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Educational handout

State of the art in electrical engineering

Intended for 2nd year electromechanical students

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Preface

Electrical engineering is one of the fundamental fields of the modern world. From the discovery of the fundamental principles of electricity to the latest progress in embedded artificial intelligence and renewable energy, this discipline has transformed our lifestyles, industries, healthcare systems, and communication methods. It is hard to imagine a single day without directly (or indirectly) relying on technologies derived from electrical engineering whether through simple lighting, Smartphones, intelligent transportation networks, or cutting-edge medical devices.

This handout, entitled "State of the Art in Electrical Engineering," aims to provide a clear, concise, and up-to-date overview of the major subfields that constitute this vast discipline including electronics, electrotechnics, automatics, and telecommunications, while highlighting their tangible impact on societal, economic, and technological development.

It is intended for 2nd year undergraduate students in Electromechanics. The content of this handout is fully complies with the syllabus for the module "State of the Art in Electrical Engineering," established by the Ministry of Higher Education and Scientific Research (MESRS) for the academic year 2025/2026 (updated version).

Various technical guides, catalogues, books, theses, and other sources inspired the texts presented in this handout.

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Chapter I. Electronics

I.1 Introduction

Electronics is a key element of modern electrical engineering, encompassing the design, analysis, and application of circuits and systems that process information and control energy at the signal level. From analog and digital circuitry to embedded systems technologies, electronics enables the functionality of all contemporary devices, such as Smartphones, medical instruments, and autonomous vehicles.

This chapter provides the state of the art in electronics, including analog and digital electronics, semiconductor devices, and integrated circuit.

I.2 Definition

Electronics derived from electrical engineering fields, it deals with the study, design, and application of devices and circuit that control the flow of electrons or other charged particles in various areas, such as vacuum, gas, or semiconductors. It includes the theory and practical implementation of circuits and devices, including diodes, transistors, integrated circuits, and sensors, usually used to process, amplify, transmit, and store electrical signals for communication, computation, control, and energy conversion.

There are two electronic types: analog and digital (or numerical) electronics. An analog signal is a continuous wave in both amplitude and in time. A digital signal is composed of individual, identifiable steps. Figure.1 shows a sine wave in analog and digital form. The digital wave approximates the analog wave by representing points along the waveform.

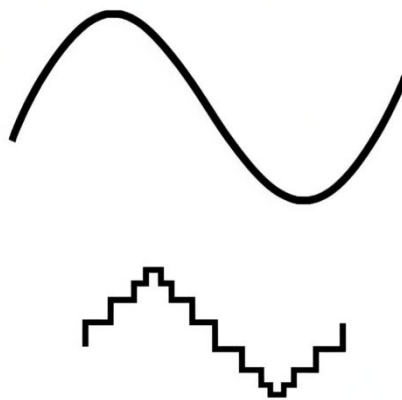


Figure 1 Basic analog and digital forms.

I.3 Analog electronics

In this type of electronics the electrical signals vary continuously over time and can take any value within a given range.

Analog electronic circuits are based on the using of passive and actives components like resistors, capacitors, inductors, diodes, transistors, amplifiers, to perform functions such as amplification, filtering, modulation, and signal conversion. Table.1 shows a comparison tables between both kinds of electronic components.

Table.1 Comparison between active and passive electronic components.

Active components	Passive components
Require power supply They have a gain function They produce energy in form of voltage or current Examples: diodes and transistors.	Do not require external power supply to operate No gain function Examples: capacitors, resistors, inductors.

I.3.1 Passive components

I.3.1.1 Resistors

It is a two-terminal passive electronic component that opposes (or limits) the flow of electric current in a circuit. It operates according the Ohm's Law, which states that the voltage (V) across a resistor is directly proportional to the current (I) passing through it, with the proportionality constant being the resistance (R), usually expressed as $V=R \times I$. Figure 2 shows the symbols of a resistor in a circuit diagram.

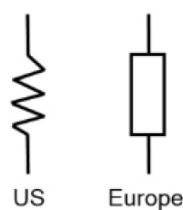


Figure 2 Symbols of resistor.

The resistance is measured in Ohms (Ω) and depends on the material, length, cross-sectional area, and temperature of the resistor. The fundamental relationship linking these quantities is given by,

$$R = \rho \frac{l}{S} \quad (1)$$

where l is the length of the conductor, S is the cross-sectional area, and ρ is the electrical resistivity of the material.

I.3.1.2 Capacitors

Capacitor is an electrical device that can store charge (Figure 3). They are applied for different purposes, including smoothing out spikes or drops in voltage and releasing quick bursts of power in applications such as a camera flash.

A capacitor is constructed of two layers, or plates, of conductive material separated by an insulator. When voltage passes through a capacitor, it creates an electric field in the insulating material, called the dielectric, situated between the two layers. The field holds an electric charge in the dielectric.

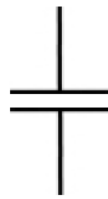


Figure 3 Symbol of capacitor.

Capacitance (in farads, F) is the ability to store electric charge per unit voltage, it is given by:

$$C = \varepsilon \frac{S}{d} \quad (2)$$

where, S is the area of the effective surface area of the plates, d is the distance between the two plates, and ε is the permittivity (dielectric constant).

The variation of current $i(t)$ through the capacitor is expressed by the following differential equation:

$$i(t) = C \frac{d}{dt} u(t) \quad (3)$$

where, $\frac{d}{dt} u(t)$ is the time derivative of the voltage, the rate at which the voltage changes over time.

The electrostatic energy E_{el} stored in the capacitor depends on the voltage across its terminals and its capacitance, and is given by:

$$E_{el} = \frac{1}{2} C (u(t))^2 \quad (4)$$

I.3.1.3 Inductor

It stores energy in the form of a magnetic field when electric current flows through it. It typically consists of a coil of wire, and its behavior is governed by the principles of electromagnetic induction.



Figure 4 Symbol of inductor.

The voltage across its terminals $u(t)$ is proportional to the rate of change of the current flowing through it. This relationship is described by,

$$u(t) = L \frac{d}{dt} i(t) \quad (5)$$

where L is the inductance (in henrys, H). $L(t) = \Phi(t)/i(t)$ is the auto-induction coefficient.

The energy E_m stored in terms of magnetic field of an inductor is given by,

$$E_m = \frac{1}{2} L (i(t))^2 \quad (6)$$

I.3.2 Active components

Devices that require an external power source to operate and can control the flow of current in different types of electrical circuits. They are able of amplifying signals, generating energy, or switching electrical signals within a circuit. The transistors and diodes are the main active components.

I.3.2.1 Diodes

Diodes are the technology that made early radio transmission and reception possible and they are essential in converting alternating current (AC) to direct current (DC). They prevent damage to electronics from high voltages. The use of diodes to create logic gates makes possible the computations that are the backbone of computers.

I.3.2.1.1 Structure and operation

Diodes have two terminals: a positive terminal, called an “anode”, and a negative terminal, “cathode” (Figure 5).

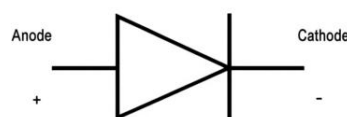


Figure 5 Symbol of diode.

Diodes are components that permit electricity to flow in a single direction and act against its flow in the opposite direction. When a diode is forward-biased (Figure 6), it means that:

- The positive voltage is applied to its anode.
- And the negative voltage is connected to its cathode.

In this configuration, and if the applied voltage exceeds the diode's threshold voltage (~ 0.7 V for a silicon diode, as shown in (Figure 7), the diode conducts current (on-state, ZONE 1). But, when the diode is reverse-biased, there no current flow in the circuit (blocked, ZONE 2).

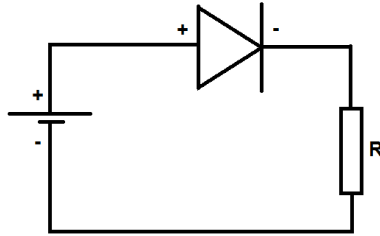


Figure 6 Diode forward-biased configurations.

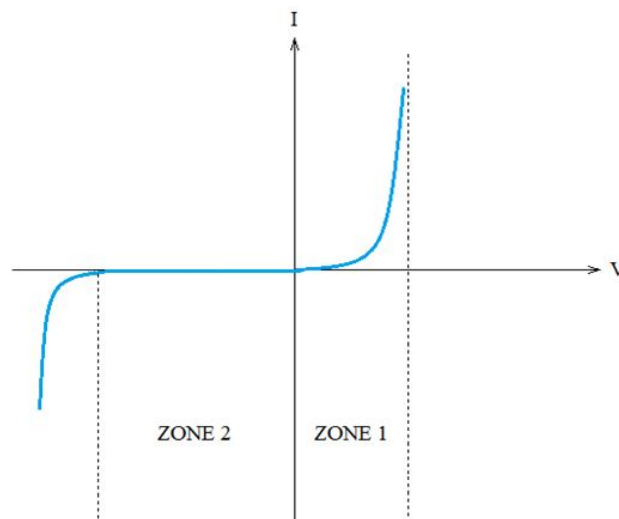


Figure 7 Current-voltage characteristics of diode.

a. Half-wave rectification

In order to rectify an AC signal that has already been stepped down by a transformer, we use the circuit shown in Figure 8.

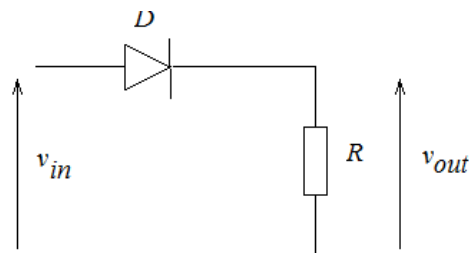


Figure 8 Half-wave rectifier circuits.

As a result, we obtain a rectified output signal v_{out} , as shown in Figure 9 (b).

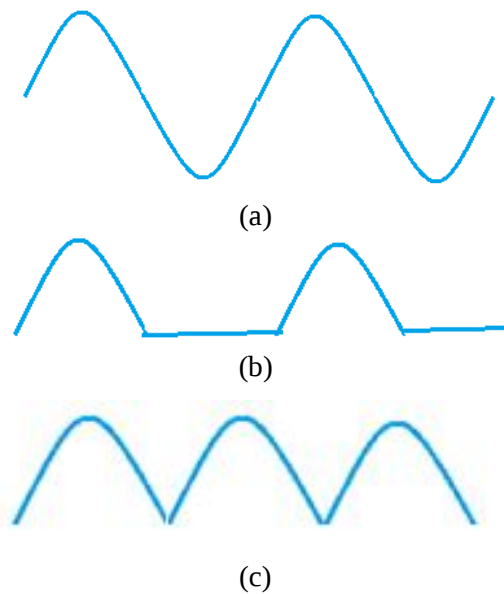


Figure 9 (a) Input AC signal v_{in} . (b) Half-wave rectified output signal v_{out} .
(c) Full-wave rectified output signal v_{out} .

The diode is made by two semiconductor (SC) materials with different doping types: the first is an N-type semiconductor and the second is a P-type semiconductor (Figure 10).

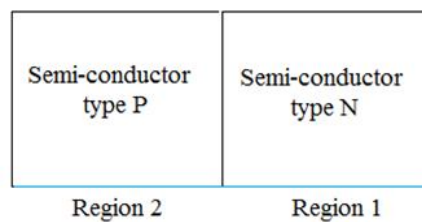


Figure 10 Basic structure of a PN diode.

b. Full-wave rectification

A diode bridge is based on the using of four diodes circuits, as shown in Figure 11. During the positive half-cycle, diodes D_2 and D_3 conduct current while the other diodes are reverse-biased (blocked). But, during the negative half-cycle, diodes D_4 and D_1 conduct current, and the others are blocked. This configuration enables full-wave rectification (Figure 9 (c)).

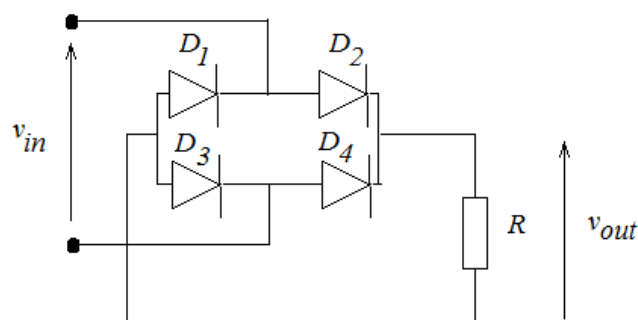


Figure 11 Diode bridge rectifier circuits.

c. Different types of diodes

Table 2 presents the most commonly used diodes in the field of electronics. It highlights their essential attributes, including key characteristics, electrical properties, and typical applications, from power conversion (Schottky diodes) and voltage regulation or signal control (Zener diodes) to optoelectronic functions (LED and photodiodes).

Table.2 Different kinds of diodes.

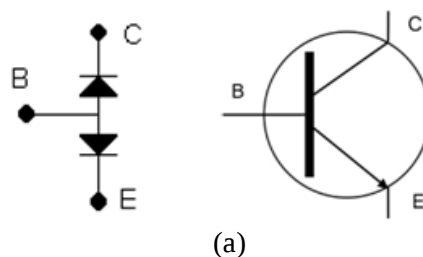
Type	Characteristics	Applications
PN Junction Diode	Basic diode Allows current in one direction only	General rectification Signal demodulation
Schottky Diode	Metal-semiconductor junction; Fast switching, low forward voltage	High-frequency circuits Power rectification Clamping
Zener Diode	Operates in reverse breakdown; Maintains stable voltage	Voltage regulation Overvoltage protection
Light Emitting Diode (LED)	Emits light when forward biased	Indicators Displays
Photodiode	Generates current when exposed to light	Light sensors Optical communication
PIN Diode	Has intrinsic (I) region between P and N Suitable for RF switching	RF switches attenuators, Photodetectors

I.3.2.2 Transistors

A transistor is an electronics component that amplifies signals or acts as a switch in different types of circuit. Transistors enable us to control the amount of current that flows through a circuit, diverting it or even reversing it.

I.3.2.2.1 Bipolar transistors (BTs)

BTs are basically made on two diodes put end to end, as shown in Figure 12. Therefore, we have two different configurations: NPN transistor (Figure 12(a)) and PNP transistor (Figure 12(b)). Moreover, each transistor contains three terminals: emitter (E), base (B), collector (C).



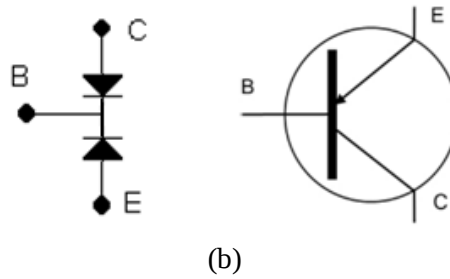


Figure 12 (a) NPN transistor and (b) PNP transistor.

The transistor's operation depends on the biasing of the two diodes (BE and BC). The following formulas show the operation of the transistor in various cases.

- When BE junction is forward-biased and BC junction is reverse-biased, we have an active region and the transistor acts as an amplifier. The amplification effect is called gain, which can be written as $\beta = I_c / I_b$, where I_c and I_b are the collector current and the base current, respectively.
- When both junctions (BE and BC) are forward-biased, we have saturation region and the transistor is a conductor, and a high current flows from collector to emitter.
- When both junctions are reverse-biased, the transistor is an open switch and cuts off the current flow.

I.3.2.2.2 Field-effect transistors (FETs)

The MOSFET transistor, or Metal-Oxide-Semiconductor Field-Effect Transistor, is the fundamental building block of digital integrated circuits (CI), memory devices, sensors and MEMS, RF and wireless communications.

The structure of an MOSFET (Figure 13) is fabricated on a P-type semiconductor substrate, within which two N⁺-type regions are created, called the Source and the Drain. In addition, we have three terminals: gate (grille in French), source, drain.

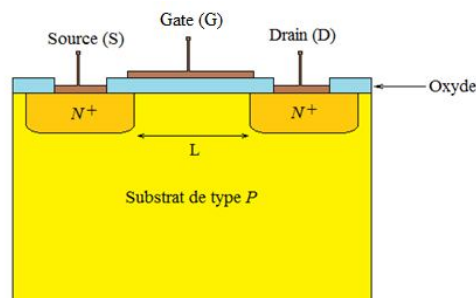


Figure 13 Basic structure of an MOSFET (N-channel).

The operation of the MOSFET transistor depends on the biasing of the gate to source V_{GS} electrode and the drain to source V_{DS} .

We obtain two main cases:

- $V_{GS} < V_T$: In this case, the transistor is in the OFF state, and no current flows between source and drain region. The transistor is either in accumulation ($V_{GS} < 0$) or in depletion region ($V_{GS} > 0$).
- $V_{GS} \geq V_T$: The transistor is in the ON state. And, a current flows between the source and drain, known as the drain-current I_D . The transistor is in the inversion mode, leading to the formation of an N-type conductive channel that electrically connects the source to the drain.

Figure 14 shows the variation of the drain current I_D as a function of V_{GS} for a fixed value of V_{DS} . This curve represents the transfer characteristic of the MOSFET.

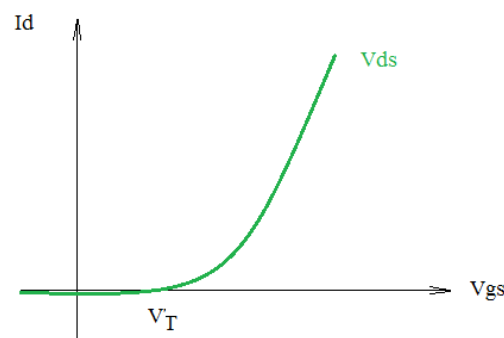


Figure 14 Transfer characteristics of MOSFET (N-channel).

There are other kinds of FET devices, such as:

- JFET: Junction Field-Effect Transistor.
- MESFET: Metal-Semiconductor Field-Effect Transistor.
- MODFET: (Modulated-Doping Field-Effect Transistor), also known as HEMT (High Electron Mobility Transistor), is a high-electron-mobility transistor characterized by a heterostructure design.

I.3.2.3 integrated circuits

An integrated circuit (IC), also known as a microchip or simply a chip, is a miniaturized electronic circuit fabricated on a single piece of semiconductor material, usually Silicon and Germanium. One IC integrates a lot of electronic components, such as transistors, diodes, resistors, and capacitors, along with their interconnecting wiring, into a compact, unified structure. ICs revolutionized electronics by replacing bulky discrete components with highly reliable, low-power, and cost-effective systems that can be mass-produced using

photolithographic techniques. ICs are manufactured through a complex, multi-step process called semiconductor fabrication or wafer processing

Modern ICs can contain billions of transistors on one single chip, with feature sizes now measured in nanometers (recently 3 nm or 5 nm). The most common technology for digital ICs is CMOS (Complementary Metal-Oxide-Semiconductor), which uses both NMOS and PMOS transistors to achieve low static power consumption and high noise immunity.

Table 3 summarizes the classification, functionality, and applications of various types of integrated circuits.

Table.3 Different types of integrated circuits.

Classification	Description	Applications
Analog ICs	Process continuous signals; used for amplification, filtering, and signal conditioning	Operational amplifiers, voltage regulators, RF transceivers
Digital ICs	Process discrete binary signals (0s and 1s); form the basis of computing	Microprocessors, memory chips (RAM, ROM), logic gates
Mixed-Signal ICs	Combine analog and digital circuits on a single chip	Analog-to-Digital Converters (ADCs), Digital-to-Analog Converters (DACs), system-on-chip (SoC)
By Scale of Integration	Based on number of transistors per chip	SSI (Small Scale), MSI (Medium Scale), LSI (Large Scale), VLSI (Very Large Scale), ULSI (Ultra Large Scale)

I.4 Digital electronics

I.4.1 Microprocessors

In modern systems, microprocessors are at the heart of almost every electronic device and systems, such as computers, smartphones, and industrial controllers. Their evolution has led to remarkable improvements in processing speed, power efficiency, and integration density, enabling increasingly complex and intelligent applications.

A microprocessor-based system is described by the diagram shown in Figure 15. In this type of system, we find: the main memory bloc, the input/output interfaces, the central processing unit (CPU), and the bus communication system. It based on the Von Neumann architecture, in which data and program instructions are stored in one same memory.

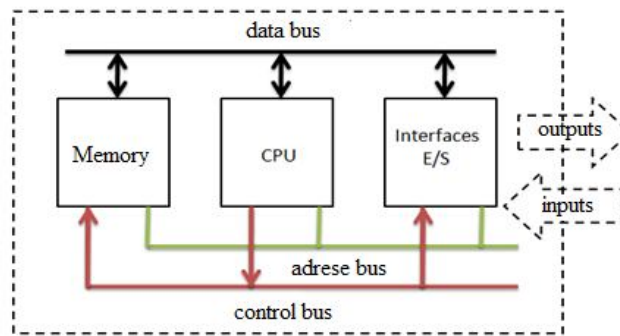


Figure 15 Basic architecture of microprocessor.

Structurally, as shown in Figure 16 a CPU includes the arithmetic and logic unit (ALU), which performs arithmetic operations (addition, subtraction, etc.) and logical operations (AND, OR, NOT, etc.), and the control unit (CU), which interprets program instructions to sequence of operations.

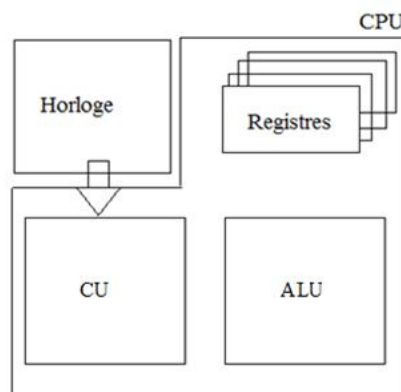


Figure 16 Internal architecture of central processing unit (CPU).

The microprocessor executes the program instructions stored in memory and controls the entire operation of the system. Therefore, the microprocessor carries out three fundamental tasks: fetching instructions and data from memory, decoding the instructions with CU to determine the required operations, executing instructions using ALU.

On the other hand, there are other kinds of microprocessors, designed specifically to process digital signals in real time, called a digital signal processor (DSP). These types of microprocessor are used in a wide range of modern technologies, such as: audio and speech processing (noise reduction, echo cancellation, compression), image and video processing (enhancement, compression, recognition), and telecommunications (modulation/demodulation, channel equalization, error correction).

I.4.2 Microcontrollers

A microcontroller is a fundamental electronic circuit able to communicate and controls different electronic devices types, such as sensors and motors. It is usually based on Harvard

architecture that physically separate memory for instructions and data (Figure 17), allowing the processor to fetch instruction and access data simultaneously, which increases processing speed.

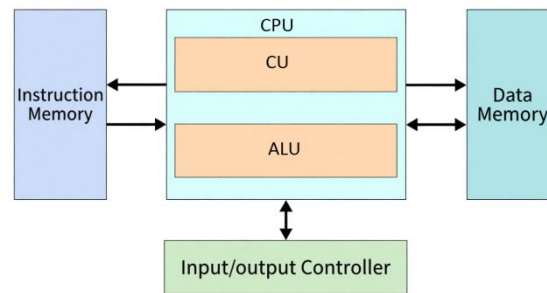


Figure 17 Harvard architecture based microcontroller.

I.4.3 FPGAs

Field-Programmable Gate Arrays (FPGAs) are integrated circuits designed to be configured by the user after manufacturing. The main role of an FPGA is to provide a flexible, reprogrammable hardware platform that enables the implementation of digital circuits with the speed of hardware and the adaptability of software. FPGAs have been introduced in the logic circuits market since 1980s with the two largest manufacturers Xilinx and Altera.

An FPGA is typically composed of three key components arranged in a grid (Figure 18):

- Configurable logic blocks (CLBs): the fundamental building blocks for implementing user logic.
- Programmable interconnect: the network of wires and switches that connect CLBs and other resources.
- Input/output (IOB) blocks: Interfaces for connecting the FPGA core logic to external pins and devices.

Key aspects of the main role of FPGAs are shown in Table 4.

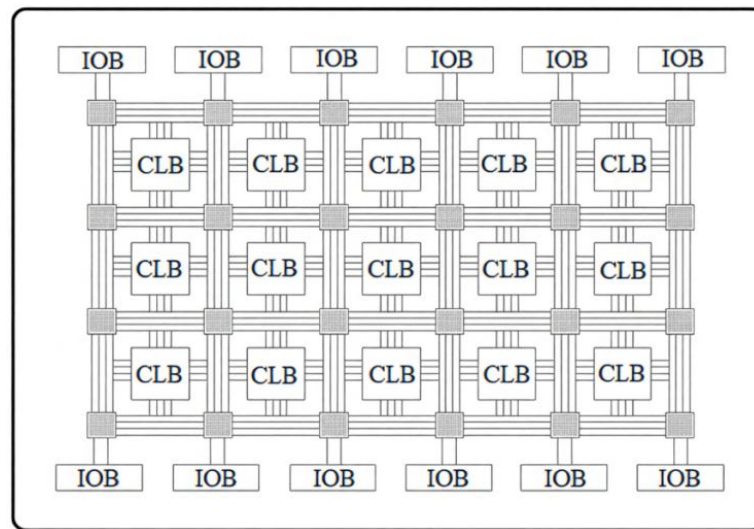


Figure 18 Main architecture of FPGA.

Table.4 Main application of FPGAs.

Application	Description
Parallel processing	FPGA can execute operations in parallel at the hardware level. For example, 1000 operations can run simultaneously, unlike CPUs that handle tasks sequentially (even with multi-core). This enables ultra-low latency and high throughput.
Hardware acceleration	FPGAs are widely used to accelerate specific, computationally intensive tasks (like signal processing, encryption, and AI inference) by offloading them from CPUs/GPUs, improving efficiency and power consumption.
Prototyping	FPGAs allow engineers to test and validate custom digital designs before committing to expensive ASIC fabrication. They are essential in research and development for aerospace, medical devices, telecom, and autonomous systems. This makes FPGA ideal for prototyping, rapid iteration, and applications requiring updates.
Real-time system	Because FPGAs operate at the hardware level with predictable timing, they are ideal for real-time control systems, such as robotics, and industrial automation, automotive systems.

Chapter II. Electrotechnics

II.1 Introduction

Electrical engineering is one of the foundational pillars of modern technology and industrial development. It deals with the study, design, and application of equipment, devices, and systems that use electricity and electromagnetism, especially in the generation, transmission, distribution, and exploitation of electrical energy.

This chapter introduces the state of the art and key concepts of Electrotechnics.

II.2 Single-phase system

A single-phase current can be obtained from a three-phase supply by connecting either one of the three phases to the neutral, or by connecting two of the three phases.

The expression of a single-phase sinusoidal voltage is given by,

$$u = U_m \sin(\omega t + \varphi) \quad (7)$$

where, U_m is amplitude (V), ω is pulsation (rad.s^{-1}), φ is initial phase (rad), and $\omega t + \varphi$ is instantaneous phase.

In this context,

- The average value of a sinusoidal signal is zero $\langle u \rangle = 0$.
- The voltage effective value is equal to $U = U_m / \sqrt{2}$.

II.2.1 Power in single-phase systems

In single-phase alternating current (AC) circuits, electrical power is described through several complementary concepts, each serving a distinct purpose in the analysis and design of electrical systems. Understanding these different forms of power, such as instantaneous, active, and apparent, is essential for evaluating energy efficiency, sizing equipment, and ensuring optimal performance of electrical installations.

II.2.1.1 Apparent power, symbolized by S and expressed in volt-amperes (VA), it is directly calculated by the product of the voltage and current:

$$S = U \times I \quad (8)$$

It reflects the total power that the source must supply to the circuit. Apparent power is crucial for sizing generators, transformers, and wiring, as these components must handle the total current flow, regardless of how much of it is actually converted into useful work.

II.2.1.2 Instantaneous power, defined as the product of the instantaneous voltage and current at any given moment:

$$P(t) = U(t) \times I(t) \quad (9)$$

This quantity varies continuously with time and represents the exact rate at which energy is delivered to the load. In the case of sinusoidal systems, $P(t)$ oscillates at twice the supply frequency, reflecting the dynamic exchange of energy between the source and reactive components (such as inductors or capacitors).

II.2.1.3 Active power (real power)

It denoted by P and measured, it is the energy really usable by the load in the form of mechanical work, heat, etc.

$$P = U \times I \cos(\varphi) \quad (10)$$

It is the useful energy per unit time that is actually converted by the load into work, heat, light, or mechanical motion.

The relationship between active and apparent power is quantified by the power factor k , defined as $k = P/S$. Under sinusoidal steady-state conditions $k = \cos(\varphi)$.

II.2.1.4 Reactive power

The energy exchanges between a source and an inductance or a capacitance (with zero average value).

$$Q = U \times I \sin(\varphi) \quad (11)$$

Also, the three types of power are related by $S^2 = P^2 + Q^2$.

II.3 Three-phase systems

Approximately all the major power generation and distribution systems in the world to-day are three-phase ac systems. Three-phase systems offer significant advantages over single-phase systems, such as the same amount of power delivered to user, a three-phase line incurs only half the Joule (resistive) losses compared to a single-phase line, and it also allows for substantial savings in conductor material, in particularly copper due to more efficient power transmission with fewer or smaller conductors.

In a three-phase system, there are three sinusoidal quantities forming a balanced system if they have the same effective value and they are equally phase-shifted with respect to each other, as shown in Figure 19.

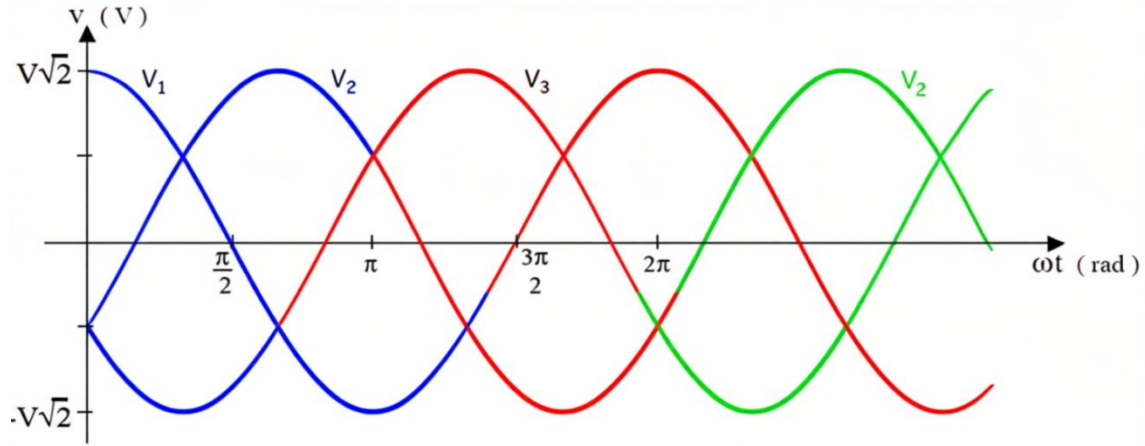


Figure 19 Balanced three-phase voltages.

Such a system is said to be positive sequence (or direct sequence) if, after labeling the three quantities with indices 1, 2, and 3, the second quantity lags the first by $2\pi/3$ and the third lags the first by $4\pi/3$, therefore we get:

$$\begin{aligned} V_1 &= V\sqrt{2} \cos(\omega t) \\ V_2 &= V\sqrt{2} \cos(\omega t - 2\pi/3) \\ V_3 &= V\sqrt{2} \cos(\omega t - 4\pi/3) \end{aligned} \quad (12)$$

In a three-phase system, two types of voltages are defined, phase voltages (simple voltages) and line voltages (line-to-line voltages). The phase voltage, denoted v_i , is the voltage measured between any one phase conductor and the neutral point. The line voltage u_{ij} , is the voltage between two phase conductors $u_{ij} = v_i - v_j$, as shown in Figure 20.

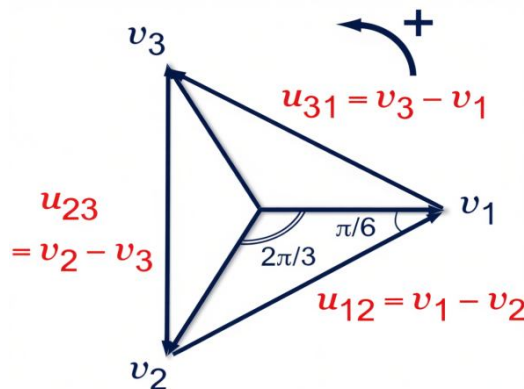


Figure 20 Phase and line-to-line voltages in three-phase systems.

II.3.1 Power in three-phase systems

Since we have $V_{1eff} = V_{2eff} = V_{3eff} = V_{eff}$ and $I_{1eff} = I_{2eff} = I_{3eff} = I_{eff}$, the active power in a three-phase systems (sinusoidal case) could be written as,

$$P = 3V_{eff}I_{eff} \cos(\varphi) \quad (13)$$

Similarly, the reactive power in a three-phase system could be written as,

$$Q = 3V_{eff}I_{eff} \sin(\varphi) \quad (14)$$

II.4 Transformer

A transformer enables the transfer of energy (in alternating form) from a source to a load while changing the voltage level. The voltage can be either increased or decreased, depending on the intended application. This change from one voltage level to another occurs through the effect of a magnetic field.

Transformers are widely used across various fields due to their ability to efficiently transfer electrical energy while changing voltage levels. In electronics, they are essential for providing low-voltage power supplies in devices such as chargers and adapters, and for impedance matching to maximize power transfer between circuits, particularly in audio and radio-frequency applications. In electrical engineering, transformers are fundamental to voltage transformation for electricity transmission and distribution, enabling efficient long-distance power delivery by stepping up voltage at generation sites and stepping it down for consumer use; they also supply low-voltage power for applications like halogen lighting. In the domain of measurement, specialized transformers ensure safe and accurate monitoring: current transformers (CTs) scale down high currents to measurable levels, while voltage (or potential) transformers (VTs/PTs) reduce high voltages for use with standard instrumentation, thereby protecting both equipment and personnel.

II.4.1 Structure and operation

A transformer is basically consists of three components (Figure 21):

- **A core (magnetic circuit)**, which serves to channel and concentrate the magnetic flux.
- **A primary winding**, electrically insulated and connected to the alternating current (AC) source, usually called the *primary*.
- **A secondary winding**, where an induced electromotive force (EMF) is generated, this is known as the *secondary*.

The core provides a low-reluctance path for the magnetic flux produced by the primary winding, providing efficient coupling of energy between the windings through electromagnetic induction.

When AC voltage is applied to the primary, it generates a time-varying magnetic field in the core, which in turn induces a voltage in the secondary winding according to Faraday's law of electromagnetic induction. The ratio of turns between the primary and secondary windings determines whether the transformer steps up or steps down the voltage.

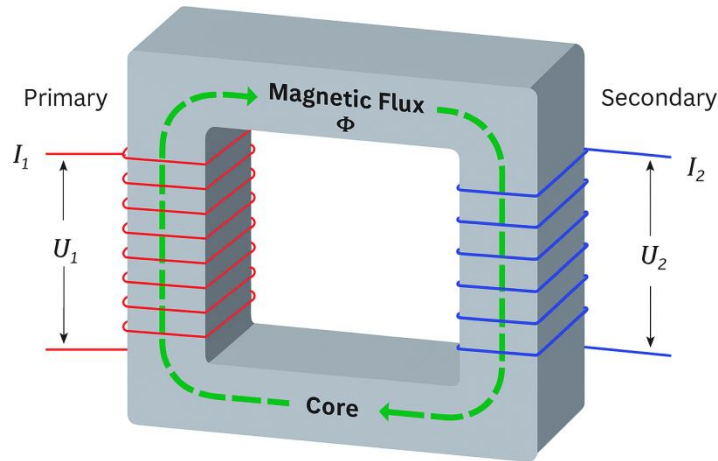


Figure 21 Fundamental structure of a transformer.

II.4.2 Ideal transformer

An ideal (perfect) transformer is a theoretical model of a transformer that assumes no energy losses, perfect magnetic coupling between windings. Therefore, it transfers the electrical energy from one circuit to another through electromagnetic induction with 100% efficiency.

The turns ratio m , is a parameter that characterizes the voltage transformation behavior of an ideal transformer. It is defined as the ratio of the secondary voltage (U_2) to the primary voltage (U_1), and is equal to the ratio of the number of turns in the secondary winding (N_2) to the number of turns in the primary winding (N_1):

$$m = \frac{N_2}{N_1} = \frac{U_2}{U_1} \quad (15)$$

II.4.3 Real transformer

In this case, the transformer's efficiency is less than 100%. Moreover, the voltage ratio between will not be exactly equal to the turns ratio n_1/n_2 , and the secondary voltage will also vary depending on the load. The equivalent circuit of a real transformer is shown in Figure 22.

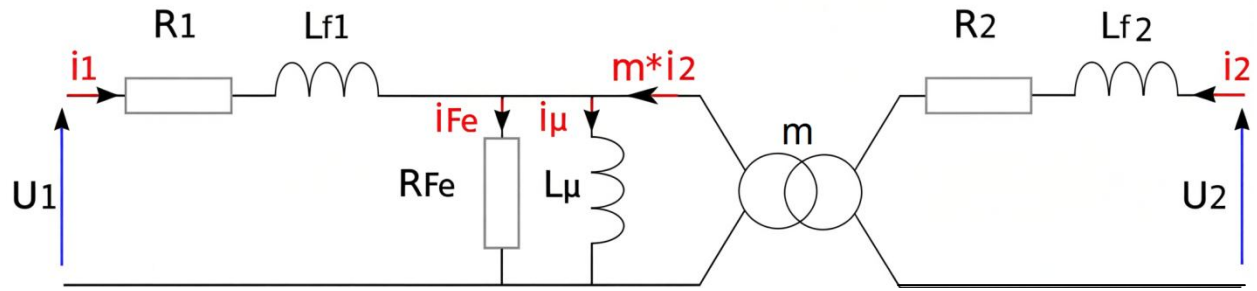


Figure 22 Equivalent circuit of real transformer.

The equivalent circuit of the real transformer includes,

- The copper wire resistance is represented by resistances $R1$ and $R2$ for the primary and secondary windings, respectively.
- The leakage losses in the primary and secondary windings are represented by leakage inductances $Lf1$ and $Lf2$, for the primary and secondary, respectively.
- The core losses are represented by a resistance RFe in parallel with the magnetizing inductance $Lμ$.

The efficiency of a transformer is defined as,

$$\eta = \frac{P_2}{P_1} \quad (16)$$

here, $P1$ and $P2$ are the delivered power by the primary and secondary, respectively + iron losses (P_{Fer}) + total Joule losses (P_{Jt}), with $P1 = P2 + P_{Fer} + P_{Jt}$.

Therefore, to measure the efficiency of a transformer, P_{Fer} , and P_{Jt} , four measurement types are carried out:

- **DC test:** It allows measurement of the resistances $R1$ and $R2$ of the primary and secondary windings, respectively.
- **Open-circuit test:** Measurement of iron losses power absorbed by the primary winding with an open circuit of the secondary (Figure 23).

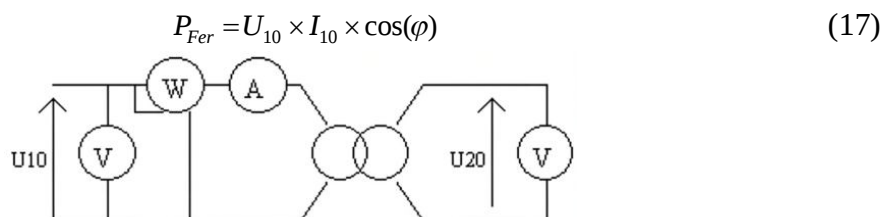


Figure 23 Transformer open circuits for the measurement of iron losses power.

- **Resistive load test at rated secondary current $I_2 = I_{2N}$:** In this case, the efficiency is given directly by the ratio,

$$\eta = \frac{P_2}{P_1} = \frac{U_{20} I_{2N} \cos(\varphi_2)}{U_{10} I_{1N} \cos(\varphi_1)} \quad (18)$$

- **Short-circuit test at rated secondary current $I_{2cc} = I_{2N}$:** This test allows measurement of the total Joule losses in the primary and secondary windings: $P_{Jt} = P_{1cc}$.

II.5 Electric power transmission and distribution

The figure 24 shows the structure of an electric power transmission and distribution network. It illustrates the complete path electricity follows, from its generation (not shown here) to its final use by consumers. The electricity flows in this order: Generation → Transmission (EHV/HV) → Sub-transmission (HV/MV) → Delivery (MV/LV) → Distribution (LV) → Consumers.

a. Transmission

Electricity is transmitted at extra-high voltage (EHV: 225 kV or 400 kV) or high voltage (HV: 63–150 kV) to carry power over long distances while minimizing energy losses by using high voltages, the current in the lines is reduced, which significantly lowers losses due to the Joule effect.

Key of components,

- Overhead high-voltage power lines (horizontal cables at the top of the diagram).
- Power transformers (circular symbols with two windings) to change voltage levels between stages.
- The label “EHV/HV” shows where electricity enters this part of the network—usually from a power plant or a major substation. “AT” stands for supply transformers.

b. Regional distribution

The voltage level in power distribution systems is typically High Voltage (HV: 20-150 kV, or MV: 1-36 kV). These voltage levels are used to efficiently distribute electricity across different geographic areas or to supply large industrial customers. By maintaining a relatively high voltage, the system reduces energy losses during transmission and ensures that sufficient power

can be delivered locally, either directly to large users or to local distribution substations, where the voltage is further stepped down for end-use.

Key of components,

- Substations (also called primary substations): connection points between the transmission grid and local distribution networks.
- HV/MV transformers to step down the voltage.
- Switchgear like circuit breakers and disconnectors (shown as small square or round symbols).

c. Delivery to local distribution

Medium Voltage (MV: 1-36 kV), is stepped down to low-voltage (LV) levels of 230 V (single-phase) or 400 V (three-phase) to deliver electricity safely and efficiently to local distribution networks. This voltage transformation is essential for supplying power to end-users, as it adjusts the electrical supply to levels suitable for residential homes, small businesses, and other low-power applications, ensuring compatibility with standard appliances and equipment while maintaining safety and reliability in the distribution system.

Key of components,

- MV/LV transformers (small ground-level or cabinet-mounted units) that reduce voltage to usable levels.
- Delivery substations: transition points between the sub-transmission network and the final distribution network.

d. Final Distribution

Low Voltage (LV) systems operate at 230 V for single-phase and 400 V for three-phase supplies and are designed to deliver electricity directly to end-users, including residential homes, shops, and small businesses. This voltage level is safe, standardized, and compatible with the vast majority of household appliances, lighting, and commercial equipment, making it the final stage in the electrical distribution chain.

Key of components,

- Tree-like (radial) network: each branch powers a group of houses or buildings.
- Meters, circuit breakers, and individual safety devices.

- “MV/LV” labels mark the final transformers—often found in street cabinets or on utility pole.

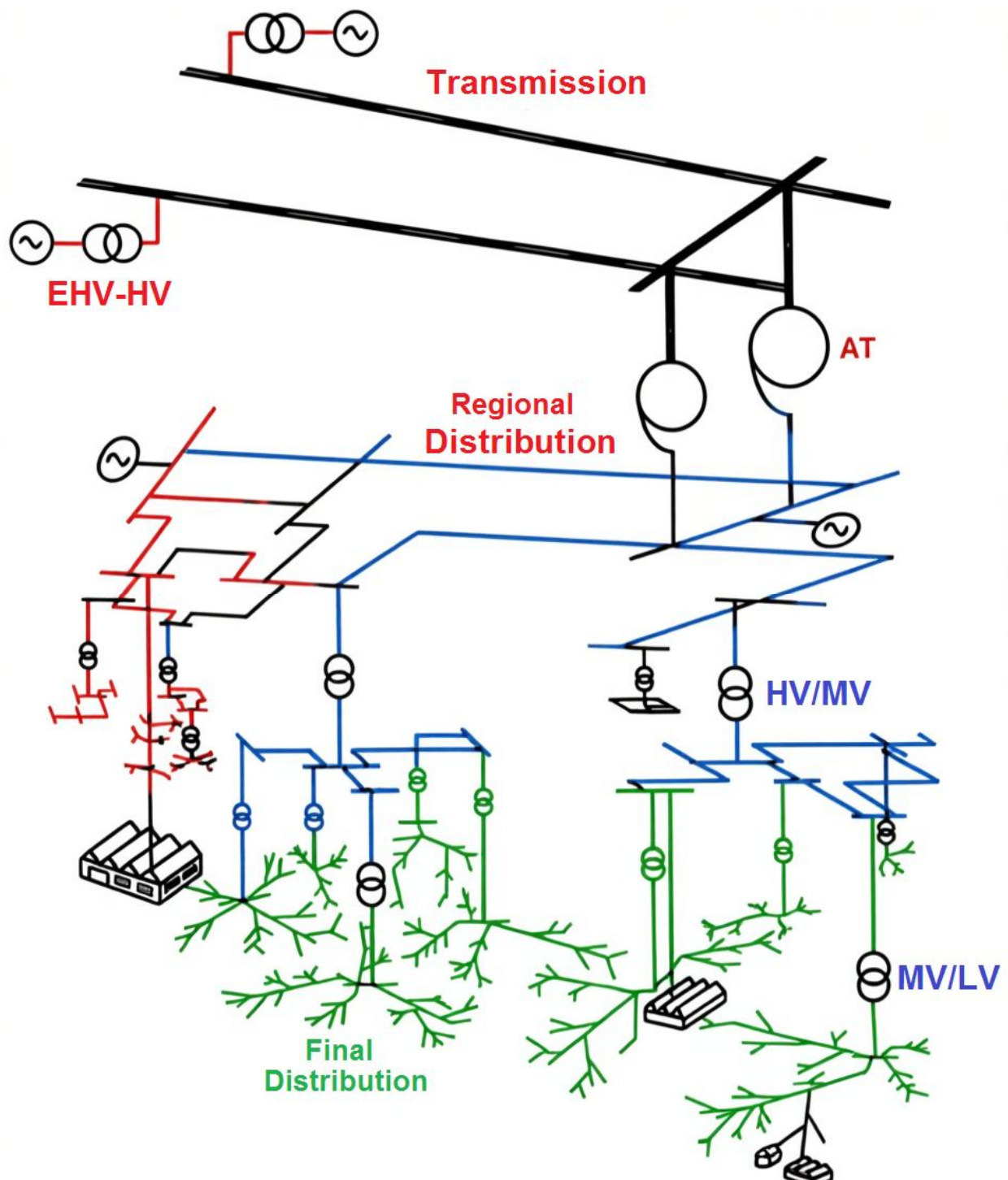


Figure 24 Electric power transmission and distribution.

II.6 Electricity generation

The electrical energy is usually created by converting mechanical energy using alternators.

II.6.1 Hydraulic turbines

Hydraulic turbines are type of machines that convert the energy of flowing or falling water into mechanical energy, which used to generate electricity. Usually installed in dams or hydroelectric power plants, these turbines operate by directing water through blades or buckets, causing a rotor to spin. The most common types are Pelton and Kaplan turbines, each suited for different water flow rates and head conditions. Hydraulic turbines are a reliable and efficient source of renewable energy, playing a vital role in clean power generation worldwide.

Figure 25 illustrate a side-by-side two different types of hydroelectric turbines, the Kaplan turbine on the left, and the Pelton turbine on the right. Both turbine diagrams illustrate the key components and operational principles of each one within its respective water channel system.

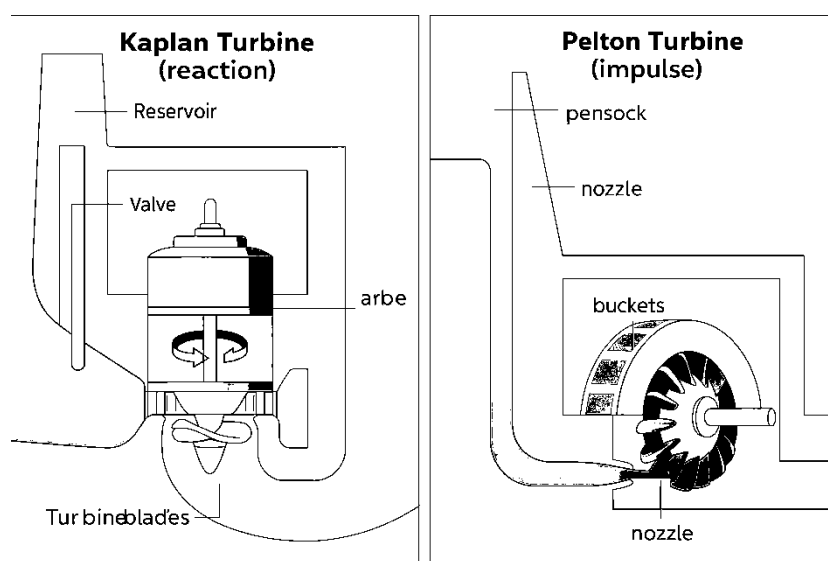


Figure 25 Hydraulic turbines.

The Kaplan turbine is a reaction turbine type, where water flows through the turbine blades under pressure. The main components shown are:

- **Reservoir:** The source of water, positioned at a higher elevation.
- **Generator:** Located above the turbine, connected to the shaft to convert mechanical energy into electrical energy.
- **Valve:** Controls the flow of water into the turbine.
- **Shaft:** Transmits the rotational force from the turbine runner to the generator.
- **Turbine Blades:** The angled, propeller-like blades that are rotated by the flowing water. The diagram shows water entering axially and exiting radially, indicating its axial-flow design.

The Pelton turbine is an impulse (action) turbine, which operates by converting the kinetic energy of a high-velocity water jet into mechanical energy. Its key components include:

- **Reservoir:** The elevated water source.
- **Penstock:** A pressurized pipe that delivers water from the reservoir to the turbine.
- **Nozzle:** Converts the water's pressure energy into a high-speed jet.
- **Jet:** The focused stream of water that strikes the turbine buckets.
- **Buckets:** The spoon-shaped cups mounted on the turbine wheel. The jet impacts these buckets, causing the wheel to rotate and transfer energy to the shaft.

I.6.2 Wind turbine

A wind turbine is a device that converts the kinetic energy of wind into clean, renewable electricity. It typically consists of large blades mounted on a tall tower. When the wind blows, it spins the blades, which turn a shaft connected to a generator inside the nacelle (the housing at the top of the tower). This generator produces electricity that can be fed into the power grid. Wind turbines are a key technology in sustainable energy systems, helping to reduce reliance on fossil fuels and lower greenhouse gas emissions.

Figure 26 illustrate the cross-sectional view of a wind turbine, including the external structure and the internal mechanisms housed within the nacelle (the housing at the top of the tower). Its main parts include,

- **Blades:** They capture the wind's kinetic energy and convert it into rotational motion.
- **Nacelle:** The streamlined enclosure at the top of the tower that houses the generator, gearbox, and other critical machinery.
- **Brake:** A mechanical brake used to stop the rotor from turning for maintenance or during emergencies.
- **Gearbox:** A gearbox that increases the rotational speed from the slow-turning rotor to the high speed required by the generator.
- **Generator:** The device that converts the mechanical energy from the rotating shaft into electrical energy.
- **Electrical regulation system:** Controls the flow of electricity generated, ensuring it matches the grid's requirements for voltage and frequency.
- **Yaw system:** A mechanism that rotates the entire nacelle to face the wind, maximizing energy capture.

- **Tower:** The tall tower that supports the nacelle and rotor, elevating them to a height where wind speeds are higher and more consistent.
- **Foundations:** The concrete base that anchors the tower securely to the ground.
- **Electrical connection cabinet:** The equipment that connects the turbine's output to the electrical grid.

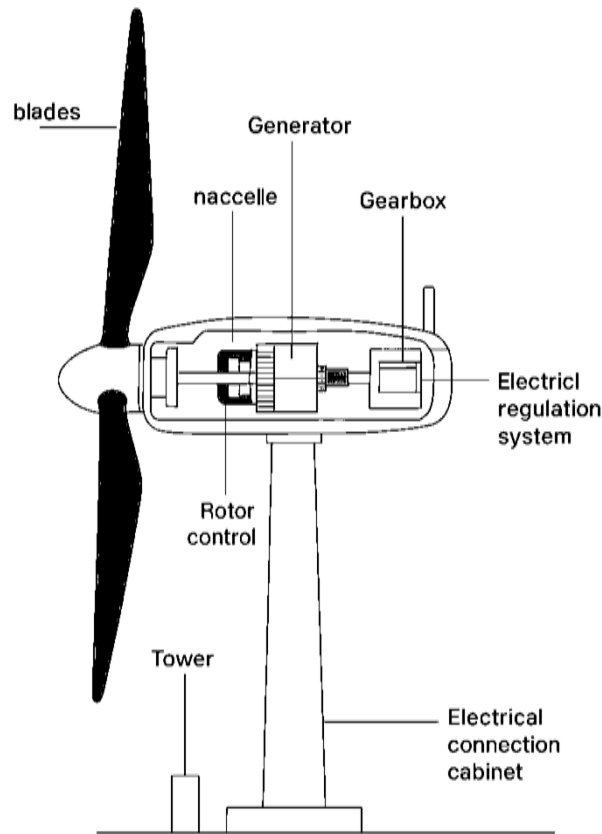


Figure 26 Cross-sectional view of a wind turbine.

II.6.3 Thermal turbine

Steam and gas turbines are essential thermal machines used in electricity generation and industrial propulsion. Their operation is based on converting thermal energy into mechanical energy, which can then be transformed into electrical energy via a generator.

This thermal energy derives from various sources:

- **Chemical energy:** Fuels such as oil, natural gas, wood, or waste are combusted in a combustion chamber. This combustion releases heat (thermal energy), which—depending on the turbine type—is either used to boil water and produce high-pressure steam (in steam turbines) or directly generates hot, pressurized gases (in gas turbines).

- **Nuclear energy:** In nuclear power plants, the fission of Uranium releases a large amount of heat. This thermal energy is used to produce high-pressure steam, which then drives a steam turbine.

In both cases, the steam or hot gases are directed onto the turbine blades, causing the rotor to spin. This rotation constitutes usable mechanical energy, representing a key step in the energy conversion chain: Chemical or nuclear energy → Thermal energy → Mechanical energy → (optionally) electrical energy.

Chapter III. Automatics

III.1 Introduction

Automation is the science that studies automatic control systems including technological device that replaces the human operator in operating a machine, a process, or an industrial installation.

This chapter introduces core concepts of classical control theory: the Laplace transform for frequency-domain analysis of linear time-invariant systems, the transfer function as a concise representation of system dynamics, block diagram reduction techniques for simplifying complex interconnections, Bode diagrams for assessing frequency response and stability, and system identification methods for first- and second-order systems.

III.2 Definitions

- Automation is the science that studies automatic control systems.
- Automatic system is the technological device that replaces the human operator in operating a machine, a process, or an industrial installation.
- Process (or system): The entire installation that must be controlled. It is characterized by input and output signals, as well as physical and mathematical laws linking these signals.
- A system is a set of evolving processes. Actions on the system (inputs, set points, commands) are performed to achieve specific objectives (outputs, responses).
- The signals related to a system are of two types:
 - Input signals: They are independent of the system and can be controlled (set points) or uncontrolled (disturbances).
 - Output signals: They depend on the system and the input signal. To evaluate the objectives, these signals must be observable using sensors.

III.3 Control design

Figure 27 illustrates the structure of a control system including an input command, output, and disturbance. The control block is the unit that converts the set point into a command magnitude compatible with the system. The command is capable of changing the system state, especially the output state.

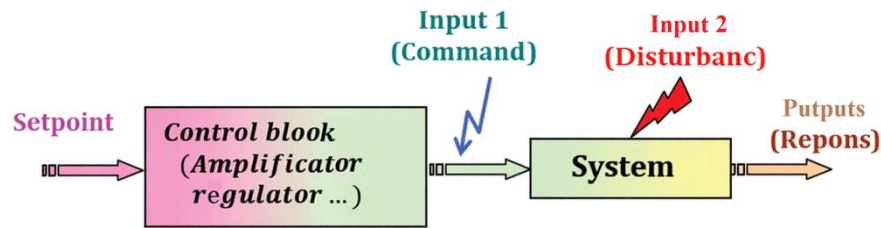


Figure 27 General control systems.

III.3.1 Open-loop systems

In an open-loop system, there is no information about the output and no feedback from the output to the input (Figure 27).

Because of disturbances, it is often impossible to guarantee the desired output, and correction is not feasible since there is no information about the actual output, and there no adjustment strategy to achieve the desired result.

III.3.2 Closed-loop systems

In a closed-loop system, the output is continuously measured and fed back to the input for comparison with the desired reference value (Figure 28). This feedback allows the system to automatically adjust its behavior in response to disturbances or changes in operating conditions. By comparing the actual output with the desired output, the controller can compute an error signal and apply corrective actions to minimize this error. Therefore, closed-loop systems offer improved accuracy, stability, and robustness compared to open-loop systems, making them well-suited for applications where precise control is essential.

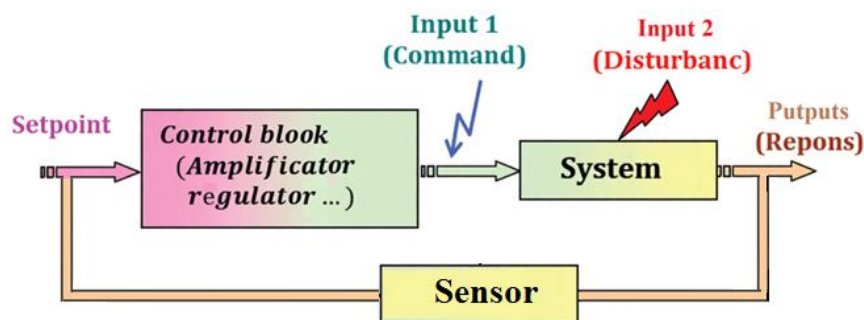


Figure 28 Closed-loop systems.

A servomechanism (controlled system) is a closed-loop system that can be described by the block diagram of Figure 29.

- Controller (comparator and compensator), it is the “thinking part” of the system. It generates the control command by taking into account the input and the output measurement provided by the sensor.
- Actuator (motor, cylinder, etc.), it supplies the necessary power required to carry out the physical process.
- Physical process, it evolves according to its own physical laws: laws of dynamics, electrical circuit laws, etc. The output of the physical process can fluctuate due to external disturbances.

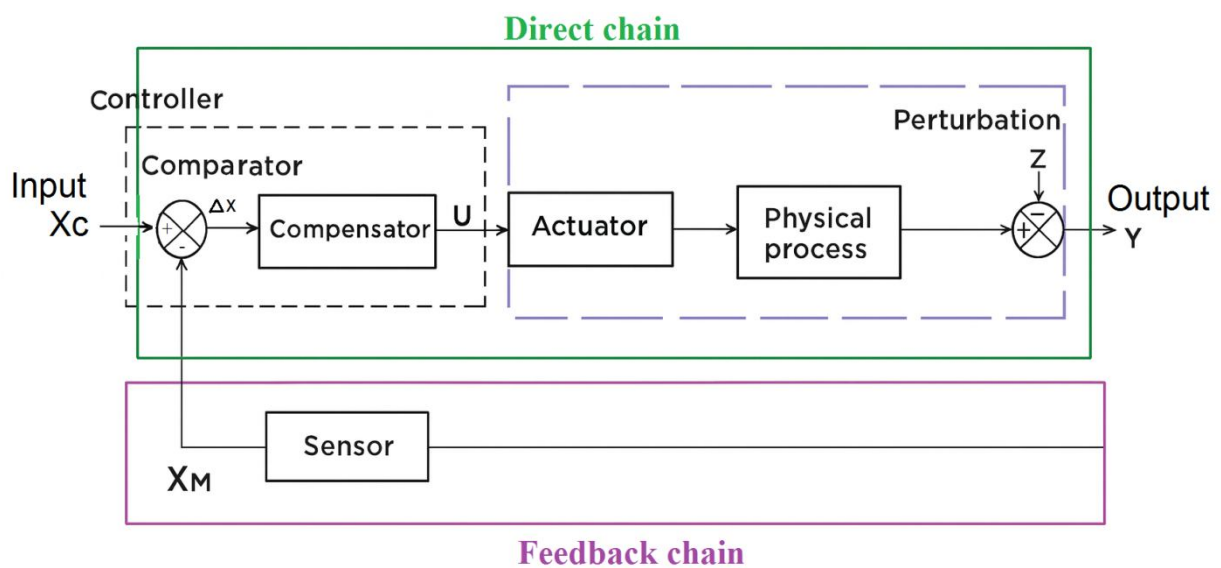


Figure 29 A servomechanisms bloc diagram system.

III.4 Laplace transform

The Laplace transform is useful mathematical tool widely used in engineering, particularly in the analysis and design of linear time-invariant systems, such as those encountered in control theory (automatic control or asservissement).

The bilateral Laplace transform of a function $f : t \rightarrow f(t)$ is:

$$L[f(t)] = F(p) = \int_{-\infty}^{+\infty} f(t) e^{-pt} dt \quad p \in C \quad (19)$$

In the case where $f(t) = 0$ for $t < 0$, we use the unilateral Laplace transform:

$$L[f(t)] = F(p) = \int_0^{+\infty} f(t) e^{-pt} dt \quad p \in C \quad (20)$$

The key properties of the Laplace transform are :

- Linearity,

$$\begin{aligned}
L[f(t) + g(t)] &= L[f(t)] + L[g(t)] \\
L[\lambda f(t)] &= \lambda L[f(t)] \\
L[0] &= 0
\end{aligned}
\tag{21}$$

- Time-delay theorem,

$$L[f(t - T)] = e^{-Tp} F(p) \tag{22}$$

- Initial and final value theorems:

$$\begin{aligned}
\lim_{t \rightarrow 0} f(t) &= \lim_{p \rightarrow +\infty} pF(p) \\
\lim_{t \rightarrow \infty} f(t) &= \lim_{p \rightarrow 0} pF(p)
\end{aligned}
\tag{23}$$

- Derivation,

$$\begin{aligned}
L\left[\frac{df(t)}{dt}\right] &= pf(p) - f(0) \\
L\left[\frac{d^2 f(t)}{dt^2}\right] &= p^2 f(p) - pf(0) - f'(0)
\end{aligned}
\tag{24}$$

- Integration,

$$L\left[\int_0^t f(u) du\right] = \frac{F(p)}{p} + \frac{f(0)}{p} \tag{25}$$

Under zero initial conditions (Heaviside conditions):

$$\begin{aligned}
L\left[\frac{df(t)}{dt}\right] &= pf(p) \\
L\left[\frac{d^2 f(t)}{dt^2}\right] &= p^2 f(p) \\
L\left[\int_0^t f(u) du\right] &= \frac{F(p)}{p}
\end{aligned}
\tag{26}$$

Table 5 summarizes the most commonly used Laplace transform pairs, listing time-domain functions alongside their corresponding Laplace-domain expressions.

Table.5 Laplace transform table.

$f(t)$	$F(p)$
K	$\frac{K}{p}$
Kt	$\frac{K}{p^2}$
Kt^n	$\frac{Kn!}{p^{n+1}}$
$e^{at}t^n$	$\frac{n!}{(p-a)^{n+1}}$

$1 - e^{-\frac{t}{T}}$	$\frac{1}{p(1+Tp)}$
e^{-at}	$\frac{1}{p+a}$
$\sin(wt)$	$\frac{w}{p^2 + w^2}$
$\cos(wt)$	$\frac{p}{p^2 + w^2}$
$sh(wt)$	$\frac{w}{p^2 - w^2}$
$ch(wt)$	$\frac{p}{p^2 - w^2}$
$e^{-at} \sin(wt)$	$\frac{w}{(p+a)^2 + w^2}$
$e^{-at} \cos(wt)$	$\frac{p+a}{(p+a)^2 + w^2}$
$\frac{w_0}{\sqrt{1-m^2}} e^{-mw_0 t} \sin(w_0 \sqrt{1-m^2} t)$	$\frac{1}{p \left(1 + \frac{2m}{w_0} p + \frac{p^2}{w_0^2} \right)}$
$1 - \frac{w_0}{\sqrt{1-m^2}} e^{-mw_0 t} \sin(w_0 \sqrt{1-m^2} t + \varphi)$	$\frac{1}{1 + \frac{2m}{w_0} p + \frac{p^2}{w_0^2}}$

III.5 Transfer function

To study linear feedback systems, we focus on the relationship between input $e(t)$ and output $s(t)$ signals. These signals may represent voltage, current, velocity, or any other physical quantity. We use the Laplace transform of the differential equations linking these signals to determine the transfer function:

$$H(p) = \frac{S(p)}{E(p)} \quad (27)$$

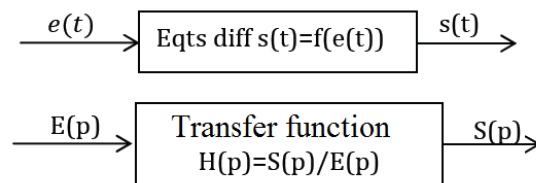


Figure 30 From differential equation to Laplace transfer function.

Transfer functions play a central role in control system design. They are essential for analyzing system responses such as step, ramp, impulse, and sinusoidal signals, which helps predict real-world behavior under various operating conditions. Furthermore, the location of poles in the transfer function's denominator provides critical insight into system stability, poles

in the left half of the complex plane indicate a stable response, while those in the right half suggest instability. Transfer functions also form the foundation for designing controllers, including PID controllers, using powerful graphical and analytical methods such as root locus, Bode plots, and Nyquist diagrams. In addition, they enable the modeling and simplification of complex interconnected systems, like those involving series, parallel, or feedback configurations, through the systematic application of block diagram algebra, thereby facilitating both analysis and synthesis of automatic control systems.

III.6 Fundamental concept of block diagram

A block connects a single input to a single output. The relationship between these two variables is represented by the transfer function H .

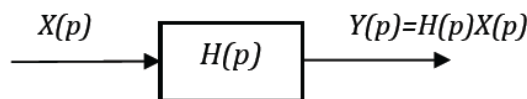


Figure 31 Representation of basic block.

The output of a summing junction is the algebraic sum of its inputs.

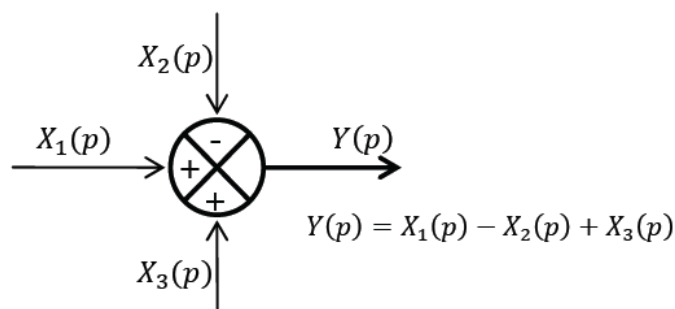


Figure 32 Summing junction block.

The tapped branch (2) transmits the same signal as the main branch (1) and does not affect it.

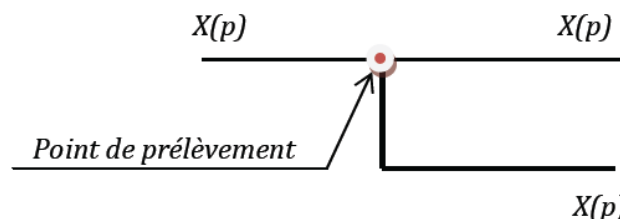
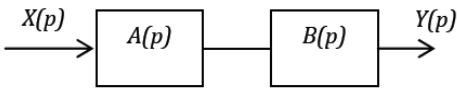
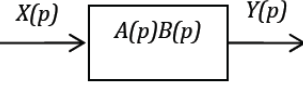
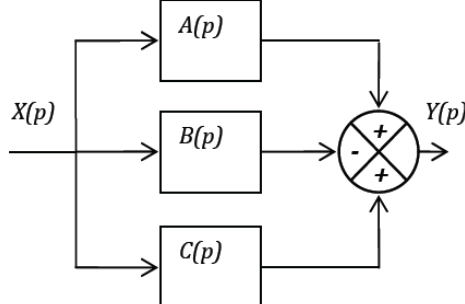
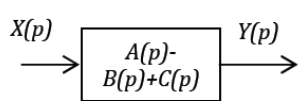
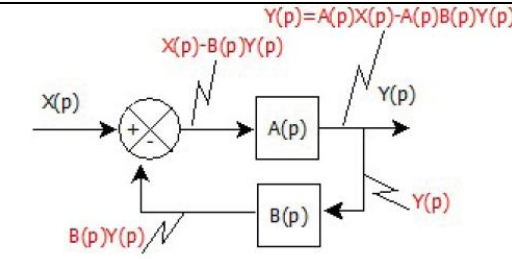
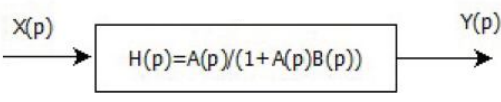
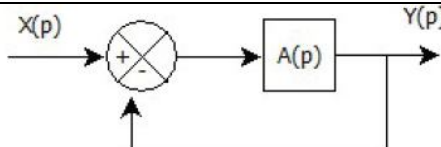
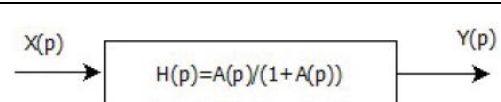


Figure 33 Take-off point.

Table 6 summarizes the main block diagram simplification rules for the cascade connection, parallel blocks, closed-loop systems, and unit feedback configurations.

Table.6 Block diagram simplification rules.

Block type	Description	Simplification
Cascade		
Parallel		
Closed-loop		
Unit feedback		

The overall block diagram of a system is composed of a combination of elementary block diagrams. Therefore, certain fundamental manipulation techniques must be known to properly simplify or restructure these diagrams. These techniques include the relocation of a take-off (or branch) point, shown in Figure 34 and the movement of a summing junction, both of which allow for equivalent transformations that preserve the system's input-output behavior while facilitating analysis or reduction of the diagram (Figure 35).

Moreover, any non-unit feedback system can always be converted into an equivalent unit feedback system (Figure 36).

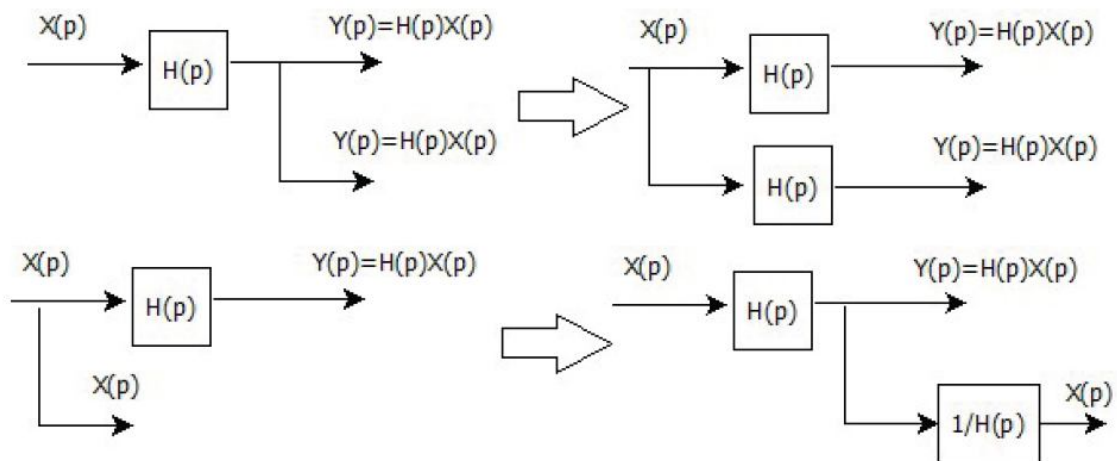


Figure 34 Relocation of a take-off point.

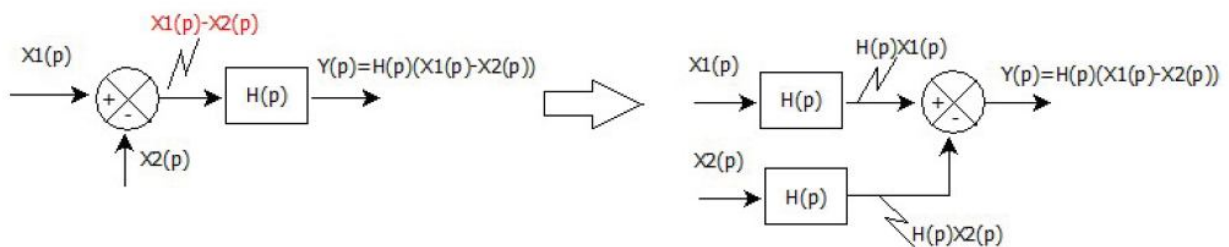


Figure 35 Movement of a summing junction.

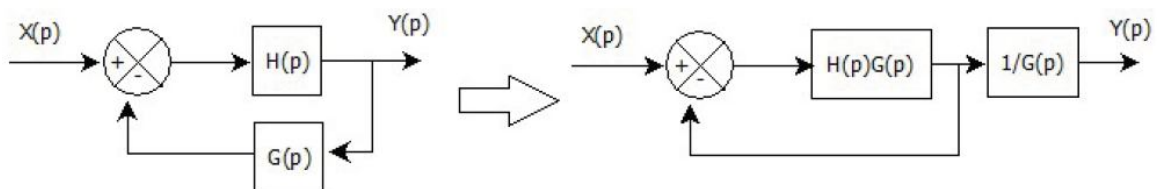


Figure 36 Non-unit feedback conversions to equivalent unit feedback.

III.7 First and second-order system

A system is a first order if the relationship between its input and output is described by a first-order differential equation,

$$y(t) + \tau \dot{y}(t) = Kx(t) \quad (28)$$

where, K is the static gain and τ is the time constant of the system.

The transfer function of the first-order system has the form,

$$H(p) = \frac{K}{(1 + \tau p)} \quad (29)$$

A response is called step or indicial if the input is a step function. On the other side, a response is called impulse if the input is a Dirac delta function.

A system is a second-order if the relationship between its input and output is described by a second-order differential equation:

$$\ddot{y}(t) + 2m\omega_0 \dot{y}(t) + \omega_0^2 y(t) = k\omega_0^2 x(t) \quad (30)$$

where,

k : static gain (ratio of output units to input units).

m : damping coefficient (dimensionless).

ω_0 : undamped natural frequency (in Rad/s).

The transfer function of a second-order system has the following form,

$$H(p) = \frac{k}{1 + \frac{2m}{\omega_0} p + \frac{p^2}{\omega_0^2}} \quad (31)$$

If the input is $x(t) = au(t)$ (a step of amplitude), then in the Laplace domain:

$$X(p) = \frac{a}{p} \quad (32)$$

Then, we obtain:

$$Y(p) = H(p)X(p) = \frac{ka}{p \left(1 + \frac{2m}{\omega_0} p + \frac{p^2}{\omega_0^2} \right)} \quad (33)$$

Three cases must be considered, depending on the sign of the (reduced) discriminate of the denominator polynomial $1 + \frac{2m}{\omega_0} p + \frac{p^2}{\omega_0^2}$ and $\Delta' = \frac{1}{\omega_0^2} (m^2 - 1)$.

- $\Delta' > 0 \Rightarrow m > 1$: Aperiodic regime without overshoot.
- $\Delta' = 0 \Rightarrow m = 1$: Critically damped regime without overshoot.
- $\Delta' < 0 \Rightarrow m < 1$: Underdamped (pseudo-periodic) regime with overshoot.

Chapter IV. Telecommunications

IV.1 Introduction

Telecommunications is the discipline that enables the exchange of information over distance using electrical, optical, or electromagnetic systems, it stands as one of the most dynamic and transformative pillars of modern electrical engineering.

This chapter provides the state of the art in telecommunications, including information transmission chain, signal modulation, and the primary types of transmission channels.

IV.2 Electromagnetic wave

Communication refers to the exchange of information between a transmitter and a receiver. The information exchanged may be a video, image, or audio data. The signal used corresponds to an electromagnetic wave (Figure 37).

An electromagnetic wave can propagate through a medium such as vacuum or air, traveling at a speed close to that of light. It corresponds to the coupled oscillations of an electric field and a magnetic field, whose amplitudes vary sinusoidally with time.

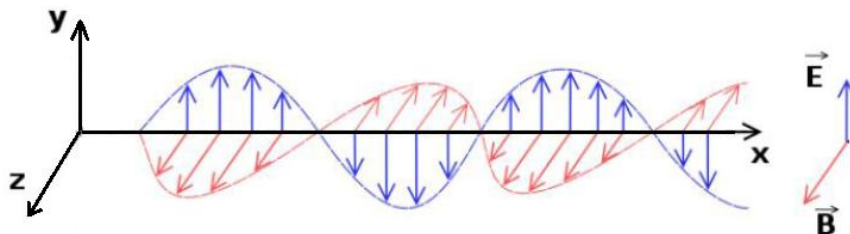


Figure 37 Electromagnetic wave form.

In this sense,

$$\vec{E}(x,t) = E_0 \cos(kx - \omega t + \phi) \hat{y} \quad (34)$$

$$\vec{B}(x,t) = B_0 \cos(kx - \omega t + \phi) \hat{z} \quad (35)$$

where, E_0 is electric field amplitude, B_0 is magnetic field amplitude, k is wave number ($2\pi/\lambda$), λ is wavelength, and $\hat{y}, \hat{z}$ are polarization directions.

It should be noted that electromagnetic waves equations are derived from Maxwell's equations by taking the curl of Faraday's law and using the Ampère Maxwell's equation, and combining them to eliminate either. This produces two identical wave equations. And, their solutions are sinusoidal traveling waves, where are perpendicular and propagate at the speed of light.

IV.3 Information transmission chain

The fundamental structure of a communication system is based on five main blocks (Figure 38) involving transmission information from a source to a destination. It starts with the emission transducer, the emitter (or transmitter), the transmission channel, the receiver, and the receiver transducer.

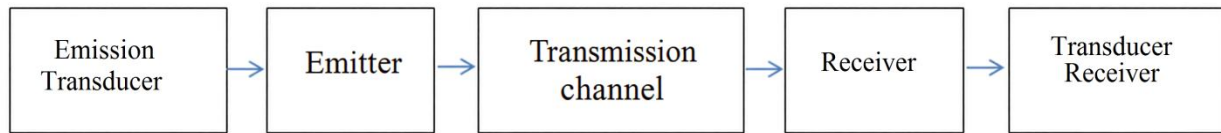


Figure 38 Blocks diagram of the transmission chain.

IV.3.1 Emission transducer

It converts the original signal (voice, image, etc.) into an electrical signal suitable for the transmitter.

Table.7 Examples of emission transducer.

Transducer	Original signal
Microphone	Humane voiced
Keyboard	Pressed key
CCD sensors	Object movement
Thermocouple	Measure temperature

IV.3.2 Emitter

There are three distinct fundamental processes at the emitter level (Figure 39): coding, modulation, and signal amplification. These are shown as separate, parallel blocks, indicating key functional stages that can occur at different points within a system, rather than necessarily in a strict linear sequence.

- Coding signal, it involves converting the original information (e.g., text, audio, and video) into a specific format or code suitable for transmission or storage. This often includes source coding (for data compression) and channel coding (for error detection and correction).
- Modulation, the coded information signal is used to modify a carrier wave's properties (such as its amplitude, frequency, or phase), it is essential for transmitting signals efficiently over long distances through a channel, especially when the original signal is not suitable for direct transmission.
- Amplification, it involves increasing the power or amplitude of a signal, it is crucial for compensating for signal loss (attenuation) that occurs during transmission through the

channel, ensuring the signal remains strong enough to be accurately detected and processed by the receiver.

These three functions represent critical steps in preparing, transmitting, and maintaining the integrity of a signal within any modern communication system.

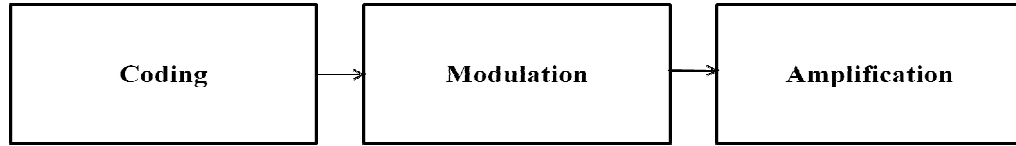


Figure 39 Emitter blocks diagram.

IV.3.2.1 Signal modulation

The information is a low-frequency (LF) signal, making it highly susceptible to various sources of interference known as noise. To overcome this problem, a high-frequency (HF) carrier wave is used, which is better suited to the transmission medium. Hence, this carrier wave is modulated in amplitude (AM), phase (PM), or frequency (FM).

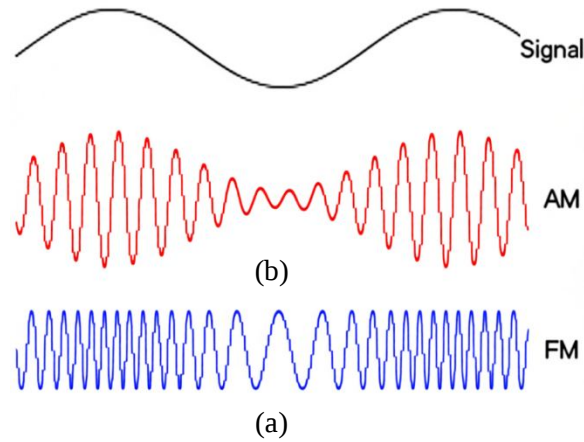


Figure 40 Frequency modulated (a) and amplitude modulation (b) signal.

IV.3.2.1.1 Amplitude modulation

First, the modulated signal $U_m'(t)$ is shifted by a positive DC voltage U_0 . Therefore, the modulated signal $U_m'(t)$ is given by the equation:

$$u_m'(t) = u_m(t) + U_0 = U_m \cos(2\pi f_m t) + U_0 \quad (36)$$

where, $m = U_m/U_0$ is the modulation index.

Next, the modulated signal is obtained using a multiplier. It performs the product of the carrier signal $u_p(t)$ and the shifted modulated signal $U_m'(t)$, scaled by a coefficient k (gain) that depends on the multiplier, we get :

$$u_s(t) = k \times u_p(t)(u_m(t) + U_0) \quad (37)$$

$$\begin{aligned} &= kU_p \cos(2\pi f_p t)(U_m \cos(2\pi f_m t) + U_0) \\ &= kU_p \cos(2\pi f_p t) \times U_m \cos(2\pi f_m t) + kU_0 U_p \cos(2\pi f_p t) \end{aligned} \quad (38)$$

$$= kU_p U_m \left(\frac{1}{2} \right) (\cos(2\pi f_p t + 2\pi f_m t) + \cos(2\pi f_p t - 2\pi f_m t)) + kU_0 U_p \cos(2\pi f_p t)$$

Finally, putting $A = kU_0 U_p$ and $m = U_m/U_0$, we get:

$$u_s(t) = \frac{Am}{2} \cos(2\pi(f_p + f_m)t) + \frac{Am}{2} \cos(2\pi(f_p - f_m)t) + A \cos(2\pi f_p t) \quad (39)$$

We observe that there are three frequencies ($f_p - f_m$, f_p , $f_p + f_m$) with corresponding amplitudes ($A_m/2$, A_m , $A_m/2$), as shown in Figure 41(b).

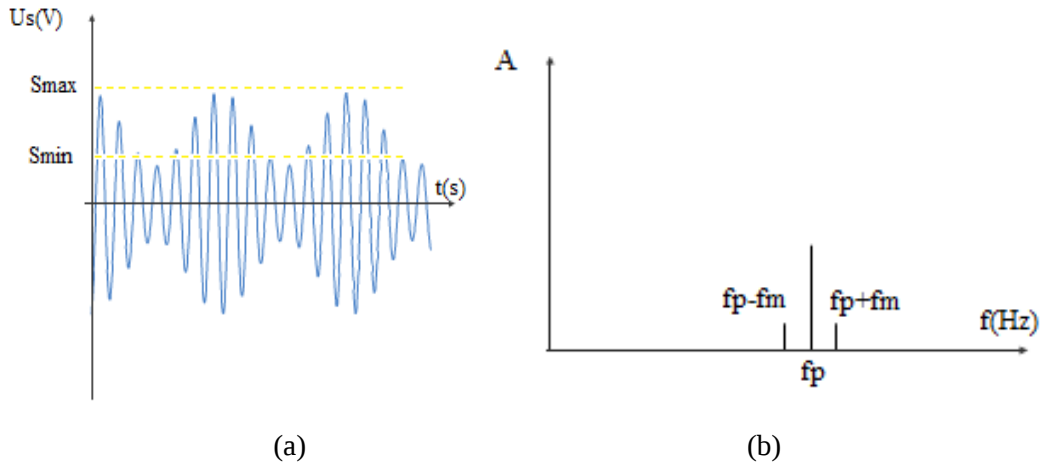


Figure 41 Amplitude-modulated signals (a) and signal spectrum (b).

IV.3.2.1.2 Frequency modulation

In frequency modulation, the baseband signal to be transmitted is encoded in the instantaneous frequency of the carrier wave. Thus, the instantaneous frequency of the modulated signal varies with the modulating signal around the carrier frequency.

$$f(t) = f_p + KU_m(t) \quad (40)$$

where, k is a proportionality factor, usually referred to as the modulator sensitivity.

The mathematical expression of the modulated signal is given as follows:

$$\begin{aligned} U_s(t) &= U_p \cdot \cos(2\pi \cdot f_p \cdot t + \phi(t)) \\ &= U_p \cdot \cos(2\pi \cdot f_p \cdot t + \phi(t)) \\ &= U_p \cdot \cos(2\pi \cdot f_p \cdot t + 2\pi \cdot K \int_0^t U_m(t) \cdot dt) \end{aligned} \quad (41)$$

After integration, we obtain the final expression of the frequency-modulated (FM) signal:

$$U_s(t) = U_p \cdot \cos(2\pi \cdot f_p \cdot t + \frac{KU_m}{f_m} \sin(2\pi \cdot f_m \cdot t)) \quad (42)$$

In the final expression of the FM signal, it is clearly evident that the instantaneous frequency of the modulated signal (modulated carrier) depends on the modulating signal $U_m(t)$.

- The frequency deviation (also called frequency excursion) is given by $\Delta f = KU_m$.
- The ratio $m = \Delta f / f_m$ is the modulation index (if $m < 1$, the modulation is narrowband).
- The transmitted power is given by $P = U_p^2 / 2$.

Figure 42(b) shows the frequency-modulated signal.

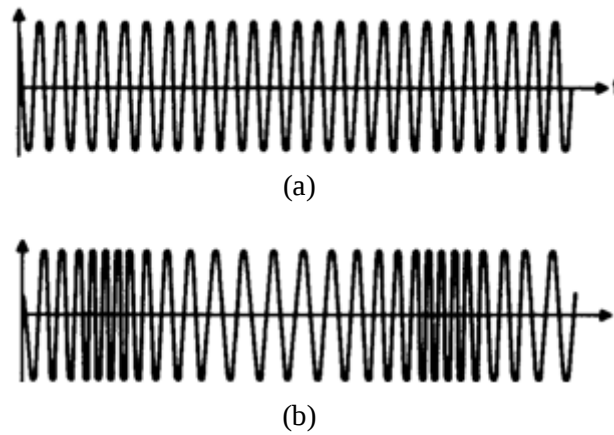


Figure 42 Carrier signal (a) and frequency-modulated signals (b).

Therefore, the final expression of the frequency-modulated (FM) signal is:

$$U_s(t) = U_p \cdot \cos(2\pi \cdot f_p \cdot t + m \sin(2\pi \cdot f_m \cdot t)) \quad (43)$$

The frequency-modulated signal $U_s(t)$ is a complex signal, we can use Bessel functions to express $\cos(m \cdot \sin(x))$ as an infinite sum of *cosine* and *sine* terms, Therefore, we obtain:

$$\begin{aligned} U_s(t) = & U_p \cdot J_0(m) \cdot \cos(2\pi \cdot f_p \cdot t + \phi_0) \\ & + U_p \cdot J_1(m) \cdot \cos(2\pi \cdot (f_p \pm f_m) \cdot t + \phi_1) \\ & + U_p \cdot J_2(m) \cdot \cos(2\pi \cdot (f_p \pm 2f_m) \cdot t + \phi_2) \\ & + U_p \cdot J_3(m) \cdot \cos(2\pi \cdot (f_p \pm 3f_m) \cdot t + \phi_3) \\ & + \dots \end{aligned} \quad (44)$$

where, $J_0(m)$, $J_1(m)$, $J_2(m)$, ... are Bessel functions of the first kind, parameterized by the modulation index m .

The spectrum of the frequency-modulated signal is shown in Figure 43.

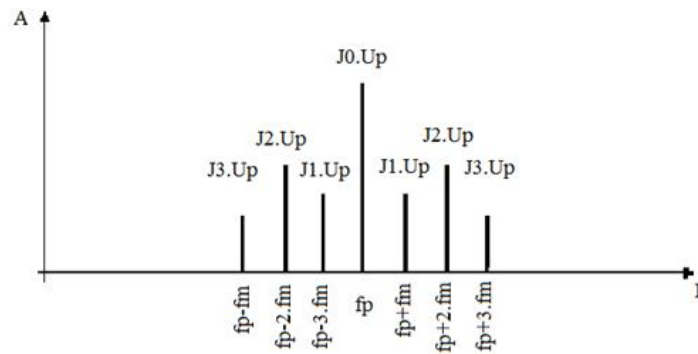


Figure 43 Spectrum of the frequency-modulated signal.

IV.3.3 Receiver

A receiver serves to capture the transmitted signal and to convert it into a form compatible with the output transducer. Therefore, it performs the following tasks:

- Filtering, it removes unwanted parts of the received signal (noise, interference, or extraneous frequency components), isolating only the useful information.
- Decoding: decoding may involve converting from analog to digital (or vice versa), or decrypting the received data.
- Demodulation, the signal was modulated (amplitude, frequency, phase, or by other modulation scheme), the receiver demodulates it to extract the original baseband information (voice, data).
- Amplification: because the signal arriving at the receiver is often very weak (after propagation losses, attenuation, noise), it must be amplified so that it can drive the output transducer or further processing stages.

IV.3.4 Receiving transducer

It provides information in a form that can be used by the user (Table 8).

Table.8 Examples of receiving transducer.

Transducer	Original signal
Loudspeaker	Voice
Screen	Images
Control signal	Actuator control (valve, pump)

IV.4 Transmission channel

Transmission channels are the media that allow the transfer of information between the transmitter and the receiver. They can be classified into two main categories: guided media (using physical supports) and unguided media (using electromagnetic waves propagating in

space). The choice of transmission channel depends on several factors including distance, required data rate, cost, and environmental constraints.

IV.4.1 Copper Cables

Copper cables are a traditional guided transmission media. They use copper conductors to transmit electrical signals.

- Twisted pair cables: Consist of two copper wires twisted together to reduce electromagnetic interference. They are used in telephone networks and local area networks (LANs). There are two types (Figure 44):
 - Unshielded twisted pair (UTP): Most common, economical, but more susceptible to interference
 - Shielded twisted pair (STP): Has additional shielding for better protection against interference

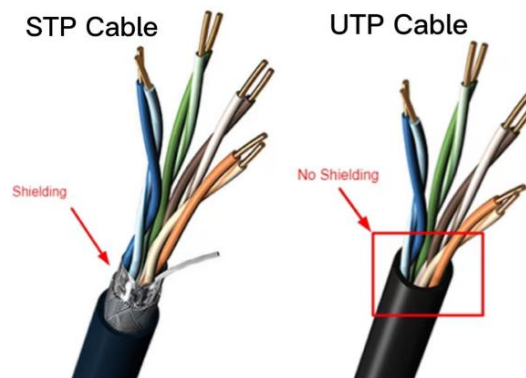


Figure 44 Twisted pair cables.

- Coaxial cables: composed of a central copper conductor surrounded by an insulating layer, a metallic shield, and an outer protective jacket. They offer better bandwidth and noise immunity than twisted pair cables and are used for cable television (CATV) and broadband internet (Figure 45).

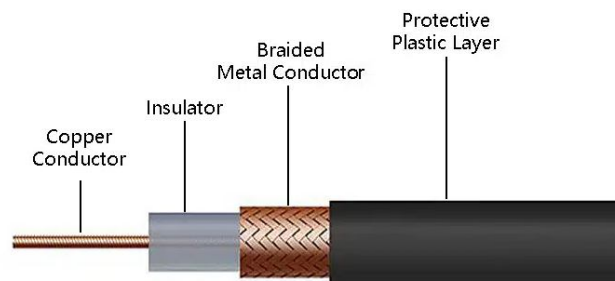


Figure 45 Coaxial cables.

IV.4.2 Optical fibers

Optical fibers represent a revolutionary technology in guided transmission. They use light pulses to transmit data through glass or plastic fibers.

Figure 46 shows the structure of an optical fiber, which is used as a transmission channel for high-speed data communication. The fiber is composed of several concentric layers, each with a specific function:

- Outer Jacket, it provides the mechanical protection, shielding the fiber from physical damage, moisture, and environmental stress.
- Glass Buffer (buffer coating), it protects the internal glass structure from shocks, micro-bending, and temperature variations.
- Glass cladding, made of glass with a lower refractive index than the core for total internal reflection, which keeps light trapped inside the core and guides it along the fiber.
- Glass core, the part where light signals travel. It is made of ultra-pure glass to minimize attenuation.

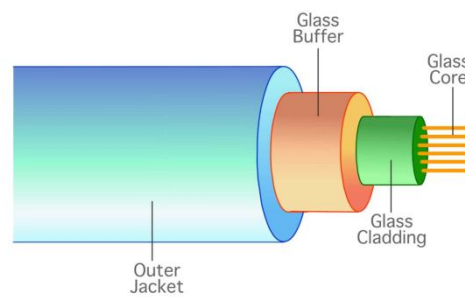


Figure 46 Structure of optical fibers.

Light entering the glass core is reflected by the cladding walls due to the refractive-index difference. This keeps the light confined and allows long-distance, high-bandwidth communication with very low signal loss, immunity to electromagnetic interference, and enhanced security.

There are two type optical fibers:

- Single-mode fiber: Small core diameter (8-10 μm), allows only one light path, used for long-distance transmission
- Multi-mode fiber: Larger core diameter (50-62.5 μm), allows multiple light paths, used for shorter distances

Therefore, optical fibers are widely dedicated to long-distance telecommunications, high-speed internet, medical imaging, and industrial applications.

IV.4.3 Radio wave

Up to now we have discussed guided transmission. The signal is guided or conducted down some sort of a “pipe.” The “pipes” we have covered included wire pair, coaxial cable, and fiber optic cable. Radio transmission, on the other hand, is based on radiated emission.

Radio waves are electromagnetic waves that propagate through space without requiring a physical medium. They are characterized by their frequency and wavelength (Table 9).

Table.9 Radio frequency bands and their applications.

Signal type	Frequency	Application
LF (Low Frequency)	30 kHz – 300 kHz	Long-wave (LW) AM radio broadcasting, air navigation (e.g., NDBs)
MF (Medium Frequency)	300 kHz – 3 MHz	AM radio broadcasting, maritime radio, avalanche beacons
HF (High Frequency)	3 MHz – 30 MHz	Shortwave broadcasting, amateur radio, aviation air-to-ground comms, maritime comms
VHF (Very High Frequency)	30 MHz – 300 MHz	FM radio, television (VHF), air traffic control, marine VHF, two-way land mobile radio
UHF (Ultra High Frequency)	300 MHz – 3 GHz	TV broadcasting, GPS, mobile phones (GMS, LTE), Wi-Fi, Bluetooth, microwave ovens (ISM)
SHF (Super High Frequency)	3 GHz – 30 GHz	Satellite communication, radar, point-to-point wireless links, 5G/6G, Wi-Fi 6E/7
EHF (Extremely High Frequency)	30 GHz – 300 GHz	Radio astronomy, security scanning, high-speed wireless (WiGig), military systems
THF (Tremendously High Frequency)	300 GHz – 3 THz	Experimental communications, imaging, spectroscopy

Table 10 presents a comparative analysis of the principal guided and unguided transmission media, such as copper cables, optical fibers, and radio waves, evaluating them across key performance and deployment criteria. These criteria include bandwidth capacity, maximum transmission distance, security, installation and maintenance costs, susceptibility to interference, and ease of deployment.

Table.10 Comparative analysis of transmission media.

Criteria	Copper cables	Optical fibers	Radio waves
Bandwidth	Limited (up to 10 Gbps)	Very high (up to 100+ Tbps)	Variable (depends on frequency)
Distance	Limited (100m for UTP)	Very long (100+ km without repeaters)	Long range (global with satellites)
Security	Moderate (can be tapped)	High (difficult to tap without detection)	Low (signals propagate in all directions)
Cost	Low to moderate	High initial cost, low maintenance	Moderate to high (infrastructure costs)
Installation	Easy	Complex (requires expertise)	Moderate (antenna placement critical)
Interference	Susceptible to EMI	Immune to EMI	Susceptible to atmospheric conditions

Chapter V. Impact of electrical engineering on societal development

V.1 Introduction

Electrical engineering stands as one of the most transformative disciplines in modern human history, fundamentally reshaping how societies function, communicate, heal, and progress. From the earliest discoveries of electricity to today's sophisticated digital ecosystems, this field has consistently driven innovation across every sector of human activity.

The scope of electrical engineering's influence is vast and multifaceted. It encompasses the microscopic world of semiconductor devices that power our digital lives, the macroscopic systems that automate industrial processes, the intelligent machines that perform tasks once thought impossible for automation, the global networks that connect billions of people instantaneously, and the life-saving medical devices that extend and improve human health. Each of these domains represents fundamental shift in how humans interact with their environment and with each other.

This chapter explores the impact of electrical engineering on five critical areas where which transformed society, such as advances in microelectronics that have miniaturized computing power and made it ubiquitous, automation and supervision systems that have revolutionized manufacturing and infrastructure management, robotics that have extended human capabilities in both industrial and personal contexts, telecommunications that have collapsed geographical barriers and created a truly global society, and medical instrumentation that has revolutionized healthcare delivery and outcomes.

V.2 Microelectronics

The revolution in microelectronics represents one of the most dramatic technological transformations in the human history. Beginning with the invention of the transistor in 1947 and accelerating with the development of integrated circuits in the late 1950s, microelectronics has enabled the miniaturization of electronic devices to an extraordinary degree, fundamentally altering the technological landscape of society.

At its core, the advancement in microelectronics follows by Moore's Law the observation that the number of transistors on a microchip doubles approximately every two years, while the cost of computers is halved. While this trend has begun to slow in recent years due to physical limitations, the cumulative effect over six decades has been staggering. Early integrated circuits contained a few dozen transistors, today's most advanced processors contain over 100 billion

transistors on a single chip. This exponential growth in computational density has enabled the proliferation of computing power throughout society, making sophisticated electronics affordable and accessible to billions of people worldwide.

The societal impact of microelectronics advancement is profound and multifaceted. Economically, it has created entirely new industries while disrupting traditional ones. The personal computer revolution of the 1980s and 1990s democratized computing, moving it from specialized laboratories and large corporations into homes, schools, and small businesses. The Smartphone revolution that followed has put more computing power in the pockets of ordinary citizens than existed in entire research institutions just decades earlier. This accessibility has transformed how people work, learn, communicate, and access information.

Microelectronics has also enabled the Internet of Things (IoT), where everyday objects, from refrigerators to traffic lights are embedded with sensors and computing capabilities. Smart homes can optimize energy usage, monitor security, and enhance comfort, smart cities can manage traffic flow, reduce pollution, and improve public services. These applications rely on the continued miniaturization and cost reduction of electronic devices that microelectronics advancement has made possible.

The educational sector has been particularly transformed by microelectronics. Digital learning platforms, interactive educational software, and online resources have made high-quality education accessible to students regardless of geographical location. Portable computing devices enable learning to occur anywhere, while sophisticated simulation software allows students to experiment with complex systems that would be too expensive or dangerous to build physically.

For electrical engineers, the field of microelectronics continues to offer exciting opportunities. Research in nanoelectronics, quantum computing, and neuromorphic engineering promises to overcome the current limitations and enable new capabilities. Materials science advances, such as, the development of graphene and other 2-D materials, may revolutionize semiconductor technology once again.

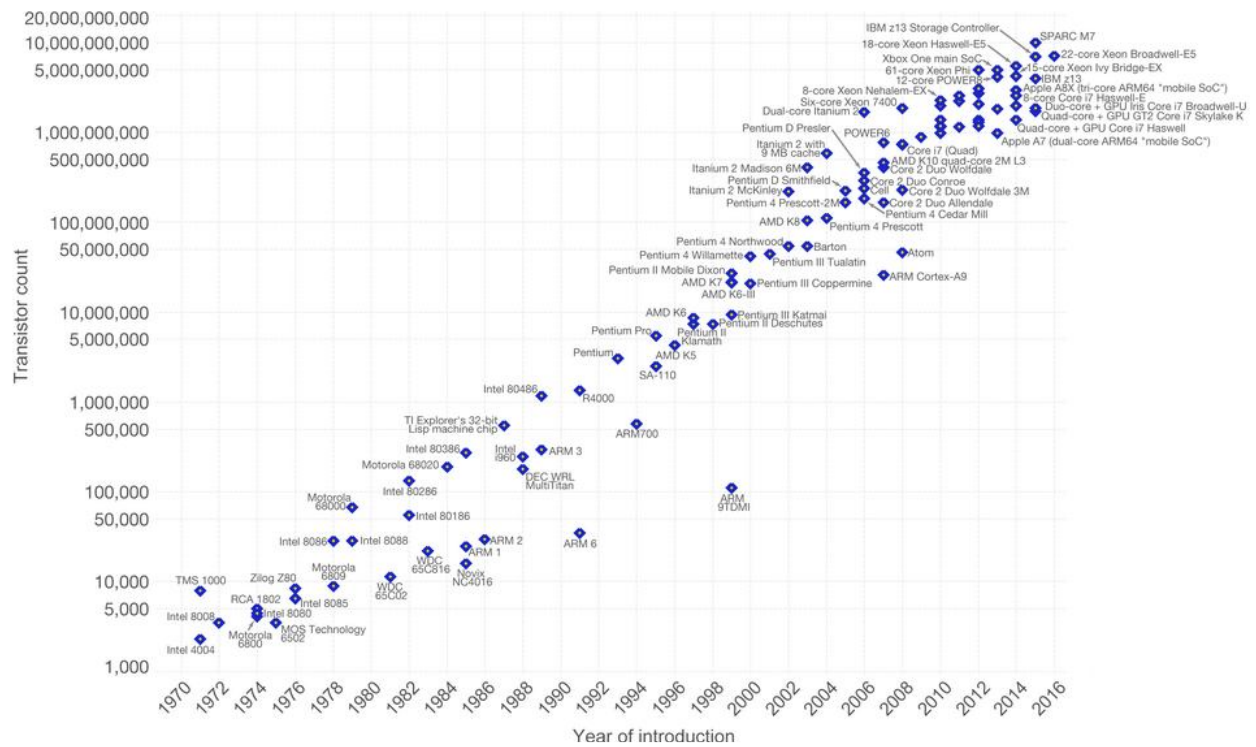


Figure 47 Evolution of integrated circuits.

V.3 Automation and supervision systems

Automation and supervision systems combine electrical engineering with control theory, computer science, and systems engineering to create intelligent systems that can operate with minimal human intervention. These systems have transformed industrial processes, infrastructure management, and daily life in ways that have fundamentally altered economic structures and social patterns.

The evolution of automation can be traced through several key phases. The first industrial revolution mechanized production using water and steam power, the second used electricity to enable mass production, and the third, introduced digital automation through programmable logic controllers (PLCs) and computer numerical control (CNC) systems. Today, we are experiencing what many call the fourth industrial revolution (Industry 4.0), characterized by the integration of cyber-physical systems, the internet of things, and artificial intelligence into manufacturing and other processes.

In industrial settings, modern automation systems have dramatically increased productivity while improving quality and safety. Robotic assembly lines can operate continuously with precision that exceeds human capabilities, while sophisticated sensor networks monitor

equipment health and predict maintenance needs before failures occur. Supervisory control and data acquisition (SCADA) systems provide operators with comprehensive views of complex processes, enabling real-time decision-making and optimization. These advances have made manufacturing more efficient, reduced waste, and enabled the production of increasingly complex products at competitive prices.

Beyond manufacturing, automation has transformed infrastructure management. Smart grid technologies use advanced sensors and control systems for better electricity distribution, integrate renewable energy sources, and improve grid reliability. Water treatment plants employ automated monitoring and control to ensure water quality while minimizing chemical usage and energy consumption. Building automation systems manage heating, ventilation, air conditioning, lighting, and security to optimize comfort while reducing energy consumption, making these systems crucial for sustainability.

The societal impact of automation extends far beyond technical efficiency. Economically, it has created new industries and job categories while displacing others. The demand for skilled workers in programming, system integration, and maintenance has grown substantially, while routine manual jobs have declined. This shift has created both opportunities and challenges, requiring workforce retraining and education system adaptation. Socially, automation has changed workplace dynamics, enabling remote monitoring and control of processes, which has become particularly important during global events that limit physical presence.

However, automation also raises significant ethical and social questions. The potential for job displacement, particularly in sectors employing large numbers of low-skilled workers, requires careful consideration of transition strategies and social safety nets. Security concerns are paramount, as automated systems increasingly connect to networks, creating vulnerabilities to cyber attacks that could disrupt critical infrastructure. The concentration of automation capabilities in the hands of a few large corporations raises questions about economic power and competition.

For electrical engineers, the field of automation and supervision offers diverse career paths. Control systems engineering, industrial networking, cybersecurity for industrial systems, and human-machine interface design are all growing areas. Understanding the principles of feedback control, real-time systems, networking protocols, and safety engineering is essential preparation for these roles.

Looking forward, the integration of artificial intelligence and machine learning into automation systems promises even greater capabilities. Predictive maintenance using AI algorithms can anticipate equipment failures before they occur. Adaptive control systems can optimize processes in real-time based on changing conditions. Autonomous systems can

coordinate complex operations without human intervention. As future engineers, there will be need for balance technical excellence with ethical considerations, ensuring that automation systems enhance human capabilities rather than replace human judgment in critical decisions.

V.4 Robotics

Robotics represents the physical embodiment of electrical engineering's convergence with mechanical engineering, computer science, and artificial intelligence. From industrial manipulators to surgical assistants, from autonomous vehicles to household helpers, robots have moved beyond science fiction to become integral components of modern society, extending human capabilities and transforming industries in profound ways.

The field of robotics has evolved dramatically since the first industrial robot, Unimate, was installed in a General Motors plant in 1961. Early robots were simple, repetitive machines operating in controlled environments, performing tasks like welding and material handling. Today's robots are increasingly sophisticated, featuring advanced sensors, adaptive control algorithms, and artificial intelligence capabilities that enable them to operate in unstructured environments and interact safely with humans.

Industrial robotics has revolutionized manufacturing processes. Modern automotive assembly lines employ hundreds of robots working in precise coordination, performing tasks from spot welding to final assembly with accuracy and consistency that exceeds human capabilities. These systems operate continuously, reducing production costs while improving quality and safety by removing workers from hazardous environments. The economic impact is substantial—countries that have embraced industrial robotics have seen significant productivity gains, though this has also raised questions about workforce displacement and the need for new skills training.

Beyond manufacturing, robotics has transformed healthcare through surgical robots like the Da. Vinci system, which enables surgeons to perform minimally invasive procedures with enhanced precision and dexterity. Rehabilitation robots help patients recover mobility after injuries or strokes, while robotic exoskeletons are restoring movement to individuals with paralysis. In logistics and warehousing, autonomous mobile robots (AMRs) are optimizing inventory management and order fulfillment, enabling the rapid delivery services that consumers now expect.

Service robotics is an emerging field with enormous potential. Domestic robots like robotic vacuum cleaners have become commonplace in many households, while more advanced systems are being developed for elder care, education, and personal assistance. Agricultural robots are automating tasks from planting and harvesting to crop monitoring, helping to address food security challenges while reducing the environmental impact of farming. Search and rescue

robots can operate in environments too dangerous for humans, from disaster zones to contaminated areas.

The societal implications of robotics are complex and multifaceted. On one hand, robots can perform dangerous, dirty, or repetitive tasks, improving worker safety and quality of life. They can extend human capabilities in precision surgery, space exploration, and deep-sea operations. On the other hand, the widespread adoption of robotics raises concerns about employment displacement, particularly in sectors involving routine physical tasks. The ethical questions surrounding autonomous weapons systems, privacy implications of surveillance robots, and the psychological impact of human-robot interaction require careful consideration.

For electrical engineers, robotics offers exciting opportunities in sensor design, control systems, power electronics, and embedded systems. The development of more capable, affordable, and energy-efficient sensors is crucial for robotic perception. Advanced control algorithms enable robots to adapt to changing environments and interact safely with humans. Power management systems determine operational duration and capabilities. Communication systems enable coordination between multiple robots and with human operators.

The future of robotics will likely see increased integration with artificial intelligence, enabling robots to learn from experience and make more autonomous decisions. Soft robotics, using flexible materials that mimic biological systems, promises safer interaction with humans and operation in delicate environments. Swarm robotics, inspired by social insects, could enable large numbers of simple robots to coordinate complex tasks.

V.5 Telecommunications

Telecommunications engineering has perhaps the most visible impact on daily life among all electrical engineering disciplines. From the telegraph to 5G networks, the evolution of telecommunications has continuously shrunk the world, enabling instant communication across vast distances and creating the interconnected global society we experience today. This transformation has fundamentally altered how humans interact, conduct business, access information, and participate in cultural and political life.

The journey of telecommunications began with simple electrical signaling systems in the 19th century. Samuel Morse's telegraph (1837) demonstrated that information could be transmitted electrically over wires, followed by Alexander Graham Bell's telephone (1876) which enabled voice communication. These early systems relied on analog signals and copper wiring, with limited capacity and range. The 20th century saw the development of digital communications, satellite technology, and fiber optics, which dramatically increased capacity and enabled global connectivity.

The digital revolution in telecommunications began in earnest with the development of integrated circuits and microprocessors. Digital signal processing enabled more efficient use of bandwidth, error correction improved reliability, and compression algorithms made it possible to transmit complex data like images and video. The transition from analog to digital cellular networks (1G to 5G) illustrates this progression. First generation networks supported only voice calls, while fifth generation networks can handle massive numbers of connected devices, ultra-high-definition video streaming, and mission critical communications with millisecond latency.

The societal impact of advanced telecommunications is profound. Economically, it has created entirely new industries, e-commerce, digital media, cloud computing, and the economy while transforming traditional ones. Small businesses can now reach global markets, freelancers can work remotely for clients worldwide, and financial transactions can occur instantaneously across borders. Socially, telecommunications has redefined human relationships, enabling families separated by geography to maintain close connections, facilitating the formation of global communities around shared interests, and providing platforms for social movements and political organization.

Access to information has been democratized in unprecedented ways. Educational resources, news, research papers, and cultural content are now available to anyone with internet access. This has empowered individuals in developing countries, enabled remote learning opportunities, and accelerated scientific collaboration. However, it has also created challenges related to information overload, misinformation, and the digital divide between those with and without access to high-speed connectivity.

The infrastructure required for modern telecommunications is itself a marvel of electrical engineering. Undersea fiber optic cables carry terabits of data across oceans, cellular base stations provide coverage in urban and rural areas, satellite constellations enable global coverage, and data centers process and store the enormous volumes of information generated daily. The energy consumption of this infrastructure is substantial, driving innovation in energy-efficient networking equipment and renewable energy integration.

Security and privacy concerns have grown alongside telecommunications capabilities. The same networks that enable convenient communication also create vulnerabilities to cyber attacks, surveillance, and data breaches. The engineering challenge is to design systems that are both highly functional and secure, protecting user privacy while enabling legitimate law enforcement and national security activities.

For electrical engineers, telecommunications offers diverse career paths in network design, signal processing, wireless systems, optical communications, and cybersecurity. Understanding fundamental concepts like modulation techniques, channel coding, antenna design, and network

protocols is essential preparation. The field continues to evolve rapidly, with research in terahertz communications, quantum communications, and integrated sensing and communications promising even greater capabilities.

Looking forward, the convergence of telecommunications with artificial intelligence will enable smarter networks that can optimize themselves in real-time, predict failures before they occur, and provide personalized services to users. The expansion of 5G and development of 6G networks will enable new applications like holographic communications, advanced augmented reality, and massive internet of things deployments. As future engineers, you will need to balance technical innovation with ethical considerations, ensuring that telecommunications technology serves humanity's best interests while protecting fundamental rights and freedoms.

V.6 Instrumentation in healthcare development

Medical instrumentation represents one of the most life affirming applications of electrical engineering, where technological innovation directly translates to improved human health, extended life spans, and enhanced quality of life. From simple diagnostic tools to complex therapeutic systems, electrical engineering has revolutionized healthcare delivery, making it more precise, accessible, and effective while transforming the relationship between patients and healthcare providers.

The evolution of medical instrumentation can be traced through several key breakthroughs. Early electrical medical devices included the electrocardiogram (ECG) developed by Willem Einthoven in the early 20th century, which enabled non-invasive monitoring of heart activity. The mid-20th century saw the development of medical imaging technologies, X-ray computed tomography (CT) in the 1970s, magnetic resonance imaging (MRI) in the 1980s, and ultrasound imaging, each relying on sophisticated electrical engineering principles to create detailed images of the human body without invasive procedures.

Modern medical instrumentation encompasses a vast array of technologies. Diagnostic equipment includes advanced imaging systems (PET, SPECT, functional MRI), laboratory analyzers that can process hundreds of blood samples per hour, and portable diagnostic devices that can perform complex tests at the point of care. Therapeutic devices range from implantable pacemakers and defibrillators that regulate heart rhythm to radiation therapy systems that precisely target cancer cells while sparing healthy tissue. Monitoring systems track vital signs continuously in intensive care units, while telemedicine platforms enable remote consultations and chronic disease management.

The impact on healthcare outcomes has been dramatic. Early detection of diseases through advanced imaging and laboratory testing has significantly improved survival rates for conditions

like cancer and cardiovascular disease. Minimally invasive surgical techniques, enabled by sophisticated imaging guidance and robotic assistance, reduce patient recovery time, minimize complications, and improve outcomes. Continuous monitoring systems enable earlier intervention when patients' conditions deteriorate, preventing complications and saving lives.

Beyond clinical applications, medical instrumentation has transformed public health. Wearable health monitors enable individuals to track their fitness and health metrics, promoting preventive care and early intervention. Remote monitoring systems allow elderly patients to age in place while maintaining contact with healthcare providers. Portable diagnostic devices bring healthcare to remote and underserved communities, reducing health disparities and improving access to quality care.

The integration of artificial intelligence with medical instrumentation is creating new possibilities. AI algorithms can analyze medical images with accuracy rivaling or exceeding human experts, identifying patterns that might be missed by the human eye. Predictive analytics can forecast patient deterioration before clinical symptoms appear. Personalized medicine approaches use genetic and biomarker data to tailor treatments to individual patients, improving efficacy while reducing side effects.

However, the advancement of medical instrumentation also presents significant challenges. The high cost of sophisticated equipment can exacerbate healthcare disparities, both within and between countries. Data privacy and security concerns are paramount, as medical devices collect highly sensitive personal information. The rapid pace of technological change requires continuous training for healthcare professionals and creates challenges for regulatory approval processes. Ethical questions arise around the use of AI in diagnosis and treatment decisions, and the potential for technology to depersonalize healthcare.

For electrical engineers, biomedical instrumentation offers exciting opportunities at the intersection of engineering and life sciences. Signal processing expertise is crucial for extracting meaningful information from noisy biological signals. Sensor design requires understanding both electrical principles and biological constraints. Power management is critical for implantable devices that must operate for years on tiny batteries. Communication systems enable data transfer between devices and healthcare providers while maintaining security and privacy.

Emerging areas include neural interfaces that can restore function to damaged nervous systems, smart implants that can monitor and respond to physiological changes in real-time, and nanoscale devices that can deliver drugs precisely to target sites.

The future of medical instrumentation will likely see increased integration with telecommunications and artificial intelligence, creating truly intelligent healthcare systems. Wearable and implantable devices will provide continuous health monitoring, while AI systems

analyze this data to provide personalized health recommendations. Point-of-care diagnostic devices will become increasingly sophisticated, enabling complex testing in home settings. As future engineers, you will have the opportunity to contribute to technologies that literally save lives and improve human well-being, making this one of the most rewarding applications of electrical engineering.

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