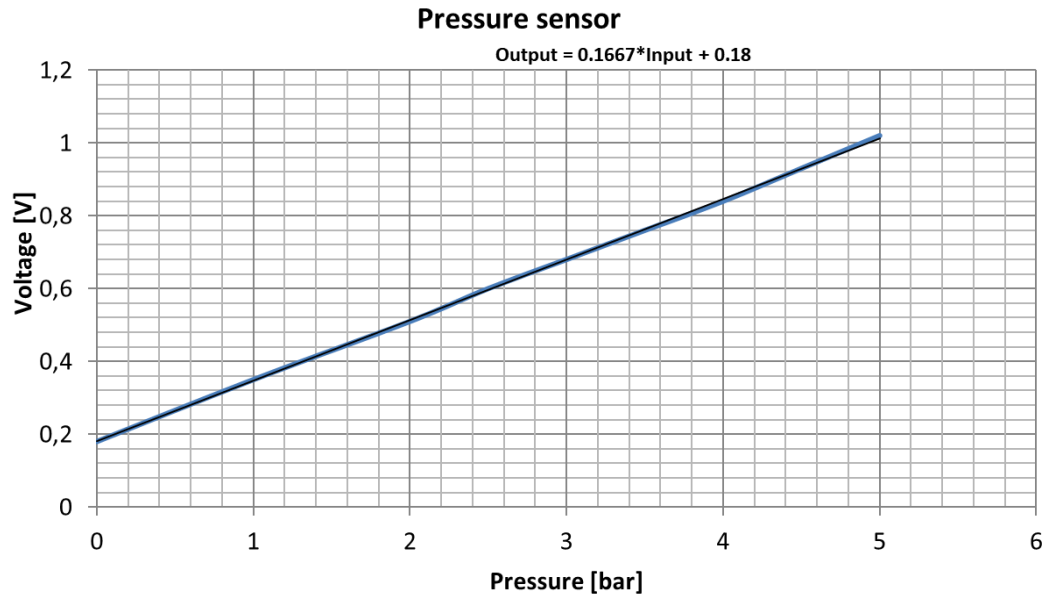


Figure 37 Linear Feature of a Pressure Sensor

3.2.10 HYSTERESIS

The value measured depends on the direction of variation of this measure, when the physical quantity varies in one direction rather than the other.

Sensor hysteresis is manifested by differences in the S_1 and S_2 response of the sensor for the same pressure input value P (Figure 38).

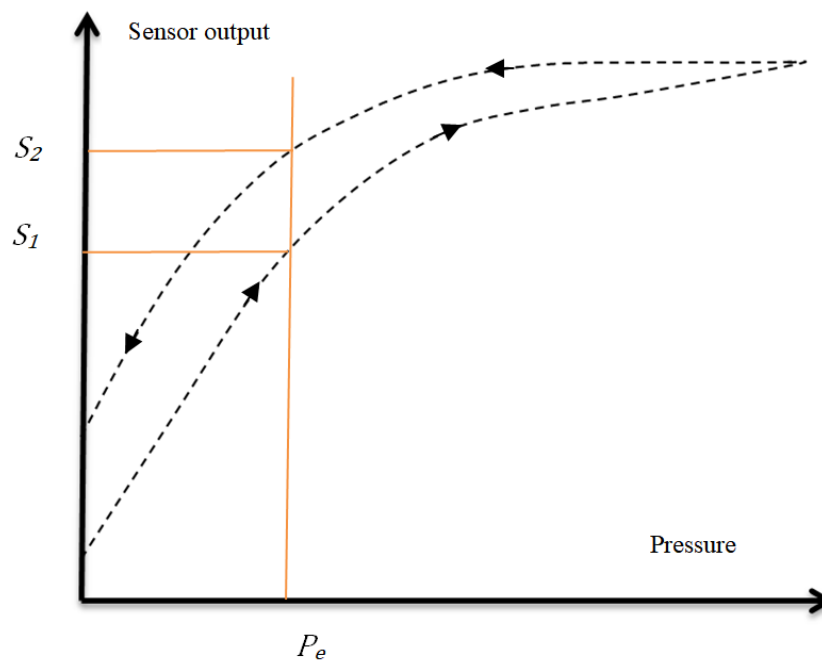


Figure 38 Hysteresis cycle of a pressure sensor

To minimize the effects of hysteresis, certain techniques can be used, such as software correction, calibration, or sensor design with specific materials and mechanisms to reduce this phenomenon.

3.2.11 SPEED

The speed of a sensor refers to its ability to detect and react quickly to a change in the quantity it is measuring. It is often measured in terms of response time, which represents the time it takes for the sensor to produce stable output in response to a change in the input quantity.

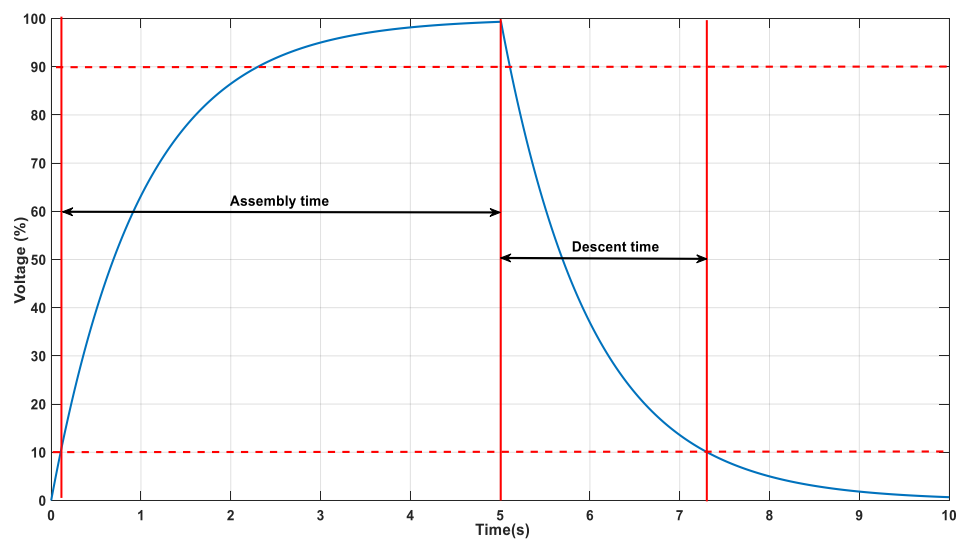


Figure 39 Response time

Several factors can influence the speed of a sensor:

- Mechanical inertia: Some sensors, especially those involving mechanical components, may have inertia that affects their ability to quickly track changes in the measured quantity.
- Signal processing electronics: The speed of the sensor's electronic circuit can play an important role. Fast signal processing allows the sensor to provide quick responses.
- Physical nature of the sensor: Some sensors, such as optical sensors or sensors based on chemical reactions, may have faster response times than others, such as thermal sensors.

The response time of a sensor can be specified by the manufacturer in the product specifications. It is important to select a sensor with an appropriate speed for the specific application, especially if the dynamics of the changes in the measured quantity are rapid.

3.3 CRITERIA FOR CHOOSING A SENSOR

There are three criteria to consider when choosing a sensor:

- The field of operation
- Performance
- Project Constraints

3.3.1 OPERATING AREA

The measurand and the influence quantities greatly determine the operating area of a sensor. They are classified into four categories of use.

3.3.1.1 NOMINAL DOMAIN

The nominal domain defines the measuring range (MR) that corresponds to the normal conditions of use of the sensor.

3.3.1.2 DOMAIN OF NON-DETERIORATION

The sensor may exceptionally operate outside its measurement range, but this damage may be reversible. Therefore, the sensor will easily recover its normal characteristics.

3.3.1.3 NON-DESTRUCTION DOMAIN

As soon as the sensor gets within this range, it can only be reused once it has been recalibrated, so that it can operate in the nominal range.

3.3.2 DESTRUCTION DOMAIN

The sensor can no longer be used and even a calibration cannot change it, the sensor is unusable.

Exemple 7: -

- To measure the temperature varying between 0°C and 50°C and sometimes this temperature will reach 60°C, to carry out this measurement we have the choice between the following three sensors:

Sensor	Domain			
	nominal	Limit of non-deterioration	Non-destruction limit	Destruction Limit
Has	0 °C to 20 °C	30 °C	40 °C	> 40 °C
B	0 °C to 50 °C	75 °C	100 °C	> 100 °C
C	0 °C to 100 °C	150 °C	200 °C	> 200 °C

The nominal measurement temperature is 50°C, it is normal to choose the B sensor.

Nominal		Limit of non-deterioration						Non-destruction limit					Non-destruction limit
0° C	50° C	51° C	60° C	65° C	70° C	75° C	76° C	85° C	90° C	95° C	100° C	101°C	

In this case, the sensor can perform normal temperature measurements. Therefore, the temperature of 60°C will be recorded in the non-deterioration range.

- In another scenario, if the temperature continues to fluctuate **continuously** between 20°C. In other words, it is between (50-20) °C=30°C and (50+20) °C= 70°C.±

In this situation, it is inappropriate to consider the B sensor because the values of 50°C to 70°C persist constantly in the non-deterioration range.

Let's choose the C sensor:

0°C	30°C	40°C	50°C	60°C	70°C	71°C	90°C	100°C	101°C	150°C	151°C	200°C	201°C
-----	------	------	------	------	------	------	------	-------	-------	-------	-------	-------	-------

It is clear that perturbation values are part of the normal domain.

From the very beginning, we had the option to select the C sensor. But, it is decisive to remember that the values will be digitized, and if the nominal range is increased, the resolution of the sensor will be worse.

3.4 SENSOR PERFORMANCE

A sensor is considered to be efficient if its measured values are very close to the true value (value measured by a high-performance sensor).

3.4.1 STATIC SENSOR PERFORMANCE

To evaluate the performance of a sensor, it is necessary to refer to the normative vocabulary of sensors. For the intimation of the static performance of the sensor, it is necessary to follow the following steps.

- Define the value of the measurand to the true value V_v
- Wait for the measurement to stabilize before taking the measured value V_m .
- The measure is raised
- Calculation and analysis of errors.

The analysis of performance can be schematized by the organizational chart of the (Figure 40).

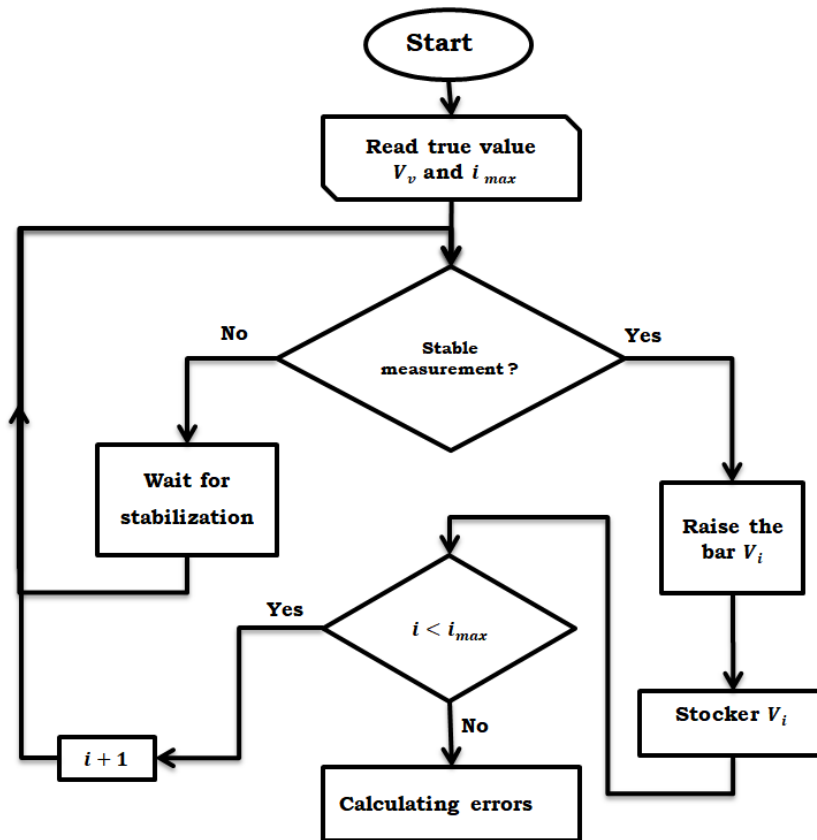


Figure 40 Steps for calculating errors

The dispersion study of the values resulting from the readings of a sensor allows the study of the performance of a sensor. For this study, it is necessary to go through the calculation of errors.

3.4.2 THE ABSOLUTE ERROR:

$$e = /V_v - V_m/$$

V_m : Measured value

V_v : True value (it is determined through a very precise measurement)

3.4.3 THE RELATIVE ERROR:

$$e_r = \frac{/V_v - V_m/}{PE} * 100\%$$

PE : Full-scale value is the maximum value of the measurement range.

3.4.4 AVERAGE VALUE

The mean shows that the measured values are close to a median. It is defined by:

$$V_{mean} = \frac{1}{n} \sum_{i=1}^n V_i$$

3.4.5 THE SYSTEMATIC ERROR:

Is the difference between the true value of the measurement and the average value of the experimental measurements.

$$e_s = V_v - V_{mean}$$

3.4.6 VARIANCE:

Variance is a measure that takes into account the scattering of all values in a dataset.

$$V = \frac{1}{n} \sum_{i=1}^n (V_i - V_{mean})^2$$

3.4.7 STANDARD DEVIATION:

Standard deviation: Evaluates the dispersion of the measurement data provided by the sensor around the mean value. When the standard deviation rate is low, the measured values are grouped around the mean value.

Under the specified conditions, standard deviation and variance are characteristics that allow the fidelity of a sensor to be expressed numerically.

Numerically, the standard deviation is the square root of the variance:

$$\sigma = \sqrt{V}$$

The advantage of the standard deviation is that it is of the same unit as the measurand.

For a good view of the results by drawing the so-called Gaussian curve which includes the measurement points, the curve tells us that for a certain value of measurand obtaining a certain probability of having this measurement, the curve has the equation:

$$p(V_i) = \frac{1}{\sigma\sqrt{2\pi}} \exp \frac{-(V_i - V_{mean})^2}{2\sigma^2}$$

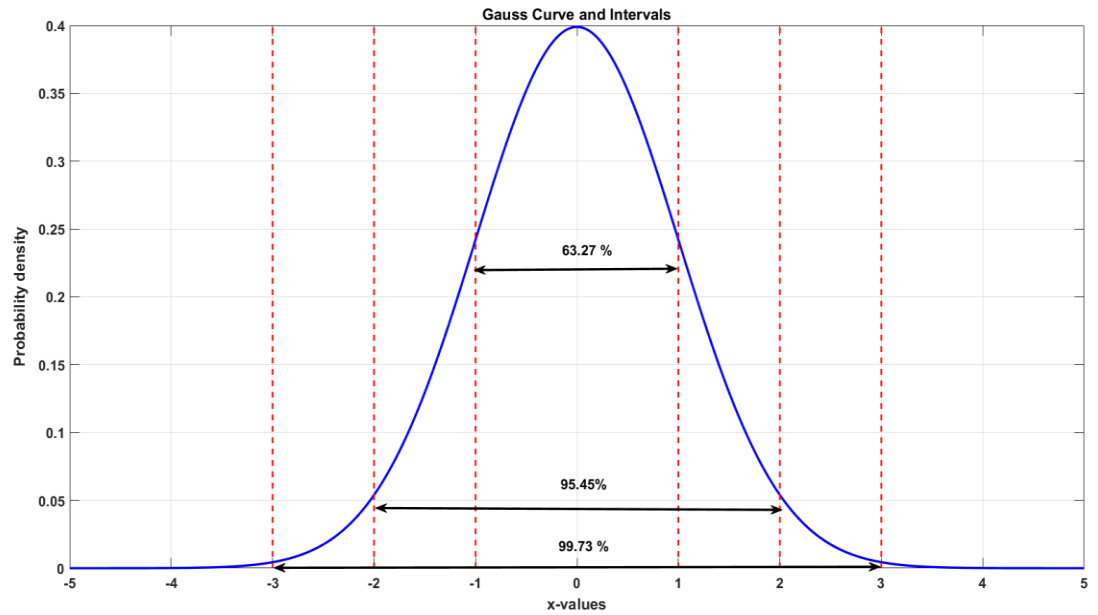


Figure 41 Probability density as a function of standard deviation

Meaning of the parameters for the sensors

σ : representation of **fidelity**

e_s : Systematic error represents **the correctness** for a sensor

Exemple 8: -

To compare the performance of three pressure sensors, the value measured is 15 bars by a very precise laboratory sensor; the results are grouped in the following table:

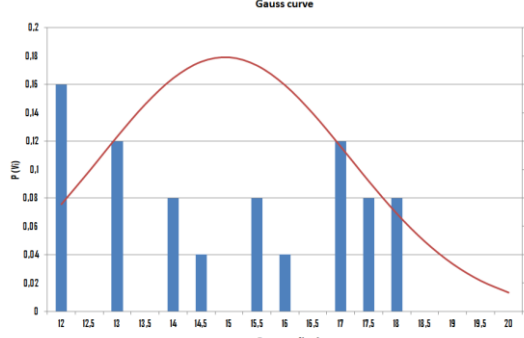
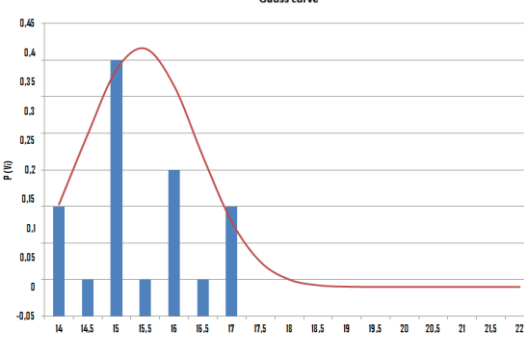
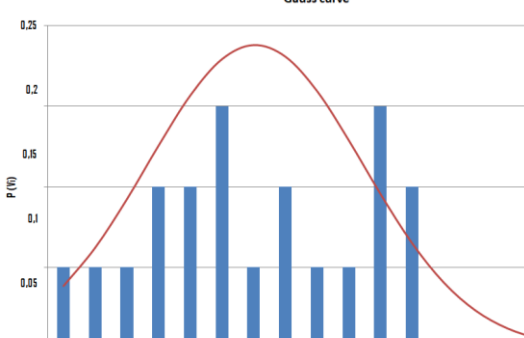
Table 0-2 Test results of 3 sensors

Nr	C1	C2	C3
1	12	15	13,5
2	17	14,5	14,5
3	17,5	15	16
4	15,5	15	14
5	14	15,5	17,5
6	17	17	17
7	14,5	15	14,5
8	17,5	17	13
9	18	15	12
10	13	17	17
11	13	15	15,5
12	15,5	16	15
13	12	14	12,5
14	17	16,5	15,5
15	16	16	17
16	12	16	14,5
17	12	14	16,5
18	18	16	14
19	14	15	17,5
20	13	14	13,5

For each sensor, we calculate:

The mean, maximum, minimum, standard deviation and systematic error.

Table 0-3 Results of the calculations of the 3 sensors

Pressure $P_v = 15$ bars		V_{mean} bar	V_{max} bar	V_{min} bar	σ bar	e_s bar
		Fidelit y		Justness		
C1						
		14,93	18	12	2,226	0,075
C2						
		15,43	17	14	0,977	0,425
C3						
		15,03	17.5	12	1,697	0,025

By comparing the results obtained (Table 0-3), it can be said that from the point of view of accuracy, the C3 sensor is the most accurate. However, C2 is the least accurate because it has the highest systematic error.

On the other hand, the C2 sensor is the most faithful of the three sensors, and the C1 sensor is the least faithful due to the dispersion of its values.

For the choice of the most accurate sensor, we adopt the sensor that converges to the same value for the same measurement. If we choose the most accurate one, we have opted for the sensor that minimizes the difference between the measurement and the true value.

To overcome this problem of choosing between accuracy and fidelity, one solution is to use a function that depends on the two variables, **fidelity** and **accuracy**, this function known as **precision**.

The error of accuracy $e_j = |V_{\text{mean}} - V_v|$

The error of fidelity $e_f = \sigma$.

The error of precision e_p

$$e_p = \sqrt{e_f^2 + e_j^2}$$

Using the previous example, we evaluate the errors. The results and observations are presented in the following table:

Table 0-4 Calculation of precision error

Sensor	$e_f = \sigma$	$e_j = \text{Systematic error}$		e_p	Remark	
		Fidelity	Justness			
C1	2,226	0,075	2,227	fair and less faithful	is not accurate	
C2	0,977	0,425	1,065	The most faithful of the 3 sensors	Most accurate of the 3 sensors	
C3	1,697	0,025	1,697	The fairest of the 3 sensors	Moderately accurate	

3.4.8 DECOMPOSITION OF THE ACCURACY ERROR

Indeed, the error of accuracy manifests itself in several errors:

- Linearity error
- Hysteresis error
- Resolution error

3.4.9 DETERMINING THE LINEARITY ERROR

To determine the linearity error, it is necessary to record the corresponding measurement for each measurement value.

After the measurement curve is drawn, the most significant affine equation (endpoints, best estimated, etc.) is determined using the available software.

Table 0-5 Estimating the Sensor Equation and Calculating Linearity Errors

Measurand	$y_{mesurée}$	$y = 2.0182 * x + 4,5273$	$e_l = y_{mesurée} - y$	$ e_l $
6	17	16,6365	0,3635	0,3635
7	18	18,6547	-0,6547	0,6547
8	22	20,6729	1,3271	1,3271
9	23	22,6911	0,3089	0,3089
10	26	24,7093	1,2907	1,2907
11	26	26,7275	-0,7275	0,7275
12	29	28,7457	0,2543	0,2543
13	32	30,7639	1,2361	1,2361
14	33	32,7821	0,2179	0,2179
15	33	34,8003	-1,8003	1,8003
16	37	36,8185	0,1815	0,1815

It is obvious that the error changes according to the measurand point. Therefore, the worst-case case is preferred, thus favoring the maximum error of 1.8003 [unit of measurement]. $|e_l| =$

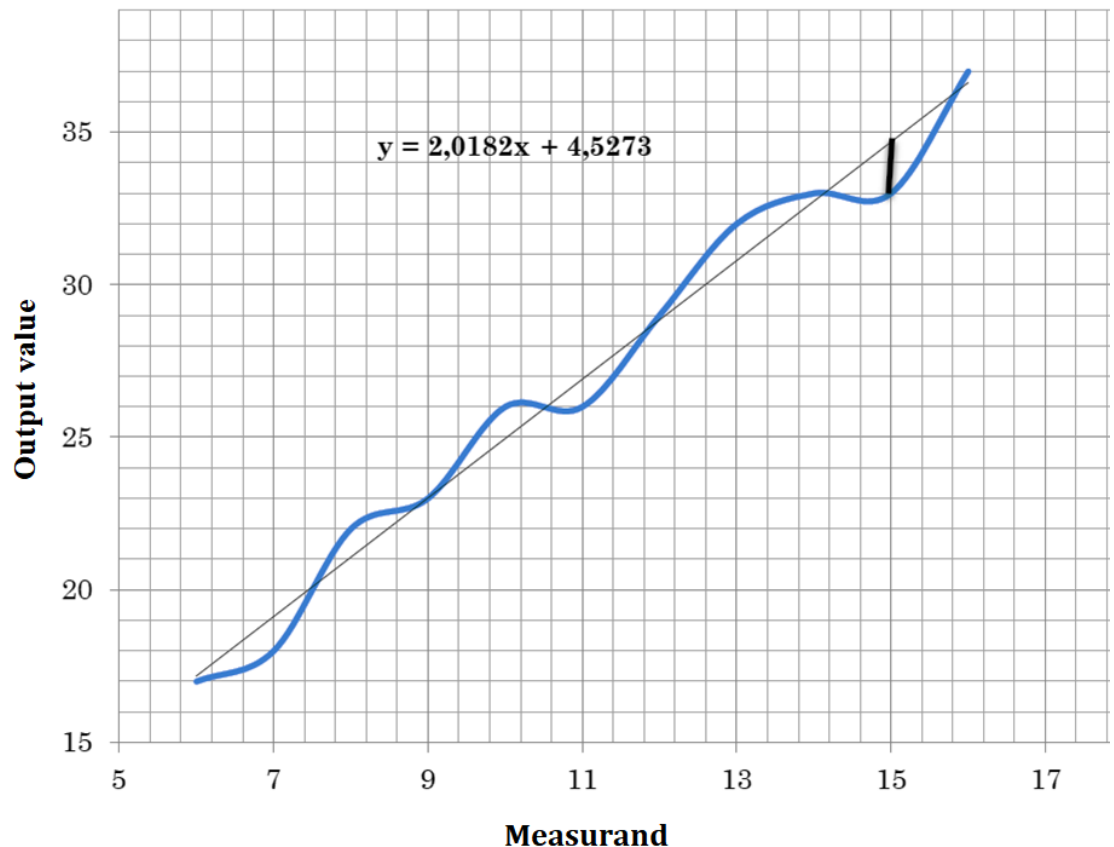


Figure 42 Measurement curve and estimation of linearity error

The equation is calculated using the trend function by Microsoft Excel software.

3.4.10 DETERMINATION OF HYSTERESIS ERROR

Two series of measurements form the hysteresis curve; the first series is oriented in an increasing manner and the second in a decreasing direction. It is obvious that for the same measurand value, there are two separate output values. For example, the thermocouple exhibits hysteresis in terms of temperature (Figure 38).

3.4.10.1 THE HYSTERESIS ERROR:

The differences between the two series vary for each measurand value. To determine the hysteresis error, look for the maximum deviation e_{H-max} , the most unfavorable case.

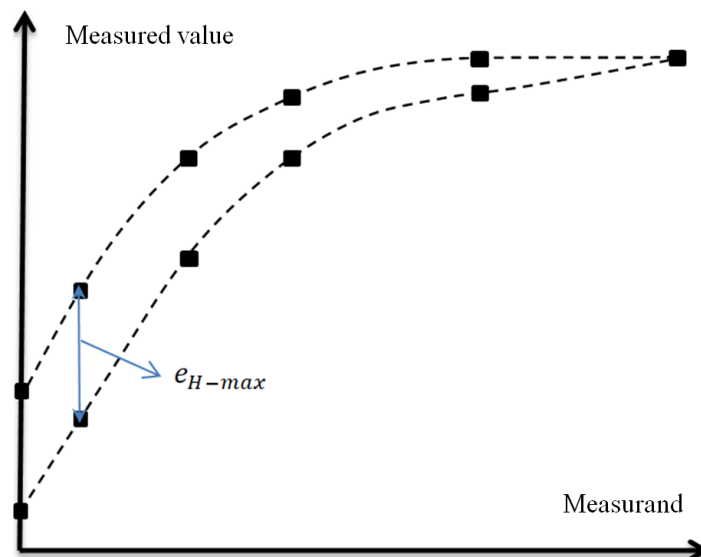


Figure 43 Determination of hysteresis error

3.4.10.2 DETERMINING THE LINEARITY ERROR OF A HYSTERESIS CYCLE

It is clever to take into account only the average value of the cycle for the calculation of the linearity error. Then, we proceed in the same way by calculating the best estimated line.

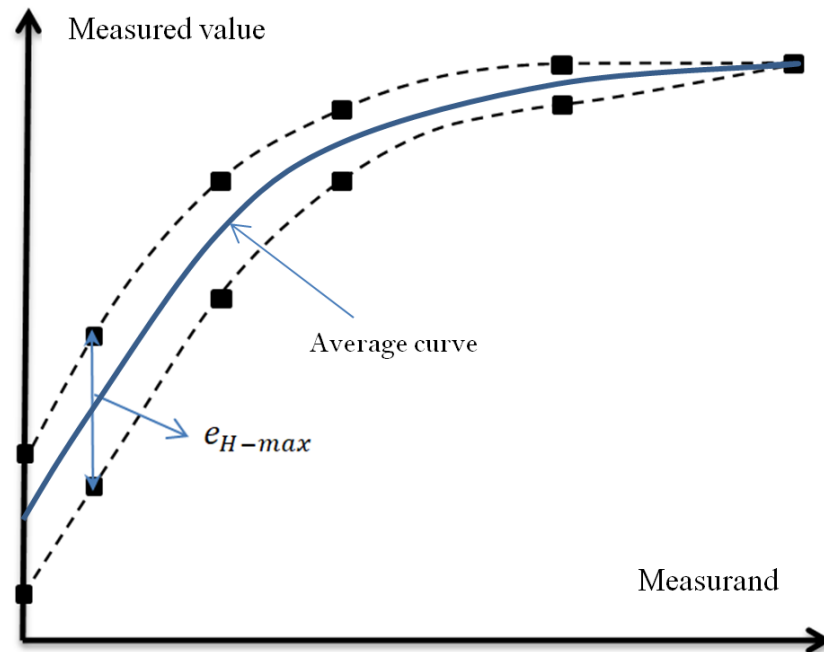


Figure 44 Determination of the average curve of a hysteresis cycle

Exemple 9: -

The calculation of the optimal line, this done with the help of Microsoft Excel or Matlab software, we determine the equation of the estimated best line of the mean hysteresis curve of the sensor.

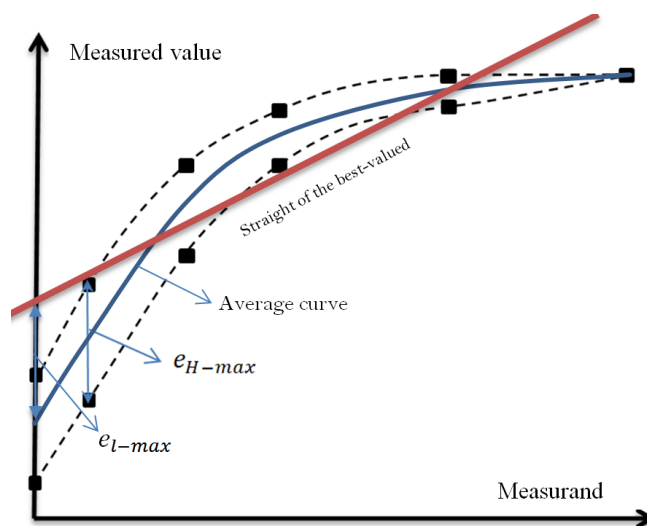


Figure 45 Average hysteresis cycle of a sensor and the best fit line

And the maximum linearity error is taken as the linearity error. $e_l = /e_{max}/$

We calculate the overall total error (hysteresis + linearity) using the formula:

$$e_{H-l} = \sqrt{e_H^2 + e_l^2}$$

3.4.11 RESOLUTION ERROR

- Analog Resolution Error

Analog resolution error refers to the inability of an analog measurement system or device to accurately detect or represent small variations in a measured physical quantity, due to the limitation of its ability to resolve these fine variations.

Exemple 10: -

An analog pressure sensor, its output is an analog voltage proportional to the measured pressure. The sensor has a measuring range of 0 to 100 bars, with a specified accuracy of ± 1 bar.

The problem is that if the pressure varies by 0.5 bars due to insufficient resolution, the sensor cannot detect this change. As a result, the measurements may be subject to additional uncertainty due to the limitation of resolution. For example, even if the sensor is specified to measure with an accuracy of ± 1 bar, it might not be able to detect smaller pressure changes than this value.

The pressure sensor has a resolution of 10 bars. This means that even though the sensor can measure with an accuracy of ± 1 bar, it cannot detect pressure variations of less than 10 bars.

Impact: If the pressure changes by 2 bars, the sensor will not be able to detect this small variation and will provide the same output value, resulting in a measurement error.

Exemple 11: -

The sensor used here is a wound resistor used to measure an angle. It is obvious that in the case of a specific rotation. The value of the resistance only changes when the rotation reaches a minimum value $\Delta\theta$, called resolution.

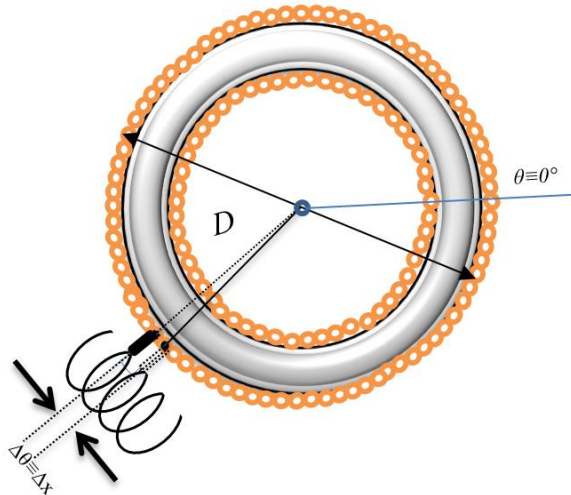


Figure 46 Illustration of a potentiometer measuring from an angle

The displacement between two consecutive coils joined this fat by a pitch Δx ; equivalent angle $\Delta x = \Delta \theta \cdot \frac{D}{2}$ i.e. $\Delta \theta = \frac{2\Delta x}{D}$ is similar to a variation of the resistance $\Delta R = \rho \frac{\Delta x}{s}$ (s : section of the resistor wire and ρ the resistivity of the resisting wire, D : average diameter of the toroidal support of the resistor) Hence the resolution error is:

$$\Delta R = \frac{D}{2} \cdot \frac{\rho}{s} \cdot \Delta \theta$$

Exemple 12: -

The digital resolution error of a sensor is the error associated with the discretization of the analog signal measured in a finite number of digital levels. It is mainly determined by the number of bits of the analog-to-digital converter used by the sensor.

3.4.12 OFFSET OF A SENSOR

The offset value is the output value of the sensor for a zero input value.

The offset of a sensor refers to the difference between the value measured by the sensor at zero and the actual value of the physical quantity at zero. This can be considered as a systematic error that is added to the measured value for all measurements made with the sensor.

Offset can be caused by factors such as sensor imperfections, calibration errors, defects in the associated measurement circuit, etc. It can be corrected by calibrating the sensor to compensate for this systematic error, either by manual calibration or by automatic calibration integrated into the associated measurement circuit.

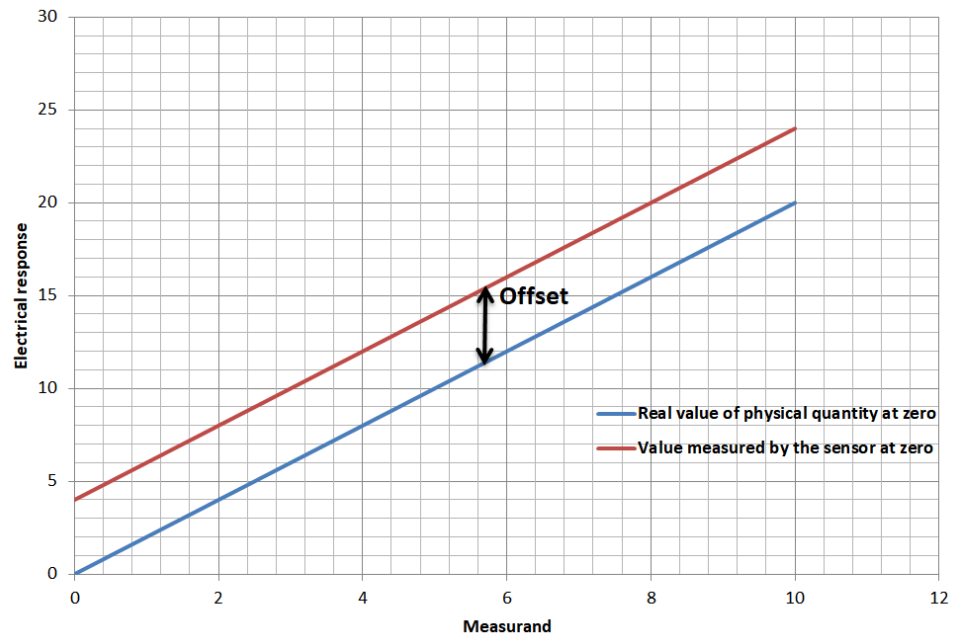


Figure 47 Overview of Offset of a Sensor

It is important to consider the offset of a sensor to ensure that the measured data is reliable and accurate. In particular, for critical applications, it is important to select a sensor with minimal offset and calibrate it regularly to maintain its long-term accuracy.

3.5 SENSOR CLASSIFICATION

Sensors can be classified into two broad categories based on the power source they use: passive sensors and active sensors.

3.6 PASSIVE SENSORS

A passive sensor is a dipole whose impedance varies depending on the quantity being measured.

Passive sensors are sensors that need an external power source to operate. They work by using a physical phenomenon to convert a physical quantity into a measurable output. Passive sensors are often simpler and less expensive than active sensors, but they can also be less accurate and less reliable due to their reliance on external factors such as temperature and humidity. Examples of passive sensors include temperature resistors, gauges, etc.

3.7 ACTIVE SENSORS

These are sensors that could be modeled by generators such as photovoltaic and electromagnetic systems. An active sensor is generally based

in principle on a physical effect that ensures the conversion of a power component specific to the physical quantity to be sampled (thermal, mechanical, magnetic, radiation, etc.) into an electrical quantity. They do not need any external energy input to operate (e.g. thermistor, potentiometer, mercury thermometer, etc.).

3.7.1 RANKING ACCORDING TO THEIR EXIT SIGNALS

Sensor output signals can be classified into three families depending on the type of information they return.

3.7.1.1 LOGIC OR DIGITAL SENSORS:

The sensor returns logical information, i.e. 0 or 1 (Figure 49). In other words, the output can take only two states. For example, a keyboard is a matrix of logic sensors, because each key is a switch (or contact) that can be either "open" or "closed".

3.7.1.2 ANALOG SENSORS

This type of sensor returns a proportional value to the measured physical quantity. For example, a photoresistor (light sensor) is a sensor that converts brightness into electrical value. There are analog sensors; its output can take an infinite number of continuous values, either a linear response or a response following a different curve (Figure 48).

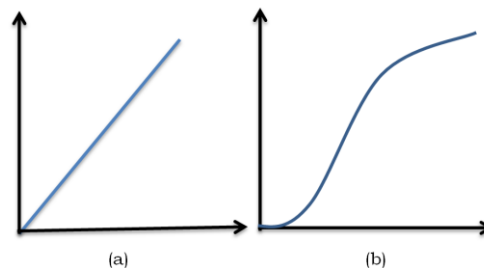


Figure 48 Different curves (A-linear curve, B-nonlinear curve)

For a sensor, a linear curve means that the progression of its value follows a constant and regular progression. A nonlinear curve belongs to a more complex function whose value does not also progress over time.

3.7.1.3 DIGITAL SENSORS:

The output is a sequence of logical states that, by following each other, form a number. The output can take a large number of discrete values (Figure 49).

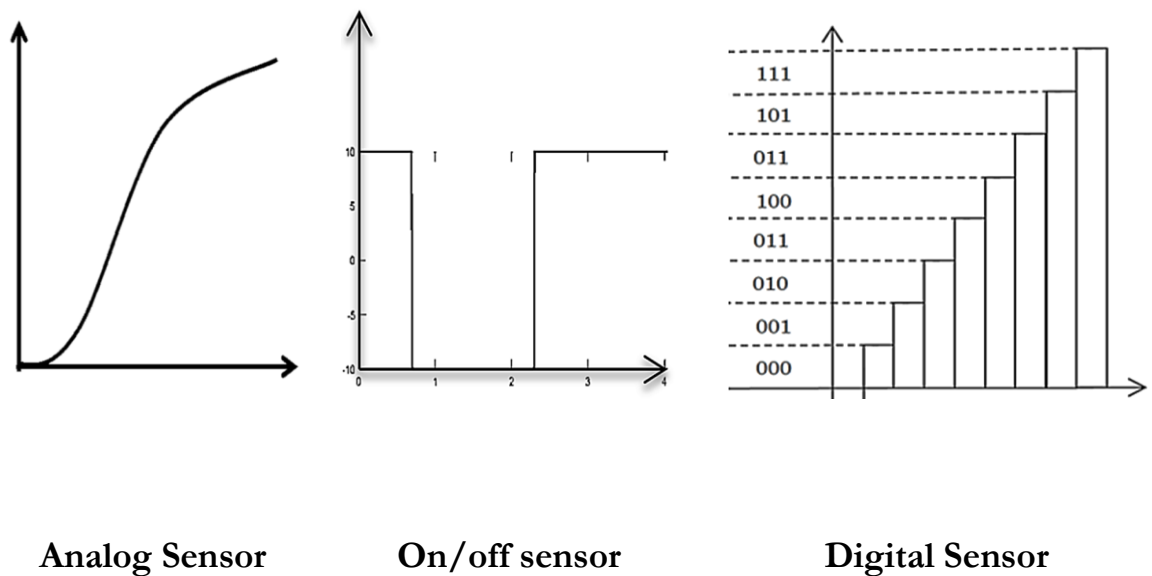


Figure 49: Transfer function of different sensor classes

3.8 CLASSIFICATION ACCORDING TO THE ENTRY SIZE

There are several different families of sensors, each designed to measure specific quantities. Examples of sensor families include:

3.8.1 TEMPERATURE SENSORS:

Temperature sensors are designed to assess temperature and can be used to measure the temperature of air, water or other substances.

Example: thermistor, thermocouple, thermopile, junction thermistor, RTD (heating time resistance), etc.

3.8.2 PRESSURE SENSORS:

Pressure sensors are used to measure the pressure of a liquid or gas. They can also be used to measure atmospheric pressure, tire pressure, etc.

These include absolute, relative, differential, diaphragm, piezoelectric pressure sensors, etc.

3.8.3 POSITION AND MOTION SENSORS:

These sensors measure the position and movement of an object and can be used to measure the position of a read head on a hard drive, the movement of a vehicle, and more.

Examples include incremental, absolute, reflector, Hall Effect, optical resource, electronic compass, etc.

3.8.4 LIGHT AND IMAGE SENSORS:

Light sensors measure the brightness of an object or image capture is done using light and image sensors.

Let's talk about photoresistors, photodiodes, etc.

3.8.5 FORCE AND TORQUE SENSORS:

Their purpose is to measure the force and torque exerted on an object. They can be used to measure the force exerted by an actuator or the load of an object.

In this category we find load, strain, force, torque, piezoelectric sensors, etc.

3.8.6 PROXIMITY AND DISTANCE SENSORS:

These sensors assess the distance between an object and can be used to detect the presence of objects.

For example, cable, ultrasonic, capacitive, etc.

There are many other types of sensors, each designed to measure specific physical quantities. Selecting the right sensor depends on the needs and requirements of the application.

CHAPTER 4.

MEASUREMENT CHAIN AND PACKAGING CIRCUIT OF A SENSOR

SUMMARY OF CHAPTER 4

Chapter Four explores the measurement chain and conditioning circuit of a transducer. It begins by explaining the role of a signal conditioner, which prepares and adjusts the signal from the transducer before it is processed. The conditioner can perform tasks such as amplification and filtering to eliminate unwanted noise.

The chapter then looks at current-to-voltage conversion and signal scaling to make it compatible with downstream systems. Signal digitization is also an essential aspect, and the use of an analog-to-digital converter (ADC) is explained, with details of its operation and characteristics, such as resolution and sampling frequency.

The chapter also introduces digital-to-analog converters (DACs), used to reconstruct analog signals from digital values. ADC and DAC architectures, such as successive approximation and weighted resistance converters, are examined to explain their operation and use in accurate signal reconstruction. Finally, concepts such as sampling, quantization and signal coding are discussed to complete the signal processing chain in measurement systems.

4.1 DEFINITION

The "measurement chain" refers to the set of components, instruments and processes used to measure a physical quantity. This chain typically begins with the sensor or measuring device that converts the physical quantity into a measurable signal, and then includes items such as signal amplifiers, filters, analog-to-digital converters (ADCs), data processing units, display and recording devices, and any other components necessary for the accurate and reliable measurement of the desired quantity.

4.2 SYNOPTIC DIAGRAM OF AN INDUSTRIAL REGULATION CHAIN

A synoptic diagram of an industrial control chain is a schematic representation that shows the individual components and their connection in an industrial control system. The main elements that could be included in such a synoptic are:

Sensors: These are the devices that measure physical quantities such as pressure or force transducers and convert these quantities into analog electrical signals.

Transmitters: Analog electrical signals from sensors are often weak and need to be amplified and conditioned to be used effectively by other system components. Transmitters perform this task.

Control system: Consisting of a regulator or programmable logic controller (PLC), this system receives signals from the sensors, compares them to the set values, and sends signals to the actuators to adjust the process accordingly.

Actuators: These are devices that make the physical changes necessary to adjust the industrial process, such as valves, motors, pneumatic or hydraulic actuators, etc.

Operator Interface: This is the user interface that allows operators to monitor and control the control system, usually using a touchscreen, computer, or dashboard.

Communication and networks: In modern systems, the various components of the control chain can be connected via communication networks, such as Ethernet networks, fieldbuses (such as Profibus (Process Field Bus), Modbus, etc.), allowing fast and efficient communication between the different elements of the system.

This synoptic provides an overview of how the different components interact to keep an industrial process within specified limits, adjusting actions based on variations detected by the sensors.

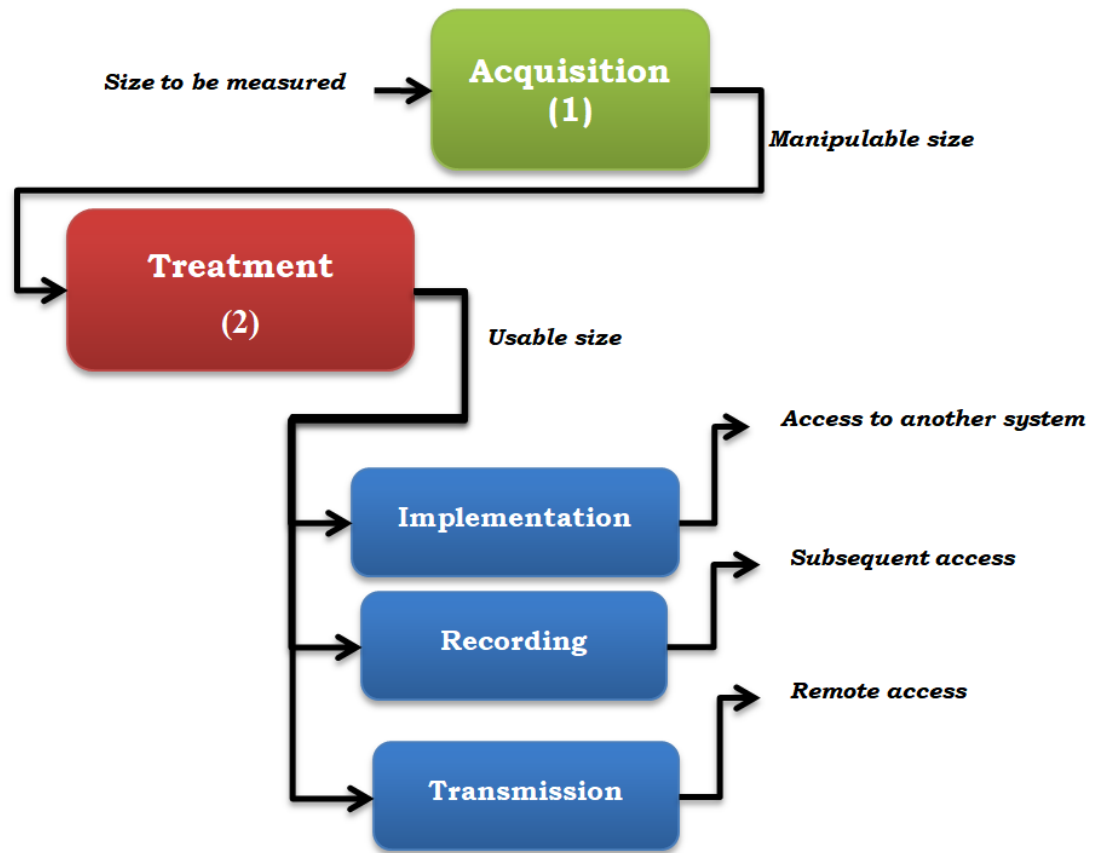


Figure 50 Blocks of a Chain of Measure

In order to use the measured quantity, it is imperative to go through three stages: acquisition, processing and exploitation. The purpose of the acquisition chain (Block 1) is to collect and convert the quantity to be measured into a format suitable for its use. Block 2 is the second processing device that aims to transform the analog signal into a digital signal. Another step is to exploit the signal, i.e. send it to another processing system where it can be saved for later use, or shared remotely Figure 50.

A measurement chain is therefore made up of three essential blocks Figure 51:

- To transform the measured quantity into a manipulable quantity, an acquisition block called a conditioning block is generally used, which goes through amplification and filtering step.
- The second block processes the signal from the acquisition block, in order to make the signal suitable for processing by a computer.

- The third step is reserved for the exploitation of the signal, either for recording or for implementation so that the signal can be processed by another system where it will be sent remotely either for information or other useful processing.

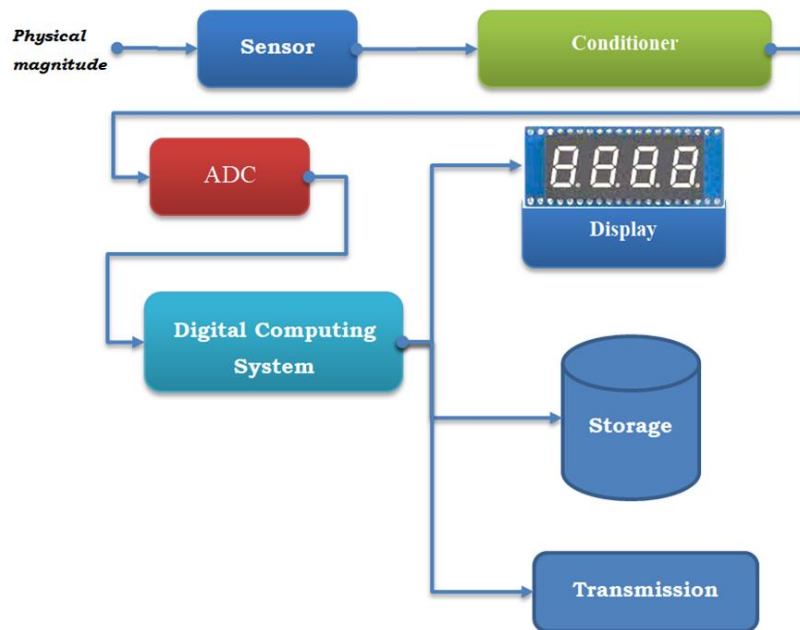


Figure 51 Processing chain

Sensors transform a physical quantity into an electrical quantity. The transition from one to the other is obtained by a calibration curve. The modeling of the curve gives a mathematical equation relating the physical quantity to the electrical quantity.

This mathematical model requires a computational operation to determine the value of the physical quantity associated with the value of the electrical quantity obtained. For this purpose, an automatic calculation device, always numerical, is used (represented here by the numerical calculation system).

In industry and laboratories, we need to detect many physical quantities, for example: temperature, luminous flux, displacement, force, pressure, speed, etc.

The essential element that comes into play is the sensor that allows these physical quantities to be measured.

4.3 CONDITIONER

A conditioner is an electronic device that processes signals from a sensor. The use of this technology offers the possibility of reducing the interface of

the sensor with the data acquisition system. The intervention of the conditioner is located between the sensor and the interface in a measurement chain.

4.3.1 ROLE OF A CONDITIONER

The electrical quantity from the sensor is generally not directly usable. For example: a temperature sensor (thermocouple) gives a voltage in " mV " that will have to be amplified; a load cell delivers a variation in resistance to be converted into a variation in voltage. The conditioner is used to transform this unusable electrical quantity into another adapted to the data acquisition device.

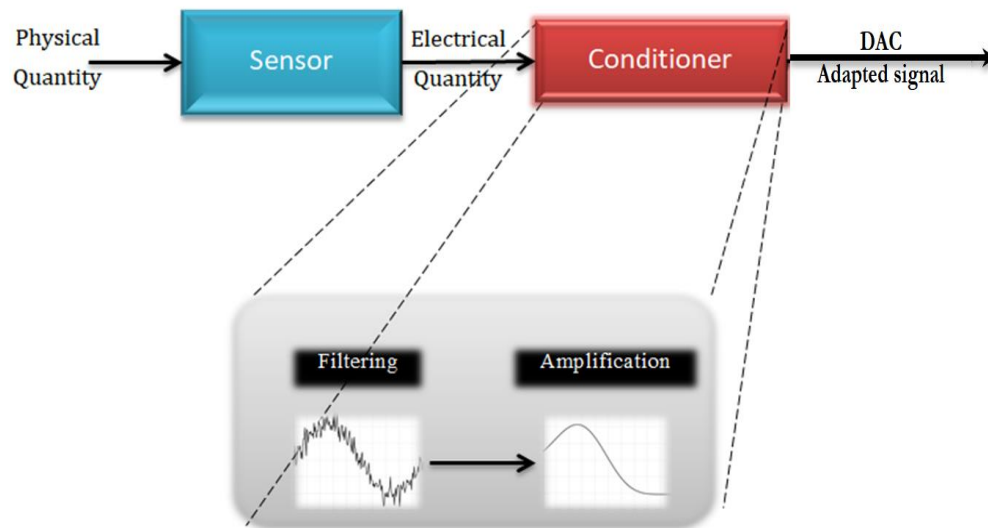


Figure 52 Sensor signal conditioning

A signal conditioner is a device that prepares a signal produced by a sensor for analysis. It can perform several operations such as:

4.3.1.1 AMPLIFICATION:

Its role is to increase the amplitude of the signal to compensate for losses or to facilitate signal measurement. Since it has been studied at the University of California, OP-AMPs can be used to amplify the input signal, depending on the desired value of the gain.

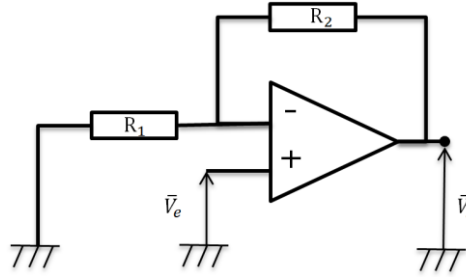


Figure 53 Amplifier mounting with OP-Amp

The assembly is linear so: $V^- = V^+$

$$V^+ = V_e$$

$$V^- = \frac{\frac{V_s}{R_2}}{\frac{1}{R_1} + \frac{1}{R_2}} = \frac{\frac{R_1 V_s}{R_1 R_2}}{\frac{R_1 + R_2}{R_1 R_2}} = \frac{R_1 V_s}{R_1 + R_2} = V_e$$

$$V_s = \frac{R_1 + R_2}{R_1} V_e = \left(1 + \frac{R_2}{R_1}\right) V_e$$

To amplify the signal, it is necessary to play with the ratio $\frac{R_2}{R_1}$.

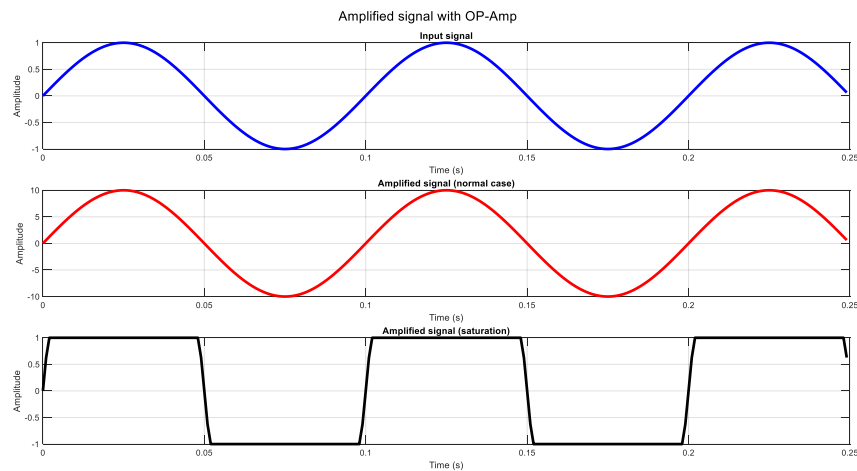


Figure 54 Amplification of a sinusoidal signal

4.3.1.2 FILTRATION

Filtering a signal from a sensor is necessary if it has spurious signals. Filtering presents the operation of shaping an electrical quantity (current or voltage) in order to remove any frequencies from the signal below the sampling frequency.

Different types of filters are available classified according to their internal component, the passive component-based filter, with a gain equivalent to the unit called the passive filter and active filters are filters that use variable gain OP-AMPS. Another name based on the levels of the purified frequencies.

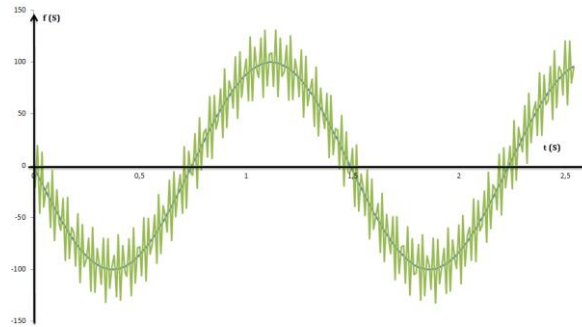


Figure 55 Example of a noisy signal

- low-pass filter, reveals low frequencies of the spectrum and eliminates high frequencies;
- high-pass filter transmits high frequencies and eliminates low frequencies;
- Band-pass filter allows a band of frequencies to pass around a center frequency.

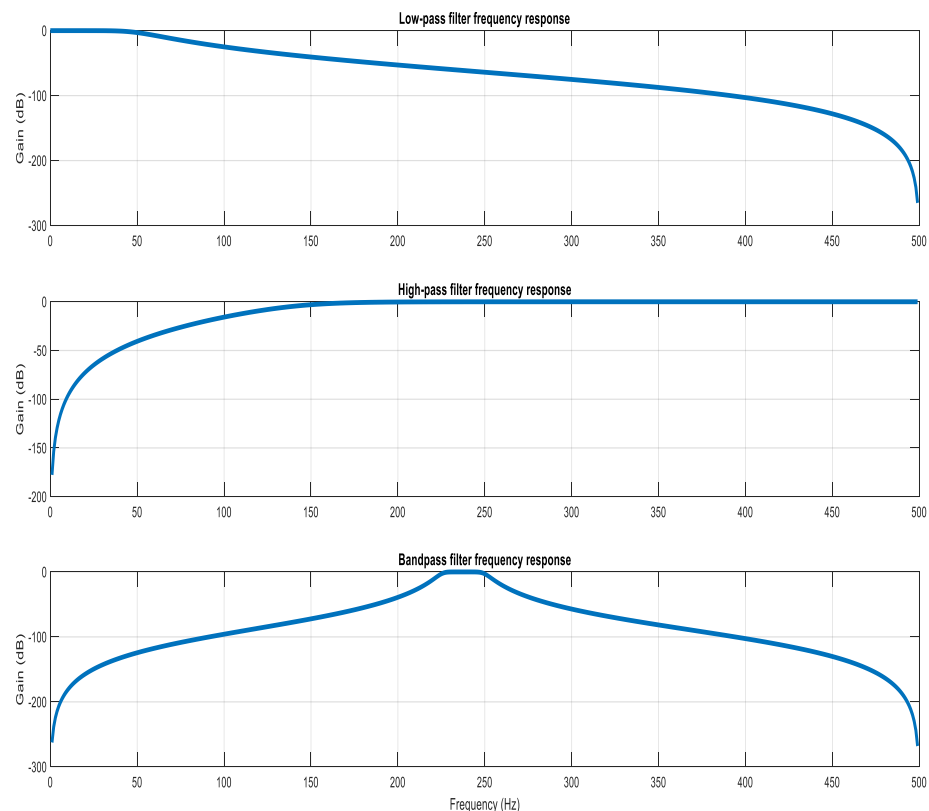


Figure 56 Different types of filters

(Example: $f_{c_{low}} = 50 \text{ Hz}$; $f_{c_{high}} = 150 \text{ Hz}$; $f_{c_{band}} = [150\text{Hz}, 250 \text{ Hz}]$)

Signal filtering is the process of attenuating or removing unwanted components of a signal to obtain a purified signal. There are two main categories of filtering: low-pass filtering and high-pass filtering.

1. Low-pass filter: A low-pass filter only lets low frequencies through and attenuates high frequencies. It is often used to remove stray high-frequency components that can affect signal quality.

- LOW-PASS FILTER WITH PASSIVE COMPONENTS

Calculation of the passive low-pass filter:

The filter diagram is represented by the (Figure 57).

Using the notions of the voltage divider (see CHAPTER 1).

It should be noted that everything we observed for the case where we used resistors is applicable to impedances.

$$\bar{Z}_R = R$$

$$\bar{Z}_C = 1/jc\omega = -j/c\omega$$

$$\bar{V}_s = \frac{\bar{Z}_C}{\bar{Z}_R + \bar{Z}_C} \bar{V}_e = \frac{1/jc\omega}{R + 1/jc\omega} \bar{V}_e = \frac{1}{1 + jRc\omega} \bar{V}_e$$

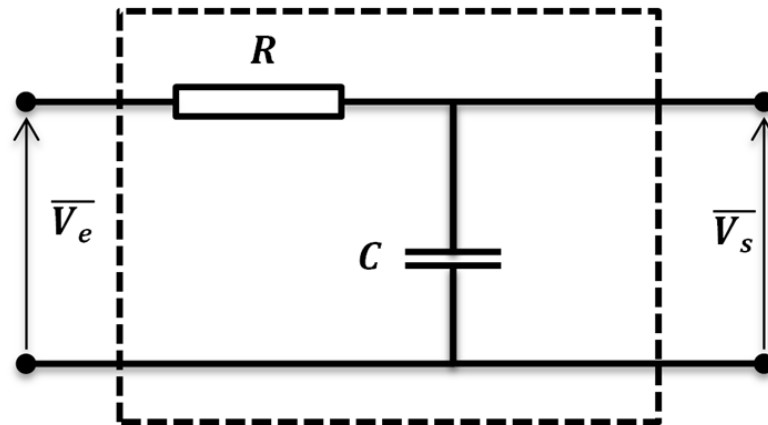


Figure 57 Diagram of a low-pass filter with passive components

$$\bar{V}_s = \frac{1}{1 + jRc\omega} \bar{V}_e = \frac{A}{1 + j\frac{\omega}{\omega_c}} \bar{V}_e, \text{ this is the equation of a 1st order filter}$$

$$\omega_c = \frac{1}{RC} : \text{is the cut-off pulsation and } A = 1 \text{ is the gain.}$$

Based on this equation, it can be seen that when the frequency is high, the capacitor operates as a closed switch, producing a zero output voltage. In contrast, at low frequencies, the output voltage has a specific value that depends on this frequency and the passive components.

Equivalent diagram of a low-pass filter:

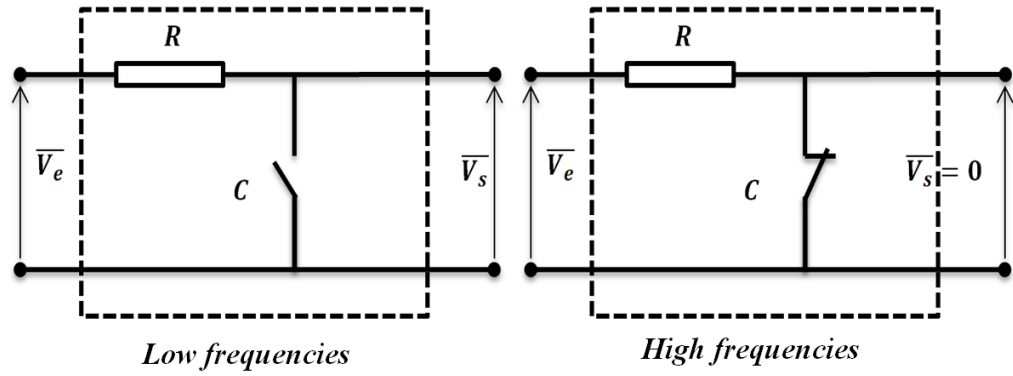


Figure 58 Representative diagram of a low-pass filter operating at two different frequency levels

- OAMP-BASED LOW-PASS FILTER

The diagram of a low-pass filter with an operational amp (active component)

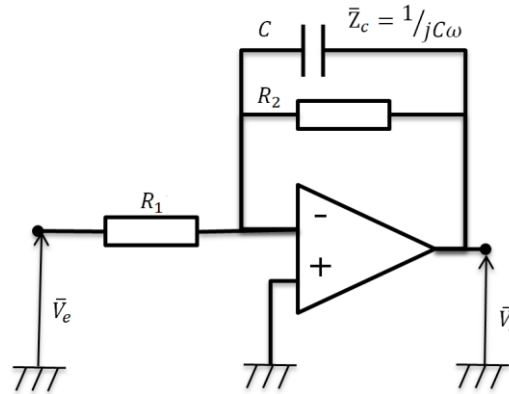


Figure 59 Diagram of a low-pass filter with active components

The editing is linear, you can write

$$V^- = V^+ = 0$$

Using Millman's theorem

$$V^- = \frac{\frac{\bar{V}_e}{R_1} + \frac{\bar{V}_s}{Z_c} + \frac{\bar{V}_s}{R_2}}{\frac{1}{R_1} + \frac{1}{Z_c} + \frac{1}{R_2}} = 0 \quad \text{so} \quad \frac{\bar{V}_e}{R_1} + \frac{\bar{V}_s}{Z_c} + \frac{\bar{V}_s}{R_2} = 0$$

$$\bar{V}_s \left(\frac{1}{Z_c} + \frac{1}{R_2} \right) = -\frac{\bar{V}_e}{R_1} \quad \text{rewrite the relation in the standard form} \quad \bar{V}_s = \frac{A}{1 + j\frac{\omega}{\omega_c}} \bar{V}_e$$

$$\bar{V}_s = \bar{V}_e \frac{-R_2/R_1}{(jCR_2\omega + 1)}$$

$$\bar{V}_s = -\frac{\bar{V}_e}{R_1} \left(\frac{R_2}{jR_2c\omega + 1} \right) = \bar{V}_e \left(\frac{-R_2/R_1}{1 + jR_2c\omega} \right)$$

$\omega_c = \frac{1}{R_2 C}$: is the cut-off pulsation and $A = -R_2/R_1$ is the gain.

Similar remark as before: if f is high $V_s = 0$, on the other hand, it keeps a known value for low frequencies.

In conclusion, a low-pass filter is a filter that allows low frequencies to pass through and attenuates high frequencies, which are those that exceed the cut-off frequency.

- HIGH-PASS FILTER BASED ON PASSIVE COMPONENTS

A high-pass filter only allows high frequencies to pass through and attenuates low frequencies. It is often used to separate low-frequency background signals from high-frequency signals of interest.

Following the same steps as before:

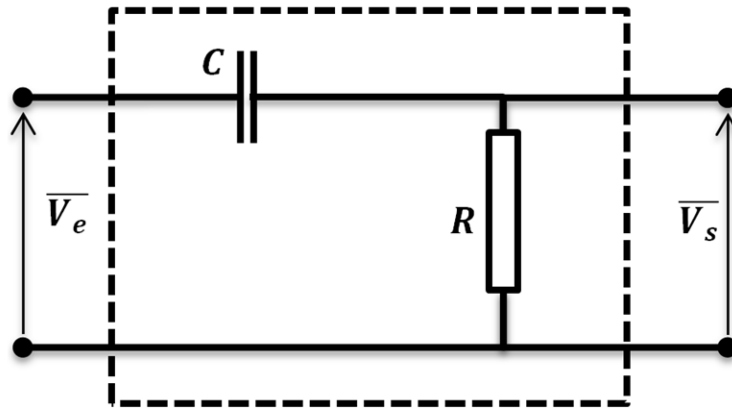


Figure 60 Passive high-pass filter

Using the notions of the voltage divider

$$\begin{aligned}\bar{Z}_R &= R \\ \bar{Z}_C &= 1/jc\omega = -j/c\omega \\ \bar{V}_s &= \frac{\bar{Z}_R}{\bar{Z}_R + \bar{Z}_C} \bar{V}_e = \frac{R}{R + 1/jc\omega} \bar{V}_e = \frac{jRc\omega}{1 + jRc\omega} \bar{V}_e \\ \bar{V}_s &= \frac{1}{\left(\frac{1}{jRc\omega} + 1\right)} \bar{V}_e\end{aligned}$$

The gain is then 1

The cut-off pulsation $\omega_c = \frac{1}{Rc}$

It is obvious when f that tends to infinity $\bar{V}_s = \bar{V}_e$ on the other hand, for if f tends to zero the value of $\bar{V}_s$ also tends to zero. See the following representative figure.

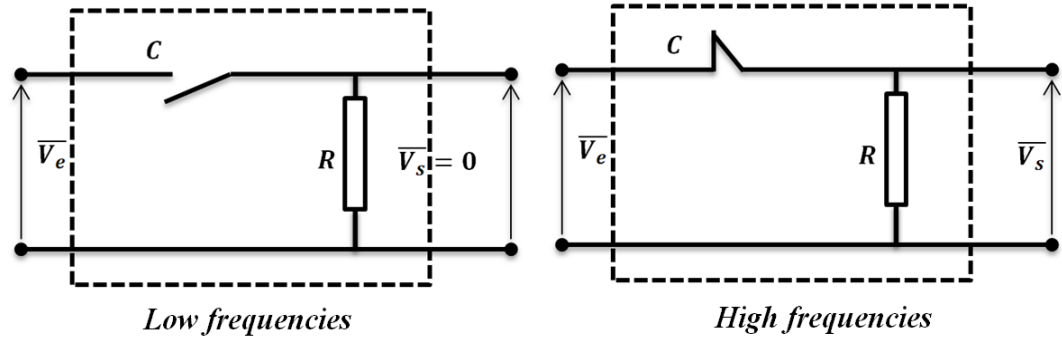


Figure 61 Representative diagram of a high-pass filter operating at two different frequency levels

- OP-AMP-BASED HIGH-PASS FILTER

The active high-pass filter is represented by the Figure 62

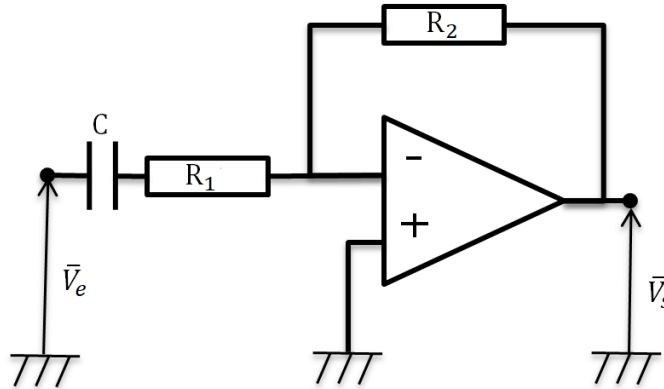


Figure 62 Active high-pass filter (with OP-amp)

$$\begin{aligned}
 V^- &= V^+ = 0 \\
 V^- &= \frac{\bar{V}_e}{\bar{Z}_c + R_1} + \frac{\bar{V}_s}{R_2} = 0 \\
 \bar{V}_s &= -\frac{R_2}{\bar{Z}_c + R_1} \bar{V}_e \text{ Let's replace } \bar{Z}_c \text{ with } \frac{1}{j\omega C} \\
 \bar{V}_s &= -\frac{R_2}{\frac{1}{j\omega C} + R_1} \bar{V}_e \rightarrow \bar{V}_s = -\frac{jR_2\omega C}{1 + jR_1\omega C} \bar{V}_e \\
 \bar{V}_s &= -\frac{jR_2\omega C}{1 + jR_1\omega C} \bar{V}_e \\
 \bar{V}_s &= -\frac{R_2}{R_1} \frac{1}{\left(\frac{1}{jR_1\omega C} + 1\right)} \bar{V}_e
 \end{aligned}$$

The gain is then $\frac{R_2}{R_1}$

The cut-off pulsation $\omega_c = \frac{1}{R_1 C}$

We notice that if $R_1 = R_2 = R$ we find the same relationship calculated for the passive high-pass filter.

- BANDPASS FILTER

There are also combination filters, such as band-pass filters, which allow only a certain frequency band to pass through, and notch filters, which remove a certain frequency band. Filters can be analog or digital, depending on the type of signal to be filtered and the complexity of the filtering required.

- Passive band-pass filter

Let's look at the proposed arrangement of a passive filter schematized by the Figure 63 .

$$\bar{Z}_1 = R + \frac{1}{j\omega C}, \bar{Y}_2 = \frac{1}{R} + j\omega C$$

To calculate the output voltage, let's use the notion of the voltage divider.

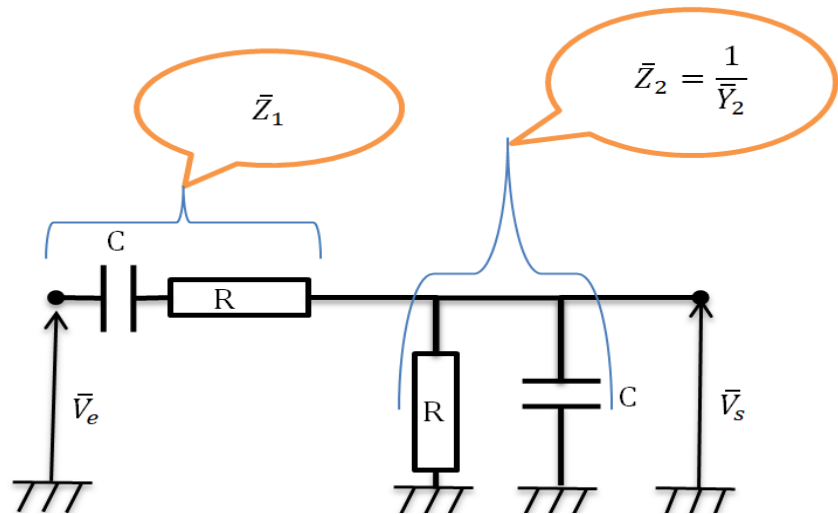


Figure 63 Band-pass Filter Circuit Diagram

$$\bar{V}_s = \frac{\bar{Z}_2}{\bar{Z}_1 + \bar{Z}_2} \bar{V}_e, \bar{V}_s = \frac{1/\bar{Y}_2}{\bar{Z}_1 + 1/\bar{Y}_2} \bar{V}_e$$

$$\bar{V}_s = \frac{\bar{Y}_2}{\bar{Y}_2} \cdot \frac{1/\bar{Y}_2}{\bar{Z}_1 + 1/\bar{Y}_2} \bar{V}_e$$

$$\bar{V}_s = \frac{1}{\bar{Z}_1 \bar{Y}_2 + 1} \bar{V}_e = \frac{1}{\left(R + \frac{1}{j\omega C}\right) \cdot \left(\frac{1}{R} + j\omega C\right) + 1} \cdot \bar{V}_e$$

$$\bar{V}_s = \frac{1}{1 + jRc\omega + \frac{1}{jRc\omega} + 1 + 1} \cdot \bar{V}_e$$

$$\bar{V}_s = \frac{1}{3 + jRc\omega + \frac{1}{jRc\omega}} \cdot \bar{V}_e$$

$$\bar{V}_s = \frac{1}{3 + j(Rc\omega - \frac{1}{Rc\omega})} \cdot \bar{V}_e$$

To understand the behavior of this filter, we calculate $\bar{Z}_2$

$$\bar{Z}_2 = \frac{R - jR^2c\omega}{1 + (Rc\omega)^2} = \frac{R}{1 + (Rc\omega)^2} - \frac{jR^2c\omega}{1 + (Rc\omega)^2}$$

The equivalent scheme is as follows:

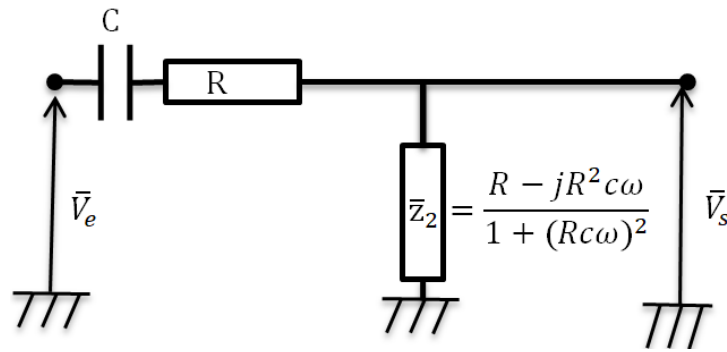
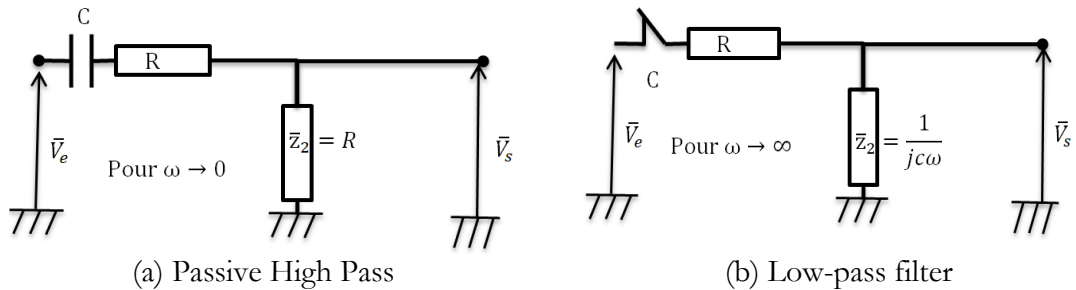


Figure 64 Passive global band-pass filter

We deduce the equivalent patterns for the two different pulsation states.



It is observed that for low frequencies, the circuit behaves like a high-pass filter, allowing high frequencies to pass through while attenuating low frequencies. Conversely, for high frequencies, the circuit works as a low-pass filter, allowing low frequencies to pass through and attenuating high frequencies. As a result, this circuit acts as a band-pass filter, allowing the passage only of frequencies within a specific range, determined by the values of the chosen passive components.

- ACTIVE BANDPASS FILTER:

The band-pass filter consisting of an operational amp is schematized by the Figure 65.

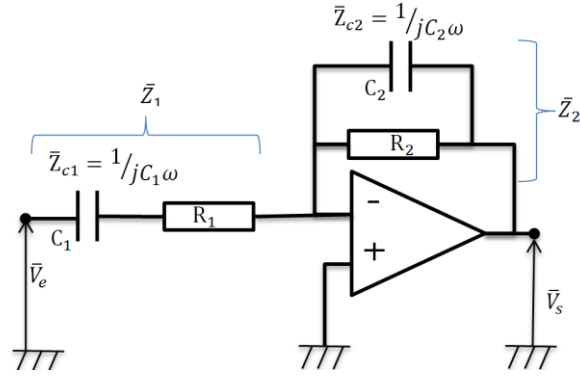


Figure 65 Active Band-pass Filter

$$\bar{Z}_1 = R_1 + \frac{1}{jC_1\omega} \text{ and } \bar{Z}_2 = R_2 \parallel \frac{1}{jC_2\omega}$$

$$\bar{Z}_2 = \frac{R_2 * \frac{1}{jC_2\omega}}{R_2 + \frac{1}{jC_2\omega}} = \frac{\frac{R_2}{jC_2\omega}}{\frac{1 + jR_2C_2\omega}{jC_2\omega}} = \frac{R_2}{1 + jR_2C_2\omega}$$

On the other hand, the assembly is linear,

$$V^- = V^+ = 0$$

$$V^- = \frac{\frac{\bar{V}_e}{\bar{Z}_1} + \frac{\bar{V}_s}{\bar{Z}_2}}{\frac{1}{\bar{Z}_1} + \frac{1}{\bar{Z}_2}} = 0, \text{ which gives } \bar{V}_s = -\frac{\bar{Z}_2}{\bar{Z}_1} \bar{V}_e$$

$$\bar{V}_s = -\frac{\frac{R_2}{1 + jR_2C_2\omega}}{R_1 + \frac{1}{jC_1\omega}} \bar{V}_e, \text{ we can derive the relationship:}$$

$$\bar{V}_s = -\frac{\frac{R_2}{1 + jR_2C_2\omega}}{\frac{jR_1C_1\omega + 1}{jC_1\omega}} \bar{V}_e \text{ therefore } \bar{V}_s = -\frac{jR_2C_1\omega}{(1 + jR_2C_2\omega)(1 + jR_1C_1\omega)} \bar{V}_e$$

$$\bar{V}_s = -\frac{jR_2C_1\omega}{(1 + jR_2C_2\omega)(1 + jR_1C_1\omega)} \bar{V}_e$$

Let's say :

$$\omega_1 = \frac{1}{R_1C_1} \text{ and } \omega_2 = \frac{1}{R_2C_2}$$

$$\bar{V}_s = -\frac{jR_2\frac{R_1}{R_1}C_1\omega}{(1 + j\frac{\omega}{\omega_2})(1 + j\frac{\omega}{\omega_1})} \bar{V}_e$$

Finally, we find:

$$\bar{V}_s = -\left[\frac{R_1}{R_2}\right] \left[\frac{1}{(1 + j\frac{\omega}{\omega_2})}\right] \left[\frac{j\frac{\omega}{\omega_1}}{(1 + j\frac{\omega}{\omega_1})}\right] \bar{V}_e$$

Or also ($\omega_i = 2\pi f_i$)

$$\bar{V}_s = - \left[\frac{R_1}{R_2} \right] \left[\frac{1}{(1 + j \frac{f}{f_{c2}})} \right] \left[\frac{j \frac{f}{f_{c1}}}{(1 + j \frac{f}{f_{c1}})} \right] \bar{V}_e$$

f_{c1} and f_{c2} represent the frequencies of outages

- $\frac{R_1}{R_2}$: Is the amplification gain.
- $\frac{1}{(1 + j \frac{f}{f_{c2}})}$: Draw the low-pass filter.
- $\frac{j \frac{f}{f_{c1}}}{(1 + j \frac{f}{f_{c1}})}$: Draw the high-pass filter.

The study is similar as we studied for the previous filters.

Remark:

According to the previous calculations, it can be seen that a filter with passive components does not do amplification. Passive filters, which use resistors, capacitors, and inductors, change the frequency response of the signal without increasing its power. Their main role is to select or block certain frequencies of the incoming signal, but they do not provide gain. On the other hand, amplification, which increases the signal strength, requires active components such as transistors or operational amplifiers. Amplifier circuits incorporate active elements to augment the signal, while passive crossovers simply manipulate the signal without amplification.

4.4 CONVERSION OF CURRENT TO VOLTAGE:

The role is to convert a current signal into a voltage signal for more convenient analysis.

Assembly:

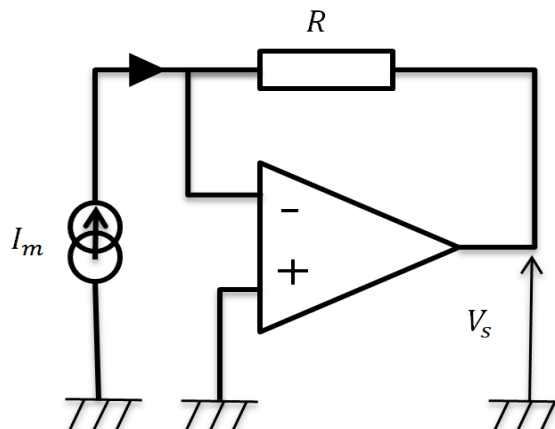


Figure 66 Voltage Current Converter

For an ideal amp, current. $i^- = 0$

We can then write $i_m = i$.

Therefore:

$$V_s = -Ri$$

The current is i converted into voltage V_s through the resistor R .

4.5 SCALING

A sensor emits a weak signal, but the transmitter transmits it more powerfully. In this way, the measurement can be transmitted over a large distance from the measuring point.

Scaling is the process of adapting the measurement range of the signal to meet the needs of the application.

We mainly know the analog signals from 0 to 10V based on the voltage and from 0 to 20 mA which is based on the current intensity.

The 0-10V signal has two disadvantages. The first concern is the presence of a voltage drop, especially when the distance between the sensor and the measuring point is very far. It requires a location closest to the measurement point. The second problem is its influence by the magnetic field, in order to prevent electromagnetic waves, it is recommended to use a faradized (shielded) cable.

To overcome these problems, 0-20 mA is used, eliminating the voltage drop as well as the faradization (shielding) of the cable, and to have a good analysis and good operation, another 4-20 mA scale is used to detect in the event of a break in the sensor wiring.

There are several advantages to using the analog signal in 4-20 mA current; allowing transmission over long distances by eliminating voltage drops, measuring a current of 4 mA allows differentiation between measurement zero and a transmission interruption.

The signal conditioner is a crucial part of the measurement chain, as it can influence the accuracy and reliability of the measured data. It is therefore important to select a signal conditioner that is suitable for the requirements of the application to ensure that the measured data is reliable and accurate.

4.6 DIGITIZING A SIGNAL

Signal digitization is the process of converting an analog signal into a digital signal for further analysis and processing.

Digitization involves the following steps:

1. Sampling: The analog signal is measured at regular intervals, resulting in a series of digital samples.
2. Quantification: Samples will be converted to numerical values using a set level scale.
3. Coding: Numeric values are encoded in binary form for easy manipulation in a numeric system.

The choice of sampling intervals, level scale, and number of bits used to encode numeric values can affect the accuracy and quality of the scan. Therefore, it is important to select the appropriate settings according to the requirements of the application to ensure quality scanning.

Voltage digitization is an important element in the measurement chain for most modern applications, as it enables precise and efficient analysis and processing of the measured signal.

4.7 ANALOG-TO-DIGITAL CONVERTER (ADC)

An analog-to-digital converter ADC, sometimes called an A/D converter, is the abbreviation for (Analog to Digital Converter, or A/D) allows you to convert an analog signal from a transmitter (sensor + conditioner assembly) into a signal with a digital value encoded on several bits, digital that can be understood and used by the digital computing system. It therefore allows the

passage from a set containing infinity of values (the analog world) to a set containing a finite quantity of numbers (the digital world). The converted signal is in the form of an electrical voltage.

4.7.1 CONVERTER SYMBOL:

The standard symbol for an analog converter is as follows:

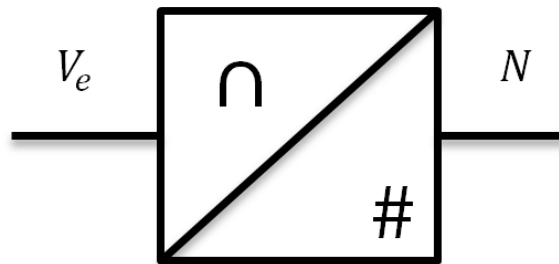


Figure 67 Standardized analog-to-digital converter symbol

The output N shows the bit conversion result, in the diagram following the 4-bit output.

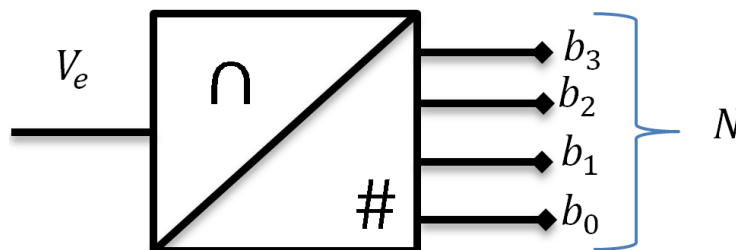


Figure 68 Diagramming the Outputs of a 4-Bit ADC Converter

b_0 : LSB (Least Significant Bit) has the lowest weight.

b_3 : MSB (Most Significant Bit) has the heaviest weight.

4.7.2 QUANTUM OF AN ADC

The quantum, often referred to by the acronym LSB in general terms, represents a proportion of a quantity in a whole. In other words, the quantum is the smallest voltage deviation that can be detected by the ADC, for an ADC it is given by the relationship.

$$q = \frac{V_{Max} - V_{min}}{2^n}$$

Where:

V_{Max} : Maximum voltage that the converter can provide

V_{min} : Minimum voltage that the converter can overcome

V_e : Converter input voltage (voltage to be converted)

n : Number of Converter Bits

N : Conversion result

Example: For a 3-bit DAC converter with a voltage ranging from 0V to 5V, the quantum is $\frac{5-0}{2^3} = 0.3125V$.

4.7.3 TRANSFER FEATURE

The transfer function expresses the output of the ADC as a function of its input, which corresponds to the numerical number N as a function of the input voltage V_e .

The transfer function is given by the relation:

$$N = \frac{V_e}{q} = k \cdot V_e$$

k : Slope of the ideal line of the transfer function.

Example: Let's plot the transfer characteristic of a 4-bit ADC, for a voltage V_e varying from 0V to 5V.

$$\text{In this case: } q = \frac{5}{2^4} = 0.3125V, k = 3.2V^{-1}$$

The equation for the transfer characteristic is: $N = 3.2 * V_e$ (see Figure 69).

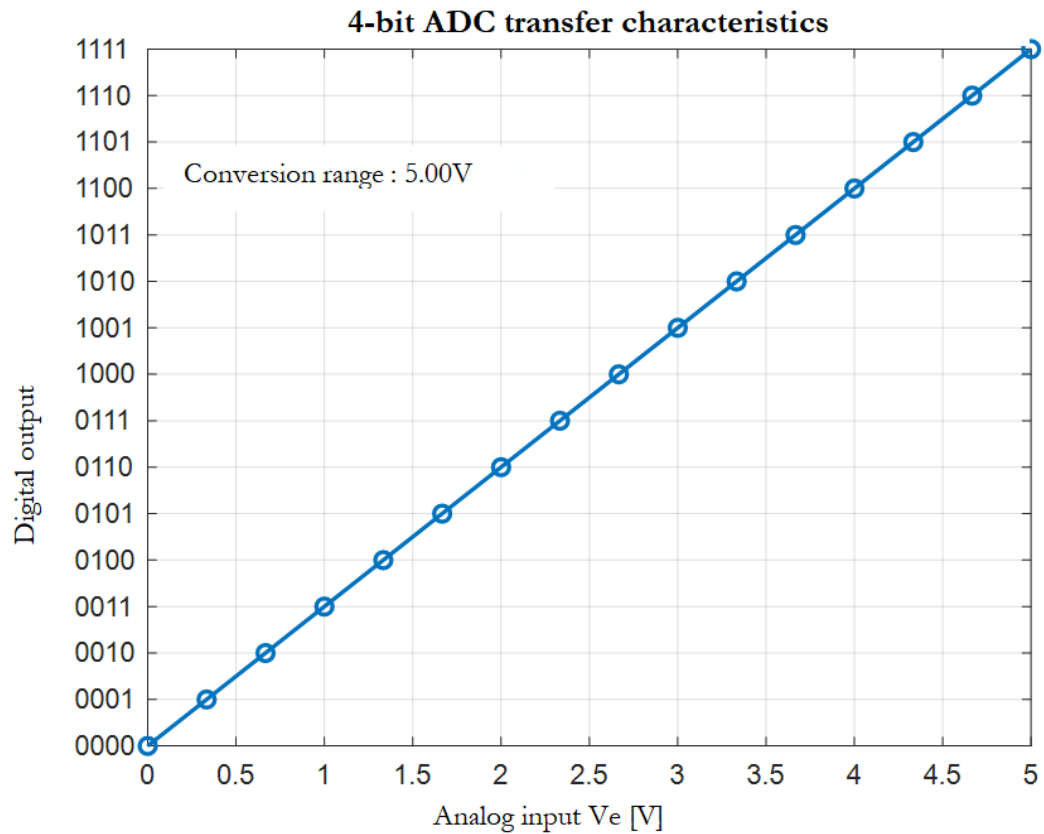


Figure 69 Transfer characteristic of a 4-bit ADC, $V_{ref}=5V$.

4.7.4 FULL-SCALE EXCURSION OF A ADC

The term "full-scale excursion" refers to the measurement of the maximum voltage variation that a sensor can record in relation to its total measurement range.

For an ADC the equation is given by:

$$PE = V_{Max} - V_{min}$$

$$PE = 2^n \cdot q$$

Example 13: -

The example cited in the Figure 69, the ADC has a $V_e = 5V$, $n=4$ bits,

$$q = \frac{5}{2^4} = 0.325V$$

$$PE = 2^n \cdot q = 2^4 * \frac{5}{2^4} = 5V$$

Example 14: -

A ADC its voltage varying from $\pm 15V$ sound

Consider an ADC with its voltage V_e varying between $-15V$ and $+15V$.

$$PE = V_{Max} - V_{min} = 15 - (-15) = 30V.$$

4.7.5 SOLVING AN ADC

For ADC converters, there are two concepts of resolution, bit resolution and percentage resolution.

4.7.5.1 BIT RESOLUTION OF AN ADC

The bit resolution of an analog-to-digital converter corresponds to its output, i.e., its number of bits n .

$$R_b = n$$

For the example (Figure 69), the $R_b = n = 4$.

4.7.5.2 RESOLUTION AS A PERCENTAGE OF AN ADC

The percentage resolution is the inverse of the number of quantification levels, expressed as a percentage, and gives a measure of the accuracy of the ADC in terms of the fraction of the total measurement range that each level of quantification represents.

$$R_{\%} = \frac{100}{2^n} \%$$

Exemple 15: -

For the ADC of the (Figure 69), the bit resolution is $R_b = 4$ and the percentage resolution is:

$$R_{\%} = \frac{100}{2^4} \% = 6.25\%$$

4.8 SAMPLING:

Sampling is the collection of the values of a signal at precise intervals, which are frequently regular. It produces a set of discrete values, known as samples.

4.8.1 SAMPLING TIME

The analog-to-digital converter takes samples of the analog signal at equal time intervals T_e , called the sampling period.

4.8.2 SAMPLING FREQUENCY

The sampling frequency $f_e = \frac{1}{T_e}$ is the number of samples taken per second (number of measurements made per second). It defines the number of values taken from the analog signal per second.

$$f_e = \frac{1}{T_e} [\text{Hz, MHz ...}].$$

Note: f_e must be greater than or equal to twice the frequency of the signal (*Shannon's theorem*).

$$f_e \geq 2 * f_{Max} = 2 * f_{Signal}$$

Remark:

The sampling rate is adjustable. It cannot exceed the maximum value specified by the manufacturer.

If an analog signal were to be digitized without loss, it would require an infinite number of samples.

This is of course not possible due to:

- information processing times
- the amount of data that would characterize the analog signal

But this impossibility has a direct consequence on the accuracy of the conversion linked to sampling.

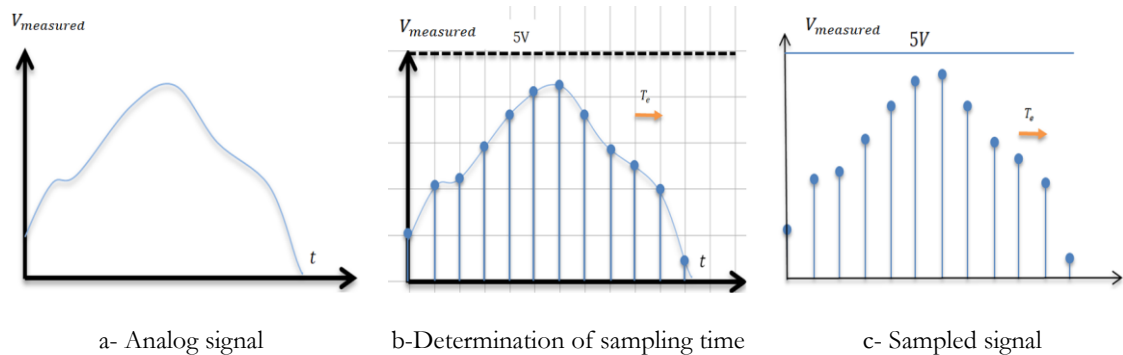


Figure 70 Sampling an analog signal

Exemple 16: -

Let be the scrambled signal of a frequency $f = 10\text{Hz}$ presented by the (Figure 71).

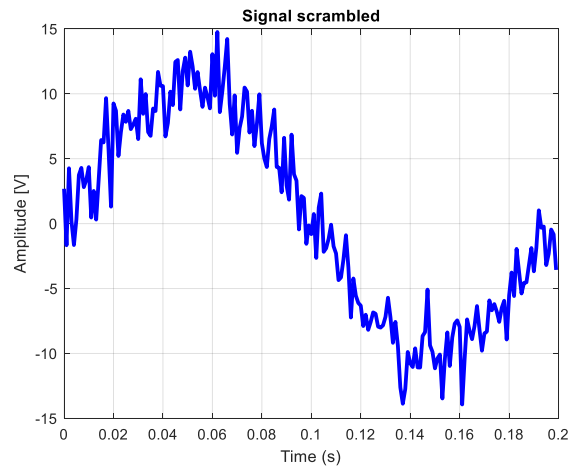


Figure 71 Scrambled signal

Before sampling the signal, it must be filtered, using a low-pass filter of order 6 (filters at 36 dB/octave) with a cut-off frequency of 10 Hz.

The filtered signal is presented by the (Figure 72).

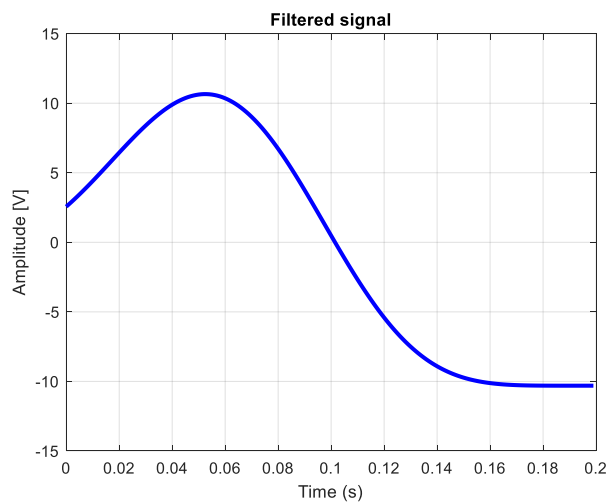


Figure 72 Signal from the output of the low-pass filter (36dB/octave, $f_c=10\text{Hz}$)

4.8.3 SAMPLER / BLOCKER

In a chain, the ADC is always followed by an essential system called a sampler/blocker.

The sampler-blocker is used to perform the following tasks:

- Perform the sampling operation at a given time. $T_e = 1/f_e$
- Blocks signal input during ΔT_e
- Memorizes this sample; generate a voltage equal to that of the sample stored at the output.

4.8.4 SYMBOL AND CONSTRUCTION OF A SAMPLER/BLOCKER

The sampler-blocker is an electronic circuit consisting of a controlled electronic switch and a capacitor.

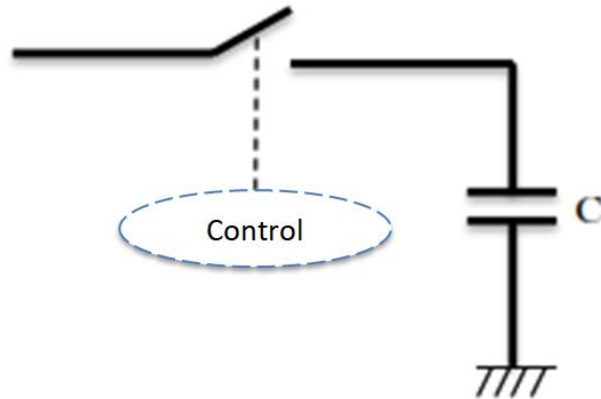


Figure 73 Symbolization of the sampler-blocker

Here is a simple example of a sampler-blocker consisting of an OP-AMP and a field-effect transistor.

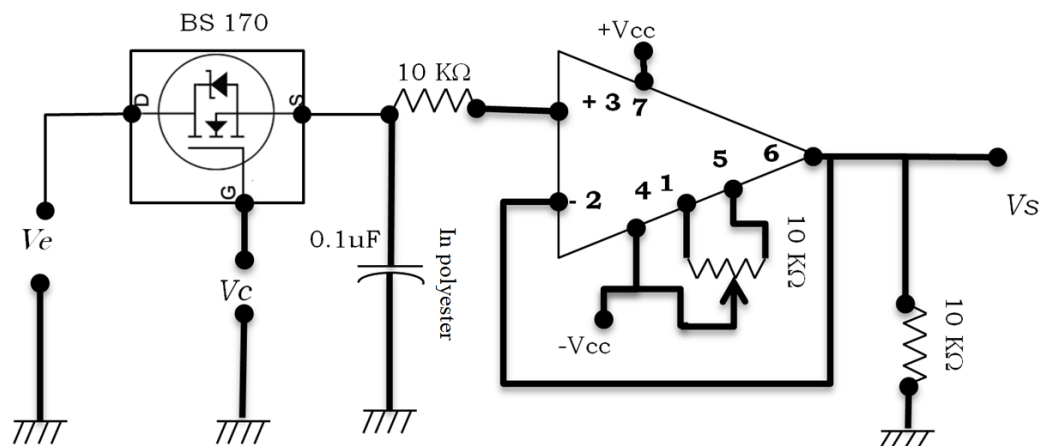


Figure 74 Example of a blocker sampler by an AOMP

The sample-and-hold circuit uses a uA741 operational amplifier and a BS170 MOSFET to sample and hold the value of an input signal V_e ; the analog input voltage to be sampled. The MOSFET acts as a switch controlled by a V_c trigger control voltage, enabling capacitor C_1 to store the sampling voltage. When the control voltage cancels, the capacitor retains the sampled voltage, and the circuit provides a stable output equivalent to the stored sample.

Exemple 17: -

The following figure shows the analog signal in the example of the (Figure 72). After a blocker sampler has passed, the signal sampled with an equal frequency. ($f_e = 100 \text{ Hz}$, $T_e = 10 \text{ ms}$)

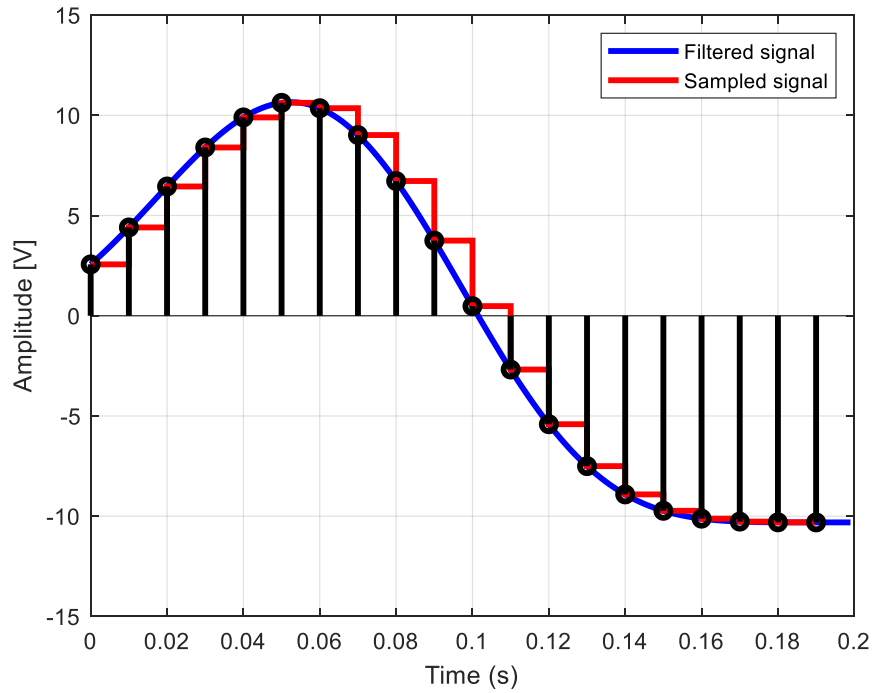


Figure 75 Signal sampled with blocker

4.9 QUANTIZATION:

An analogical quantity represents a succession of real numbers with a considerable number of decimal places. Computer memory is not infinite; it is restricted. Sampling consists of taking certain values from a continuous function. However, to limit the number of values, we will make an approximation:

We will remember that the values according to a certain step p of quantification or the quantum.

$$p = q = \frac{\text{Measurement range}}{2^n} = \frac{EM}{2^n}$$

n : Number of Bits

The small variation in analog voltage located by an analog-to-digital converter, and another parameterized showing the decomposition width of the measured value (voltage, current, etc.) called the quantum given by:

$$q = \frac{V_{max} - V_{min}}{2^n} = \frac{EM}{2^n} = \frac{PE}{2^n}$$

Quantification is therefore to assign a level to each sample taken. Each value is rounded to the nearest allowable value by default. The signal is therefore quantized and can only take certain discrete values. Example:

We want to quantify the analog signal of the previous example (Figure 72) knowing that $V_{max} = 10V$ and $V_{min} = -10V$, we quantize it in $n = 3$ bits.

$$q = \frac{10 - (-10)}{2^3} = \frac{20}{8} = 2.5V$$

The 8 possible voltage values are:

Level	0	1	2	3	4	5	6	7
Value Range (V)	$-10 < u \leq -7.5$	$-7.5 < u \leq -5$	$-5 < u \leq -2.5$	$-2.5 < u \leq 0$	$0 < u \leq 2.5$	$2.5 < u \leq 5$	$5 < u \leq 7.5$	$7.5 < u \leq 10$

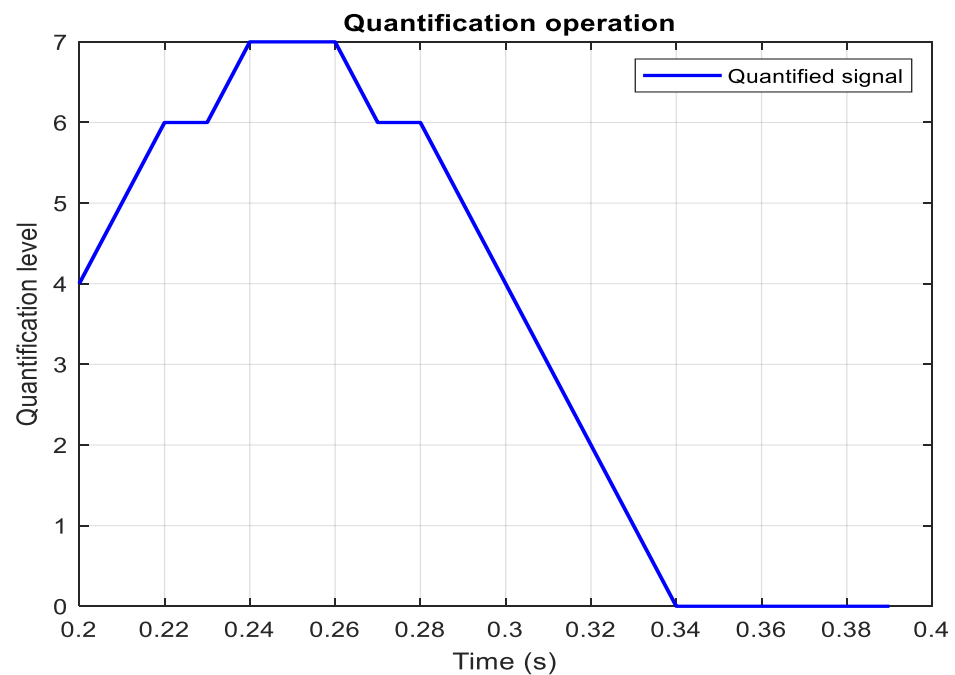


Figure 76 3-bit quantized signal

4.10 SIGNAL CODING

Signal coding is the process of representing a signal in digital form. It can be used to store, transmit, or process information from an analog signal.

The allowed value is encoded by a binary number. The digitized values will be stored as bits. A bit is a unit of information that can only take two values: 0 or 1.

The choice of encoding method depends on the application and the required accuracy and bandwidth requirements.

Exemple 18: -

After quantization, each level is encoded in natural binary

Level	0	1	2	3	4	5	6	7
Value Range (V)	$-10 < u \leq -7.5$	$-7.5 < u \leq -5$	$-5 < u \leq -2.5$	$-2.5 < u \leq 0$	$0 < u \leq 2.5$	$2.5 < u \leq 5$	$5 < u \leq 7.5$	$7.5 < u \leq 10$
Code (n=3 bits)	000	001	010	011	100	101	110	111

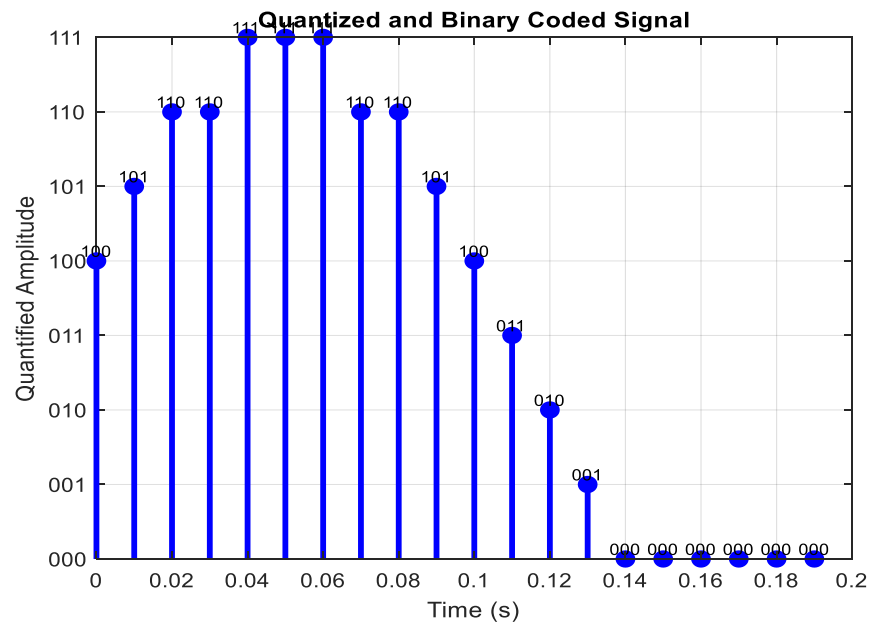


Figure 77 Quantized signal $q=2.5V$ and encoded in $n=3$ bits and sampled at a time $T_e=10$ ms

Exemple 19: -

4-bit resolution acquisition card with f_e sampling frequency offers $2^4 = 16$ possible combinations. The signal varies between -2V and 2V.

- Analog signal sampling:

Points of the curve obtained after sampling at the period T_e .

$$q = p = \frac{EM}{2^n} = \frac{2 - (-2)}{(2^4 = 16)} = 0,25V$$

The resolution of the signal obtained at the output will depend on the converter used. In other words, on the electronics used. The theoretical limit of the resolution is defined by the number of bits of the analog-to-digital converter.

For example, an analog signal encoded on 1 bit, only two values are possible for this bit, either "0" or "1". The accuracy is then very low and does not allow a satisfactory result.

When the encoding is carried out on 2 bits, each bit can take two values ("0" or "1"), $2^2 = 4$ values will be stored, i.e. a quantization step of 2.5 V.

$$q = p = \frac{EM}{2^n} = \frac{10 - (0)}{(2^2 = 4)} = 2,5V$$

In this example, the signal has amplitude of 10 volts:

- 0 to 2.5 V, the code will be "00"
- 2.5 V to 5 V, the code will be "01"
- 5 V to 7.5 V, the code will be "10"
- 7.5 V to 10 V, the code will be "11"

Exemple 20: -

Below (Figure 78 to the Figure 83) is an example of a sampled signal for $T_e = 10ms$, varying from 0 to 10V for various numbers of bits for encoding. Note that the higher the number of bits, the better the accuracy, but the more memory the signal occupies.

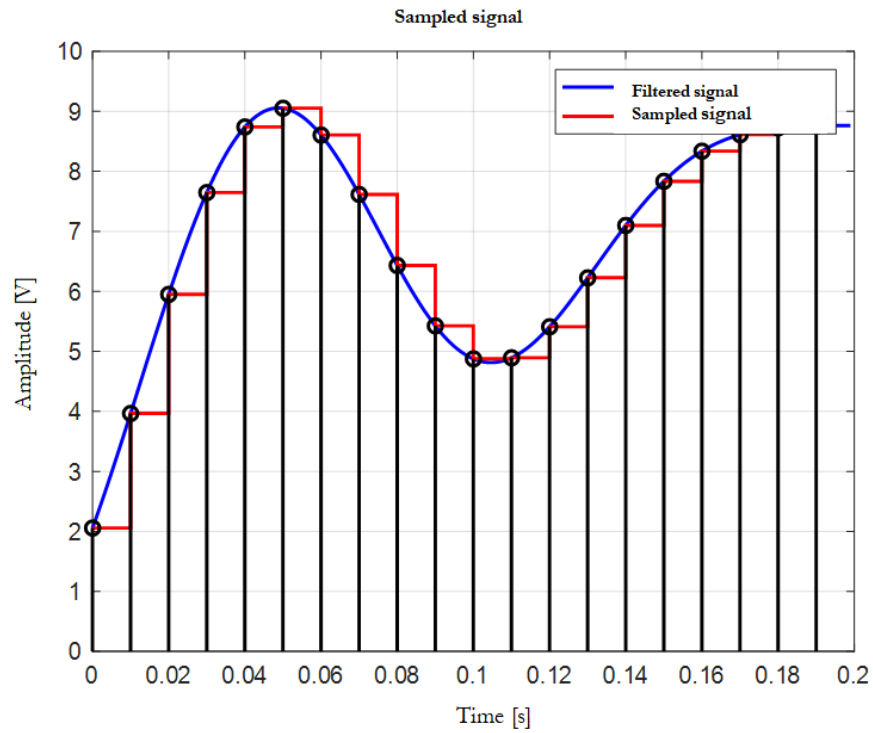


Figure 78 Sampled signal for $T_e=10$ ms

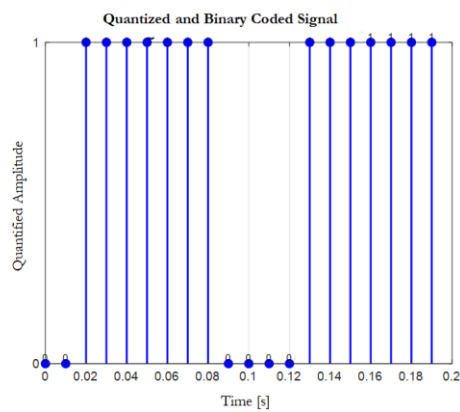


Figure 79 Encoding on a 1-bit ($T_e=10$ ms)

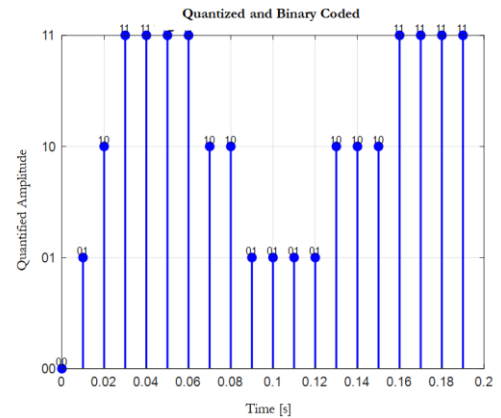


Figure 80 2-bit encoding ($T_e=10$ ms)

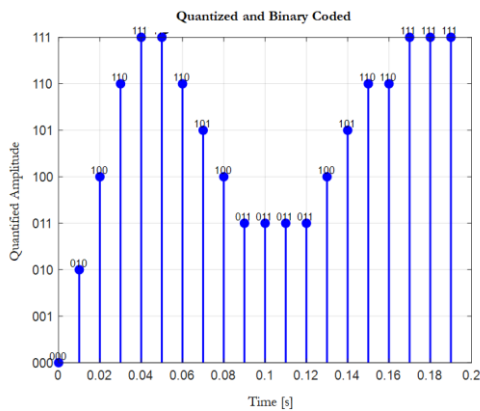


Figure 81 3-bit encoding ($T_e=10$ ms)

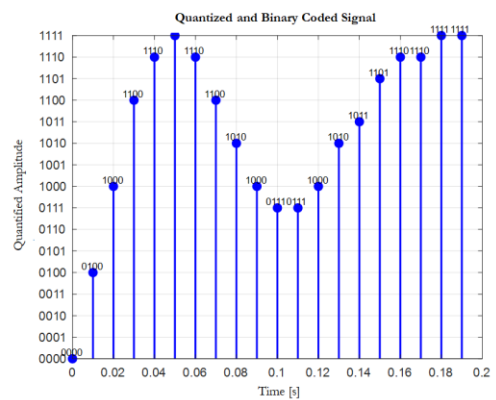


Figure 82 4-bit encoding ($T_e=10$ ms)

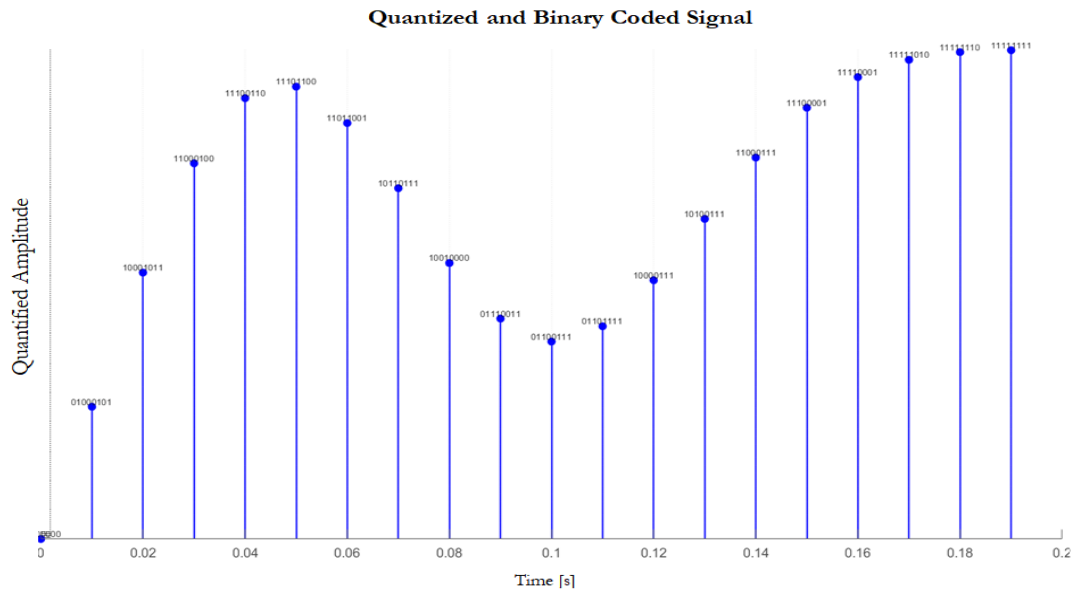


Figure 83 8-bit encoding ($T_e = 10$ ms)

4.11 ADC ARCHITECTURE

Different digital conversion methods are available. The performance of each conversion technique is different. Mainly with regard to the specifications, the accuracy of the numerical result obtained the ease of conversion, the complexity and the cost. The three conversion categories are represented in the (Figure 84).

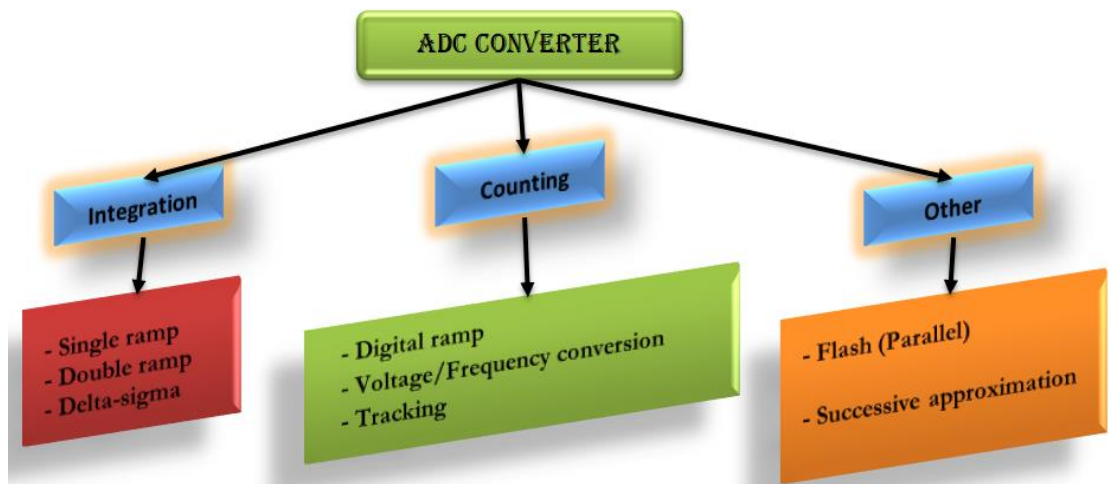


Figure 84 Types of converters

The following table shows a comparison between some converters.

Table 0-1 Comparison between some types of ADC converter

Type	Conversion time	Benefits	Disadvantage	Maximum Resolution	Usage	Precision
Single ramp	Slow (ms)	Simple and cheap	Conversion time depends on the value to be measured.	---	Inaccurate measurements	10^{-3}
Delta-sigma	Limiting the variation of the input signal V_e	Very good dynamic performance	Presence of hysteresis on unnatural signals	32-bit	Acquisition (Sound, Noise)	very accurate
Double ramp	Slow (ms)	Accurate, cheap	Low speed	20-bit	Multimeters	10^{-5}
Successive approximation	Fast (μs)	Good speed-to-resolution ratio	Without conceptual aliasing protection	18-bit	Data acquisition	10^{-3}
Flash (parallel)	Very fast (ns)	Fastest	Low bit resolution, very complex	12-bit	Digital Oscilloscope	Low accuracy

4.11.1 INTRODUCING A PARALLEL CAN (FLASH)

Principle:

A flash ADC has been set up to solve the problem of the processing time of the stair or ramp ADC.

Its slowness is due to the fact that it resets with each new value to be converted. The processing of the input values is done in series, and the processing time of each sample is related to the value of the voltage processed.

The flash ADC consists of 2^n resistors for the constitution of the voltage divider and $2^n - 1$ comparators, in this converter the samples are processed instantaneously by the corresponding comparator see the example of the (Figure 85).

For educational purposes, we will present a simple 2-bit ADC.

The flash ADC therefore consists of $2^2 - 1 = 3$ comparators and $2^2 = 4$ resistors for the voltage divider to obtain the 3 different reference voltage levels (Figure 85).

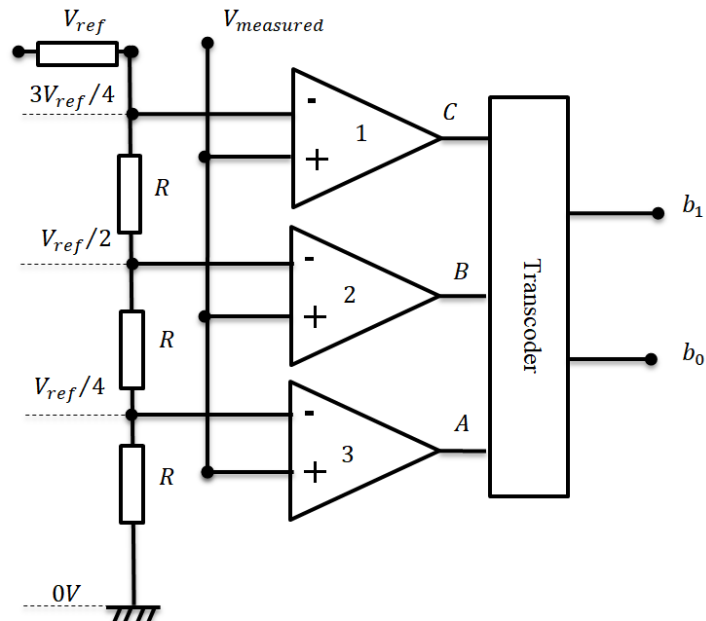


Figure 85 Diagram of a 2-bit ADC

In order to design the internal schematic of the transcoder, we must go through the following steps:

- Karnaugh map:

V_e	A	B	C	b_0	b_1
$[0, \frac{V_e}{4}]$	0	0	0	0	0
$] \frac{V_e}{4}, \frac{V_e}{2}]$	1	0	0	1	0
$] \frac{V_e}{2}, \frac{3V_e}{4}]$	1	1	0	0	1
$] \frac{3V_e}{4}, V_e[$	1	1	1	1	1

- Karnaugh maps:

b_0				
A\BC	00	01	11	10
0	0			
1	1		1	0

b_1				
A\BC	00	01	11	10
0	0			
1	0		1	1

- Logical equations:

$$\begin{cases} b_0 = C + A\bar{B} \\ \text{et} \\ b_1 = B \end{cases}$$

- Proposal of the schema by the logic gates:

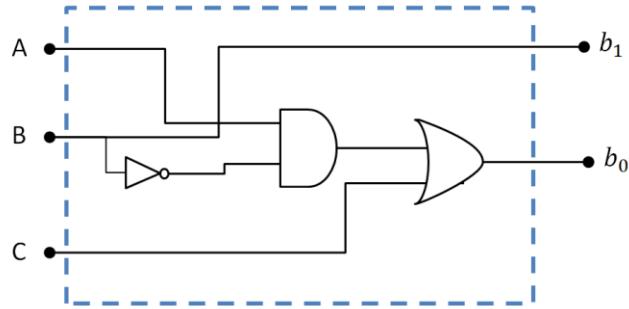


Figure 86 Transcoder logic circuit

Usually, it is recommended to use universal logic gates to reduce the number of integrated circuits and increase the speed of information transmission, for example, the 7400 integrated circuit which is composed of 4 gates with two outputs.

Modifying the following equations:

$$b_0 = A\bar{B} + C = \overline{\overline{A\bar{B}} + \overline{C}} = \overline{\overline{A\bar{B}} * \overline{C}}$$

$$b_1 = B = \bar{\bar{B}}$$

This gives the following circuit:

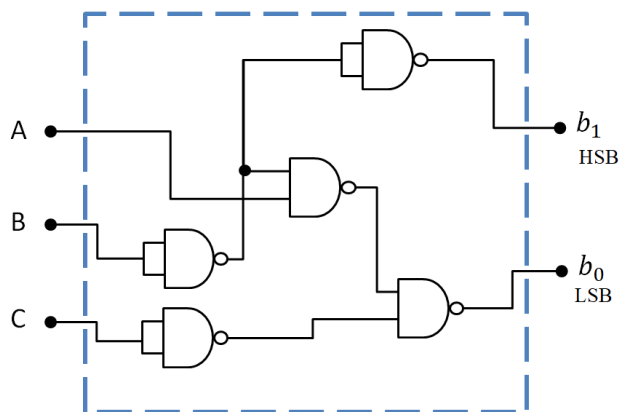


Figure 87 Transcoder logic circuit using NAND universal gates

The main disadvantage is the number of components used which increases 2^n (number of bits). On the other hand, this CAN is a precise monk.

4.11.2 SUCCESSIVE APPROXIMATION CAN

The Successive Approximation Analog-to-Digital (ADC) Converter is a type of converter that uses the successive approximation method (Dichotomy) to convert an analog signal into a digital value. This type of

ADC is usually where you need to have high accuracy. The structure of this converter is illustrated in the figure below.

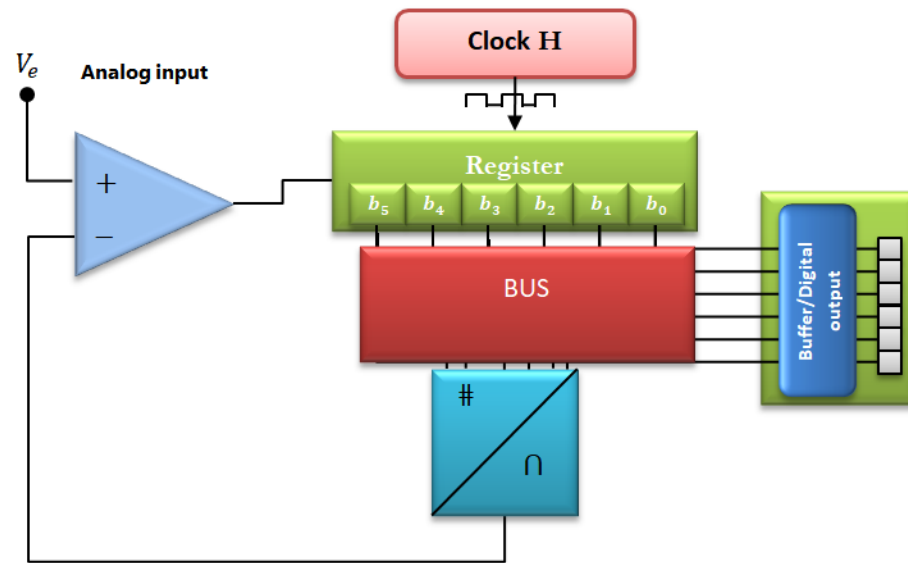


Figure 88 Structure of an ADC with successive approximations

4.11.2.1 HOW A SUCCESSIVE APPROXIMATION ADC WORKS

The conversion steps are as follows:

The analog signal V_e is sampled at a frequency set by the clock. During the sampling period, a signal value is captured and maintained during the conversion. The conversion initially starts with a numeric value of zero. The ADC uses a shift register (or a comparison register) and a digital-to-analog converter (DAC see 4.12 page 88) to approximate the value of the analog signal. The successive approximation algorithm compares the analog signal with a voltage generated by the DAC.

4.11.3 OPERATION

At the rate of the clock, the register assigns the value 1 to the most significant weight (MSB) in the (Figure 88) corresponds to the bit b_5 , the binary word is then (100000) this numerical value converted into an analog value by a DAC by its transfer function ($V_{CNA} = q \cdot N$), then it is compared to the voltage to be converted using a comparator (AOMP). If the voltage $V_{CNA} > V_e$ analog voltage is maintained the value 1 if not, we assign 0 to the bit (b_5) and at the same time a 1 to the next bit (b_4). The approximation process continues for the other bits up to the lowest weight bit (LBS) b_0 . At the end, the final numerical code identified represents the

analog value being measured. For this type of ADC, the number of steps is equal to the number of bits.

Exemple 21: -

To concretize this process, we take the example of an 8-bit converter with a reference voltage of 15V and a conversion voltage equal to 8,25V.

The calculations give:

Table 0-2 Calculation results of an 8-bit ADC /Vref=15V.

Q	0.05859 V	58.59 mv
$N=V_e/Q$	140.8 V	10001100
Bit resolution		8-bit
Percentage resolution		0,390625 %

The conversion process for each step is clearly outlined in the table below (The conversion steps for an 8-bit ADC are shown in the following table, to convert a voltage of 9.5V to a reference voltage of 15V.

Table 0-3). At each step, a 1 is applied starting with the MSB, the "N" is converted to decimal, and then the corresponding analog voltage is calculated using the DAC transfer function. Then, a comparison is made if the voltage V_{CNA} proposed by the DAC is higher than the analog voltage V_e . If the test is positive, we keep the 1, while if it is the opposite, we replace the bit with 0 and we propose a 1 (in black on the table) for the bit that succeeds it. The process continues in the same way up to the LSB bit. Once the process is complete, the result is displayed.

The conversion steps for an 8-bit ADC are shown in the following table, to convert a voltage of 9.5V to a reference voltage of 15V.

Table 0-3 Overview of the ADC Conversion Process with Successive Approximations

	MBS								LSB	Conversion Binary/Dec.	Voltage DAC Analog	Comparator	Output		
Step	b7	b6	b5	b4	b3	b2	b1	b0	N (decimal)	V _{CNA} =q*N	V _{CNA} >V _e	Logique	Value	Stage result	
1st stage	1	0	0	0	0	0	0	0	128	7,5 V	TRUE	1	Bit held	11000000	
Assign 1 to b6	1	1	0	0	0	0	0	0	192	11,25 V	FALSE	0	Bit held		
2nd stage	1	0	0	0	0	0	0	0			TRUE	1	Bit maintained	10100000	
Assign 1 to b5	1	0	1	0	0	0	0	0	160	9,375 V	TRUE	1			
3rd step	1	0	1	0	0	0	0	0			TRUE	1	Bit rejected	10110000	
Assign 1 to b4	1	0	1	1	0	0	0	0	176	10,3125 V	FALSE	0			
4th stage	1	0	1	0	0	0	0	0			TRUE	1	Bit rejected	10101000	
Affecter 1 à b3	1	0	1	0	1	0	0	0	168	9,84375 V	FALSE	0			
Stage 5	1	0	1	0	0	0	0	0			TRUE	1	Bit rejected	10100100	
Affect 1 to b2	1	0	1	0	0	1	0	0	164	9,609375 V	FALSE	0			
6th stage	1	0	1	0	0	0	0	0			TRUE	1	Bit maintained	10100010	
Assign 1 to b1	1	0	1	0	0	0	1	0	162	9,4921875 V	TRUE	1			
Stage 7	1	0	1	0	0	0	1	0			TRUE	1	Bit rejected	10100011	
Assign 1 to b0	1	0	1	0	0	0	1	1	163	9,55078125 V	FALSE	0			
8th stage	1	0	1	0	0	0	1	0	162	9,4921875	TRUE	1	Bit rejected	10100010	
	b7	b6	b5	b4	b3	b2	b1	b0	Results Presented in 8bits						
	1	0	1	0	0	0	1	0	10100010						

The successive approximation method offers a good compromise between conversion speed and accuracy. Successive approximation ADCs offer good accuracy, especially because of their ability to gradually refine the approximation of the analog signal.

4.12 ANALOG-DIGITAL DAC CONVERTER (DAC)

The function of the digital-to-analog converter is to reproduce the digital signal identical to the original one. The input signal is a discrete signal over time, and the output varies continuously.

4.12.1 DAC SYMBOL:

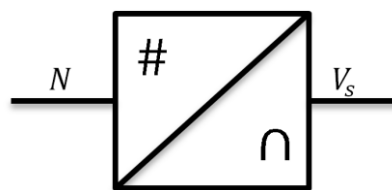


Figure 89 Standardized symbol for the digital-to-analogue converter

In this circumstance, the input is digital, consisting of N bits identical to the number of bits of the digital signal to be reconstituted.

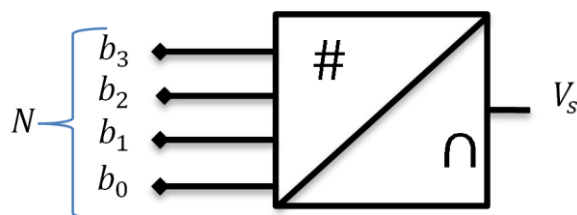


Figure 90 Diagramming the inputs and outputs of a 4-bit DAC converter

4.12.2 QUANTUM OF A DAC

For a DAC, the quantum is calculated by the following relationship:

$$q = \frac{V_{Max} - V_{min}}{2^n - 1}$$

4.12.3 TRANSFER CHARACTERISTIC OF AN DAC

The transfer function of a DAC expresses the output voltage V_s based on its digital input N .

The transfer function is given by the relation

$$V_s = N \cdot q$$

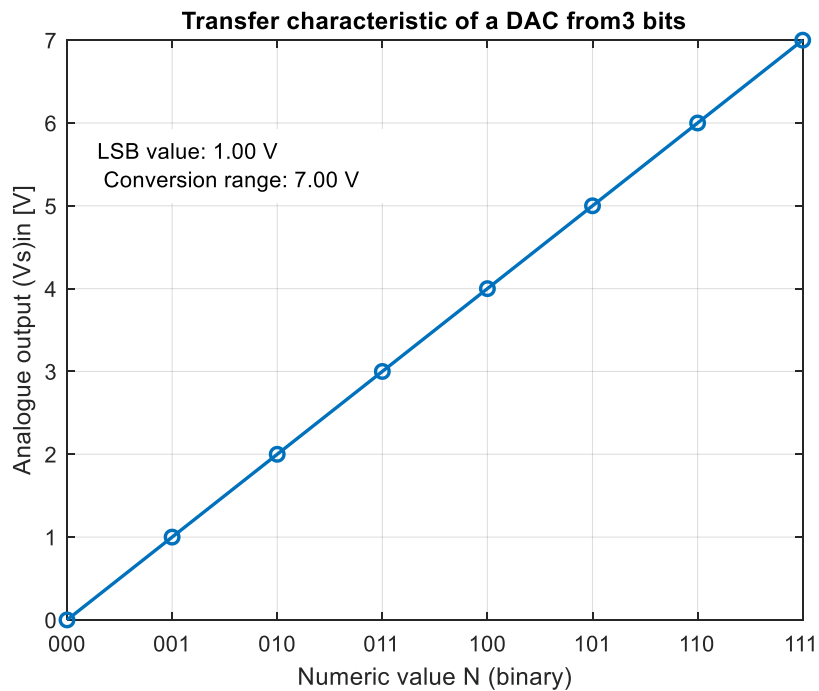


Figure 91 Transfer Characteristic of a 3-bit DAC

4.12.4 FULL-SCALE EXCURSION OF ADC

In the construction documents, the full-scale PE excursion of an ADC commonly referred to as FSR (Full-Scale Range). It is used to indicate the maximum value of the output analog quantity.

$$PE = (2^n - 1) \cdot q$$

Exemple 22: -

For a DAC of the (Figure 91) of quantum $q = 1V$ and $n = 3 \text{ bits}$ input, The full-scale voltage is:

$$PE = (2^3 - 1) \cdot 1 = 7 \cdot 1 = 7V$$

4.12.5 THE RESOLUTION OF A ADC

The resolution of a CNA is

1. Bit resolution:

$$R_b = q$$

2. The percentage resolution:

The relationship is the same for an ADC it is equal to:

$$R_{\%} = \frac{100}{2^n} \%$$

4.13 RECONSTRUCTION OF AN ANALOG SIGNAL

For the reconstruction of the analog signal, we first use a sampler to hold the sample value for a period of T_e time. Then a filter is used to maintain the mean value between two samples, called an averaging filter, to smooth the wavy signal the filter's function is to suspend the signals harmonics emitted by the sampler.



Figure 92 Chain of restitution

4.13.1 DAC ARCHITECTURE

Digital-to-analog converters (DACs or DACs) can adopt a different architecture depending on specifications and performance requirements. When choosing the architecture of a DAC, it is important to consider several factors such as the required accuracy, conversion speed, cost, and design complexity. The advantages and disadvantages are present in architecture.

The following table presents the advantages and disadvantages of a few types of DACs.

Table 0-4 Comparison entries the different types of NAC

TYPE	ADVANTAGE	Disadvantages
CURRENT-OUTPUT (CURRENT-OUTPUT DAC)	- Has a wide range of outputs and high speeds. - Less affected by temperature variations compared to resistors.	- Complex to design and calibrate - Can introduce noise if currents are not well controlled.
SIGMA-DELTA	- Offers very high resolution and excellent conversion quality. - Quantization noise is generally well filtered.	- More complex and expensive. - Can introduce latency due to the process of oversampling and filtering.
Weighted Resistors	- Easy to design and understand. - Cheaper to produce. - Good time response for simple applications.	- Less accurate due to variations in resistances. - Stability is affected by temperature. - Requires a large number of precise resistances.
DIGITAL RESISTANCE (R-2R LADDER DAC)	- Relatively simple to design with reasonable accuracy. - Good accuracy and linearity when the resistors are well matched.	- The accuracy of the conversion depends on the accuracy of the resistors used. - Are not the fastest compared to other architectures.
SEGMENTED DAC	- Provides better accuracy in a wider range of values. - Can result in high conversion speeds.	More complex to design compared to DAC/R-2R.
DAC TO PULSE WIDTH MODULATION (PWM) (PULSE WIDTH MODULATION)	- Simple to implement. - Generally less expensive in terms of equipment.	- The quality of the analog signal depends on the filter used to eliminate high-frequency components. - May introduce noise if filtering is not appropriate.
MULTI-RESISTANCE (MULTI-BIT DAC)	- Provides high resolution and good accuracy. - Less affected by temperature variations and noise.	- More complex to design and calibrate. - More expensive due to the number of resistors or circuits required.

Below, we present some architecture of the simplest and most commonly used converters.

4.14 DAC WITH WEIGHTED RESISTORS

The DAC with weighted resistors, or Digital Analog Meter with weighted resistors, is a circuit used in electronics to convert digital signals into analog signals. This type of DAC is appreciated for its simplicity and ease of implementation, although it may not offer the accuracy or stability of other types of DACs, such as DACs to R-2R.

4.14.1 GENERAL OPERATION

The DAC receives a numerical code as input. This code is often provided by a register or other digital circuit. A network of resistors is used, the values of which are chosen according to a weighted scheme. These resistors are arranged in such a way as to represent the bit weights of the numerical code. For example, in a 5-bit DAC, resistors could be chosen to represent proportional values $2^0, 2^1, 2^2, 2^3, 2^4$. The numerical code is converted to a proportional analog voltage. This is usually done by using a resistor array that divides the reference voltage based on the applied numerical code (Figure 93).

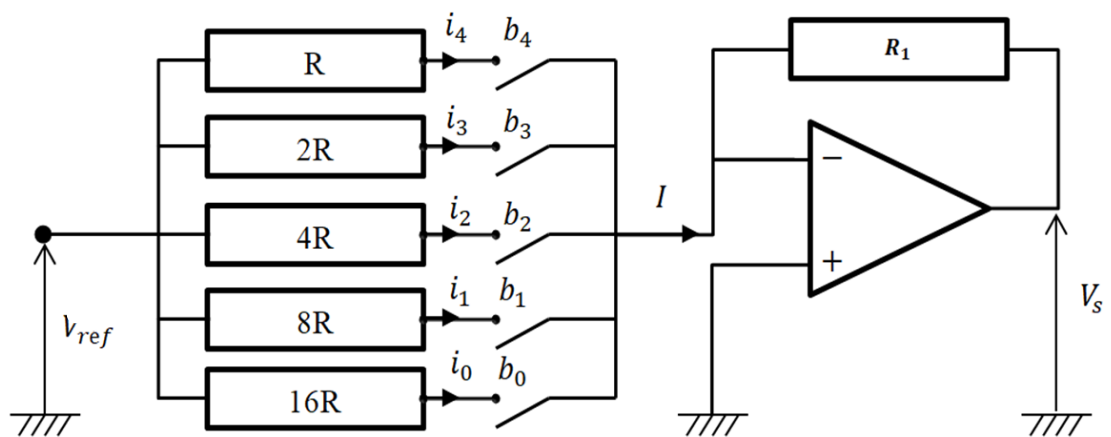


Figure 93 5-bit weighted resistor DAC

The output signal is an analog voltage that corresponds to the digital input value. This voltage is usually smooth and continuous, unlike the digital input signal which is discrete.

4.14.2 SIMPLIFIED EXAMPLE

Let's calculate a 5-bit DAC (Figure 93), the current $I = -V_s/R_1$ (see Mounting current-to-voltage conversion).

On the other hand, the current, $I = i_0 + i_1 + i_2 + i_3 + i_4$.

And $i_0 = V_{ref}b_0/16R, i_1 = V_{ref}b_1/8R, i_2 = V_{ref}b_2/4R, i_3 = V_{ref}b_3/2R, \text{ and } i_4 = V_{ref}b_4/R$

Therefore: $I = b_0 \frac{V_{ref}}{16R} + b_1 \frac{V_{ref}}{8R} + b_2 \frac{V_{ref}}{4R} + \frac{b_3 V_{ref}}{2R} + b_4 \frac{V_{ref}}{R} = \frac{-V_S}{R_1}$

$$V_S = -\frac{R_1}{R} V_{ref} \left(\frac{b_0}{16} + \frac{b_1}{8} + \frac{b_2}{4} + \frac{b_3}{2} + \frac{b_4}{1} \right)$$

We can rewrite this equation by multiplying it and valuing it by 16.

$$V_S = -\frac{R_1}{16.R} V_{ref} (b_0 + 2.b_1 + 4.b_2 + 8.b_3 + 16.b_4)$$

Finally:

$$V_S = -\frac{R_1}{2^4.R} V_{ref} (2^0 b_0 + 2^1 b_1 + 2^2 b_2 + 2^3 b_3 + 2^4 b_4)$$

We use n resistors in parallel and the generalized equation is therefore for n bits:

$$V_S = -V_{ref} \frac{R_1}{R.2^{n-1}} \sum_{p=0}^{n-1} 2^p b_p$$

This type of DAC is characterized by its simple architecture and ease of implementation, although it may not offer the required accuracy or stability of other DAC types, such as DACs to R-2R.

4.15 DAC TO R-2R.

The R-2R converter converts a digital signal to an analog signal using a network of specific resistors to obtain an output voltage proportional to the digital input value. It is usually composed of series and parallel resistors arranged so that it forms a binary-scale network. Each bit of the digital signal is represented by a resistor in the network (Figure 94).

Exemple 23:

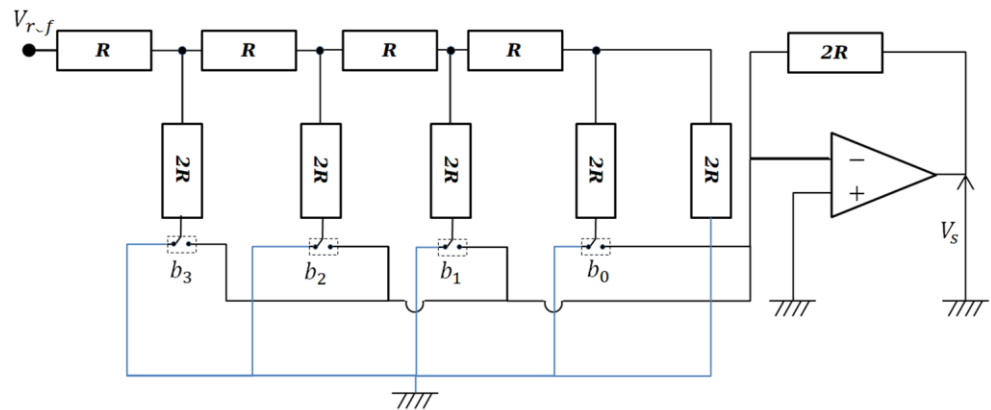


Figure 94 4-bit R/2R resistor DAC

$$V_s = -2I_s R = -2R(I_0 + I_1 + I_2 + I_3)$$

Let's calculate the currents in each branch:

- The relationship between tensions

$$V_3 = \frac{V_{ref}}{2}$$

$$V_2 = \frac{V_3}{2} = \frac{V_{ref}}{2^2}$$

$$V_1 = \frac{V_2}{2} = \frac{V_3}{2^2} = \frac{V_{ref}}{2^3}$$

$$V_0 = \frac{V_1}{2} = \frac{V_2}{2^2} = \frac{V_3}{2^3} = \frac{V_{ref}}{2^4}$$

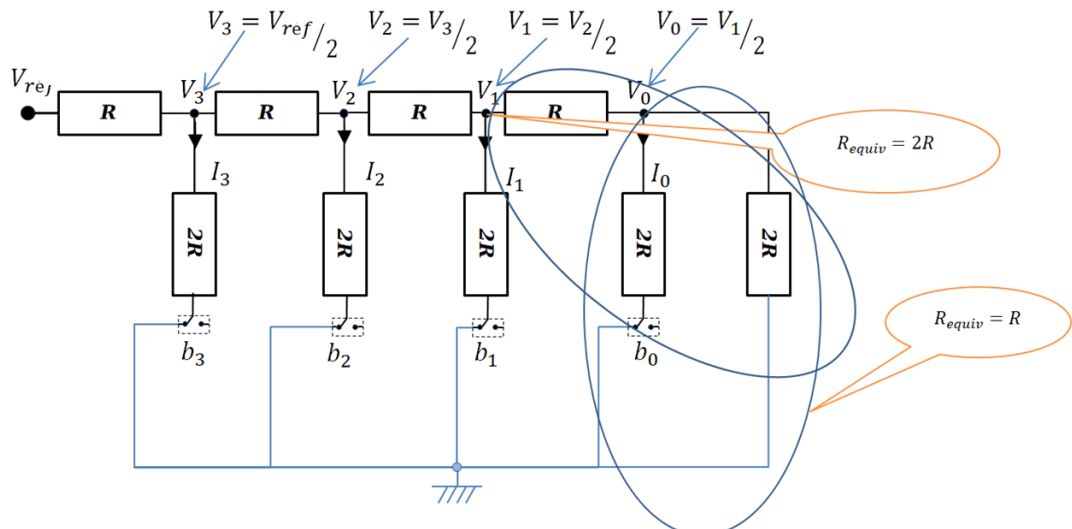


Figure 95 Equivalent diagram of the R-2R mount for all bits are grounded

- The relations of currents

The bits switch the current either to ground or $b_i = 0$ to the input V^- to the OP amp wired as a summator $b_i = 1$.

$$\begin{aligned} I_3 &= b_3 \frac{V_3}{2R} = b_3 \frac{V_{ref}}{4R} = b_3 \frac{V_{ref}}{2^2 R} \\ I_2 &= b_2 \frac{V_2}{2R} = b_2 \frac{V_{ref}}{2^3 R} \\ I_1 &= b_1 \frac{V_1}{2R} = b_1 \frac{V_{ref}}{2^4 R} \\ I_0 &= b_0 \frac{V_0}{2R} = b_0 \frac{V_{ref}}{2^5 R} \end{aligned}$$

Let's replace the currents with their values

$$\begin{aligned} V_s &= -2I_s R = -2R(b_0 \frac{V_{ref}}{32 \cdot R} + b_1 \frac{V_{ref}}{16 \cdot R} + b_2 \frac{V_{ref}}{8 \cdot R} + b_3 \frac{V_{ref}}{4 \cdot R}) \\ V_s &= -2I_s R = -R(b_0 \frac{V_{ref}}{16 \cdot R} + b_1 \frac{V_{ref}}{8 \cdot R} + b_2 \frac{V_{ref}}{4 \cdot R} + b_3 \frac{V_{ref}}{2 \cdot R}) \\ V_s &= -2RI_s = -V_{ref} \left(b_0 \cdot \frac{1}{2^4} + b_1 \cdot \frac{1}{2^3} + b_2 \cdot \frac{1}{2^2} + b_3 \cdot \frac{1}{2} \right) \end{aligned}$$

The factor is 2^4 as follows:

$$V_s = - \left(\underbrace{\frac{V_{ref}}{2^4}}_q * \underbrace{(2^0 + 2^1 + 2^2 + 2^3)}_N \right)$$

We can then write a generalized formula for n bits:

$$V_s = - \frac{V_{ref}}{2^n} \sum_p^{n-1} b_p \cdot 2^p$$

R-2R converters are used in a variety of electronic applications where digital-to-analog conversion is required, such as in digital audio systems, and measuring instruments.

The architecture of the R-2R is relatively simple to design and implement compared to other types of DACs.

The resistors used are of precise value, which allows a digital-to-analog conversion with good precision.

GENERAL CONCLUSION

This manuscript has explored the fundamental principles of operational amplifiers, sensors, and measurement chains, covering key concepts necessary for the design and application of advanced electronic systems.

The first chapter laid the groundwork for operational amplifiers and their crucial role in signal processing, highlighting various feedback configurations and their diverse applications, such as in linear amplifiers or current-to-voltage converters. These concepts are essential for understanding the principles of amplification and signal management in electronic circuits.

The second chapter delved into the physical phenomena that form the basis of sensor operation, emphasizing the importance of effects such as the thermoelectric, piezoelectric, and photovoltaic effects, which enable the detection of a wide range of physical parameters in applications from temperature and pressure to magnetic fields.

The third chapter focused on the characteristics of sensors, defining performance criteria such as sensitivity, accuracy, and response time, while distinguishing between passive and active sensors and detailing errors that may affect their operation. This section allowed for a deeper understanding of the importance of proper sensor selection and calibration for high-quality measurements.

Finally, the fourth chapter detailed the measurement chain and conditioning circuits, highlighting the role of analog-to-digital and digital-to-analog converters in processing and transmitting signals to downstream systems. Managing noise, digitizing, and converting signals were key aspects in ensuring the integrity of measured data in complex systems.

In conclusion, this manuscript provides a comprehensive overview of the principles and applications of operational amplifiers and sensors, underscoring their essential role in modern electronic systems. The

knowledge gained here not only enhances the understanding of the theoretical concepts underlying these technologies but also facilitates their practical application in designing efficient and reliable signal measurement and processing systems. The rapid advancement of sensor and amplification technologies paves the way for numerous innovations across various fields, from medical instrumentation and industrial automation to communication systems and the Internet of Things.

BIBLIOGRAPHY

1. **Bedwani, ch.** bedwani.ch/electro. *INTRODUCTION A L'ELECTRONIQUE*. [Online] <http://www.bedwani.ch/electro/ch21/>.
2. **Courtellemontles, Pierre.** *EMB7000-Introduction aux systèmes embarqués-circuit conditionnement pour les capteurs.*
3. **Gaëtan, ANNECCA.** *CAPTEURS - Conditionnement des Signaux - Instrumentation Industrielle.*
4. *Utilisation d'un convertisseur courant-tension.* **DONNINI, Jean-Marie, PAYAN, Rogert and RENUCCI, Pierrette.** s.l.: BULLETIN DE L'UNION DES PHYSICIENS, 1994, BULLETIN DE L'UNION DES PHYSICIENS, pp. 834-248.
5. **DEMONCHY, Marc, LE GOFF, Robert and EIFFEL-CACHAN, L.S.I. Gustave.** *CONVERTISSEURS NUMERIQUE/ANALOGIQUE.* s.l. : DIDALAB, 2007.
6. **DHALLUIN, Bernard and DUTERTRE, Jean-Max.** *Electronique Analogique 1 - AMPLIFICATEUR OPERATIONNEL Partie 3.* 2021-2022.
7. **De Conto, Jean-Marie.** *Capteurs. 1. Capteurs et conditionneurs .* s.l. : IUT1 Grenoble, 2012.
8. **VIM.** *Concepts fondamentaux et généraux et termes associés (VIM) » Version 3.* La deuxième édition : JCGM 200, 1993 .
9. **DUTERTRE, J.M.** Page professionnelle de Jean-Max Dutertre. *documents / cours_convertisseurs.pdf.* [Online] www.emse.fr/~dutertre/enseignement.html.
10. **ROUSSEAU, Jean-Jacques.** Physique et simulations Numériques. *Faculté des Sciences exactes et naturelles.* [Online] janvier 3, 2024. <https://ressources.univ-lemans.fr/AccesLibre/UM/Pedago/physique/02/electro/canrampe.html>.
11. **Grant, Maloy Smith.** DEWESOFT. *Types de convertisseurs ADC .* [Online] février 13, 2024 . <https://dewesoft.com/fr/blog/types-de-convertisseurs-adc>.
12. **Blop, Ben.** *Trigger de Schmitt, explication détaillée et exemple d'utilisation.* Octobre 2021.

13. **POULICHET, Patrick.** *Cours sur l'électronique de conditionnement du capteur, TS3 : conditionnement du signal du capteur*. s.l. : ESIEE, 2006.
14. **École d'ingénieur à Brest, France.** UV 1.7 : Capteurs et systèmes de mesure - 2017 2018 - Cours n°1 - Erreurs Statiques. s.l. : École d'ingénieur à Brest, France.
15. —. UV 1.7 : Capteurs et systèmes de mesure - 2017 2018 - Cours n°2 - Circuits Conditionneurs. s.l. : École d'ingénieur à Brest, France.
16. *OpenAI*. [Online] <https://chat.openai.com>.
17. **Wafa, Wafa.** Conversion numérique analogique. [Online] <https://fr.slideshare.net/slideshow/conversion-numrique-analogique/7486300>.