

People's Democratic Republic of Algeria
Ministry of Higher Education and Scientific Research
Abbes Laghrour University of Khenchela



Faculty of Science and Technology
Department of Electrical Engineering

COURSE HANDOUT

LMD Educational System

Materials and Introduction to High Voltage

Level: Third Year – License in Electrotechnics

Field: Sciences and Technologies

Stream: Electrical Engineering

Specialization: Electrotechnics

Prepared by:

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Preamble

1. Course Description

This module, "**Materials and Introduction to High Voltage**," is structured into two core parts. The first part focuses on the dielectric, mechanical, and thermal properties of **electrotechnical materials**. The second part establishes the **fundamental principles of high voltage**, including generation, measurement, breakdown phenomena, and insulation coordination. The course adopts a practical approach, deconstructing complex power systems (e.g., transmission lines) into fundamental components to analyze material behavior and system protection. It provides the essential foundation for engineers specializing in electrical power systems.

2. Target Audience

This course is designed for third-year students enrolled in the **Electrical Engineering (Electrotechnics)** degree program.

3. Prerequisites

A solid understanding of the following topics is required:

- Atomic structure and the basic constituents of matter.
- Electrostatics and electric field theory.
- Fundamentals of electrical discharge in gases.

Students are strongly advised to review these concepts before the start of the course.

4. Learning Outcomes

Upon successful completion of this module, students will be able to:

- Explain the mechanisms of high-voltage generation and the techniques for measuring AC, DC, and impulse voltages.
- Analyze the properties, behavior under electrical stress, and applications of solid, liquid, and gaseous insulating materials.
- Evaluate the insulation requirements and design principles for basic high-voltage equipment.
- Perform standard high-voltage laboratory tests and utilize simulation software for basic electric field analysis.

5. Assessment Scheme

- **Final Examination: 60%**
- **Continuous Assessment (40%):** comprising quizzes, homework assignments, and projects.

Foreword

High-voltage engineering is built upon two foundational pillars: the science of **insulating materials** and the principles of **high-voltage technology**. This module is designed to systematically guide you through these interconnected areas.

We begin by examining the essential properties of materials that must endure significant electrical stress. This foundation is then applied to understand the core techniques for generating, measuring, and safely managing high voltages within power systems. This logical progression (from material properties to system-level application) aims to equip you with the critical knowledge and conceptual tools required for a career in electrotechnics and power engineering.

I wish you a productive and engaging learning experience.

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Part I

Electrotechnical Materials

Chapter 1

Conductive Materials

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1.1 Introduction

Atoms form the fundamental building blocks of all materials, defining their electrical characteristics, such as how readily they conduct electric current. To simplify the study of these electrical properties, an atom is often represented using a simplified model consisting of its valence electrons (which participate in electrical interactions) and a core that includes the nucleus and all inner electron shells.

- **Core electrons:** these are located close to the nucleus and do not significantly interact with other atoms.
- **Valence electrons:** these are in the outermost shells of the atom and are involved in forming interatomic bonds and molecules.
- **Conduction electrons:** these are responsible for carrying electric current.

The characterization of a material is often a multidisciplinary endeavor. Based on their application, materials can be divided into: conductors, superconductors, dielectrics (insulators), and semiconductors.

- Electrical conductors** are metals with resistivities on the order of $10^{-8} \Omega \cdot \text{m}$.
- Superconductors** are materials that, below a certain critical temperature, exhibit zero electrical resistance to the flow of current.
- Insulators**, or very poor conductors (used to insulate electrical conductors), such as liquefied noble gases, have resistivities ranging from $10^{10} \Omega \cdot \text{m}$ to $10^{16} \Omega \cdot \text{m}$.
- Semiconductors** are materials whose resistivity is midway between that of conductors and insulators. They are used for manufacturing electronic power switches.

The choice of material depends primarily on its electrical properties (resistivity, permeability, dielectric constant, etc.) and cost, but also on its physical and mechanical properties (density, thermal expansion, melting point, corrosion sensitivity, hardness, elasticity, etc.). Fig. 1.1 shows the resistivity scale for the different types of materials.

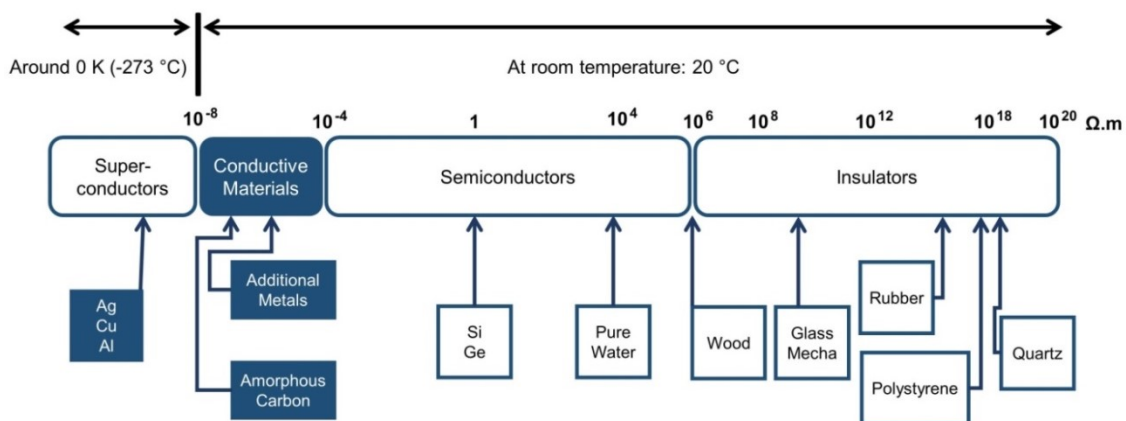


Fig. 1.1. Resistivity scale for different types of materials.

This foundational understanding of conductive materials sets the stage for the entire field of electrical engineering and High Voltage (HV) systems. The selection, behavior, and limits of these materials directly dictate the efficiency, safety, and feasibility of power generation, transmission, and conversion. Mastering their properties is essential for designing everything from microscopic circuits to continental-scale power grids that operate reliably under extreme electrical stresses.

1.2 Definition and basic concepts

An electrical conductor is a material characterized by the presence of mobile charge carriers that can move freely in response to an electric field. An electric current arises from the net movement, either actual or effectively represented, of these charge carriers, which may be either positively or negatively charged.

Two primary mechanisms of electrical conduction are generally identified:

- Electronic conduction, in which the charge carriers are electrons.
- Ionic conduction, in which the charge carriers are ions.

The most effective electrical conductors are pure, single-element metals, such as copper, silver, gold, and aluminum. The atomic structure of these elements features a single valence electron that is only loosely bound to its atom. These weakly attached electrons can readily become detached, forming a "sea" of delocalized or free electrons that facilitate electrical conduction.

Due to this fundamental property, conductive materials are integral components of all electrical systems, devices, and machinery. Consequently, a wide variety of conductors have been developed and can be classified based on their specific applications.

1.3 Electrical conduction: nature and mechanisms

An electrical conductor is defined as any material or medium that contains freely mobile electric charges, capable of moving under the influence of an applied electric field. This movement of charges constitutes an electric current. The nature of these charge carriers defines the type of conduction.

Common types of conductive media include metals, electrolytes, and plasmas.

The primary conduction mechanisms are categorized as follows:

- **Metallic conductors:** characterized by free electrons. In metals, the outermost atomic electrons are delocalized, forming a "sea" of electrons that can move freely throughout the crystalline lattice, enabling high conductivity.
- **Electrolytes:** conduct electricity through the movement of positive and negative ions in a solution or molten state. This form of conduction is essential for electrochemical processes, such as those in batteries and biological systems.
- **Pure (intrinsic) semiconductors:** exhibit conductivity through the generation of pairs of charge carriers: free electrons and holes (electron vacancies that act as positive charges). Their conductivity is highly dependent on temperature.
- **Doped (extrinsic) semiconductors:** the primary charge carriers depend on the nature of the doping.
 - ✓ *n-type* semiconductors have electrons as the majority carriers due to the addition of donor impurities.
 - ✓ *p-type* semiconductors have holes as the majority carriers due to the addition of acceptor impurities.

This controllable conductivity is the foundation of modern electronics.

- **Plasmas:** often called the "fourth state of matter," plasmas are ionized gases that conduct current via free electrons and positive ions. They are found in stars, lightning, and neon signs.

1.4 Characterization of conductive materials

Choosing the right conductive material for an application depends on understanding its essential properties, which govern performance, efficiency, and durability under electrical and thermal stress.

1.4.1 Resistance and resistivity

Experimental evidence demonstrates that most metals can sustain an electric current, I , when a voltage, V , is applied across two points on their surface, as illustrated in Fig. 1.2.

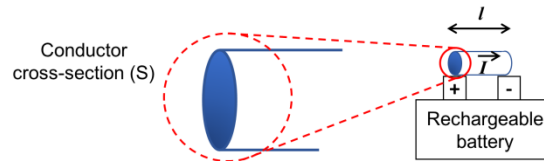


Fig. 1.2. Measurement of the voltage-current (V - I) relationship in a metallic conductor.

The electrical resistance of a conductor is defined by Ohm's law (first described by Ohm in 1826) in the well-known form: $V = R \times I$.

where R is the resistance of the conductor (Ω).

Knowing the geometric dimensions of the conductor (i.e., the cross-sectional area and length), the electrical resistivity ρ of the conductor can be calculated using the formula:

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

Where:

- ρ is the resistivity of the material [$\Omega \cdot \text{m}$];
- l is the length of the conductor [m];
- S is the cross-sectional area of the conductor [m^2].

Ohm's law can therefore also be expressed in the following form: $V = \frac{(\rho \times l \times I)}{S}$.

Table 1.1. Electrical resistivity of various pure metals (at 300 K).

Material	Resistivity ρ ($\Omega \cdot \text{m}$)
Silver (Ag)	16×10^{-9}
Copper (Cu)	17×10^{-9}
Gold (Au)	22×10^{-9}
Aluminium (Al)	28×10^{-9}
Magnesium (Mg)	43×10^{-9}
Zinc (Zn)	61×10^{-9}
Nickel (Ni)	87×10^{-9}
Iron (Fe)	100×10^{-9}
Platinum (Pt)	111×10^{-9}
Tin (Sn)	120×10^{-9}
Lead (Pb)	208×10^{-9}
Mercury (Hg)	941×10^{-9}

Table 1.2. Electrical resistivity of various alloys materials (at 300 K).

Material	Composition	Resistivity ρ ($\Omega \cdot \text{m}$)
Bronze	Cu-Sn	55×10^{-9}
Brass	Cu-Zn	71×10^{-9}
Constantan	Cu-Ni (55-45%)	500×10^{-9}
Nichrome	Ni-Cr (~80-20%)	$1,000 \times 10^{-9}$
Stainless Steel	Fe-Cr-Ni Alloy	$\sim 700 \times 10^{-9}$

1.4.2 Electrical conductivity

Electrical conduction, the movement of charge through a material, is a cornerstone of modern technology. It enables applications from long-distance power transmission to resistive heating.

This process is governed by Ohm's law at the microscopic level: the current density J (A/m^2) is proportional to the applied electric field E , with the material's conductivity σ (S/m) as the constant: $J = \sigma \times E$.

$$J = \sigma \times E$$

With: J current density such that: $J = \frac{I}{S}$.

Conductivity is an intrinsic property determined by the formula: $\sigma = n \times q \times \mu$.

where:

- n is the charge carrier density (m^{-3}).
- q is the charge per carrier (C).
- μ is the carrier mobility ($\text{m}^2/\text{V} \cdot \text{s}$).

Charge carriers can be negative (electrons) or positive. In solids, positive conduction is often described via "holes", effective quasiparticles representing the absence of an electron, which move as if they were positive charges.

1.4.3 Temperature dependence of resistivity

When a metallic conductor is in thermal equilibrium without an external electric field, the energy of the photons emitted from collisions between electrons and atoms is balanced by the energy input from the surrounding environment, maintaining a net zero energy balance. The application of an electric field disrupts this equilibrium by inducing a drift velocity in the electrons, which slightly increases the frequency of collisions. Although minimal, this increase generates additional heating described by the relationship $P = R \times I^2$. This rise in temperature enhances the thermal agitation of the electrons and the collision frequency, thereby reducing their mobility μ_c and the material's conductivity σ . Consequently, the resistivity ρ of the conductor increases with temperature, illustrating the effect of thermal agitation on the electrical properties of the material.

At temperatures near ambient conditions, the resistivity of a conductor generally increases with temperature and can be expressed by the following relation: $\rho(T) = \rho_0[1 + \alpha(T - T_0)]$.

Where:

- ρ_0 is the resistivity at reference temperature T_0 (in $\Omega \cdot m$);
- α is the temperature coefficient of resistivity (in $^{\circ}C^{-1}$);
- T_0 is the reference temperature (usually $20^{\circ}C$).

Table 1.3. Typical values of resistivity (ρ) and temperature coefficient (α) for pure metals.

Conductor	Resistivity, ρ ($\Omega \cdot m$) at $20^{\circ}C$	Temperature coefficient, α ($^{\circ}C^{-1}$) at $20^{\circ}C$	Melting point ($^{\circ}C$)
Aluminum (97% pure)	2.82×10^{-8}	4.0×10^{-3}	658
Hard-Drawn Silver	1.60×10^{-8}	3.8×10^{-3}	960
Chromium	2.60×10^{-8}	3.9×10^{-3}	1875
Hard-Drawn Copper	1.60×10^{-8}	4.2×10^{-3}	1083
Tin	11.5×10^{-8}	3.4×10^{-3}	232
Hard-Drawn Gold	2.23×10^{-8}	3.7×10^{-3}	1063
Platinum	11.00×10^{-8}	4.2×10^{-3}	1771
Lead	22.00×10^{-8}	4.5×10^{-3}	327
Tungsten	5.60×10^{-8}	3.7×10^{-3}	3370
Zinc	5.80×10^{-8}	3.7×10^{-3}	419

Therefore, a conductor carrying an electrical current will heat up. This temperature rise, in turn, causes an increase in the conductor's resistivity. The higher resistivity leads to greater power dissipation (for the same current), further amplifying the heating effect. This creates a self-reinforcing feedback loop: current $\rightarrow$ heating $\rightarrow$ increased resistivity $\rightarrow$ more heating.

Consequently, the conductor's internal operating temperature becomes highly dependent on the effectiveness of its cooling conditions.

A conductor's resistance increases when it carries a high-frequency Alternating Current (AC). This observed phenomenon is called the skin effect.

1.4.4 Influence of impurities

The significance of the impurity rate in a base metal also leads to an increase in the electrical resistivity of the material in question, according to the relationship: $\rho_{imp} = A \times C_{imp}(1 - C_{imp})$.

Where A is a constant independent of the composition, which is a function of the impurity and the base metal, and C_{imp} is the impurity concentration as an atomic proportion (at%) of the base metal.

1.4.5 Thermal conductivity

Thermal conductivity, denoted by the symbol λ (lambda) or k , is an intrinsic physical property that quantifies a material's ability to conduct heat. It is defined as the constant of proportionality in Fourier's law of heat conduction for a one-dimensional, steady-state heat flow.

The defining equation is: $\mathbf{q} = -\lambda \times \nabla T$.

where:

- $\mathbf{q}$ is the local heat flux density (W/m^2),
- ∇T is the temperature gradient (K/m).

The SI unit for thermal conductivity is the watt per meter-kelvin ($\text{W}\cdot\text{m}^{-1}\cdot\text{K}^{-1}$). This unit is interpreted as follows: a thermal conductivity of $1 \text{ W}\cdot\text{m}^{-1}\cdot\text{K}^{-1}$ indicates that one watt of heat energy transfers through a one-meter thickness of the material, across an area of one square meter, under a steady-temperature difference of one kelvin (or degree Celsius, for a temperature interval).

A material's capacity to insulate is inversely related to its thermal conductivity. Materials with high λ values (e.g., metals) are efficient thermal conductors, while those with low λ values (e.g., aerogels, foams) are effective thermal insulators.

It is critical to note that the thermal conductivity coefficient is not an absolute constant but is dependent on several factors, primarily temperature and, for porous materials, moisture content.

1.5 Physical properties of conductive materials

Electrical conductors are primarily metals or metallic alloys. They are characterized by their ability to allow the easy flow of electric charge, which is attributed to their cloud of free electrons. These materials possess the following key characteristics:

- **Low electrical resistivity:** typically less than $10^{-6} \Omega\cdot\text{m}$ (and consequently, a high electrical conductivity greater than $10^6 \text{ S}/\text{m}$ (Siemens per meter)).
- **High thermal conductivity:** approximately $100 \text{ W}/(\text{m}\cdot^\circ\text{C})$. This property is often correlated with electrical conductivity, as free electrons also transport thermal energy (Wiedemann-Franz Law).
- **Mechanical state:** generally exist as hard solids at room temperature. Notable exceptions include:
 - ✓ **Mercury (Hg):** the only metal that is liquid at room temperature.
 - ✓ **Sodium (Na) and Lead (Pb):** these are known for their relative softness.
- **High density:** typically around $10 \text{ g}/\text{cm}^3$. However, there are significant exceptions:
 - ✓ **Aluminum (Al):** $\sim 2.7 \text{ g}/\text{cm}^3$ (noted for its light weight).
 - ✓ **Gold (Au), Platinum (Pt), and Tungsten (W):** $\sim 19\text{-}21 \text{ g}/\text{cm}^3$ (very high density).
- **Significant temperature influence:**
 - ✓ **On resistivity:** resistivity increases with temperature. A 100°C temperature rise can lead to an increase in resistivity of approximately 40% for many pure metals.

- ✓ **On linear expansion:** metals expand when heated. A 100°C temperature rise typically results in a linear expansion of a few millimeters per meter (e.g., Copper expands about 1.7 mm/m per 100°C).
- **Significant frequency influence (skin effect):**
 - ✓ In AC systems, high frequencies cause the current to concentrate near the surface (the "skin") of the conductor rather than being uniformly distributed across its entire cross-section.
 - ✓ This skin effect effectively reduces the useful cross-sectional area, leading to an increase in the conductor's AC resistance compared to its Direct Current (DC) resistance.
 - ✓ **Mitigation strategy:** to counteract this at high frequencies, conductors are often composed of many thin, insulated strands woven together. This is known as Litz wire (from the German *Litzendraht*, meaning "braided wire"), which maximizes the surface area for current flow and maintains low resistance.

1.6 Applications of conductive materials

1.6.1 Power transmission and distribution

Power transmission and distribution involves the materials and design strategies for moving electrical energy from generation to end users. It covers the conductors, configurations, and insulation methods used in overhead power lines and insulated cables to achieve efficient, safe, and reliable electricity delivery over long and short distances.

1.6.1.1 Power grid transmission

HV transmission lines use bare, overhead conductors without insulation, supported by steel pylons. Insulation is omitted because, at very HVs (49 kV to 765 kV), it would be too heavy, costly, and bulky, and would impede conductor cooling.

The conductors are elevated to a safe height for public safety. Common materials are:

- **AAC (All Aluminium Conductor):** pure aluminium.
- **ACSR (Aluminium Conductor Steel Reinforced):** an aluminium core with a steel core for added strength.

These cables have a circular cross-section and are made of multiple, smaller stranded wires, as illustrated in the following Fig. 1.3.

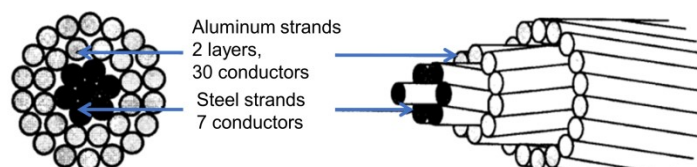


Fig. 1.3. Transmission network conductor cable with a circular cross-section.

It is also common to use multiple separate conductors per phase (a "bundle"), spaced a distance apart d (Fig. 1.4).

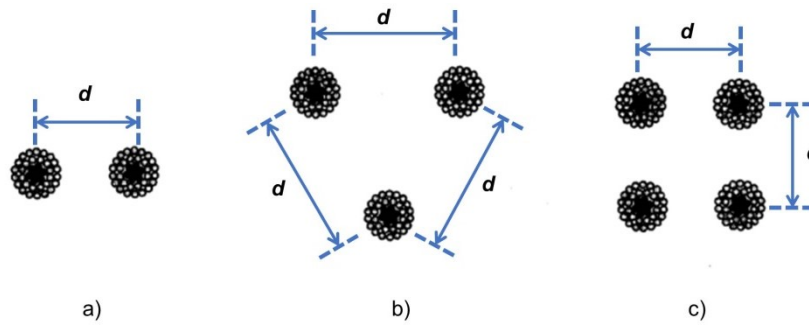


Fig. 1.4. Bundled conductors used in transmission line: a) twin, b) three, and c) four conductor bundle.

This configuration provides two key advantages:

- It increases the apparent diameter of the conductor, which reduces the electric field intensity at the surface and minimizes power losses from the corona effect.
- It increases the surface area exposed to the ambient air, improving heat dissipation and allowing for a higher current-carrying capacity compared to a single, solid conductor of the same total cross-section.

1.6.1.2 Electrical cables

There are two types of cables: bare overhead cables, which are exposed to the atmosphere and suspended from pylons, and insulated cables, which are used for underground, submarine, or short-distance overhead lines (Fig. 1.5).

Insulated cables consist of a conductive core and an insulating sheath, and are categorized as either multiconductor cables (which feature an assembly of electrically distinct conductors mechanically bound within a common jacket, sheath, or armor) or single-conductor cables (which feature a single insulated conductor covered by a protective sheath).



Fig. 1.5. Electrical cables: (a) bare overhead cables and (b) insulated cables.

1.6.2 Machine windings and transformers

This category covers the use of conductive materials (primarily copper and aluminum) to create paths for current flow. Copper offers the lowest resistivity, while aluminum, being lighter and more economical despite higher resistivity, is commonly used for HV transmission lines.

These materials are also fundamental in transformers, where they are wound into insulated coils to form the primary and secondary windings, enabling efficient electromagnetic induction and voltage transformation.



Fig. 1.6. Transformer windings.

1.6.2.1 Winding wire (magnet wire)

Magnet wire, typically composed of insulated copper or aluminum, is engineered for constructing electromagnetic coils in devices such as transformers, motors, and generators. It is characterized by a thin yet robust polymer insulation, such as polyurethane or polyester, that offers essential dielectric strength while maintaining a minimal cross-sectional profile to maximize winding density. Its primary function is to generate a concentrated magnetic field upon energization. For this reason, it is extensively employed in electrical engineering where magnetic fields are required. To effectively guide and amplify the magnetic flux, these windings are frequently coupled with a ferromagnetic core (Fig. 1.6).

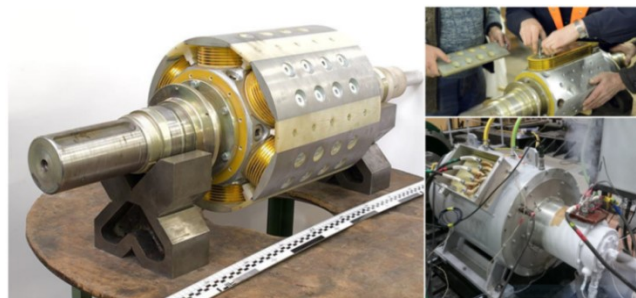


Fig. 1.6. Electrical machines winding.

1.6.3 Electrical contacts and connections

Electrical contacts and connections are the materials and techniques used to create reliable conductive pathways between components. This includes fixed interfaces, sliding contacts like brushes, and permanent wiring methods like soldering, each designed to minimize resistance, heat, and wear in their specific applications.

1.6.3.1 Fixed contacts and contact improvement

An electrical contact is a critical interface that establishes continuity between conductors, with common configurations being junctions (end-to-end) and taps (branch connections). These points are susceptible to parasitic effects such as Joule heating, voltage drops, and electromotive force generated by the galvanic coupling of dissimilar materials. To mitigate these issues and enhance performance in components like contactors, circuit breakers, and dis-connectors, the

contact surfaces are engineered with specialized materials. These materials are selected for high electrical conductivity, a high melting point, and resistance to arcing, wear, and welding. Consequently, precious metals like silver, gold, and platinum (often applied as a coating over a base metal like copper) are employed to improve contact resistance and the service life of components such as fuses, HV dis-connector blades, and contactors.

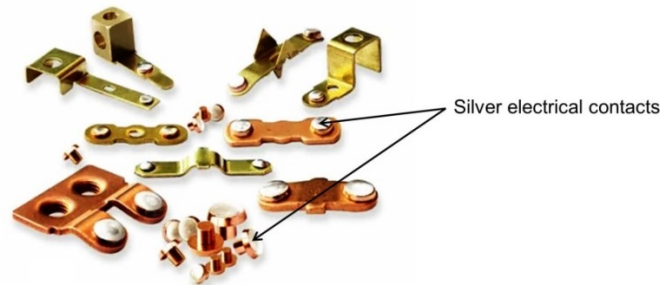


Fig. 1.7. Electrical contacts improvement by silver material.

1.6.3.2 Sliding contacts (slip rings and brushes)

Sliding contacts are essential components designed to maintain electrical continuity between stationary and moving parts, such as in motor brushes on commutators or trolley poles on overhead lines. The primary material challenge is to combine adequate electrical conductivity with self-lubricating properties and high resistance to mechanical wear. For this purpose, amorphous carbon (or graphite-based composites) is widely employed for brushes in DC and synchronous machines.

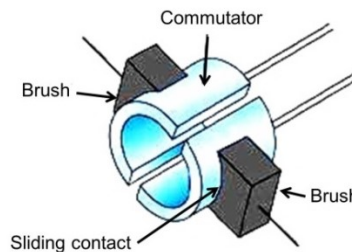


Fig. 1.8. Carbon brushes and commutators that highlight the sliding contact.

Despite its mediocre bulk resistivity, this material is favored because it provides a stable contact resistance and, crucially, is non-abrasive, thereby preventing damage to rotating components like commutators and slip rings. In applications requiring higher mechanical strength, such as the pantograph contacts with railway catenaries, bronze is typically used due to its durability and good conductive properties.

1.6.3.3 Wiring and soldering techniques

In electrical systems, wiring constitutes the physical installation of conductors to form a functional circuit, requiring precise sizing and routing to minimize parasitic effects like resistance, voltage drop, and heat. For creating permanent, low-resistance connections in these circuits, soldering is the predominant low-temperature metallurgical joining process. This process utilizes

a solder alloy, such as tin-lead (Sn-Pb) or a lead-free alternative like Sn-Ag-Cu, selected for its low melting point which is crucial for applications like Printed Circuit Board (PCB) assembly (Fig. 1.9). A chemical flux is essential during soldering to clean surfaces and prevent oxidation, thereby ensuring a reliable bond. The specific application dictates the material choice; for instance, in microelectronics, silver-based solders are used for chip attachment, while gold or aluminum is employed for ultra-fine wire bonding (10-500 μm).

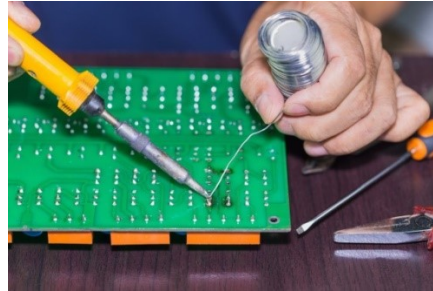


Fig. 1.9. Soldering circuit boards.

1.6.4 Resistive components

These are purpose-built materials and devices engineered to offer specific electrical resistance. Their design dictates their function, enabling applications like power dissipation, circuit regulation, heating, or lighting.

1.6.4.1 Wire-wound resistors

Wire-wound resistors are constructed by winding a high-resistivity metal wire around an insulating ceramic core. The requisite high resistivity, significantly greater than that of standard cable conductors, typically on the order of $100 \times 10^{-8} \Omega \cdot \text{m}$, is achieved through the use of specific alloys such as Nickel-Chromium (NiCr), Iron-Chromium-Aluminum (FeCrAl), or cupronickel. This design confers significant advantages, including high power ratings, excellent long-term stability, and precise resistance values, making these resistors ideal for applications in power supplies, braking circuits, and precision test equipment. A primary limitation, however, is their inherent inductance due to the coiled structure, which renders them unsuitable for high-frequency AC applications.

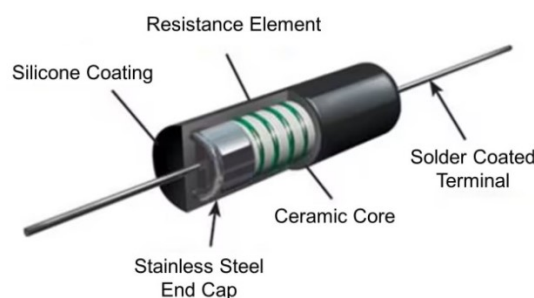


Fig. 1.10. Wire-wound resistor.

1.6.4.2 Heating elements (incandescent lamps)

Incandescent lamps (Fig. 1.11) operate on the principle of incandescence, wherein light is produced by heating a material to a high temperature until it glows. The key to this process is the filament, which is constructed from tungsten due to its exceptionally high melting point of approximately 3400 °C. When an electric current passes through the thin, resistive tungsten filament, it is heated to white-hot temperatures between 2500 and 3000 Kelvin. At these temperatures, the filament emits visible light; however, this method is highly inefficient, as the vast majority (around 90%) of the input electrical energy is converted and emitted as infrared radiation (heat) rather than visible light.



Fig. 1.11. Conductive materials in electric incandescent lamp.

1.6.5 Discharge lamps and arc devices

Discharge lamps (Fig. 1.12) function on the principle of electroluminescence, where light is generated by passing an electric current through a specific gas or vapor, such as mercury or sodium. This electrical energy causes the gas to ionize, exciting its atoms and prompting them to emit photons of light as they return to a lower energy state. The process requires a sealed glass tube containing the chosen vapor and is initiated and regulated by a ballast to control the current. This mechanism is the foundation for various lighting technologies, including fluorescent lamps and High-Intensity Discharge (HID) street lights, and is significantly more energy-efficient than traditional incandescent lighting.

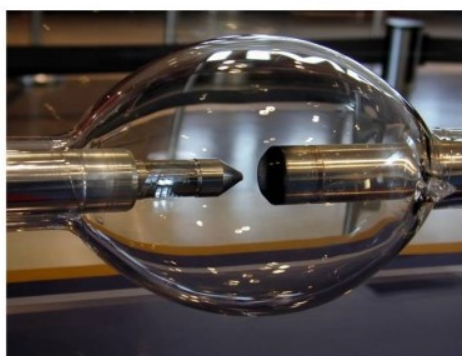


Fig. 1.12. Conductive materials in electric discharge lamp.

1.6.6 Sensing elements

Temperature probes like Resistance Temperature Detectors (RTDs), thermistors, and thermocouples convert heat into electrical signals. RTDs (e.g., PT100) use platinum's linear resistance change for stable readings from -200°C to 600°C . Thermistors are sensitive ceramic semiconductors with a non-linear response over narrower ranges. Thermocouples generate voltage from junctions of dissimilar metals, covering a wide span from -185°C to 2300°C .



Fig. 1.13. Temperature sensing probes.

1.7 Special conductive materials and components

There are many materials/devices where conduction is used for a specific, non-standard function, including:

1.7.1 Non-Ohmic resistors

Non-Ohmic Resistors are non-linear conductors that do not obey Ohm's law, meaning the voltage across them is not proportional to the current; their resistance varies with a physical parameter, such as temperature in a thermistor, voltage in a varistor, or a magnetic field in a magneto-resistor.

1.7.2 Thermocouples

Thermocouples are temperature measurement instruments that operate on the *Seebeck effect* (thermoelectric effect), generating a voltage from the temperature difference between the junctions of two dissimilar metals.

1.7.3 Fuses

Fuses are protective devices wired in series with electrical circuits, designed to melt and interrupt the circuit if the current exceeds a specified rating for a defined duration.

1.7.4 Superconductors

Superconductors are materials that, below a critical temperature (T_c) and within a critical magnetic field (B_c), lose all electrical resistance, allowing current to flow without any Joule losses.

Chapter 2

Magnetic Materials

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2.1 Introduction

Magnetic materials are fundamental to modern technology, bridging the gap between deep physics and advanced engineering. Their diverse properties, which include saturation, permeability, and core loss, make them indispensable across applications from power systems to computing. Specifically, they form the essential cores of transformers, motors, generators, and High Voltage (HV) equipment, enabling efficient energy conversion, transfer, and control. In

these critical applications, the performance of the magnetic core directly dictates the device's overall efficiency, power density, and reliability.

For engineers, designing with these materials involves a critical trade-off between cost, size, and performance. The available palette, from silicon steel to ferrites, provides a spectrum of characteristics to navigate these design challenges.

Current research is therefore focused on mastering these materials by developing accurate hysteresis models, quantifying energy losses, and creating new, high-performance alloys. This continuous evolution, driven by both scientific inquiry and technological demand, ensures magnetic materials remain a dynamic and vital field of study.

2.2 Origin of magnetism

The macroscopic magnetic properties of a material originate from the magnetic moments of its constituent electrons, which arise from two quantum-mechanical sources: the orbital motion of electrons around the nucleus, which generates an *orbital magnetic moment*, as shown in Fig. 2.1(a), and the intrinsic spin of the electrons, which produces a *spin magnetic moment*, as schematically illustrated in Fig. 2.1(b). In most materials, these individual magnetic moments cancel each other out, resulting in no net external field. However, in magnetic materials, a significant proportion of these electron moments align, producing a unified, macroscopic magnetic field. This alignment is fundamental to magnetization, demonstrating that magnetism is ultimately an electromagnetic phenomenon, as the magnetic field stems from the motion and inherent properties of charged particles.

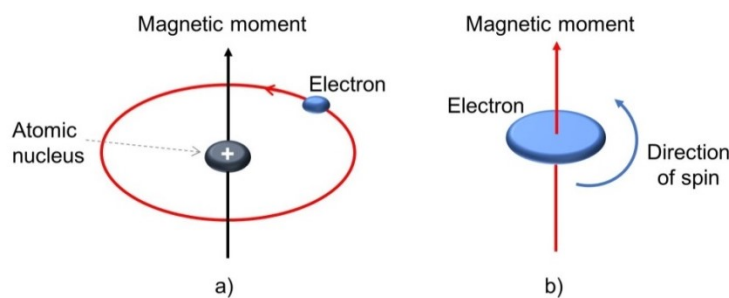


Fig. 2.1. Magnetic moment associated with (a) an orbiting electron and (b) a spinning electron.

2.3 Magnetization mechanism

The application of an external magnetic field can induce certain substances to generate their own magnetic field, both internally and in the surrounding space, a phenomenon known as magnetization or magnetic polarization. While this ability is a fundamental trait of all matter, it is most pronounced and readily observable in a specific class of substances known as magnetic materials.

The origin of this behavior lies in the quantum-level properties of electrons, primarily their intrinsic spin and, secondarily, their orbital motion around the atomic nucleus. However, for

practical engineering purposes, the collective magnetic effect of these electron behaviors is most effectively captured by the macroscopic concept of an atomic magnetic moment.

2.4 Magnetism from a macroscopic point of view

The macroscopic viewpoint is concerned with the average magnetic behavior of a material sample. Instead of considering the magnetic moments of individual atoms, we define a vector field that represents the magnetic dipole moment per unit volume at every point inside the material. This is a crucial step for applying Maxwell's equations to materials.

2.4.1 Magnetization vector ($\mathbf{M}$)

The fundamental macroscopic quantity in magnetism is the Magnetization ($\mathbf{M}$), which is defined as the net magnetic dipole moment per unit volume, given by the formula $\mathbf{M} = \frac{\Sigma \boldsymbol{\mu}}{V}$, where $\Sigma \boldsymbol{\mu}$ is the vector sum of all the individual magnetic moments ($\boldsymbol{\mu}$) within a small volume V . With units of Amperes per meter (A/m), magnetization physically describes the density and alignment of magnetic dipoles within a material, where a strong, uniform $\mathbf{M}$ indicates that a large number of these dipoles are aligned in the same direction.

2.4.2 Magnetic field in materials: the $\mathbf{H}$ -field

When a magnetic material is placed in an external magnetic field, the total magnetic field ($\mathbf{B}$) inside arises from two sources: the macroscopic "free current" (I_f) in the external circuit and the microscopic "bound current" due to the material's internal magnetization. To account for this, we introduce the Auxiliary Magnetic Field ($\mathbf{H}$), defined by the relationship $\mathbf{B} = \mu_0(\mathbf{H} + \mathbf{M})$, which can be rearranged as $\mathbf{H} = \frac{\mathbf{B}}{\mu_0} - \mathbf{M}$, where μ_0 is the magnetic permeability of free space in T·m/A. The $\mathbf{H}$ -field, measured in Amperes per meter (A/m), is physically significant because Ampere's circuital law for $\mathbf{H}$ states that $\oint \mathbf{H} \cdot d\mathbf{l} = I_f$, meaning its line integral around a closed loop is directly equal to the enclosed free current, making it an essential quantity for the design and analysis of electromagnets and magnetic circuits. The total magnetic field $\mathbf{B}$, measured in Tesla (T).

For linear, isotropic magnetic materials, the fundamental relationship between the fields is characterized by the material's response: $\mathbf{M}$ is proportional to the $\mathbf{H}$ -field that magnetizes it, defined as $\mathbf{M} = \chi_m \cdot \mathbf{H}$ where χ_m is the dimensionless magnetic susceptibility, quantifying how easily a material magnetizes. The overall ability of a material to support internal magnetic flux is given by its permeability μ , defined by $\mathbf{B} = \mu \cdot \mathbf{H}$, which relates the total magnetic field $\mathbf{B}$ to $\mathbf{H}$. Combining these definitions with the fundamental equation $\mathbf{B} = \mu_0(\mathbf{H} + \mathbf{M})$ reveals the constitutive relationship $\mu = \mu_0(1 + \chi_m)$, which is more commonly expressed using the dimensionless relative permeability $\mu_r = \frac{\mu}{\mu_0}$, leading to the key formula $\mu_r = 1 + \chi_m$.

2.5 Classification criteria for magnetic materials

2.5.1 Fundamental magnetic response (M vs. H)

While M describes a material's dipole alignment in response to H , engineers often prefer magnetic polarization ($J = \mu_0 \cdot M$) as a selection criterion because it is expressed in Teslas; a convenient unit for evaluating a material's ability to achieve high flux density in practical applications. This focus on polarization is especially important for exceptional materials like iron, steel, and their alloys, which can attain a high degree of polarization, and thus strong magnetization, in a favorable magnetic environment.

2.5.2 The hysteresis loop (B-H loop)

The hysteresis loop, the fundamental $B - H$ or $M - H$ graph for ferromagnetic and ferrimagnetic materials, serves as a crucial criterion for classifying them into two primary categories: soft and hard magnetic materials. This loop visually captures the material's non-linear and irreversible response to an applied field, revealing key properties like retentivity (B_r), coercivity (H_c), and magnetic saturation (S). B_r , more commonly known as remanence, and H_c , also referred to as coercive force. Fig. 2.2 show the plot of magnetic flux density (B) versus magnetic field strength (H), known as a $B - H$ curve or hysteresis loop.

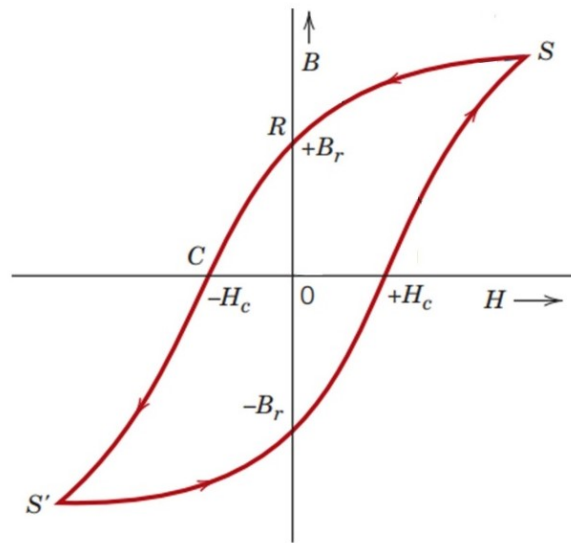


Fig. 2.2. The hysteresis loop : magnetic flux density versus the magnetic field strength.

The very shape of the loop determines its technological application: a large loop area, signifying high remanence and coercive force, is desirable for hard magnets (Permanent Magnets (PMs)) to ensure a strong, stable magnetic memory. Conversely, a narrow loop with a small area, characteristic of soft magnets like silicon steel, is essential for Alternating Current (AC) applications (e.g., transformer cores) as it minimizes hysteresis energy losses, which are quantified by the following equation (hysteresis losses):

$$P_h = k_h \times f \times (B_{\max})^n$$

Where:

- P_h is the hysteresis power loss per unit volume (W/m^3).
- k_h is the hysteresis loss coefficient or Steinmetz coefficient, a material-dependent constant.
- f is the frequency of the alternating magnetic field (Hz).
- B_{max} is the maximum flux density (T).
- n is the Steinmetz exponent, typically between 1.6 and 2.0 for most soft magnetic materials. It is often approximated as 2.

2.5.3 Retentivity (B_r) and coercivity (H_c)

B_r and H_c are the two most critical parameters read directly from the hysteresis loop fundamentally defining the distinction between "hard" and "soft" magnetic materials. B_r measures the magnetization remaining in a material after an external magnetic field is removed, indicating its strength as a permanent magnet (PM), while H_c quantifies the reverse magnetic field required to drive that magnetization back to zero, representing the material's resistance to becoming demagnetized. Hard magnetic materials are characterized by high retentivity and, most importantly, very high coercivity, making them difficult to demagnetize and ideal for PMs; in contrast, soft magnetic materials possess high retentivity but very low coercivity, allowing them to be easily magnetized and demagnetized, which is essential for efficient cores in transformers and electromagnets where minimal energy loss is critical.

The Table 2.1 presents the values of remanent magnetization and coercive field for various magnetic materials:

Table 2.1. Retentivity and coercivity for various magnetic materials.

Material	Retentivity, B_r [T]	Coercivity, H_c [A/m]
Pure iron (99.8%)	1.3	79.58
Pure iron (99.95%)	1.3	3.98
78 Permalloy	0.7	3.98
Super-Permalloy	0.7	0.4
Pure cobalt (99%)	0.5	795.8
Pure nickel (99%)	0.4	55.7
0.9% Carbon steel	1.03	5570.4
Amorphous 2605SAI	≈ 0	≈ 0

2.5.4 Magnetic domains and anisotropy

Fig. 2.3 show the domain configurations during several stages of magnetization. As shown in the figure, if the material is initially unmagnetized, then B varies as a function of H . The curve begins at the origin, and as H is increased, the B field begins to increase slowly, then more rapidly, finally leveling off and becoming independent of H . This maximum value of B is the saturation flux density B_s , and the corresponding magnetization is the saturation magnetization M_s . The

permeability of a material is a function of H . A key property often specified is the initial permeability, defined as the slope of the $B - H$ curve at its origin, where H approaches zero.

The application of an external field H drives the magnetization process through changes in the material's domain structure, as illustrated by the insets (U through Z) along the $B - H$ curve. Initially, the magnetic moments of the domains are randomly oriented, resulting in zero net magnetization (inset U). When an external field is applied, domains favorably aligned with the field grow by the movement of domain boundaries, consuming those that are unfavorably oriented (insets V through X). With a further increase in field strength, this process continues until the entire specimen comprises a single domain, nearly aligned with the field (inset Y). Finally, saturation is achieved when the magnetic moments of this single domain rotate to become perfectly aligned with the direction of the applied H field (inset Z).

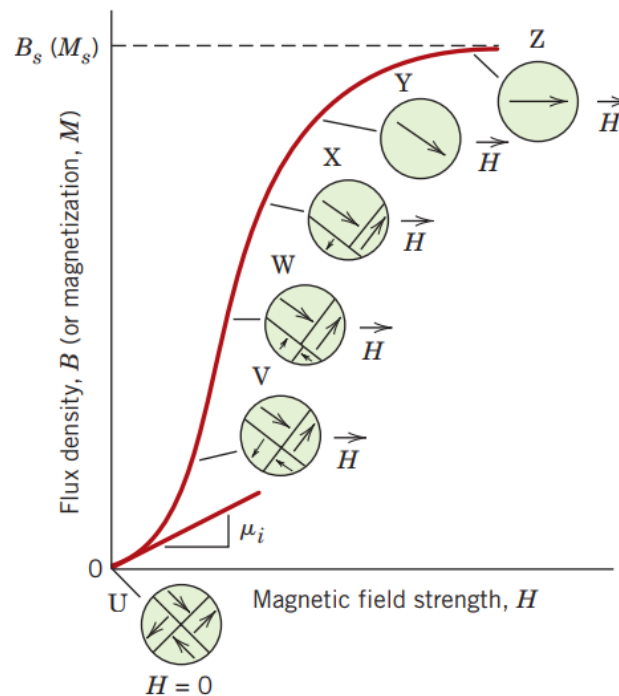


Fig. 2.3. Domain configurations during several stages of magnetization.

2.5.5 Saturation of the magnetic circuit

The practical design and operation of electric machines are critically governed by the magnetic saturation of their cores, a state where increasing the magnetic field strength (H) no longer results in a proportional increase in flux density (B), leading to a sharp drop in permeability and efficiency. This relationship is visualized on the $B - H$ curve, as shown in Fig. 2.4. Where the ideal operating point is in the *slightly saturated* "useful zone" (b); operating in the *linear zone* (a) yields a magnetic field that is too weak, while pushing into the *deeply saturated zone* (c) requires an excessively high current, generating wasteful heat and causing the machine to overheat.

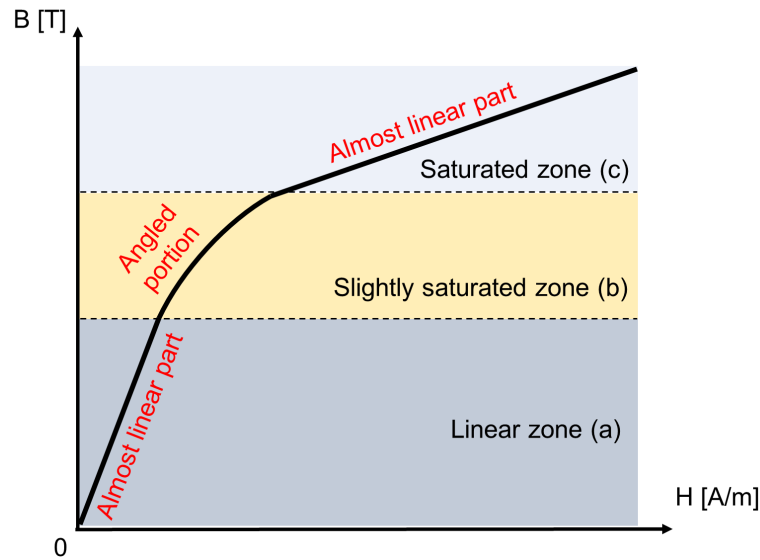


Fig. 2.4. B-H Curve and electric machine operating regions.

2.5.6 Magnetic losses (core losses)

Magnetic core losses are the energy wasted as heat in magnetic materials under alternating fields, primarily due to hysteresis (irreversible domain wall movement) and eddy currents (induced circulating currents). Minimizing these losses is vital for the efficiency of AC equipment like transformers.

Hysteresis and eddy current losses originate within the material. They are very often cumulative and referred to as "magnetic losses" or "iron losses":

$$\text{Iron Losses} = C_{\text{IRON}} \times \left(\frac{f}{f_0}\right)^k \times \left(\frac{B}{B_0}\right)^2 \times m$$

C_{IRON} : iron loss coefficient in W/kg (manufacturer's data);

$f_0 = 50$ Hz and $B_0 = 1$ T, $1.5 < k < 2$, m : mass of the magnetic circuit.

2.5.7 Eddy-current loss

In the magnetic circuits of most electrical machines, the core is subjected to a time-varying magnetic field. According to Faraday's law of induction, this alternating magnetic flux induces circulating voltages within the conductive magnetic material (such as iron). These voltages, in turn, generate circulating currents known as eddy currents. Since the core material has a finite electrical resistivity, these eddy currents result in Joule heating ($I^2 \times R$ losses), which is the fundamental origin of eddy-current loss. This energy dissipation manifests as undesirable heat within the core, reducing the machine's efficiency.

For a thin lamination (a common strategy to reduce this loss), the classical eddy-current loss per unit volume is given by:

$$P_e = \frac{(\pi^2 \times f^2 \times (B_{\text{max}})^2 \times d^2)}{(6 \times \rho \times D)}$$

A more general and widely used form is:

$$P_e = k_e \times f^2 \times (B_{\max})$$

Where:

- P_e is the eddy-current power loss per unit volume (W/m^3).
- k_e is the eddy-current loss coefficient, dependent on the material's resistivity (ρ) and physical dimensions (like lamination thickness, d (m)).
- f is the frequency (Hz).
- D is the density of the material (kg/m^3).

2.6 Classification of magnetic materials

In electrical machines, magnetic materials are essential for channeling and concentrating magnetic flux to maximize energy conversion efficiency. All materials can be categorized by their magnetic properties, primarily as diamagnetic, paramagnetic, ferromagnetic, antiferromagnetic or ferrimagnetic, based on their atomic-scale response to an external magnetic field. This response is quantified by the magnetic susceptibility (χ), a dimensionless parameter in the constitutive relation $\mathbf{B} = \mu_0(1 + \chi)\mathbf{H}$, where $\mathbf{B}$ is the magnetic induction (in Tesla), $\mathbf{H}$ is the external magnetic field (in A/m), and μ_0 is the permeability of free space. This equation reveals that for a given $\mathbf{H}$, the resulting magnetic induction $\mathbf{B}$ is directly enhanced by a higher χ . While diamagnetic and paramagnetic materials (most elements) have small, negative and small, positive susceptibilities respectively, ferromagnetic and ferrimagnetic materials (e.g., iron and ferrites) exhibit large, positive χ values. It is this property of high magnetic susceptibility that is deliberately exploited in the ferromagnetic cores of electrical machines, as it allows for the generation of a strong internal magnetic flux with a relatively weak external excitation field.

2.6.1 Diamagnetic materials

Diamagnetism is a fundamental magnetic property exhibited by all materials, arising from the precession of spinning electrons under an applied magnetic field, which induces a weak, opposing magnetization. This results in a small, negative magnetic susceptibility that is independent of both temperature and the external field's intensity.

In a purely diamagnetic material, which possesses no PM moment in the absence of an external field, this induced magnetization is transient and disappears immediately once the field is removed. While this effect is universal, it is so weak that it is typically masked by stronger paramagnetic or ferromagnetic effects in other materials; consequently, common "non-magnetic" substances like wood and plastic exhibit this bulk diamagnetic behavior. From a technological standpoint, most diamagnets are of limited interest, with the notable exception of superconductors, which exhibit perfect diamagnetism and are used for applications such as magnetic shielding.

2.6.2 Paramagnetic materials

Paramagnetic materials are characterized by a weak, positive magnetic susceptibility, typically ranging from 10^{-6} to 10^{-2} , which results from the alignment of permanent, non-zero atomic magnetic moments with an applied magnetic field, causing the magnetization to point in the same direction. This induced magnetization is transient and disappears entirely once the external field is removed due to thermal agitation that randomizes the moments. The fundamental behavior is explained by two primary models: the *Langevin* (or Classical) theory, which applies to materials with localized, non-interacting magnetic moments (e.g., certain hydrated salts) and describes how an external field causes a slight alignment against thermal disorder, leading to a susceptibility that follows the Curie law, decreasing with temperature. This is a specific case of the more general Curie-Weiss law, which incorporates interactions between moments and can indicate a transition to ferromagnetic (positive θ) or anti-ferromagnetic (negative θ) order at low temperatures. In contrast, the Pauli (or Quantum) model explains paramagnetism in metals like aluminum and platinum, where conduction electrons contribute a weak, temperature-independent susceptibility due to a spin imbalance within the band structure. Despite the existence of PM moments, these materials are generally considered weakly magnetic at room temperature, and their paramagnetic response is often masked by stronger forms of magnetism in more common elements.

2.6.3 Ferromagnetic materials

Ferromagnetic materials, such as iron, cobalt, nickel, and their alloys, are characterized by an exceptionally high and positive magnetic susceptibility, with relative permeability reaching up to 10^6 . This unique behavior originates from strong quantum mechanical exchange interactions (Heisenberg model), classically conceptualized by Weiss's molecular field, which cause atomic magnetic moments to align parallel within regions known as magnetic domains. Upon application of an external magnetic field, the material's response is non-linear and history-dependent, governed by the movement and reorientation of these domains, which leads to a significant reinforcement of the magnetic field and a high saturation magnetization. This process is described by a hysteresis loop, where permeability varies with both the magnetic induction and the sample's magnetic history. A critical property of ferromagnets is their temperature dependence; increasing thermal agitation disrupts magnetic order, causing saturation magnetization to decline until the material undergoes a phase transition at its Curie temperature (e.g., 770°C for Fe), beyond which it becomes paramagnetic and its susceptibility obeys the Curie-Weiss law. Due to their ability to intensely channel magnetic flux and their high saturation, ferromagnetic materials like silicon steel are foundational in electrical engineering for low-frequency applications. For high-frequency operations (>10 kHz), where eddy current losses are a concern, low-conductivity variants such as ferrites or amorphous materials in thin sheets are

employed, as they offer significantly lower magnetic losses despite a potentially lower saturation magnetization.

2.6.4 Antiferromagnetic materials

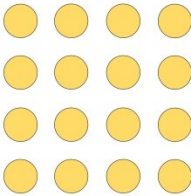
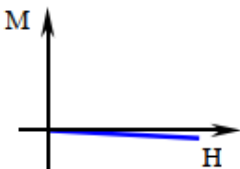
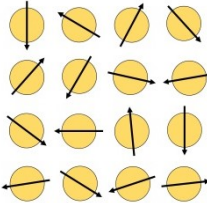
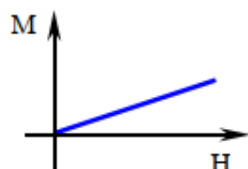
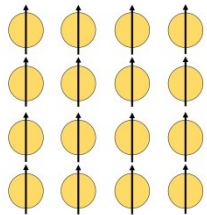
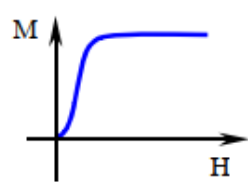
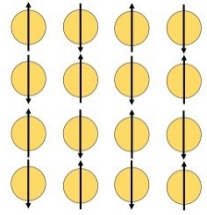
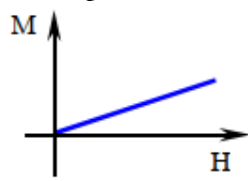
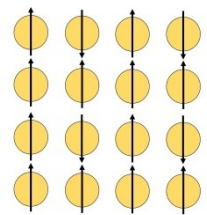
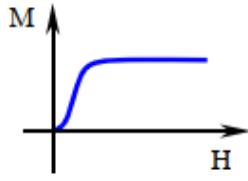
Antiferromagnetic materials, with chromium being the sole elemental example at room temperature, are characterized by a weak, positive magnetic susceptibility akin to paramagnets, as their atoms possess permanent magnetic moments. However, unlike the independent moments in paramagnets, antiferromagnets exhibit a strong exchange interaction between neighboring atoms, resulting in a systematic antiparallel alignment of these moments, a phenomenon known as antiferromagnetic coupling. This ordered arrangement causes the magnetic fields of adjacent atoms to largely cancel out, leading to a net magnetization that is nearly zero and explaining their externally paramagnetic-like behavior. This ordered state is highly temperature-dependent; as thermal energy increases, the antiparallel alignment deteriorates, making the material more susceptible to an external field. This is observed as a decrease in the inverse susceptibility $\left(\frac{1}{\chi}\right)$ with rising temperature until a critical point, the Néel temperature T_N , is reached. For chromium, this transition occurs at 37°C. Above T_N the antiferromagnetic coupling is completely overcome by thermal agitation, and the material undergoes a phase transition to a conventional paramagnetic state.

2.6.5 Ferrimagnetic materials

Ferrimagnetism is a magnetic phenomenon observed not in pure elements but in complex compounds, most notably in oxides known as ferrites, such as barium ferrite ($\text{BaO} \cdot 6\text{Fe}_2\text{O}_3$). Their crystal structure is composed of at least two distinct sublattices, sites A and B, occupied by magnetic ions with moments $\mathbf{m}_A$ and $\mathbf{m}_B$. A strong antiferromagnetic exchange interaction exists between these sublattices, forcing the magnetic moments of one set of sites to align antiparallel to the other.

However, ferrimagnetism arises because the number of A and B sites is unequal and/or because the magnitudes of the magnetic moments ($\mathbf{m}_A$ and $\mathbf{m}_B$) are different. This structural imbalance results in incomplete cancellation of the opposing magnetizations, producing a spontaneous net magnetization even in the absence of an external magnetic field. Consequently, ferrimagnets exhibit macroscopic behavior very similar to ferromagnets, including the formation of magnetic domains and magnetic hysteresis, but typically with lower saturation magnetizations. This is illustrated by barium ferrite, where specific alignments mean only a fraction of the ions contribute to the net magnetic moment, making these materials particularly valuable for applications requiring magnetic properties with lower saturation and, often, higher electrical resistivity.

Table 2.2. A summary of the different types of magnetic behavior.

Magnetic material	Magnetic susceptibility	Arrangement of moments	Magnetic behavior	Examples
Dia-magnetic	Low and Negative ($\chi < 0$)	Atoms have no magnetic moment. 	Weakly repelled by a magnetic field. M is opposite to H. 	Copper(Cu) Bismuth(Bi)
Para-magnetic	Low and Positive ($\chi > 0$)	Atoms have randomly oriented magnetic moments. 	Weakly attracted by a magnetic field. M is in the same direction as H. 	Aluminum (Al) Platinum (Pt) Beta-Tin (β -Sn)
Ferro-magnetic	Very high and Positive ($\chi \gg 0$)	Atoms have parallel aligned magnetic moments. 	Strongly magnetic and permanently magnetizable. With non-linear B-H curves. 	Iron (Fe) Cobalt (Co) Nickel (Ni)
Antiferro-magnetic	Low and Positive ($\chi > 0$)	Atoms have anti-parallel aligned magnetic moments. 	Similar to paramagnets but with a more complex temperature dependence. 	Manganese Oxide (MnO)
Ferri-magnetic	High and Positive ($\chi > 0$)	Atoms have mixed parallel and anti-parallel aligned magnetic moments. 	Similar to ferromagnets but typically with a lower magnetization. 	Iron(III) Oxide (Fe_2O_3)

2.7 Characteristics of magnetic materials for circuit design

2.7.1 Magnetic flux (Φ) and flux density (B)

Magnetic flux (Φ), measured in Webers (Wb), is the central output variable of a magnetic circuit, representing the total "amount" or number of lines of magnetic force from an induction field (B) that pass through a given area (A).

It is quantitatively defined by the equation $\Phi = B \times A \times \cos(\alpha)$, where α is the angle between the field lines and the surface perpendicular. As the primary quantity that systems like motors and transformers are designed to produce and control, it effectively quantifies the net magnetic field penetrating a specified surface.

2.7.2 Permeability of free space (μ_0) and relative permeability (μ_r)

Magnetic materials are characterized by their ability to allow lines of magnetic force to pass through with ease, a property quantified by their relative permeability (μ). However, all materials, including non-magnetic ones like a vacuum, possess a permeability. The fundamental baseline for this property is the permeability of free space (μ_0), which has a value of $4\pi \times 10^{-7}$ H/m (or T·m/A). This constant defines the ability of a vacuum and air, which behaves identically, to support a magnetic field, establishing the foundational ratio between the magnetic flux density (B) and the magnetic field strength (H) against which all other materials are measured.

Relative permeability (μ_r) is the most critical property of a magnetic material, defined as $\mu_r = \frac{\mu}{\mu_0}$, which quantifies how much more magnetizable a substance is compared to a vacuum. This value is essential when introducing a core into a coil, as it classifies materials and qualifies the ease with which magnetic flux can move within them: non-magnetic materials have a μ_r of approximately 1, as they do not facilitate the passage of flux lines, while magnetic materials, classified as diamagnetic ($\mu_r < 1$), paramagnetic ($\mu_r > 1$), or ferromagnetic ($\mu_r \gg 1$), all behave differently and possess a unique relative permeability depending on their composition.

2.7.3 Reluctance (R) and permeance (Λ)

Reluctance (R), measured in H^{-1} , is a key calculational parameter that expresses the opposition or "magnetic resistance" a material presents to the passage of magnetic flux in a circuit. It is defined as the inverse of permeance ($R = \frac{1}{\Lambda}$) and serves as the fundamental quantity that enables the use of Ohm's Law for Magnetism ($\Phi = \frac{MMF}{R}$), where MMF is the Magneto-Motive Force, allowing engineers to analyze and design complex magnetic paths.

Permeance (Λ), measured in henries [H], quantitatively expresses how easily magnetic flux (Φ) can pass through a material or region, defined by the equation $\Lambda = \frac{\Phi}{(\theta_A - \theta_B)}$, where $(\theta_A - \theta_B)$ is the magnetic potential difference. While it is a fundamental property representing the ease

of magnetic flux flow and is the direct reciprocal of Reluctance ($\Lambda = \frac{1}{R}$), it is generally less frequently used as a primary calculation tool in magnetic circuit analysis than Reluctance itself.

2.8 Soft and hard magnetic materials

Magnetic materials are broadly classified into two categories: soft and hard (PMs) on the basis of their hysteresis characteristics. Soft magnetic materials, which are easily magnetized by even weak magnetic fields, serve to guide and concentrate magnetic flux within electrical machines. In contrast, hard magnetic materials are characterized by their ability to retain a persistent state of magnetization despite exposure to strong opposing fields, making them ideal for creating the intrinsic magnetic fields required in electrical machines.

Fig. 2.5. compares the hysteresis characteristics of soft and hard magnetic materials. The hysteresis loop for soft magnetic materials is characteristically thin and narrow, resulting in a small enclosed area compared to the large, wide loop of hard magnetic materials.

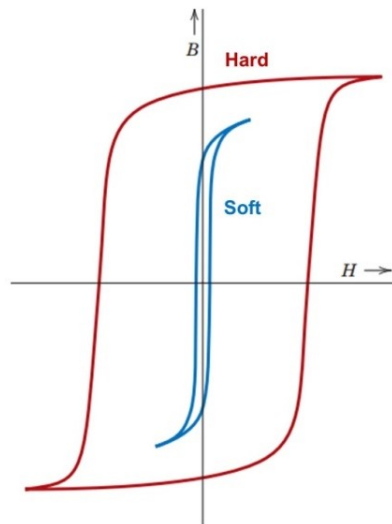


Fig. 2.5. Schematic magnetization curves for soft and hard magnetic materials.

2.8.1 Soft magnetic materials

Soft magnetic materials are characterized by a narrow hysteresis loop, featuring low coercivity and high permeability, which allows them to be easily magnetized and demagnetized by a weak external field. This fundamental property is achieved by minimizing structural defects to facilitate easy domain wall movement, resulting in low hysteresis energy losses. To operate efficiently in AC applications like transformers and motors, these materials must also minimize eddy current losses, which is accomplished by maximizing electrical resistivity through alloying (e.g., adding silicon to iron) or by using ceramic ferrites. Therefore, the optimal performance of a soft magnetic material, enabling it to channel a variable magnetic flux at high frequencies without significant overheating, is not defined by its saturation magnetization, but by the careful engineering of its coercivity and permeability through processing and microstructure to create an efficient, low-loss core.

The properties of several soft magnetic materials are shown in Table 2.3.

Table 2.3. Properties for several soft magnetic materials.

Material	Composition (wt %)	Initial relative permeability μ_i	Saturation flux density B_s [tesla]	Hysteresis loss/cycle [J/m ³]	Resistivity ρ ($\Omega\cdot\text{m}$)
Commercial iron ingot	99.95 Fe	150	2.14	270	1.0×10^{-7}
Silicon–iron	97 Fe, 3 Si	1400	2.01	40	4.7×10^{-7}
45 Permalloy	55 Fe, 45 Ni	2500	1.6	120	4.5×10^{-7}
Supermalloy	79 Ni, 15 Fe, 5 Mo, 0.5 Mn	75,000	0.8	–	6.0×10^{-7}
Ferroxcube A	48 MnFe ₂ O ₄ , 52 ZnFe ₂ O ₄	1400	0.33	~ 40	2000
Ferroxcube B	36 NiFe ₂ O ₄ , 64 ZnFe ₂ O ₄	650	0.36	~ 35	10^7

2.8.2 Hard magnetic materials

Hard magnetic materials are engineered for PMs, requiring a strong resistance to demagnetization, which is characterized by high coercivity, high remanence, and a large hysteresis loop area. Their performance is quantified by the maximum energy product (BH_{max}), a key metric known as the merit factor, which represents the maximum magnetic energy density stored; a larger value signifies a more powerful and stable magnet. This behavior is achieved by creating a microstructure, often based on iron or rare-earth elements like neodymium (Nd-Fe-B), that impedes domain wall motion, making the material very difficult to demagnetize. Consequently, these magnets provide a stable and intense magnetic field, making them essential for applications ranging from loudspeakers and electric motors to telecommunications and micro-computing, where the magnetic field must remain constant even in the presence of external disturbances.

The properties of several hard magnetic materials are shown in Table 2.4.

Table 2.4. Properties for several hard magnetic materials.

Material	Composition (wt %)	Remanence B_r [tesla]	Coercivity H_c [amp-turn/m]	BH_{max} [kJ/m ³]	Resistivity ρ ($\Omega\cdot\text{m}$)
Tungsten steel	92.8 Fe, 6 W, 0.5 Cr, 0.7 C	0.95	5900	2.6	3.0×10^{-7}
Cunife	20 Fe, 20 Ni, 60 Cu	0.54	44,000	12	1.8×10^{-7}
Sintered alnico 8	34 Fe, 7 Al, 15 Ni, 35 Co, 4 Cu, 5 Ti	0.76	125,000	36	–
Sintered ferrite 3	BaO-6 Fe ₂ O ₃	0.32	240,000	20	~ 10^4
Cobalt rare earth 1	SmCo ₅	0.92	720,000	170	5.0×10^{-7}
Sintered neodymium-iron-boron	Nd ₂ Fe ₁₄ B	1.16	848,000	255	1.6×10^{-6}

2.9 Permanent magnets

PMs are materials that can provide a magnetic flux without the need for an external power supply. They are characterized by their ability to retain a strong magnetic field after being magnetized, a property known as remanence. Their development, from early steel alloys to modern rare-earth compounds, has been pivotal in advancing technologies from data storage to renewable energy.

2.9.1 Properties of permanent magnets

The performance of a PM is defined by its $B - H$ curve (hysteresis loop). Key properties are derived from this loop.

- a) **Polarity of the PM:** all magnets have two magnetic poles which are connected by a dipolar axis. The two poles are named "north" and "south" based on the Earth's geographical poles towards which they are attracted.
- b) **Remanent induction or remanent field (remanence B_r):** is the magnetic flux density that persists within a material after the removal of an external magnetizing field. It represents the intrinsic strength of a PM. In the absence of an electric current, this remanent field (B) is defined by the equation $B = B_r = \mu_0 \times M$, meaning it is solely a product of the material's own magnetization (M).
- c) **Demagnetization coercivity (H_c):** measured in amperes per meter (A/m), is a fundamental property that quantifies a magnetic material's resistance to becoming demagnetized. It is defined as the intensity of the reverse magnetizing force, created by electric currents in a surrounding coil, that must be applied to reduce the material's magnetic induction to zero. A high coercivity value indicates a very stable magnet that can withstand strong opposing fields without losing its magnetization.
- d) **Intrinsic coercivity (H_{cj}):** the resistance to demagnetization based solely on the material's internal structure. Critical for thin magnets or those with high demagnetizing fields.
- e) **Maximum energy product (BH)_{max} :** is the single most important figure of merit. It represents the maximum magnetic energy density stored in the magnet. A higher $(BH)_{max}$ means a smaller volume of magnet is needed for a given application.
- f) **Curie temperature (T_c):** is the critical threshold above which a ferromagnetic material loses its spontaneous magnetization and transitions into a paramagnetic state. While the material's specific magnetic alignment is erased and will not be restored upon cooling, this change is reversible. Once the temperature falls below the curie point, the material regains its fundamental ferromagnetic properties and can be remagnetized.
- g) **Maximum temperature (T_{max}):** the highest temperature at which the magnet can function without sustaining permanent damage. Any loss in magnetic properties at or below this temperature is reversible upon cooling.

2.9.2 Types of permanent magnets

PMs are manufactured from a wide range of substances. These include various alloys of iron, aluminum, cobalt, copper, and other elements like carbon and oxygen. While hardened steel (composed of 98.5% iron, 1% carbon, and 0.5% manganese) has been a long-known example, modern technology has developed more powerful types. Common contemporary categories include Ferrite (ceramic) magnets, Alnico (Al-Ni-Co), and Rare earth elements (which includes Neodymium Iron Boron (NdFeB) and Samarium-Cobalt (SmCo)).

a) Ferrite (ceramic) magnets

Ferrite magnets, commonly known as ceramic magnets, are composed primarily of iron oxide (Fe_2O_3) combined with strontium or barium compounds (e.g., $\text{SrO} \cdot 6\text{Fe}_2\text{O}_3$). They are the most cost-effective type of magnet available, offering an excellent quality-price ratio that makes them ideal for high-volume applications such as loudspeakers, Direct Current (DC) motors, and magnetic holding devices. These magnets are characterized by their good resistance to demagnetization, excellent corrosion resistance, and a guaranteed long service life when used correctly. While their magnetic strength is lower than that of rare-earth magnets, they are electrically resistive, lightweight, and very hard, though brittle.

b) Alnico (Al-Ni-Co)

Alnico magnets, an alloy primarily composed of Aluminum, Nickel, and Cobalt (typically 8% Al, 14% Ni, 24% Co, 3% Cu, and 51% Fe), are distinguished by their exceptional stability in very high-temperature environments, capable of operating up to 500°C . They also possess high mechanical strength.

However, the most significant recent advancement in magnet technology involves rare-earth magnets, such as those made from neodymium or samarium-cobalt. These are now the most powerful PMs available. For instance, the Recoma series (samarium-cobalt) exhibits superior magnetic properties; specifically in Remanence (B_r) and Coercivity (H_c). For an equivalent volume, they can be three times more powerful than even the best Alnico magnets. Their primary drawback, however, is a relatively higher cost.

c) Rare earth elements

Rare earth-based alloys are known for being very stable and powerful, but they are also expensive, difficult to machine, and sensitive to corrosion. This category includes two fundamental types:

- **NdFeB:** magnets made from rare earth elements, are the most powerful PMs available. They provide an extremely high magnetic strength in a small size, making them ideal for space-constrained applications requiring high dynamic performance, such as in motors and Hard Disk Drives (HDD). Their main

drawbacks are brittleness, susceptibility to corrosion (often requiring a coating), and a relatively low maximum operating temperature.

- **SmCo:** are powerful rare-earth magnets, second in strength only to Neodymium. Their key advantage is exceptional high-temperature performance, operating reliably in environments up to 250-350°C. They are also highly corrosion-resistant and difficult to demagnetize. However, they are extremely hard and brittle, often requiring diamond tools for machining, and have a high cost due to their cobalt content.

Fig. 2.6 show the demagnetization curves for the main families of hard magnetic materials.

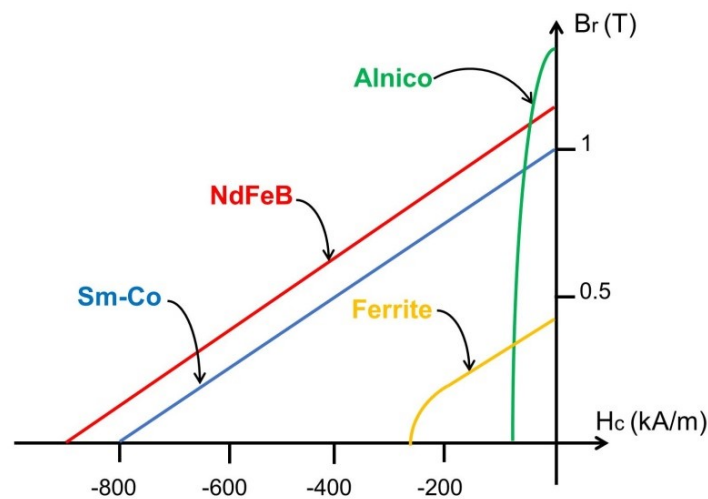


Fig. 2.6 Demagnetization curves for the main families of hard magnetic materials (PMs).

Demagnetization curves, illustrated in Fig. 2.6, plot a magnet's strength (remanence, B_r) against its resistance to demagnetization (coercivity, H_c). Among the main families, NdFeB magnets possess the highest B_r , delivering the strongest magnetic field, while Sm-Co magnets offer exceptional stability with a very high H_c , especially at elevated temperatures. Conversely, Ferrite magnets have low B_r but good H_c , making them stable and cost-effective. Finally, Alnico magnets feature high B_r but a very low H_c , resulting in good strength that is easily lost to opposing fields or heat.

2.9.3 Selection criteria for permanent magnets

Selecting the right magnet is a multi-parameter optimization problem. While crucial, magnetic strength is rarely the sole deciding factor, as the best magnet is rarely the strongest one. Furthermore, each type has its own drawbacks, making it essential to consider several selection criteria.

a) Magnetic performance:

- Required field strength (B): dictates the needed remanence (B_r).

- Stability against demagnetization: if the magnet operates under opposing fields (e.g., in a motor), high coercivity (H_c) is critical.
- Operating point: the magnet's working B and H on the demagnetization curve, determined by the external magnetic circuit.

d) Temperature considerations:

- Operating temperature: magnetic properties degrade with temperature.
- Maximum operating temperature: the highest temperature before irreversible loss of performance.
- Temperature coefficients: the rate at which B_r and H_{cj} change with temperature ($\%/^{\circ}\text{C}$). SmCo has a much lower (better) coefficient than NdFeB.

e) Corrosion and environmental resistance:

- NdFeB is highly susceptible to oxidation and must be coated (e.g., Ni, Zn, Epoxy).
- SmCo and Ferrites have excellent inherent corrosion resistance.

f) Mechanical properties:

- Ferrites and SmCo are brittle ceramics and can only be ground, not machined.
- Alnico is ductile and can be machined.

g) Cost and supply chain:

- Cost ranking (per kg): Ferrites < Alnico < NdFeB < SmCo.
- Cost per unit of performance (per kJ/m^3): Ferrites can be more economical than NdFeB for non-size-critical applications.
- Supply of Rare-Earth elements (Nd, Sm) can be volatile geopolitically.

2.9.4 Applications of permanent magnets

Applications are driven by the material properties, balancing performance, cost, and environmental factors. Table 2.5 shows the application areas of PMs and the typical materials used.

Table 2.5. Application areas of PMs.

Domain	Specific applications	Rationale	Typical material
Magnetic coupling and force	Magnetic separators, magnetic bearings, magnetic locks, refrigerator doors.	Utilize the static magnetic field to exert force, transmit torque, or hold objects.	Ferrites, neodymium magnet (NdFeB) for strong fields.
Electromechanical Conversion	Electric motors and generators (Electric Vehicles (EVs), drones, wind turbines), loudspeakers and headphones.	Convert electrical energy to mechanical motion (and vice versa). Requires high B_r and $(BH)_{\max}$ for power and efficiency.	NdFeB, Ferrites
Data storage and electronics	HDD and sensors (hall effect).	Require stable, strong, and localized magnetic fields for reading/writing data or imaging.	Thin-film NdFeB, SmCo for stability.
Medical and biological	Drug delivery systems, magnetic resonance therapy.	Use strong, uniform fields for imaging or to guide magnetic particles.	Niobium-titanium (NbTi) superconductors, PMs for ancillary systems

2.10 Modeling a magnet and its circuit

2.10.1 MMF and flux of a permanent magnet

A PM is characterized by its intrinsic MMF, calculable from its magnetic field strength H and length l_m as $R_m = H \cdot l_m$. In a magnetic circuit, the flux Φ it produces is determined by both the magnet's properties and the circuit's geometry: $\Phi = B \cdot S$, where B is the flux density and S is its cross-sectional area. Ultimately, the magnet's operating point is defined by the interaction of this MMF with the total circuit reluctance R_{total} , governed by $\Phi = \frac{F_m}{R_{total}}$. This relationship dictates how the magnet functions within an applied magnetics circuit.

2.10.2 Modeling of a magnet

Modern hard PMs (Ferrites, NdFeB, SmCo) exhibit a linear demagnetization characteristic in their second quadrant (see Fig. 2.7), which allows for a simple and powerful equivalent circuit model (see Fig. 2.8).

1. Linear material model (Fig. 2.7)

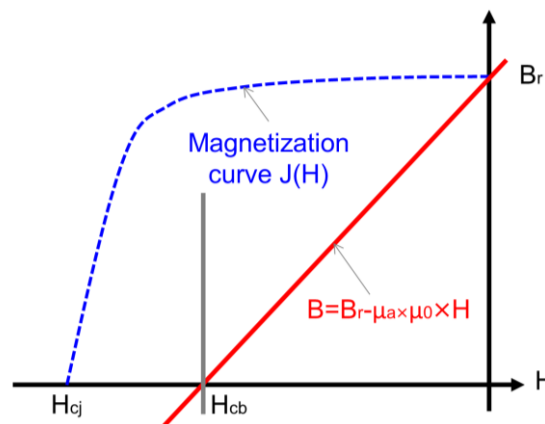


Fig. 2.7 Linear demagnetization characteristic in their second quadrant.

The core relationship is:

$$B = B_r - \mu_a \mu_0 H$$

Where:

- B_r is the remanent flux density. This is the magnetic flux density retained in the material when the external magnetizing field H is reduced to zero.
- H is the applied (demagnetizing) field strength. In the magnet's operating region, H is negative (second quadrant).
- μ_a is the recoil permeability. For modern hard magnets, it is low and very close to 1 ($\mu_r \approx 1.05$), meaning the $B - H$ line is steep.

Critical coercivity values:

- H_{cb} (coercivity at $B = 0$): this is the value of H where the flux density B becomes zero. It defines the magnet's strength against being "turned off."

- H_{cj} (intrinsic coercivity): this is the far more critical value where the magnetization J itself is driven to zero. If the operating point reaches H_{cj} , the magnet suffers irreversible demagnetization and loses a significant portion of its magnetism permanently. For stable operation, the magnet must never be exposed to fields stronger than H_{cj} .

2. Magnetic circuit model (Fig. 2.8)

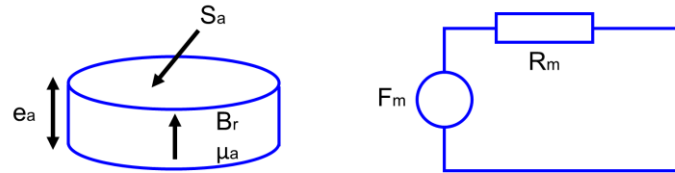


Fig. 2.8 Simple and powerful equivalent circuit model.

The linear $B - H$ relationship allows us to model the magnet as a simple linear component within a magnetic circuit.

For a magnet with constant cross-sectional area S_a and length (thickness) e_a :

$$\text{MMF} : F_m = \frac{B_r}{\mu_a \mu_0} \cdot e_a$$

$$\text{Internal reluctance: } R_m = \frac{e_a}{\mu_a \mu_0 S_a}$$

The MMF acts as a constant driving "magnetic voltage" source. It is proportional to the magnet's intrinsic strength (B_r) and its length.

The internal reluctance (R_m) represents the opposition to magnetic flux within the magnet itself. It depends on the magnet's geometry and its recoil permeability.

3. How to use the model (integration and operating point)

This creates a Thévenin equivalent circuit for the magnet. To find the magnet's operating point (the specific B and H at which it works):

- ✓ **Build the full circuit:** connect the magnet's equivalent circuit (F_m in series with R_m) to the external circuit reluctance (R_{ext}), which is dominated by the air gap reluctance $R_g = \frac{l_g}{(\mu_0 A_g)}$.
- ✓ **Calculate total reluctance:** $R_{total} = R_m + R_{ext}$
- ✓ **Solve for flux:** the magnetic flux Φ in the circuit is given by the magnetic version of Ohm's Law:

$$\Phi = \frac{F_m}{R_{total}} = \frac{\frac{B_r}{\mu_a \mu_0} \cdot e_a}{\frac{e_a}{\mu_a \mu_0 S_a} + R_{ext}}$$

- ✓ **Find operating point:** the flux density in the magnet is $B_{op} = \frac{\Phi}{S_a}$. You can then use the linear equation $B_{op} = B_r - \mu_a \mu_0 H_{op}$ to find the operating field H_{op} .

The linear model transforms a complex material into a simple two-component circuit element (F_m and R_m). This allows engineers to easily calculate how much flux a magnet will produce in a given air gap and, most importantly, to verify that the resulting operating field H_{op} is safely above the critical H_{cj} limit to prevent irreversible demagnetization.

2.10.3 Magnet in a magnetic circuit

The operating point of a PM in a magnetic circuit is determined by the intersection of its linear demagnetization curve $B_{op} = B_r - \mu_a \mu_0 H_{op}$ with the circuit's load line (see Fig. 2.9(b)). Under ideal assumptions (no flux leakage, infinite iron permeability), the load line relates B_{op} and H_{op} based on the air gap geometry:

$$B_{op} = -\mu_0 \frac{S_e}{S_a} \frac{e_a}{e} H_{op}$$

where S_a, e_a are the magnet's cross-section and length, and S_e, e are the air gap's cross-section and length (see Fig. 2.9(a)).

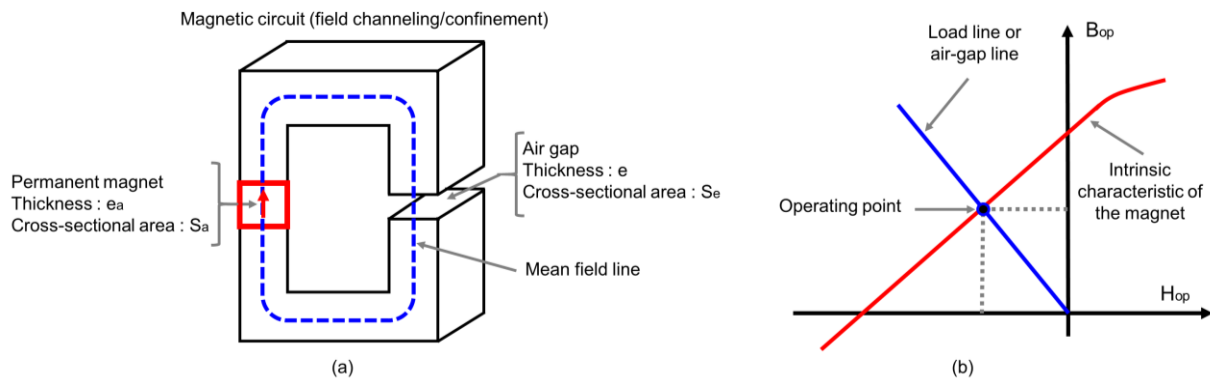


Fig. 2.9 : a) Magnetic circuit with PM and air gap, and b) determination of the operating point on the B-H plane.

To maximize energy transfer and useful flux, the magnet and air gap should be sized so that the load line slope (dictated by air gap reluctance $R_g = \frac{e}{\mu_0 S_e}$) intersects the demagnetization curve near its maximum energy product $(B \cdot H)_{max}$. This often corresponds to matching reluctances $R_g \approx R_m$, where $R_m = \frac{e_a}{\mu_a \mu_0 S_a}$ is the magnet's internal reluctance.

Key effects:

- **Variable air gap:** changes in e alter the load line slope, shifting the operating point and potentially inducing magnetic losses.
- **Extreme cases:**
 - ✓ Short-circuit ($e = 0$): $B_{op} = B_r$
 - ✓ Open circuit ($e \rightarrow \infty$): $B_{op} = 0$

- **External current:** a winding carrying current horizontally shifts the load line, modifying H_{op} and allowing field control.

This graphical method provides a clear way to predict magnet performance in practical magnetic circuits.

2.11 Benefits and economic importance of magnetic materials

Magnetic materials hold significant economic importance due to their foundational role in modern technology. Their global market evolution reflects a direct correlation with key industrial sectors. Soft magnetic materials (e.g., silicon steel, ferrites) are indispensable in electrical infrastructure, forming efficient cores for transformers, motors, and generators. Hard magnetic materials, particularly high-performance PMs (like NdFeB), are critical for compact motors in EVs, wind turbines, and consumer electronics. Thus, the drive for electrification and renewable energy places the performance and supply of these materials at the center of strategic economic and industrial planning.

PMs offer significant advantages in electromagnetic devices by providing a persistent magnetic field without the Ohmic (Joule) losses associated with field windings. This results in improved efficiency and higher power density, enabling more compact and reliable machines. PMs are essential in modern high-performance applications such as EVs and precision motors, where they enable superior acceleration dynamics in synchronous and stepper motors.

Key limitations and considerations:

- **Cost:** rare-earth magnets in particular present a significant material expense.
- **Thermal and operational limits:** PMs are subject to irreversible demagnetization if exposed to excessive temperature or high opposing magnetic fields (e.g., fault currents).
- **Control constraint:** they inherently prevent simple flux-weakening control, which is a challenge in some motor types (e.g., DC motors) and limits operational speed range in synchronous motors.

Thus, the use of PMs represents a design trade-off between efficiency, compactness, and dynamic performance against cost, thermal sensitivity, and control flexibility.

Chapter 3

Dielectric Materials

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3.1 Introduction

A dielectric material, fundamentally characterized by its inability to conduct electric current on a macroscopic scale and its high resistivity (10^8 to $10^{16} \Omega \cdot m$), is defined by its capacity to sustain an electrostatic field while dissipating minimal energy. In direct contrast to conductors, which possess abundant free charges and readily permit current flow, dielectrics have bound charges that only undergo limited displacement under an electric field. This essential behavior as

an electrical insulator stems from intrinsic polarization mechanisms (electronic, ionic, orientational, and space-charge) which are the microscopic origin of its key macroscopic property, permittivity (dielectric constant). Consequently, the primary roles of dielectric materials are electrical insulation and electrostatic energy storage. The interplay of these polarization mechanisms dictates critical performance parameters, including complex permittivity and dielectric loss, making their understanding paramount for engineering materials tailored to specific applications, from high-speed, low-loss circuits to high-energy-density capacitors.

3.2 Polar and non-polar dielectrics

Dielectric materials are fundamentally classified as either polar or non-polar based on their intrinsic molecular charge distribution. This basic molecular distinction (the presence or absence of a permanent electric dipole) underpins their vastly different polarizability and response to an electric field. Although a molecule is electrically neutral overall, the spatial arrangement of its charges is paramount. In non-polar dielectrics, the centers of gravity of positive and negative charges coincide, typically due to a symmetrical molecular structure, resulting in no permanent dipole moment. In contrast, polar dielectrics feature a permanent spatial separation of these charge centers, creating an inherent dipole moment that exists even without an external electric field. This crucial distinction originates from molecular asymmetry.

3.3 Polarization and electrostatic potential

The core phenomenon of polarization is the creation of a macroscopic dipole moment per unit volume when an electric field acts on a dielectric, stemming from the field's ability to displace charges or align molecular dipoles. Let us consider a polarized dielectric with polarization $\mathbf{P}$. The potential created by a single dipole with moment $\mathbf{p}$ at a point $\mathbf{M}$ located at a distance r is given by:

$$V_{\text{dipole}}(\mathbf{M}) = \frac{1}{4\pi\epsilon_0} \frac{\mathbf{p} \cdot \hat{\mathbf{r}}}{r^2}$$

Therefore, the potential created by the entire polarized dielectric at point $\mathbf{M}$ is given by the integral over the volume of all dipole moments $\mathbf{P}d\tau'$:

$$V(\mathbf{M}) = \frac{1}{4\pi\epsilon_0} \int_V \frac{\mathbf{P}(\mathbf{r}') \cdot \hat{\mathbf{r}}}{r^2} d\tau'$$

This expression can be rewritten in a more useful form as:

$$V(\mathbf{M}) = \frac{1}{4\pi\epsilon_0} \oint_S \frac{\sigma_b}{r} da' + \frac{1}{4\pi\epsilon_0} \oint_V \frac{\rho_b}{r} d\tau'$$

where:

- da' is the surface element around a source point $\mathbf{r}'$ located on the surface S of the dielectric. You can think of it as a tiny patch of the surface.
- $\sigma_b = \mathbf{P} \cdot \hat{\mathbf{n}}$ is the surface bound charge density.

- $\rho_b = -\nabla \cdot \mathbf{P}$ is the volume bound charge density.

Case of uniform polarization:

$\mathbf{P}$ is uniform, hence its divergence is zero:

$$\nabla \cdot \mathbf{P} = 0$$

This means the volume bound charge density is zero, $\rho_b = 0$.

The electric field produced in this case is equivalent to the field created by a fictitious surface charge density $\sigma_b = \mathbf{P} \cdot \hat{\mathbf{n}}$ distributed over the surface of the dielectric volume.

$$\mathbf{E} = \frac{1}{4\pi\epsilon_0} \oint_S \frac{\hat{\mathbf{r}}}{r^2} d\mathbf{a}'$$

Dielectric polarization arises from two distinct microscopic mechanisms depending on the material. In non-polar dielectrics, which possess no permanent dipole moment, an applied electric field $\mathbf{E}$ induces polarization by distorting the charge distribution within each molecule, creating a temporary induced dipole moment aligned with the field; this effect vanishes instantly when the field is removed. Conversely, in polar dielectrics, where molecules have a permanent dipole moment, the same external field exerts a torque that acts to orient these pre-existing dipoles, competing against randomizing thermal motion to produce a net alignment and a strong macroscopic polarization $\mathbf{P}$. In both cases, the collective response of these microscopic dipoles results in a net polarization in the direction of $\mathbf{E}$, yet the fundamental origin (charge displacement versus dipole orientation) and its transient nature differ fundamentally.

3.4 Electric displacement vector, $\mathbf{D}$

The electric displacement vector, $\mathbf{D}$, is a key macroscopic field descriptor that simplifies the analysis of electric fields in dielectric materials by accounting only for free charges, effectively filtering out the complex contributions of bound polarization charges. The electric displacement, or electric flux density $\mathbf{D}$, represents the displacement of a charge when it is subjected to a Coulomb force induced by an electric field $\mathbf{E}$.

In the presence of both free charges (Q) and induced polarization charges (Q_{ind}), Gauss's law is written as:

$$\oint_S \mathbf{E} \cdot d\mathbf{a} = \frac{Q_{\text{total}}}{\epsilon_0} = \frac{Q_{\text{free}} + Q_{\text{ind}}}{\epsilon_0}$$

With the induced charge related to the polarization $\mathbf{P}$ by:

$$Q_{\text{ind}} = -\oint_S \mathbf{P} \cdot d\mathbf{a}$$

Substituting this in, we get:

$$\oint_S \mathbf{E} \cdot d\mathbf{a} = \frac{1}{\epsilon_0} \left(Q_{\text{free}} - \oint_S \mathbf{P} \cdot d\mathbf{a} \right)$$

Rearranging terms:

$$\oint_S (\epsilon_0 \mathbf{E} + \mathbf{P}) \cdot d\mathbf{a} = Q_{\text{free}}$$

This allows us to define a new vector, $\mathbf{D}$, called the electric displacement [C/m^2]:

$$\mathbf{D} = \epsilon_0 \mathbf{E} + \mathbf{P}$$

Since for many linear dielectric materials, the polarization is proportional to the electric field, we have:

$$\mathbf{P} = \epsilon_0 \chi_e \mathbf{E}$$

where χ_e is the electric susceptibility of the material.

Substituting this into the definition of $\mathbf{D}$ gives:

$$\mathbf{D} = \epsilon_0 \mathbf{E} + \epsilon_0 \chi_e \mathbf{E} = \epsilon_0 (1 + \chi_e) \mathbf{E}$$

We now define the quantity $\epsilon_r = 1 + \chi_e$, which is called the relative permittivity or dielectric constant of the material. Therefore, we arrive at the important constitutive relation:

$$\mathbf{D} = \epsilon_0 \epsilon_r \mathbf{E} + \epsilon \mathbf{E}$$

Where $\epsilon = \epsilon_0 \epsilon_r$ is the absolute permittivity of the material.

The quantity χ_e is called the polarization coefficient or the dielectric susceptibility. Note that in a vacuum; there is no polarization, and thus $\chi_e = 0$ and $\epsilon_r = 1$.

3.5 Polarization vector, $\mathbf{P}$

The distribution of these induced electric dipoles is described by a macroscopic vector field called the polarization vector, denoted by $\mathbf{P}$. Macroscopically, the polarization vector $\mathbf{P}$ is the definitive quantitative measure of a dielectric's polarized state, defined as the net electric dipole moment per unit volume. If a volume ΔV contains N dipoles, each with an individual dipole moment $\mathbf{p}_i$, the polarization is given by:

$$\mathbf{P} = \frac{1}{\Delta V} \sum_{i=1}^N \mathbf{p}_i$$

This polarization field is the fundamental source of the macroscopic electric effects in dielectric materials. A key consequence is that a non-uniform polarization creates a bound charge density, ρ_b , within the material, while a discontinuous polarization creates a bound surface charge density, σ_b , on its surface.

The unit of polarization is the coulomb per square meter (C/m^2). This is consistent with its definition, as dipole moment has units of coulomb-meter ($\text{C}\cdot\text{m}$) and volume has units of m^3 , yielding C/m^2 . Crucially, this is also the unit of surface charge density, which aligns perfectly with

the physical interpretation of σ_b representing the bound charges accumulating on the surface of the polarized material.

3.6 Polarization phenomena

When a dielectric material is subjected to an external electric field, its internal charge carriers displace from their equilibrium positions. This macroscopic manifestation of charge displacement, termed induced polarization, was a foundational discovery made by Michael Faraday in 1837.

At the atomic scale, the electric field distorts the charge distribution, inducing a dipole moment in each atom. The proportionality constant linking the induced dipole to the local field is the polarizability (α), a fundamental atomic-scale attribute. However, as direct measurement of α is not feasible, the collective dielectric response is instead described by the macroscopic field polarization.

This vector field $\mathbf{P}$ quantifies the net dipole density, formally defined as the dipole moment per unit volume. If a material has a number density

N of atoms, each with an induced microscopic dipole moment $\mathbf{m}$, the polarization is given by $\mathbf{P} = N\mathbf{m}$, and is measured in coulombs per square meter (C/m^2).

This overarching phenomenon of polarization arises from several distinct physical mechanisms (each with its own characteristic speed and physical origin), which are classified as electronic, ionic, orientational (dipolar), and space charge (interfacial) polarization.

3.6.1 Electronic polarization

Electronic polarization is the fastest and most universal polarization mechanism, present in every atom and material. It arises from the displacement and deformation of the negatively charged electron cloud relative to the positive nucleus under the influence of an applied electric field. This process creates a temporary, induced dipole moment almost instantaneously, occurring on the order of 10^{-15} seconds, which allows it to remain active even at optical frequencies (around 10^{15} Hz), such as those of visible light. This rapid response is precisely why electronic polarization governs the optical properties of dielectric materials. Quantitatively, its contribution is expressed as:

$$\vec{P}_e = N\alpha_e\vec{E}_i$$

where N is the number of atoms per unit volume, α_e is the electronic polarizability, and $\vec{E}_i$ is the internal electric field.

3.6.2 Atomic or ionic polarization

Ionic polarization, also referred to as atomic polarization, arises from the displacement of atoms or ions within a material's structure. This mechanism is prominent in ionic or covalently

bonded materials, such as ceramic crystals (e.g., NaCl), where an applied electric field exerts opposing forces on the positively and negatively charged ions. This causes the molecular bonds to elastically stretch or bend, shifting the relative positions of the entire ions rather than just their electron clouds. Due to the significant mass and inertia of ions compared to electrons, this process is slower, with a characteristic response time on the order of 10^{-12} to 10^{-13} seconds. Consequently, its effective frequency range is limited to lower frequencies, typically up to about 10^{11} Hz. The macroscopic ionic polarization is quantified by the relation:

$$\vec{P}_a = N\alpha_a\vec{E}_1$$

where N is the number of dipoles per unit volume and α_a is the ionic polarizability.

3.6.3 Orientation/dipolar polarization

Orientational, or dipolar, polarization occurs in materials that possess permanent molecular dipole moments, such as water (H_2O). In the absence of an external electric field, these inherent dipoles are randomly oriented due to thermal agitation, resulting in a net polarization of zero. When an electric field is applied, it exerts a torque on each dipole, causing them to rotate and align with the field's direction. This collective alignment creates a macroscopic polarization in the direction of the field. However, this rotational motion is strongly hindered by molecular inertia and thermal collisions, making it a relatively slow process that is only effective at lower frequencies, typically up to around 10^8 Hz. The magnitude of this polarization is both field- and temperature-dependent, as described by the relation:

$$\vec{P}_o = N \frac{m^2}{3KT} \vec{E}_1$$

where N is the dipole density, m is the permanent dipole moment, K is Boltzmann's constant, and T is the absolute temperature.

3.6.4 Interfacial/space charge polarization

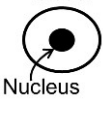
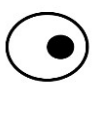
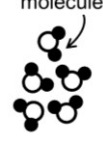
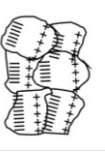
Space charge or interfacial polarization is the slowest polarization mechanism, dominating at low frequencies in heterogeneous materials such as composites, polycrystalline ceramics, or solids with defects. It occurs when mobile charges (ions or electrons) migrate over microscopic distances under an applied electric field and become trapped or blocked at physical interfaces like grain boundaries, impurities, or electrode surfaces. This accumulation of charge at these localized defects creates a macroscopic charge separation and large dipoles. For this linear response, the resulting polarization is described by:

$$\vec{P} = \epsilon_0\chi_e\vec{E}$$

where ϵ_0 is the permittivity of free space and χ_e is the electric susceptibility of the dielectric material.

Table 3.4 summarizes the different types of dielectric polarization.

Table 3.1. Types of dielectric polarization.

Type of polarization	Characteristic response Time	Typical frequency range	E=0	E≠0	Description
Electronic	$\sim 10^{-15}$ s	Up to optical frequencies ($\sim 10^{15}$ Hz)			Displacement of the center of mass of the electron cloud relative to the center of mass of the atom's nucleus.
Ionic (Atomic)	$10^{-12} - 10^{-13}$ s	Up to infrared frequencies ($\sim 10^{13}$ Hz)			The relative displacement of positively and negatively charged ions from their equilibrium positions, which creates electric dipoles (stretching the molecular bonds).
Orientation (Dipolar)	$\sim 10^{-6} - 10^{-11}$ s	Up to microwave frequencies ($\sim 10^8 - 10^{11}$ Hz)			The reorientation of permanent dipoles (e.g., in molecules) to align parallel with the applied electric field (a mechanism rarely found in crystalline materials).
Interfacial (Space Charge)	Seconds to hours	Very low frequencies ($< 10^3$ Hz)			Displacement of free charge carriers that accumulate at defects, vacancies, impurities, grain boundaries, surfaces, etc., creating interfacial polarization.

3.7 Characteristic quantities of dielectric media

Dielectric materials are characterized by several key quantities that determine their behavior in an electric field and their suitability for specific applications. These include:

3.7.1 Dielectric permittivity (ϵ) and relative permittivity (ϵ_r)

Permittivity describes a material's ability to polarize in response to an electric field, thereby reducing the electric field within the material compared to a vacuum. It is a fundamental property for capacitor design and wave propagation.

▪ Absolute permittivity:

The absolute permittivity (ϵ (F/m)) is the absolute measure of a material's permittivity. It quantifies how much the electric field is reduced due to polarization.

$$\epsilon = \frac{D}{E}$$

- ✓ D is the electric displacement field (C/m²);
- ✓ E is the electric field strength (V/m).

▪ **Relative permittivity:**

A dielectric is characterized by its relative permittivity or dielectric constant (ϵ_r). In the case of a perfect dielectric, ϵ_r is the quotient of the capacitance C_x between two electrodes, assumed to be embedded in this dielectric, divided by the capacitance C_v of the same electrode configuration in a vacuum. This is a dimensionless ratio indicates how much a material can increase the capacitance compared to a vacuum.

$$\epsilon_r = \frac{C_x}{C_v} = \frac{\epsilon}{\epsilon_0}$$

✓ ϵ_0 is the permittivity of free space ($\approx 8.854187817 \times 10^{-12}$ F/m).

The permittivity of free space, ϵ_0 , is defined by the relation:

$$\epsilon_0 = \frac{1}{\mu_0 C^2}$$

where μ_0 is the permeability of free space and C is the speed of light in a vacuum.

A higher ϵ_r means the material is a better "dielectric," allowing a capacitor to store more charge for the same voltage and geometry.

Note : The absolute permittivity ϵ is the product of the relative permittivity ϵ_r and the permittivity of vacuum ϵ_r :

$$\epsilon = \epsilon_r \times \epsilon_0$$

Table 3.2. Relative permittivity of some materials.

Material	Relative permittivity ϵ_r
Vacuum	1
Air	~ 1.0006
Paper	2.0 – 3.5
PTFE (Polytetrafluoroethylene)	2.1
Polyethylene	2.25
Polystyrene	2.4 – 2.7
PVC	3.0 – 3.5
Mica	5.4 – 6
Titanium Dioxide (TiO_2)	85 – 170
Barium Titanate (BaTiO_3)	1000 – 10000

Important note: The relative permittivity of a material is not an absolute constant. It can vary significantly with *frequency*, *temperature*, *purity*, and *manufacturing process*. The values listed in the table are typical for standard conditions.

3.7.2 Dielectric strength (G)

Dielectric strength (G) is a fundamental property defining the maximum electric field intensity a dielectric material can withstand intrinsically without undergoing electrical breakdown,

at which point it transitions from an insulating to a conductive state. It is quantitatively defined as the breakdown voltage (V) per unit thickness (L), expressed by the relation:

$$G = \frac{V}{L}$$

G is typically measured in kV/mm. This critical parameter, which sets the operational voltage limits for electrical insulation, is not an absolute constant but is highly dependent on extrinsic factors. These include the characteristics of the applied voltage (such as its frequency, waveform, and duration) as well as environmental conditions like temperature, pressure, and humidity. Furthermore, the presence of internal impurities, including air bubbles or moisture, significantly compromises the material's intrinsic strength. The dielectric strength can also be characterized as transverse or longitudinal, depending on the orientation of the electric field relative to the insulator's main surfaces. Exceeding this critical field leads to a rapid and often irreversible increase in conductivity, resulting in permanent damage to the insulating material.

Table 3.3. Dielectric strength of common dielectric materials.

Material	State	Typical dielectric strength, G (kV/cm)
Vacuum	Gas	∞ (Theoretical) / 200-400 (Practical)
Air		30
Sulfur hexafluoride (SF ₆)		80 – 90
Nitrogen (N ₂)		30 – 50
Transformer oil	Liquid	100 – 300
Silicone oil		100 – 150
Water (Deionized)		650 – 700
Teflon (PTFE)		200 – 600
Polyethylene (PE)	Solid	200 – 280
Polypropylene (PP)		200 – 300
PVC		100 – 350
Mica		1,000 – 2,000
Epoxy resin		150 – 250
Diamond		10,000 – 20,000

Important note : It is crucial to note that the dielectric strength values provided are typical ranges and can vary significantly, as they are highly dependent on specific material and test conditions. Key influencing factors include *material purity*, where impurities, moisture, or microscopic bubbles act as weak points that drastically reduce the breakdown threshold; the *thickness* of the sample, with thinner layers often exhibiting a higher apparent strength due to the "thickness effect"; and the *electrode geometry*, as sharp edges concentrate the electric field, thereby lowering the measured breakdown voltage. Furthermore, *temperature* and *pressure* are especially critical for gases and liquids, and the *voltage waveform* and *duration* (e.g., Alternating Current (AC), Alternating Current (DC), or impulse) also yield different results, as breakdown is a time-dependent phenomenon.

3.7.3 Electrical conductivity and insulation resistance

While ideal dielectrics are perfect insulators, real materials exhibit a small, but finite, electrical conductivity. This represents the leakage of current through two primary paths: volume conduction through the bulk and surface conduction along the material's interface.

- **Volume conductivity:**

Volume conductivity (σ_V (S/m)): This quantifies the ease with which electric charge can flow through the bulk of the material. It is the inverse of volume resistivity (ρ_V). It given by Ohm's Law in material form :

$$\sigma_V = \frac{J}{E}$$

where : J is the current density (A/m²) and E is the electric field (V/m).

- **Surface conductivity:**

Surface conductivity (σ_S (S)): This quantifies the ease with which electric charge can flow along the surface of the material. It is highly dependent on surface contamination (e.g., moisture, dust, salts).

In HV applications, surface conductivity (and its inverse, surface resistivity) is critical for preventing leakage currents and tracking (degradation) along the insulator's surface.

3.8 Loss angle and dissipation factor, $\tan(\delta)$

The concepts of loss angle (δ) and dissipation factor ($\tan(\delta)$) are critical for AC applications, where they directly quantify the power loss and efficiency of a dielectric material under alternating fields. In an ideal insulator, the current I leads the voltage V by 90°. In a real insulator, losses cause a phase shift less than 90°. The difference (δ) is the loss angle.

This is commonly modeled in two ways: parallel model (a perfect capacitor in parallel with a resistor, representing dielectric losses) and series model (a capacitor in series with a resistor, representing inherent losses). In both models, the dissipation factor ($\tan(\delta)$) is a key parameter. A lower $\tan(\delta)$ indicates a better, less lossy insulator. For example:

- Class 1 Ceramic (C0G): $\tan(\delta) \approx 0.001$ (Excellent)
- Aluminum Electrolytic: $\tan(\delta) \approx 0.2$ (Higher loss).

a) The series model

This model represents a real capacitor as an ideal capacitor C_s in series with a resistance R_s , known as the Equivalent Series Resistance (ESR). This R_s encompasses all losses, including those from the dielectric, leads, and plates, and the associated power loss is modeled as $I^2 \times R_s$. This

model is particularly suited for analyzing electrolytic capacitors and high-frequency behavior, where the ESR is a dominant and limiting factor.

Vector diagram of current and voltages.

The voltage across capacitor $V_C = I \times X_C = \frac{I}{\omega \times C_s}$

The voltage across resistor $V_R = I \times R_s$

The vector sum $V_{\text{total}} = V_C + V_R$

V_C lags current I by 90° and V_R is in phase with current I . The angle between V_{total} and V_C is δ (the loss angle).

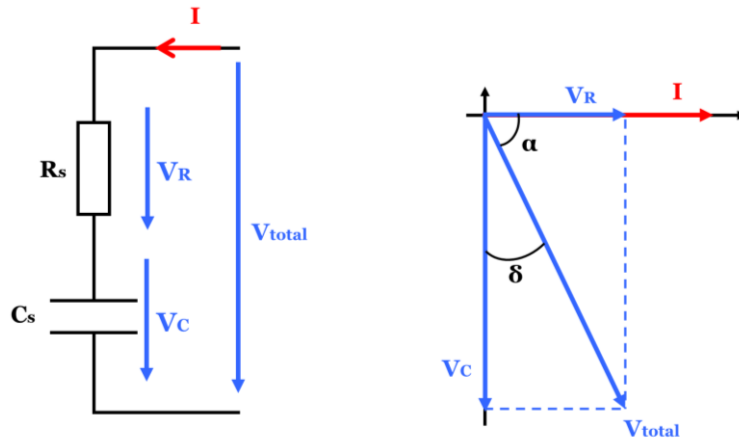


Fig. 3.1. Equivalent series circuit and the phasor diagram of the current and the voltages.

▪ Dielectric dissipation factor ($\tan(\delta)$)

From the phasor diagram shown in Fig. 3.1:

$$\tan(\delta) = \frac{V_R}{V_C} = \frac{I \times R_s}{\frac{I}{\omega \times C_s}} = \omega \times R_s \times C_s$$

▪ Dissipated power (ΔP)

$$\Delta P = I^2 \times R_s$$

b) The parallel model

This model represents a real capacitor as an ideal capacitor C_p in parallel with a high resistance R_p , which models the insulation resistance accounting for dielectric leakage currents. In this configuration, the small leakage current flowing through R_p is in phase with the voltage, causing the dielectric losses. This model is best suited for modeling low-loss capacitors, such as film or ceramic types, at low frequencies or DC where leakage current is the dominant loss mechanism.

Vector diagram of voltage and currents.

The current through capacitor $I_C = \frac{V}{X_C} = V \times \omega \times C_p$

The current through resistor $I_R = \frac{V}{R_p}$

The vector sum $I_{\text{total}} = I_C + I_R$

I_C is 90° ahead of voltage V (pure capacitive current) and I_R is in phase with voltage V (pure resistive current). The angle between I_{total} and I_C is δ .

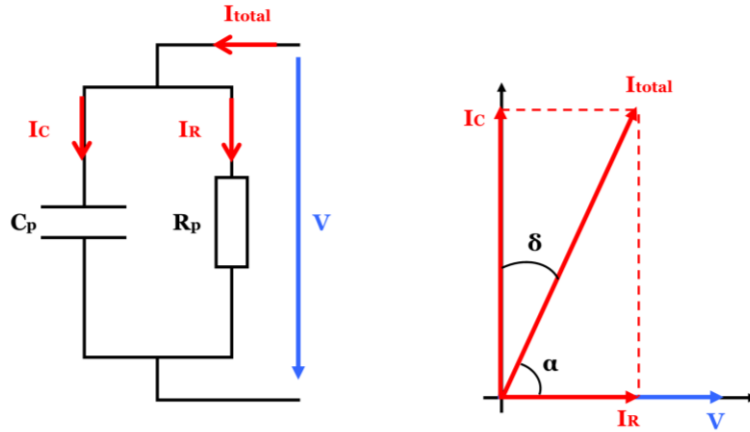


Fig. 3.2. Equivalent parallel circuit and the phasor diagram of the voltage and the currents.

▪ Dielectric dissipation factor ($\tan(\delta)$)

From the phasor diagram shown in Fig. 3.2:

$$\tan(\delta) = \frac{I_R}{I_C} = \frac{\frac{V}{R_p}}{V \times \omega \times C_p} = \frac{1}{\omega \times R_p \times C_p}$$

▪ Dissipated power (ΔP)

$$\Delta P = \frac{V^2}{R_p}$$

3.9 Polarization index (PI)

The Polarization Index (PI) is a critical diagnostic measurement used to assess the condition (or the degradation of its condition) of electrical insulation, particularly in motors, generators, transformers, and other HV equipment. It is defined as the ratio of insulation resistance measured at two different time intervals, typically after 10 minutes ($R_{t=10}$) and 1 minute ($R_{t=1}$) of applied DC voltage:

$$PI = \frac{R_{t=1}}{R_{t=10}}$$

The PI test (a practical measurement technique) evaluates the quality and dryness of the insulation. Over time, insulation can absorb moisture, become contaminated, or degrade, leading

to a reduction in its resistance. The PI test helps identify such issues by measuring how the insulation resistance changes over time under a steady DC voltage. The insulation is considered as:

- $PI < 1.5$: Poor insulation condition, likely contaminated or moist, requiring immediate investigation or repair.
- $1.5 \leq PI \leq 2.0$: Borderline condition; insulation may require monitoring or maintenance.
- $PI > 2.0$: Indicates healthy, dry, and clean insulation.

3.10 Difference between polarization and conduction

During polarization, charges are set in motion but can never leave the molecule. In contrast, conduction is the displacement of charges over large distances; they break free and leave the particles.

A comparative analysis of polarization and conduction serves as a crucial summary to solidify understanding of the two distinct charge-related processes that occur in dielectric materials. The following comparative table summarizing the key differences between polarization and conduction in dielectrics.

Table 3.4. Key differences between polarization and conduction in dielectric materials.

Feature	Polarization	Conduction
Fundamental nature	Reversible, "elastic" displacement of bound charges.	Irreversible, steady migration of free charges.
Charge movement	Limited, oscillatory movement over minute distances. Charges do not leave their parent molecules/lattice.	Continuous drift over large distances. Charges break free from their sites.
Governing mechanism	Intrinsic response of the material's atomic/molecular structure to an electric field.	Extrinsic process driven by impurities, defects, and free ions.
Dependence on field	Occurs during the application or removal of the field. The effect is transient during field change.	Occurs as long as a voltage is applied. It is a steady-state process.
Recovery	Charges return to their original positions upon removal of the external field.	No return to original state; the process is irreversible and leads to leakage current.
Primary cause	Interaction of the electric field with the dielectric's inherent structure (electronic clouds, ionic bonds, polar molecules).	Presence of mobile charge carriers within the material (e.g., impurity ions, electrons in the conduction band).

3.11 Non-linear dielectrics

Non-linear dielectrics are materials whose dielectric properties, particularly permittivity and polarization, depend on the strength of the applied electric field. In these materials, the

relationships between polarization ($\mathbf{P}$) and electric displacement ($\mathbf{D}$) with the electric field ($\mathbf{E}$) are non-linear. The polarization response becomes a complex function of the field, unlike in linear dielectrics where it follows a direct proportionality ($\mathbf{P} = \epsilon_0 \chi \mathbf{E}$ and $\mathbf{D} = \epsilon_0 \epsilon_r \mathbf{E}$). There are several types of non-linear dielectrics:

3.11.1 Ferroelectric dielectrics

Ferroelectric materials are the most typical non-linear dielectrics, acting as the electrical analogs to ferromagnetic materials. Their key characteristic is a reversible, spontaneous polarization that persists without an external electric field, a result of their asymmetric crystal structure. This leads to a distinctive $\mathbf{D} - \mathbf{E}$ hysteresis curve, analogous to the $\mathbf{B} - \mathbf{H}$ loop in magnetism, featuring remanent polarization ($\mathbf{R}_r$) and a coercive field ($\mathbf{E}_c$). Furthermore, they are defined by exceptionally high permittivity values and properties that vary with temperature, losing their ferroelectricity above a specific Curie temperature (T_c). Common examples include Barium Titanate (BaTiO_3) and PZT (Lead Zirconate Titanate), which are crucial for applications like Ferroelectric Random Access Memory (FeRAM) and high-performance capacitors.

3.11.2 Piezoelectric dielectrics

Piezoelectricity, discovered in 1880 by Pierre and Paul-Jacques Curie, describes the bidirectional energy conversion in non-centrosymmetric materials. These materials generate an electric charge under mechanical stress (the direct effect) and deform when an electric field is applied (the converse effect). This reversible coupling between mechanical and electrical energy, governed by the piezoelectric coefficient (d), makes materials like PZT ceramics and quartz invaluable for applications ranging from sensors and actuators to energy harvesters. Notably, nearly all ferroelectric dielectrics exhibit piezoelectric properties.

3.11.3 Electrets

An electret is a dielectric material that maintains a quasi-permanent electric charge or polarization after the external polarizing field is removed, analogous to how a permanent magnet creates a magnetic field. This stable, internal electric field is established by either trapping real charges (real-charge electrets) or aligning and freezing molecular dipoles (dipolar electrets) during a heating and poling process. Due to this persistent polarization, electrets are fundamental components in devices like microphones and air filters, where they provide a built-in electrostatic field.

3.12 Common dielectric media

Electrical insulating materials are vital for directing current, preventing short circuits, and ensuring the safety and efficiency of electrical systems. They are classified into three primary types: solid, liquid, and gaseous.

3.12.1 Solid insulators

Solid dielectrics provide structural insulation, spacing, and mechanical protection in electrical systems.

a) Ceramics and Glass:

- **Ceramic (e.g., Porcelain, Alumina):** excellent mechanical strength and thermal resistance. Widely used for overhead line insulators, transformer bushings, and station post insulators. Also used in HF/UHF components, capacitors, and piezoelectric devices.
- **Glass:** used for line insulators and glass fiber reinforcements. Resistant to heat and chemical agents.

b) Plastics and Polymers:

- **Thermosets:**
 - ✓ **Epoxy resin:** extremely common for encapsulating or potting transformers, coils, and semiconductor devices. Provides excellent adhesion and moisture resistance.
 - ✓ **Bakelite (phenolic):** formerly widely used for low-voltage electrical equipment like switchgear housings and connector blocks.
- **Thermoplastics:**
 - ✓ **Polyethylene (PE) and Cross-linked Polyethylene (XLPE):** the standard insulation and jacketing material for low, medium, and HV power and communication cables. XLPE offers superior thermal and mechanical performance.
 - ✓ **Polyvinyl chloride (PVC):** very common for cable sheathing and insulation, electrical tapes, and conduit due to its flexibility and cost-effectiveness.
 - ✓ **Polypropylene (PP):** used extensively in film capacitors and as a dielectric in high-frequency applications.
 - ✓ **Polytetrafluoroethylene (PTFE/Teflon):** excellent high-temperature and chemical resistance. Used in high-frequency cables, circuit breaker parts, and demanding aerospace applications.

c) Natural and composite materials:

- **Mica and Mica Composites:** highly heat-resistant. Used as sheet insulation in power transformers, slot liners in electric motors, and for heating elements. Often bonded with glass or polyester for strength.

- **Paper and Pressboard:** cellulose-based materials. When impregnated with insulating oil, they form the primary insulation system in power transformers and capacitors. "Dry-type" transformers use varnish-impregnated paper.
- **Rubber (natural and synthetic – EPDM (Ethylene Propylene Diene Monomer), Silicone):** provides excellent flexibility. Used for cable insulation, splicing kits, and protective gloves. Silicone rubber is prized for its high-temperature stability.
- **Textiles (Cotton, Silk) and laminates:** now largely superseded by synthetic materials, but still used in specific applications like tape for wrapping coils.

3.12.2 Liquid insulators

Liquid dielectrics serve a dual purpose: they act as electrical insulators and are highly effective for cooling through convection. A key advantage is their "self-healing" property, where a breakdown path is cleared after a fault.

a) Hydrocarbon oils:

- **Mineral oil:** the most common liquid dielectric in power transformers, circuit breakers, and capacitors. It is cost-effective but has a fire risk and can oxidize over time.
- **Synthetic esters and vegetable oils:** a modern, biodegradable, and fire-resistant alternative to mineral oil, increasingly used in "green" transformers.

b) Fire-resistant fluids:

- **Silicone oil:** a stable, fire-resistant fluid used in transformers where fire safety is a priority. It is more expensive than mineral oil.
- **Chlorinated hydrocarbons (Askarels, e.g., Pyralene/PCB (Polychlorinated Biphenyl)):** formerly used for their non-flammability, but banned globally due to their extreme toxicity and environmental persistence.

c) Specialty liquids:

- **Fluorinated fluids:** used in high-performance cooling systems for electronics and some HV applications.
- **Liquid nitrogen and liquid helium:** used as a coolant and insulator in cryogenic and superconducting systems.
- **Pure water:** an excellent insulator when perfectly pure, but its conductivity increases dramatically with even trace impurities. Used in specialized high-power pulse applications (e.g., particle accelerators).

3.12.3 Gaseous insulators

Gaseous dielectrics are used to insulate between live conductors and grounded enclosures, often under pressure to increase their dielectric strength.

- a) **Air:** the most abundant and widely used insulator. Its dielectric strength increases with pressure. Used in overhead power lines, Air-Insulated Switchgear (AIS), and air capacitors.
- b) **Electronegative gases:**
 - **SF₆:** an electronegative gas with excellent dielectric strength (2-3x that of air at the same pressure) and outstanding arc-quenching properties. It is the standard for Gas-Insulated Switchgear (GIS) and HV circuit breakers. Its major drawback is that it is a potent greenhouse gas, driving a search for alternatives.
- c) **Alternative and inert gases:**
 - **Nitrogen (N₂):** chemically inert, environmentally benign, and low-cost. While its dielectric strength is lower than SF₆, it is used in nitrogen-filled transformers, HV cables, and as a buffer or replacement gas in some SF₆ mixtures.
 - **Carbon dioxide (CO₂):** being researched and deployed as a more eco-friendly alternative to SF₆ for arc interruption in circuit breakers, sometimes in mixture with other gases.
 - **Dry air / Novec™ gases:** fluorinated Nitrile compounds (like 3M™ Novec™ 4710) are being developed as zero-global-warming-potential replacements for SF₆ in HV equipment.
- d) **Hydrogen (H₂):** rarely used for insulation due to its low density and explosive risk. Its primary use is as a coolant for the rotors of large hydrogen-cooled turbine generators due to its exceptionally high thermal conductivity.

3.13 Properties of a dielectric material

The overall performance and suitability of a dielectric are evaluated against a set of desired properties, typically including high dielectric strength, a low loss tangent ($\tan(\delta)$), high and stable permittivity, and excellent thermal and environmental stability. The key properties of a dielectric material (permittivity, dielectric strength, and loss tangent) do not act in isolation. They form an interdependent set of characteristics that define the material's function, limitations, and ultimate application in an electrical system.

In essence, the selection of a dielectric is a balancing act: Permittivity answers 'How much energy can it store for its size?' Dielectric Strength answers 'At what voltage will it fail?' Loss Tangent answers 'How much energy will it waste as heat, and how will it behave under sustained AC stress?' The optimal choice depends on the application's primary demand: maximum energy density, maximum voltage withstand, or minimum signal and power loss.

3.14 Factors influencing dielectric properties

The measured permittivity and dielectric dissipation factor of a material are not intrinsic constants but are influenced by a variety of factors. These can be categorized as intrinsic (related to the material's inherent structure) and extrinsic (related to the external environment and measurement conditions).

3.14.1 Chemical and physical Structure (intrinsic factors)

The dielectric behavior of a material is principally governed by its fundamental composition and structure, operating across both chemical and physical domains. Chemically, even specimens with identical bulk composition can exhibit divergent dielectric properties if their molecular architectures differ, as exemplified by thermosetting resins cured under varying conditions or polymers with distinct degrees of polymerization. Physically, the inherent anisotropy or lack of homogeneity within a material, such as in crystalline solids or laminates, imparts a directional dependence on its dielectric response. Consequently, the orientation of the applied electric field's polarization vector relative to structural characteristics, like grain direction, exerts a strong influence on the measurement. Therefore, to obtain reproducible and meaningful data, measurements must be performed with consistent reference to an identifiable material axis, as variations can otherwise arise from either chemical microstructure or physical anisotropy.

3.14.2 Microstructure

The dielectric properties of a material, while rooted in its chemical identity and physical structure, are further refined by its micro-scale architecture. This microstructural influence manifests differently across material classes. In ceramics, dielectric behavior is strongly governed by grain size and the effects of grain boundaries, which can dominate the overall polarizability. In contrast, polymers are characterized by distinct dielectric relaxation peaks, which are directly associated with the molecular motion of chain segments and side groups, such as those observed at the glass transition. Therefore, the relative permittivity is not an intrinsic property of the bulk composition alone but is also a sensitive function of this microstructural state.

3.14.3 Frequency

The dielectric properties of a material are inherently dispersive, exhibiting a strong dependence on the frequency of the applied electric field. This frequency response is governed by the finite time required for polarization mechanisms to occur. At very low frequencies, polarization can perfectly follow the alternating field, resulting in a maximized dielectric constant and minimal energy loss. Conversely, at very high frequencies, the field alternates too rapidly for polarization to establish, leading to no contribution and, again, minimal losses. The critical transition occurs in an intermediate frequency regime where polarization mechanisms begin to lag behind the electric field, causing significant energy dissipation. This dielectric loss is maximized at a specific frequency, f_m , which is intrinsically related to the material's characteristic relaxation time, τ , by the fundamental relation $\omega_m \tau = 1$, or equivalently, $2\pi f_m \tau = 1$.

3.14.4 Temperature

Temperature exerts a profound influence on the dielectric properties and operational lifespan of insulating materials. A temperature rise generally degrades insulating performance by

decreasing insulation resistance and dielectric strength, accelerating oxidation, and potentially causing softening or melting. These macroscopic effects stem from fundamental changes in molecular mobility and polarization dynamics. Specifically, increased thermal energy reduces the relaxation time of polarizations, most notably orientational (dipole) and interfacial (space charge) mechanisms. For dipoles, this is due to a decrease in viscous forces, while for space charges, it results from increased charge carrier mobility. This reduction in relaxation time shifts the associated dielectric loss peak to higher frequencies. The net effect of these changes on a material's capacitive properties is quantitatively captured by the Temperature Coefficient of Capacitance (TCC), defined as $TCC = \frac{1}{C} \times \frac{dC}{dT} \approx \frac{\Delta C}{C \times \Delta T}$ (C is the capacitance at temperature T), which expresses the normalized change in capacitance per degree of temperature change.

3.14.5 Humidity and impurities

The dielectric properties of a material are highly susceptible to alteration by environmental factors, particularly the presence of water and other contaminants. Water absorption or the formation of a surface film, due to water's high inherent dielectric constant, significantly increases the overall degree of polarization. This manifests as a rise in the measured permittivity, dissipation factor, and direct current conductivity. Similarly, impurities such as plasticizers or solvents can enhance ionic mobility and interfacial polarization, further elevating dielectric losses. Consequently, to ensure reliable and interpretable results, rigorous specimen conditioning is paramount. This necessitates strict control of humidity levels both before and during testing and guarantees that the material is free from, or affected in a known and controlled way by, contaminants introduced during sampling or processing.

3.14.6 Electric field strength

For most linear dielectric materials, the permittivity and dielectric loss are independent of the applied electric field strength, provided the field does not induce partial discharges or electrical breakdown. A significant exception to this rule is observed in ferroelectric materials. These materials exhibit a non-linear polarization response, where their spontaneous polarization domains can be reoriented or reversed by a sufficiently strong electric field, leading to a characteristic hysteresis loop. Consequently, their dielectric constant becomes strongly dependent on the field magnitude. However, this field-dependence diminishes rapidly at high frequencies, as the polarization mechanisms can no longer follow the rapid alternations of the applied field.

3.14.7 Aging and degradation mechanisms

Over time, dielectric materials undergo progressive degradation due to coupled aging mechanisms: thermal aging from sustained high temperatures, which accelerates chemical breakdown; electrical aging from partial discharges, treeing, and high field stress, which erode the

insulation structure; and environmental aging from moisture, oxidation, and contaminants, which degrade surface and bulk properties. These irreversible processes progressively weaken the material, reducing dielectric strength and increasing loss, ultimately determining the service lifetime and reliability of HV insulation systems.

3.15 The role of dielectrics in Electrotechnics

The selection and application of dielectric materials represent a critical engineering compromise, tailoring fundamental properties to meet specific functional demands. In Electrotechnics, dielectrics are fundamental for ensuring the safe, efficient, and reliable handling of HVs and large currents. Their primary roles are insulation and energy storage, with a heavy emphasis on HV endurance, long-term stability, and mechanical robustness.

3.15.1 High-voltage insulation systems

This is the most critical and widespread application in power engineering. The primary goal is to prevent catastrophic failure (breakdown) and ensure operational safety.

- **Power cables:** for insulating the current-carrying conductor from other conductors and the ground.
- ✓ **XLPE:** the modern standard for medium and HV distribution cables due to its excellent thermal stability, high breakdown strength, and resistance to environmental stress.
- ✓ **Ethylene Propylene Rubber (EPR):** used for its flexibility and resilience, often in applications where frequent movement or bending is required.
- ✓ **Oil-impregnated paper:** a classic technology still used in very HV and extra HV cables. The oil enhances the breakdown strength of the paper.
- **Transformers:** for insulating the HV windings from the low-voltage windings and the transformer's grounded core/tank.
- ✓ **Transformer oil (mineral oil):** serves as both an insulating and cooling medium. It circulates through the paper-wrapped windings, carrying heat away while providing crucial dielectric strength.
- ✓ **Kraft paper and pressboard:** cellulose-based solids used to wrap conductors and create insulating barriers and spacers within the transformer tank. They are saturated with the transformer oil to form a composite insulation system.
- ✓ **Synthetic esters and silicone oils:** used as "green" alternatives to mineral oil, especially in applications with higher fire-safety requirements.
- **Switchgear and circuit breakers:** for isolating live contacts and extinguishing the electric arc that forms when a high-current circuit is interrupted.
- ✓ **SF₆ gas:** A superb dielectric gas used in HV circuit breakers and GIS. It effectively quenches arcs and allows equipment to be much more compact.

- ✓ **Porcelain and epoxy resins:** used as insulating housings and support structures for outdoor circuit breakers and insulators, providing mechanical strength and resistance to environmental weathering.
- **Overhead line insulators:** for supporting and isolating HV power lines from transmission towers.
- ✓ **Glass or porcelain discs:** traditional materials with high mechanical compressive strength and excellent resistance to the elements.
- ✓ **Polymer (composite) insulators:** increasingly common, using a fiberglass rod for strength with a silicone rubber housing. The silicone provides hydrophobicity (sheds water) and superior performance in polluted environments.

3.15.2 Energy storage in capacitors

This is the most fundamental application. The dielectric serves to increase capacitance and withstand high operating voltages. Key material properties include:

- ✓ **High permittivity:** to achieve a higher capacitance in a smaller volume (e.g., Barium Titanate in ceramic capacitors).
- ✓ **High breakdown strength:** to prevent failure at HVs.
- ✓ **Low loss tangent ($\tan \delta$):** to minimize energy loss as heat, especially in high-frequency applications (e.g., Polypropylene in film capacitors).

3.15.3 Structural and protective components

Dielectrics provide the physical backbone for power equipment.

- **Circuit breaker housings:** made from epoxy resins filled with silica or alumina, providing excellent insulation and mechanical structure for vacuum or SF₆ interrupters.
- **Motor and generator slot liners:** sheets of insulating material (e.g., Nomex, Mylar) are used to line the slots in stator and rotor cores, preventing the copper windings from shorting to the laminated steel core.
- **Busbar insulation:** in switchgear and substations, rigid insulated bars (busbars) carry very high currents. They are often coated or enclosed in dielectric sleeves for safety and to maintain phase separation.

Chapter 4

Semiconductor Materials

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4.1 Introduction

Semiconductors are materials that occupy a unique electrical position between conductors and insulators, characterized by an intermediate and, crucially, adjustable conductivity. This tunability is the foundation for their revolutionary role in electronics and power engineering, enabling devices that can amplify signals, switch currents, and convert energy, which are impossible with passive conductors or insulators. Semiconductor materials are defined by their intermediate electrical conductivity ($10^{-6} \text{ S/m} - 10^4 \text{ S/m}$), which is highly tunable and lies between that of conductors and insulators. Unlike metals or insulators, their key scientific advantage is that this conductivity can be precisely engineered through doping, temperature, and external energy inputs like light. This controllable electronic behavior enables the creation of fundamental active components such as diodes, transistors, and integrated circuits, which form

the basis of modern electronics, from microprocessors and power control systems to photovoltaic and optoelectronic devices.

The evolution of semiconductors began with 19th-century discoveries, like Faraday's observation of unusual conductivity, which laid the groundwork for understanding these unique materials. The field was revolutionized in 1947 with the invention of the transistor at Bell Labs, which replaced bulky vacuum tubes and enabled the era of solid-state electronics. This breakthrough was followed by the development of the integrated circuit in the late 1950s, which combined multiple components onto a single chip.

The industry's growth has since been driven by Moore's Law, the observation that transistor density doubles regularly, leading to constant miniaturization and power increases. This progression required groundbreaking innovations like 3D Fin Field-Effect Transistors and new materials to overcome physical limits. Today, advancement continues through advanced 3D packaging, new materials like graphene, and specialized chips powering modern technologies like artificial intelligence, cementing semiconductors as the foundation of all modern electronics.

4.2 Fundamental properties of semiconductors

4.2.1 Atomic structure and energy bands

Solids can be classified into conductors, semiconductors or insulators depending upon width of energy band gap (forbidden band). Completely filled bands contain large number of electrons but do not contribute to the conductivity of the material. Partially filled bands are necessary for electrical conduction. The energy band diagram of conductors, semiconductors or insulators is shown in Fig. 4.1.

The solids in which conduction and valence band overlap each other are called conductors (Fig. 4.1(a)). Therefore, the energy gap between valence band and conduction band is zero. Electrons can easily jump from lower energy band to higher one and become available for conduction. An application of a small amount of voltage leads to generation of large amount of current. Hence these solids are good electrical conductors. For e.g., Lithium, Beryllium and sodium.

The solids in which the conduction and valence bands are separated by a small energy gap of less than 2 Electron-Volt (eV) are called semiconductors (Fig. 4.1(b)). For e.g. Semiconductors like Silicon has Bandgap of 1.12 eV and Germanium has bandgap of 0.72 eV. A small energy gap means that a small amount of energy is required to free the electrons and move them from the valence band to the conduction band. The semiconductors behave like insulators at 0K, because valence electrons do not have required energy to jump to the conduction band. If the temperature is increased, valence electrons acquire sufficient energy to jump into the conduction band. Therefore, the conductivity of semiconductors increases with the increase in temperature.

The solids in which the conduction band and valence bands are separated by a large energy gap of ≥ 3 eV are called insulators (Fig. 4.1(c)). At room temperature, the valence electrons do not have enough energy to jump into the conduction band, therefore insulators do not conduct current. Thus, insulators have very high resistivity and extremely low conductivity at room temperatures. For e.g. Diamond and glass.

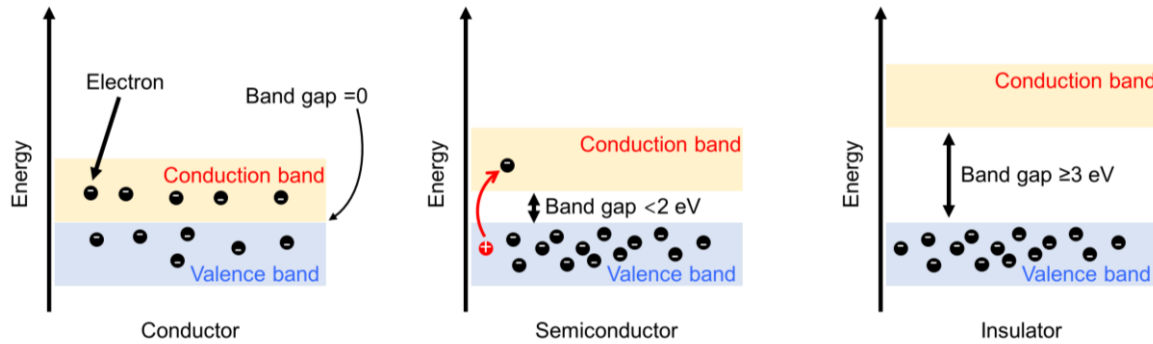


Fig. 4.1. Energy band diagram of materials.

4.2.2 Intrinsic semiconductors

An intrinsic semiconductor is a pure (chemically), crystalline solid with a perfectly regular atomic structure, whose electrical properties are inherent to the material itself, uncontaminated by impurities. In this ideal state, the concentration of free electrons in the conduction band (due to thermal excitation) is precisely equal to the concentration of holes in the valence band ($N = P$).

While truly perfect intrinsic semiconductors are theoretical, ultra-pure single-crystal silicon is a prime example that closely approximates this behavior. It forms a stable crystal lattice through covalent bonding. When thermal energy liberates an electron, it creates a mobile, negatively charged carrier and leaves behind a positively charged hole. This generation of charge carriers enables conductivity. The material remains electrically neutral overall because every free electron is matched by a hole.

When a voltage is applied across a pure semiconductor, the resulting electric field generates a current. This current consists of electrons drifting toward the positive terminal (conduction band) and holes drifting toward the negative terminal (valence band).

The conductivity of intrinsic semiconductors depends on the intrinsic carrier concentration, mobility of electrons and holes and also varies with temperature.

The energy band diagrams of silicon at $T = 0$ K and $T > 0$ K, shown in Figs. 4.2 and 4.3 respectively, illustrate the mechanism of current conduction.

At $T = 0$ K, all valence electrons in a silicon crystal are engaged in covalent bonds, and there are no free electrons available for conduction. Under these conditions, the valence band is completely filled, and the conduction band is completely empty (Fig. 4.2). Electrons in the

valence band cannot cross the forbidden energy gap; consequently, the material behaves as an insulator.

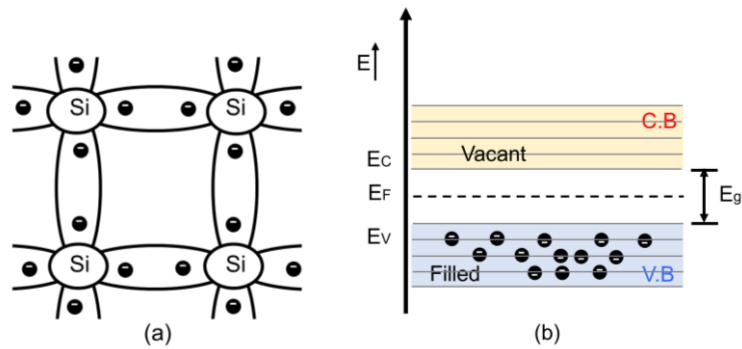


Fig. 4.2. (a) 2D representation of silicon crystal and (b) Energy band diagram of silicon at $T = 0K$

As the temperature increases ($T > 0 K$), electrons acquire sufficient thermal energy to break covalent bonds and transition from the valence band to the conduction band, requiring energy equal to the band gap, E_g . For every electron promoted to the conduction band, a hole is created in the valence band (Fig. 4.3). If n is the concentration of free electrons and p is the concentration of holes, then for an intrinsic semiconductor, $n = p = n_i$, where n_i is the intrinsic carrier concentration. Because the concentration of electrons and holes is equal, the Fermi level, E_F , is located at the middle of the forbidden gap.

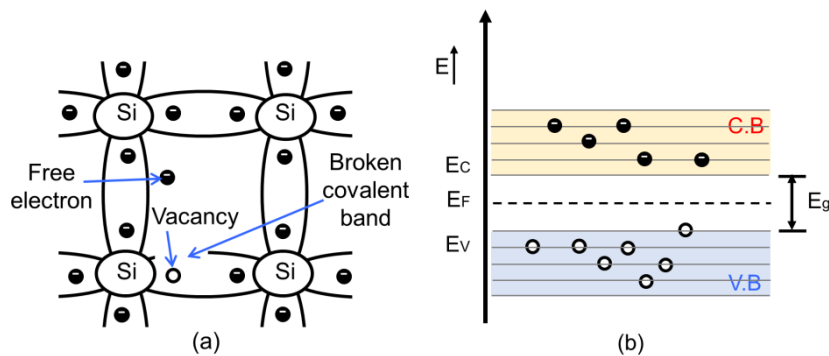


Fig. 4.3. (a) 2D representation of silicon crystal and (b) Energy band diagram of silicon at $T > 0K$

4.2.3 Extrinsic semiconductors

The electronic properties and the conductivity of an intrinsic (pure) semiconductor can be changed in a controlled manner by adding very small quantities of other elements called dopants. This can be achieved by adding impurities to the melt and then allowing it to solidify into the crystal. This process is called doping and these doped semiconductors are called extrinsic semiconductors.

Therefore, the conductivity of a doped semiconductor is determined by the type and concentration of impurity atoms, such as Group III elements (e.g., Boron, with three valence electrons, Fig. 4.4(a)) or Group V elements (e.g., Antimony, with five valence electrons, Fig. 4.4(b)).

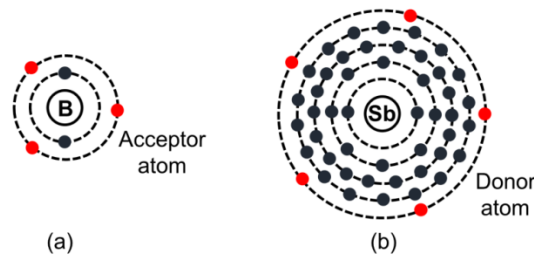


Fig. 4.4. Illustration of valence electrons in (a) trivalent and (b) pentavalent impurities.

Extrinsic semiconductors are further classified into two categories: N-type semiconductors (formed by adding a Group V element, or pentavalent impurity, to a pure semiconductor) and P-type semiconductors (formed by adding a Group III element, or trivalent impurity, to a pure semiconductor).

Impurity atoms with five valence electrons produce N-type semiconductors by contributing extra electrons. In contrast, impurity atoms with three valence electrons produce P-type semiconductors by creating a "hole," or an electron deficiency.

4.2.3.1 N-type semiconductors

An n-type semiconductor is formed by doping a pure semiconductor with a pentavalent impurity atom, such as Phosphorus or Arsenic. This donor atom bonds with four neighboring atoms using four of its five valence electrons, leaving the fifth electron unbound (Fig. 4.5). At room temperature, this excess electron is easily liberated, becoming a free charge carrier. Consequently, the addition of the donor impurity significantly increases the free electron population, making electrons the majority charge carriers and holes the minority carriers in the resulting N-type material.

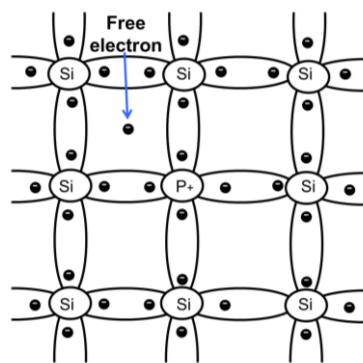


Fig. 4.5. N-type semiconductor.

Fig. 4.6 shows the energy band diagram of an N-type semiconductor. At 0K, the donor level is filled and located just below the conduction band, with the E_F situated between them; at this state, donor atoms are not ionized, the conduction band is empty, and the material behaves as an insulator (Fig. 4.6(a)). However, at higher temperatures ($T > 0K$), thermal energy causes the donor atoms to become ionized, releasing their electrons into the conduction band and leaving

behind empty, positively charged donor ions. The conduction band now contains a large number of these donated electrons, in addition to a smaller number from the valence band, which allows the material to conduct electricity (Fig. 4.6(b)). Consequently, the E_F shifts to a position below the now-empty donor level.

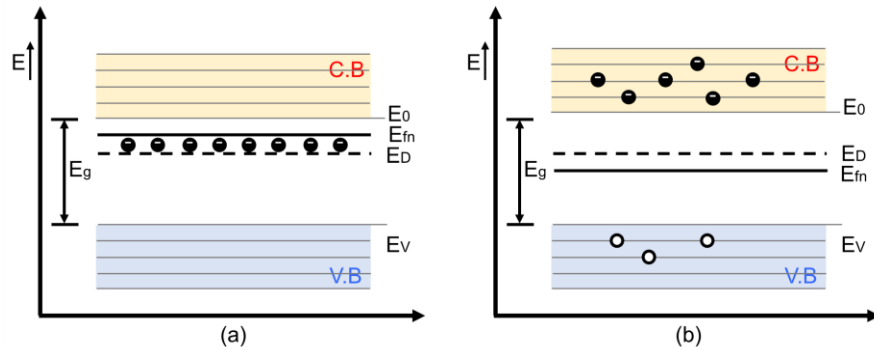


Fig. 4.6. Energy band diagram of an N-type semiconductor at (a) $T = 0K$ and (b) $T > 0K$.

4.2.3.2 P-type semiconductors

A p-type semiconductor is created by doping a pure semiconductor with a trivalent impurity atom, such as Boron or Gallium. This acceptor atom creates a hole in the crystal lattice because it is deficient by one electron to complete its bonds with four neighboring atoms (Fig. 4.7). This hole can readily accept an electron, causing the impurity atom to become a fixed negative ion upon ionization. The introduction of these acceptor impurities results in a material where holes significantly outnumber free electrons. Consequently, in a P-type semiconductor, holes are the majority charge carriers, and electrons are the minority carriers, resulting in conductivity that is predominantly due to the movement of holes.

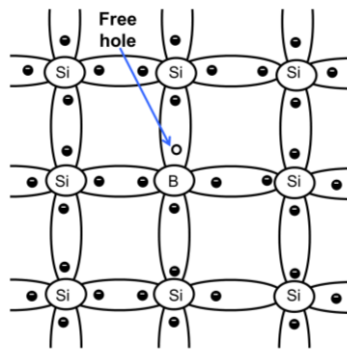


Fig. 4.7. P-type semiconductor.

Fig. 4.8 shows the energy band diagram of an N-type semiconductor. At 0 K, the acceptor levels, located just above the valence band, are empty, and the E_F lies between them and the top of the valence band. With the valence band full and the conduction band empty, the material behaves as an insulator (Fig. 4.8(a)). At higher temperatures ($T > 0K$), electrons from the valence band gain sufficient thermal energy to jump into the acceptor levels, leaving behind holes in the valence band; a smaller number also jump directly to the conduction band. This process fills the

acceptor levels, creating fixed negative ions and causing the Fermi level to shift above the acceptor level (Fig. 4.8(b)). The creation of holes in the valence band grants the material conductivity, establishing holes as the majority charge carriers and electrons as the minority carriers in the P-type semiconductor.

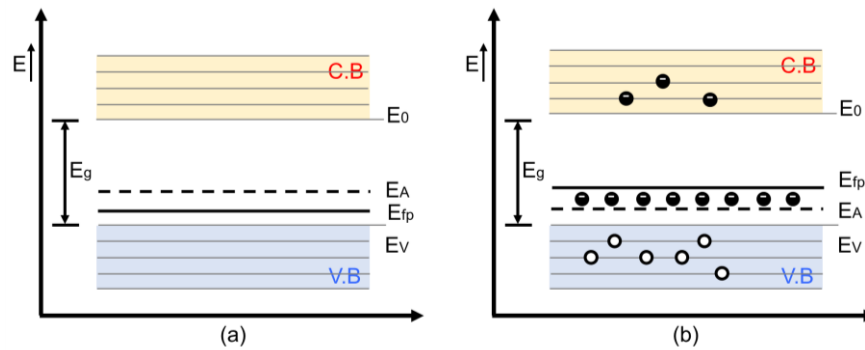


Fig. 4.8. Energy band diagram of an P-type semiconductor at (a) $T = 0K$ and (b) $T > 0K$.

Table 4.1 Comparison of N-type and P-type Semiconductors.

Property	N-type semiconductor	P-type semiconductor
Dopant / impurity	Pentavalent (e.g., Phosphorus, Arsenic)	Trivalent (e.g., Boron, Gallium, Indium)
Majority charge carriers	Electrons	Holes
Carrier concentration	Number of electrons (n_e) $\gg$ Number of holes (n_h)	Number of holes (n_h) $\gg$ Number of electrons (n_e)
Position of fermi level (E_F)	Close to the conduction band	Close to the valence band

4.2.4 Electrical conductivity in semiconductors

The characteristic electronic properties of semiconductors are primarily governed by thermal agitation, intentional impurities (doping), various lattice defects, and non-stoichiometry. This leads to the fundamental conductivity relation $\sigma = q(n\mu_n + p\mu_p)$, which exhibits strong temperature dependence.

Where :

- σ : Electrical conductivity ;
- q : Elementary charge ;
- n : Electron concentration ;
- μ_n : Electron mobility ;
- p : Hole concentration ;
- μ_p : Hole mobility.

The conduction phenomenon in semiconductors is complex, as their electrical conductivity (σ) depends on temperature, electromagnetic radiation, magnetic fields, irradiation, and defects. The variation of conductivity with temperature is a key characteristic; it increases with temperature, often following an exponential law that reveals an activation energy of up to an eV.

At room temperature, the thermal energy breaks covalent bonds, generating charge carriers. An electron excited from the valence band to the conduction band becomes free to move like an electron in a metal. When a voltage is applied, creating an electric field, the electron moves against the field, allowing current to flow. The vacancy left by the electron, called a hole, moves in the direction of the electric field as neighboring electrons fill it, creating the appearance of positive charge movement.

4.3 Classification of semiconductor materials

Semiconductor materials are foundational to modern electronics and optoelectronics. They are classified into several key groups based on their chemical composition and structure, with a fundamental distinction between elemental semiconductors (Silicon (Si) and Germanium (Ge)) and compound semiconductors (e.g., GaAs).

- a) **Elemental (type IV) semiconductors:** these are from group 14 of the periodic table, crystallizing in the diamond structure. Si and Ge are the primary examples, serving as the basis for conventional electronics.
- b) **Compound semiconductors:**
 - **III-V compounds:** alloys of group III and V elements (e.g., GaAs, InP). They typically have a zinc blende structure and are vital for high-speed and optoelectronic devices.
 - **II-VI compounds:** formed from group II and VI elements (e.g., CdSe, ZnO). They are often used in detectors and light-emitting applications.
 - **Oxide semiconductors:** metal oxides like ZnO and Cu₂O, which often feature wide band gaps suitable for transparent electronics and sensors.
- c) **Specialized crystal and non-crystalline semiconductors:**
 - **Covalent network solids:** such as Silicon Carbide (SiC), prized for high-power and high-temperature applications.
 - **Layered and chain structures:** includes lamellar (e.g., MoS₂) or chain-like (e.g., ZnP₂) semiconducting phases.
 - **Amorphous and glassy semiconductors:** non-crystalline materials like hydrogenated amorphous silicon (a-Si) for thin-film electronics, and chalcogenide glasses.
 - **Organic semiconductors:** polymers with conjugated bonds, enabling flexible and molecular electronics.

4.3.1 Wide-bandgap semiconductors

This class of materials, particularly silicon carbide (SiC), gallium nitride (GaN), and diamond (Dia), is non-negotiable for modern HV and power electronics. They are characterized by a

bandgap significantly larger (typically >3 eV) than that of silicon (1.12 eV). This property confers critical advantages: a superior breakdown electric field allows devices to withstand much higher voltages in thinner layers, enabling more compact designs; high thermal conductivity (especially for Dia and SiC) ensures efficient heat dissipation; and high operational efficiency reduces energy losses. Together, these properties enable the development of smaller, faster, more robust, and more efficient HV devices, solid-state transformers, and RF power amplifiers. Fig. 4.9 illustrates the thermal, voltage, and frequency characteristics of Si, SiC, and GaN materials.

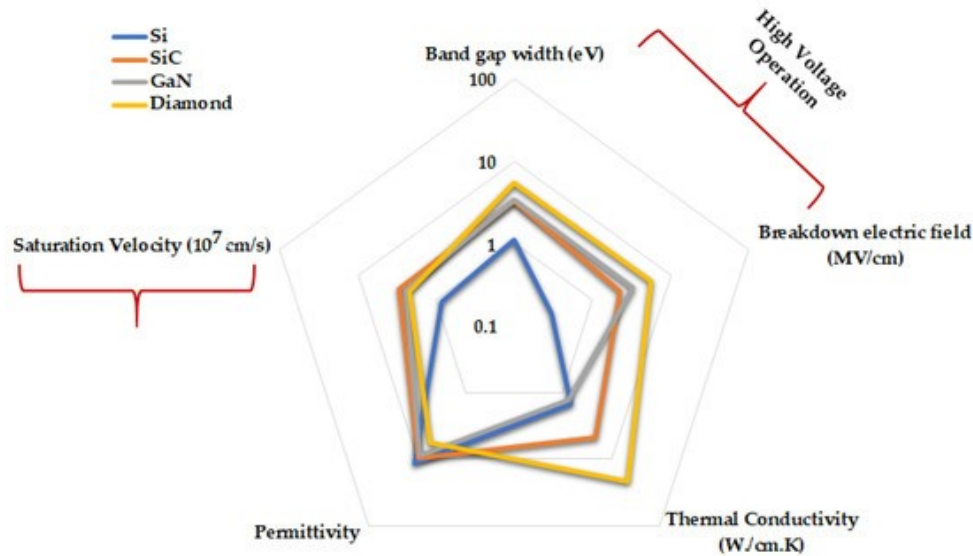


Fig. 4.9. Si, SiC, GaN, and Dia properties.

4.4 The PN junction formation

A PN junction, the fundamental building block of semiconductor devices such as diodes and transistors, is formed at the metallurgical boundary between a P-type and an N-type semiconductor. Analyzing the behavior of this junction under an external applied voltage, or bias, is essential for understanding the operation of all subsequent semiconductor components.

Due to the high concentration gradient, holes diffuse from the P-side to the N-side, while electrons diffuse from the N-side to the P-side. This movement of charge carriers creates a diffusion current.

As electrons leave the n-region, they leave behind immobile, positively charged donor ions. Similarly, as holes leave the p-region, they leave behind immobile, negatively charged acceptor ions. This creates a space-charge region on both sides of the junction, known as the transition region or depletion region, because it is depleted of free charge carriers. The electric field E_D (diffusion field) that develops across this depletion region causes charge carriers to drift in the direction opposite to the diffusion current.

Initially, the diffusion current is large, and the drift current is small. As the depletion region widens, E_D strengthens, increasing the drift current until it equals the diffusion current. At this point, a state of equilibrium is reached with no net current across the junction.

Fig. 4.10 represents the initial state of separate p-type and n-type materials (a), followed by the carrier diffusion process and the establishment of the depletion region at the junction (b).

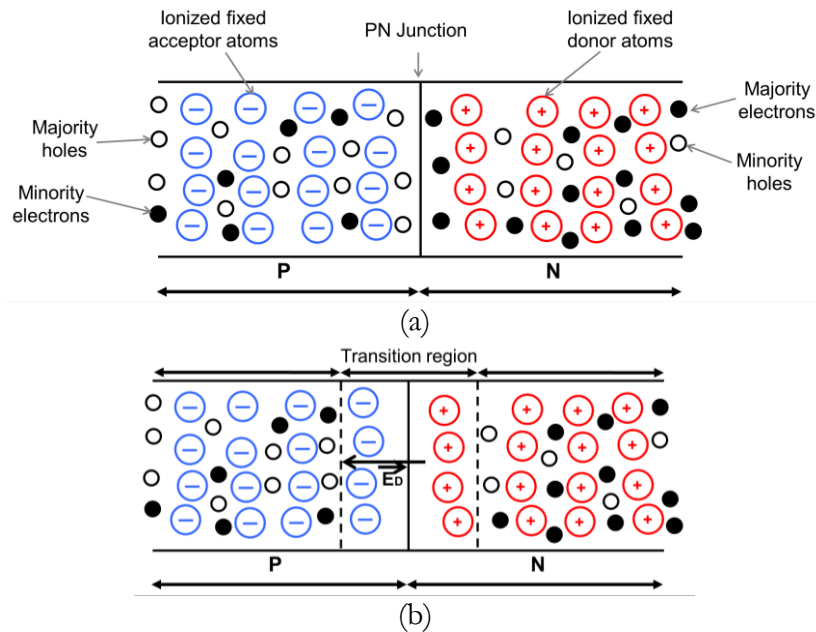


Fig.4.10. PN junction: (a) in the initial state (b) diffusion phenomenon.

4.4.1 The junction potential (depletion region)

The loss of electrons from the n-region and the gain of electrons by the P-region creates a difference of potential across the junction, known as the barrier potential or diffusion voltage (V_D), which exists between the boundaries of the transition region. The polarity of this potential is such that the N-material becomes positive relative to the P-material. This built-in potential opposes the further diffusion of majority carriers across the junction, thus maintaining the equilibrium condition.

Fig. 4.11 shows the PN junction at equilibrium (a) and the potential across the junction (b).

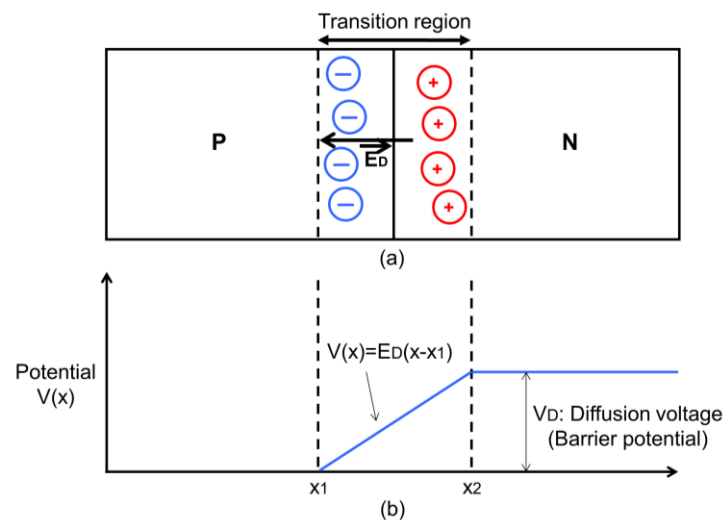


Fig.4.11. (a) PN junction at equilibrium and (b) the potential across the junction.

4.4.2 Biasing the PN junction: diode operation

A semiconductor diode is a two-terminal device, essentially a PN junction with metallic contacts for applying an external voltage (Fig. 4.12(a)). Its symbolic representation is shown in Fig. 4.12(b), where the arrow indicates the conventional direction of current flow when the diode is forward-biased. The internal equilibrium barrier potential, for an unbiased junction, can be modified by applying an external voltage (V). The following sections detail the diode's operation under forward and reverse bias conditions.

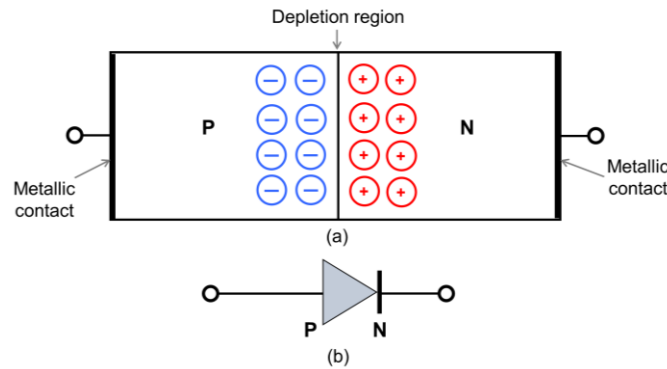


Fig.4.12. (a) Semiconductor diode and (b) symbol for PN junction diode.

4.4.2.1 Forward bias operation

When a positive voltage is applied to the P-region (anode) and a negative voltage to the N-region (cathode), the junction is said to be under forward bias.

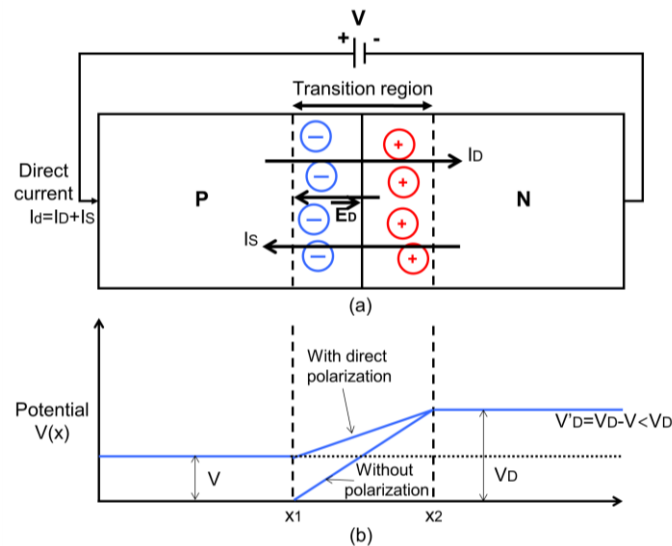


Fig.4.13. (a) PN junction diode under forward bias and (b) barrier potential.

The external voltage, V , creates an electric field that opposes the built-in field of the depletion region. This opposition reduces the junction's inherent potential barrier, also known as the diffusion potential, V_D . The effective barrier height becomes: $V'_D = V_D - V$.

Since V is positive under forward bias, the new barrier V'_D is lower than the original V_D .

The lowered potential barrier has a direct and significant effect on majority carriers. Majority carriers (holes in the P-side and electrons in the N-side) now require less energy to cross the depletion region. The necessary energy is reduced from eV_D to $e(V_D - V)$. This lower energy barrier allows a much larger number of majority carriers to diffuse across the junction. Consequently, the diffusion current, I_D , which flows from the P-side to the N-side, increases dramatically.

Under forward bias, the total current, known as the forward current (I_d), is the net result of the large I_D and the small, constant saturation current (I_S), which is due to minority carriers.

The relationship is given by: $I_d = I_D - I_S$.

Because I_D becomes much greater than I_S ($I_D \gg I_S$), the forward current can be approximated as: $I_d \approx I_D$.

The precise relationship between the voltage and the current in a PN junction is described by the Shockley diode equation:

$$I_d = I_S(T) \left[\exp\left(\frac{eV}{kT}\right) - 1 \right]$$

Where:

- ✓ I_d is the forward current.
- ✓ $I_S(T)$ is the temperature-dependent saturation current.
- ✓ e is the elementary charge (1.6×10^{-19} C).
- ✓ V is the applied forward voltage.
- ✓ k is Boltzmann's constant (1.38×10^{-23} J/K).
- ✓ T is the absolute temperature in Kelvin (K).

For a significant forward voltage (typically $V > 0.1$ V), the exponential term dominates, and the equation simplifies to:

$$I_d = I_S(T) \exp\left(\frac{eV}{kT}\right)$$

This exponential growth of current with voltage confirms that the PN junction conducts efficiently in the forward direction.

4.4.2.2 Reverse bias operation

When a positive voltage is applied to the N-region and a negative voltage to the P-region, the junction is under reverse bias. This configuration fundamentally changes the electrical behavior of the device.

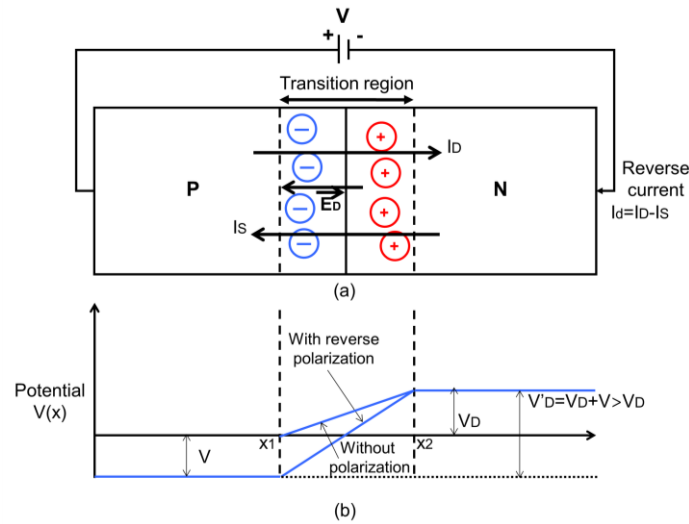


Fig.4.14. (a) PN junction diode under reverse bias and (b) barrier potential.

The external voltage, V , now creates an electric field that reinforces the built-in field of the depletion region. This additive effect increases the junction's potential barrier. The new, higher barrier becomes: $V'_D = V_D + V$.

The heightened barrier has a critical impact on charge carrier movement. Majority carriers (holes in the P-side and electrons in the N-side) now find it nearly impossible to cross the depletion region, as the required energy jumps from eV_D to $e(V_D + V)$.

The current I_D , which was dominant under forward bias, is rapidly reduced to a negligible level ($I_D \approx 0$).

With the majority carrier current effectively blocked, the only remaining current is due to the minority carriers (electrons in the P-side and holes in the N-side). The intrinsic electric field of the depletion region easily sweeps these minority carriers across the junction, generating a small, constant I_S .

The total current in this regime, called the reverse current (I_R), is given by: $I_R = I_S - I_D$.

Since the diffusion current I_D is negligible, the reverse current is approximately equal to the saturation current: $I_R \approx I_S$.

The current I_S is inherently very small (typically on the order of micro-amps or less) because it depends on the thermally generated minority carrier population, which is limited.

Therefore, the key conclusion is that the PN junction blocks current flow in the reverse direction. The very weak reverse current ($I_R \approx I_S$) remains nearly constant and is often considered negligible in most circuit applications.

4.4.3 Current-voltage (I-V) characteristic

The circuit arrangement for studying the V-I characteristics of a diode, (i.e., the variation of current as a function of applied voltage) are shown in Fig. 4.15(a) and (b). The V-I characteristic of a diode (Fig. 4.15(c)) shows it conducts current primarily in one direction. In forward bias,

current is negligible until a threshold voltage is reached ($\sim 0.2\text{V}$ for germanium diode and $\sim 0.7\text{V}$ for silicon diode), after which it increases rapidly. In reverse bias, a very small saturation current flows until a high breakdown voltage is reached. This unidirectional property is used for rectification. The resistance in forward bias is low, while in reverse bias it is very high.

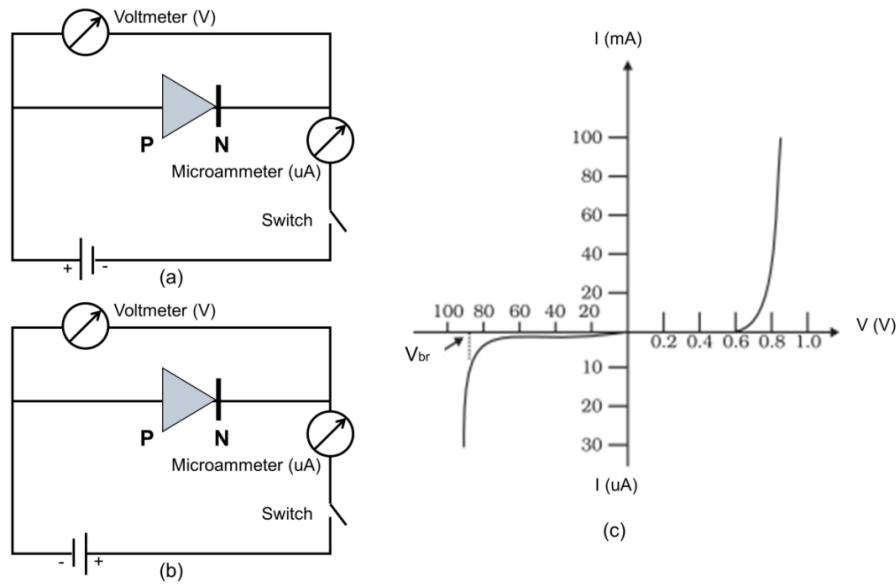


Fig.4.15. Circuit arrangement for studying V - I characteristics of a PN junction diode (a) in forward bias, (b) in reverse bias, and (c) Typical V - I characteristics of a silicon diode.

4.5 Junction breakdown mechanisms

When a diode is reverse-biased, the current remains almost constant until it reaches the breakdown voltage (V_{br}). At $V = V_{br}$, the reverse current increases sharply. A small voltage rise beyond this point causes a large current surge. If the current exceeds the manufacturer's rated limit (due to insufficient external current limiting), the diode overheats and is permanently damaged. This can happen in both reverse and forward bias if current ratings are exceeded. There are three types of breakdown.

4.5.1 Avalanche breakdown

Avalanche breakdown, primarily driven by impact ionization, occurs when a high-energy minority carrier, accelerated by a strong electric field, gains sufficient kinetic energy to liberate bound electrons through collisions, triggering a multiplicative chain reaction of electron-hole pairs; this mechanism predominates in lightly doped p-n junctions where the wider depletion region allows carriers the necessary distance to accelerate, resulting in a high breakdown voltage (typically above 7V) that increases with doping concentration. Characterized by a positive temperature coefficient (as higher temperatures impede the ionization process) and a slightly less sharp breakdown curve compared to the Zener effect, avalanche breakdown is utilized in HV rectifiers and protection circuits, with many general-purpose diodes experiencing this mode;

notably, for breakdown voltages around 5V to 7V, both Zener and avalanche mechanisms can coexist, producing a near-zero temperature coefficient ideal for precision voltage references.

4.5.2 Zener breakdown

Quantum tunneling, the primary mechanism behind the Zener effect, is a quantum phenomenon where electrons in the valence band of the p-side directly tunnel through the potential barrier into the conduction band of the n-side; this occurs predominantly in heavily doped p-n junctions because the high doping concentration creates an extremely thin depletion region and a strong built-in electric field. This tunneling results in a sharp, well-defined breakdown with a characteristically low voltage (typically below 5V, often around -5V to -2V), which decreases further with increased doping and exhibits a negative temperature coefficient, where higher temperatures facilitate easier tunneling. These precise characteristics are intentionally exploited in Zener diodes, which are essential components for voltage regulation and reference circuits.

4.5.3 Thermal breakdown

Thermal runaway is a catastrophic failure mechanism resulting in permanent device destruction, initiated when power dissipated at the p-n junction, whether under breakdown or high forward bias, generates heat faster than it can be removed, causing the junction temperature to rise. This temperature increase triggers an exponential rise in the reverse saturation current, which in turn draws more current and produces further heating, establishing a violent positive feedback loop. Ultimately, the localized junction temperature exceeds the semiconductor's melting point, destroying the crystal structure and creating a permanent short circuit; this irreversible and often spot-localized failure can occur even below rated breakdown voltages if power limits are exceeded, and is prevented by adhering to maximum power and temperature ratings, employing adequate heat sinking, and utilizing current-limiting resistors.

4.6 Main semiconductor components

Semiconductor components are the fundamental building blocks of modern electronics, enabling the control, rectification, amplification, and switching of electrical signals and power.

4.6.1 The diode

A diode is a two-terminal device that allows current to flow easily in one direction (forward bias) and blocks it in the opposite direction (reverse bias). This property is known as rectification.

Rectifier diodes: used primarily to convert Alternating Current (AC) to Direct Current (DC). They are the key component in power supply units. In a bridge rectifier circuit, four diodes are arranged to guide the AC waveform so that the output is a pulsating DC voltage, which is

then smoothed by a capacitor. Fig.4.16 shows a diamond arrangement of four diodes with an AC input and a DC output across a load resistor.

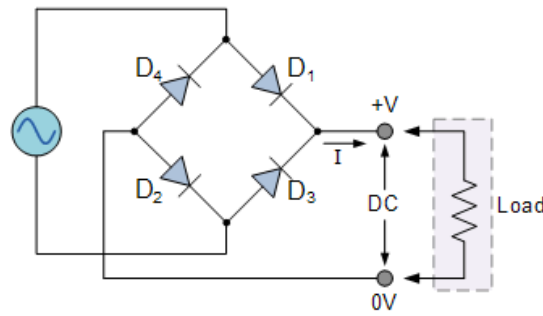


Fig.4.16. Voltage regulator using Zener diode.

Zener diodes : operated in reverse bias. Unlike standard diodes, they are designed to have a sharp and specific breakdown voltage (Zener voltage). When the reverse voltage reaches this point, the diode allows current to flow, stabilizing the voltage across it. These Zener Diodes are commonly used to provide a stable reference voltage in power supplies, protecting circuits from overvoltage. Fig.4.17 shows a Zener diode in reverse bias parallel to the load, with a series resistor to limit current.

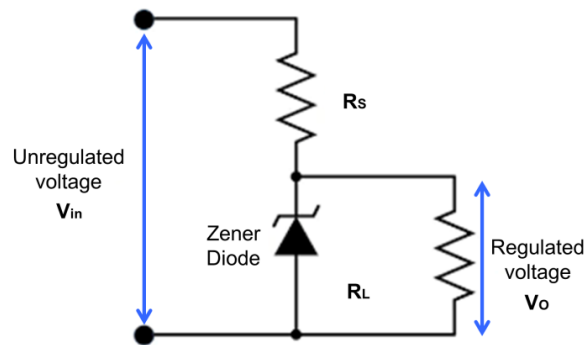


Fig.4.17. Voltage regulator using Zener diode.

4.6.2 The bipolar junction transistor (BJT)

A BJT is a three-terminal device (Emitter, Base, Collector) used to amplify current or act as an electrically controlled switch. Current flowing through the base terminal controls a much larger current between the collector and emitter. A BJT is divided into two types (NPN and PNP): NPN: A layer of P-type semiconductor is sandwiched between two N-type layers. Current enters the collector and exits the emitter, controlled by base current. It is the more common type. PNP: An N-type layer is sandwiched between two P-type layers. Current enters the emitter and exits the collector, controlled by base current.

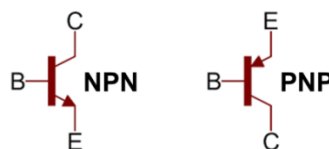


Fig.4.18. Circuit symbols for both the NPN and PNP BJT.

4.6.3 The power MOSFET

The Power MOSFET is a voltage-controlled, three-terminal semiconductor switch essential for high-frequency, high-efficiency power electronics. It is turned on by applying a voltage to its insulated gate, which creates a conductive channel between drain and source. Key advantages include very high switching speeds (kHz to MHz range) and negligible gate current in steady state, reducing drive complexity and control losses.

Physically optimized for power handling, it uses a vertical structure to support high voltages while minimizing on-state resistance ($R_{DS(on)}$), which directly affects conduction losses. An intrinsic body diode provides reverse conduction. Power MOSFETs are widely used in switch-mode power supplies, DC-DC converters, motor drives, and Class-D amplifiers. However, in very high-voltage and high-current applications (above $\sim 600V$), conduction losses can become excessive, leading to the use of IGBTs for higher power, medium-frequency applications.

Fig.4.19 shows the commonly used schematic symbols for enhancement-mode MOSFETs, with both the N-channel and P-channel variant.

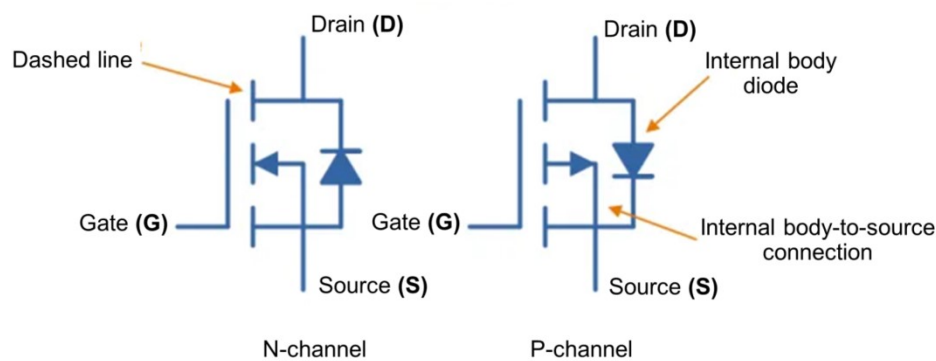


Fig.4.19. Circuit symbols for enhancement-mode MOSFETs, with both the N-channel and P-channel variant.

4.6.4 The insulated-gate bipolar transistor (IGBT)

The IGBT is the workhorse of modern medium- to HV power conversion, finding critical use in traction systems and inverters. It is best understood as a hybrid device that combines the easy voltage control of a MOSFET with the high-current handling capability of a BJT. It has three terminals: Gate, Collector, and Emitter. The voltage applied to the insulated Gate controls the flow of current between the Collector and Emitter.

The MOSFET component requires very little steady current to drive the gate, simplifying control circuits. The BJT component has a low voltage drop when turned on, leading to lower conduction losses and heat generation at high currents.

IGBTs are the dominant switch in modern Variable-Frequency Drives (VFDs) and Uninterruptible Power Supplies (UPS). They switch on and off thousands of times per second to synthesize an AC waveform from a DC source (e.g., a battery or rectified AC). IGBTs are also

used in Electric Vehicle (EV) motor controllers, industrial motor drives, and HV power transmission systems.

Fig.4.20 shows six IGBTs with anti-parallel diodes arranged in a bridge configuration to drive a three-phase motor.

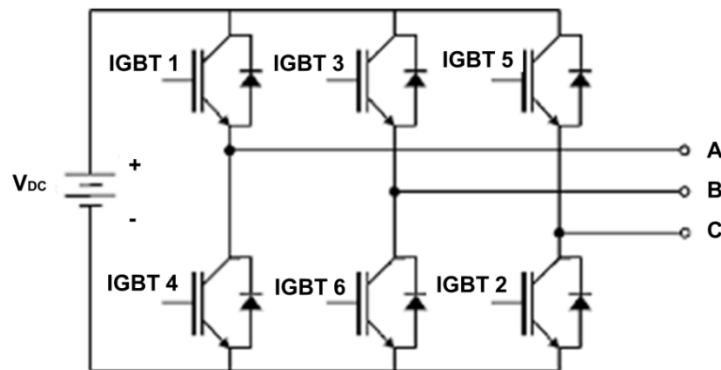


Fig.4.20. Three-phase IGBT inverter bridge circuit.

4.6.5 The thyristor (SCR - Silicon Controlled Rectifier)

The thyristor is the cornerstone of classic high-power, HV control, fundamental to High Voltage Direct Current (HVDC) transmission valves and large industrial motor drives. A Thyristor is a four-layer (PNPN), three-terminal (Anode, Cathode, Gate) semiconductor device. It acts as a bi-stable switch, exhibiting a latching behavior where it remains off until triggered by a gate pulse and then remains on (latched) even after the gate signal is removed, conducting until the main current is interrupted. It can be thought of as two coupled transistors (PNP and NPN). In the off state, it blocks current. A brief positive pulse to the gate "latches" the two transistors on, allowing current to flow from anode to cathode. The primary turn-off method is natural commutation, where it only turns off when the main current naturally falls below a holding threshold (e.g., when an AC waveform crosses zero). For DC circuits, forced commutation circuits are required to actively reduce the anode current to zero. By precisely timing the gate pulse relative to the AC waveform (phase-angle control), an SCR can control the average power delivered to a motor, thus regulating its speed. Fig.4.21 illustrates how delaying the trigger pulse cuts portions of the AC sine wave, reducing average voltage.

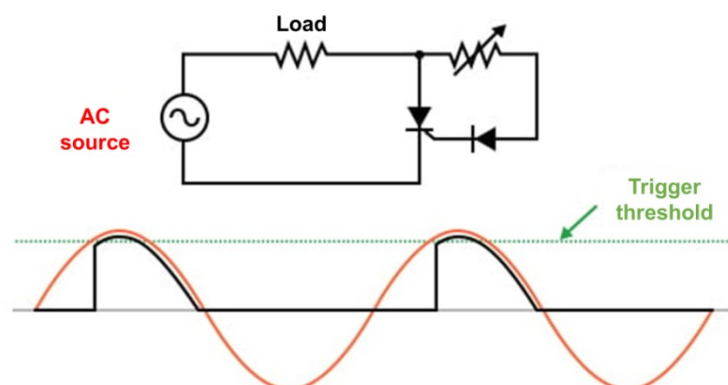


Fig.4.21. SCR phase control waveform.

4.7 Key applications of semiconductors

Semiconductors are fundamental to modern technology. Their unique electrical and photonic properties enable three critical applications: Photovoltaic Cells, which harvest solar energy; LASERs (Light Amplification by Stimulated Emission of Radiation), which generate coherent light; and Infrared (IR) detectors, which sense thermal radiation. Each transforms light into usable electrical signals or precise optical beams for essential functions in energy, communications, and sensing.

4.7.1 Photovoltaic cells

The photovoltaic effect is the process by which light is converted directly into electricity, representing a form of direct energy conversion. Photons are absorbed by a semiconductor material, exciting electrons across its band gap to create electron-hole pairs. The built-in electric field of a semiconductor p-n junction then separates these charges, generating a DC voltage. This direct current (DC) can either power DC sources directly or be fed into the electrical grid using grid-tie inverters, which typically rely on power semiconductor switches like IGBTs and MOSFETs to convert DC to AC. The efficiency of this process depends on the material's band gap, with crystalline silicon being the dominant commercial choice, while other materials like Gallium Arsenide and Perovskites are also used or researched for specific applications.

4.7.2 Infrared detectors

IR radiation, discovered by William Herschel in 1800, occupies the spectral region between visible light and radio waves, spanning from 0.8 to 1000 μm and typically categorized into near, mid, and far-IR bands. Its detection relies on specialized IR detectors that use narrow-bandgap semiconductors, such as InSb or HgCdTe, which absorb low-energy IR photons to generate either a photocurrent in photovoltaic detectors or a change in conductivity in photoconductive detectors. Due to their sensitivity, these detectors often require cryogenic cooling to minimize thermal noise, enabling critical applications in thermal imaging, missile guidance, astronomy, and gas sensing. A key industrial application is the critical condition monitoring of HV equipment, where IR thermography is used to identify overheating connections, failed components, or other thermal faults before they lead to catastrophic failures.

4.7.3 Lasers

A LASER produces a coherent, monochromatic, and highly directional beam of light through the process of light amplification by stimulated emission of radiation. This is achieved by exciting an active medium with an external energy source to create a population inversion. When the excited electrons return to their stable state, they emit light that is amplified within an optical cavity. For example, in a semiconductor LASER diode, population inversion occurs in a PN junction under forward bias. LASERs are defined by the active medium (solid, liquid, or gas)

which determines their wavelength, and are widely used in telecommunications, manufacturing, medicine, and electronics for tasks ranging from cutting and welding to data storage and surgery. In the field of electrical power systems, semiconductor LASERs are essential for fiber-optic communication, enabling the reliable control and protection signaling in HV substations, and are also used for precise optical measurement of distances and component alignment.

Chapter 5

Superconducting Materials

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5.1 Introduction to superconductivity

5.1.1 Definition and fundamental concept

A highly specific state of certain solid materials in which the material loses all electrical resistance. For a material to be considered superconducting, it must exhibit two distinct properties below a characteristic material temperature, called the Critical Temperature (T_c):

- Complete absence of electrical resistivity (zero resistance).
- Perfect diamagnetism (the Meissner effect).

These fundamental properties of zero resistance and perfect diamagnetism are the cornerstones of all superconducting applications.

When a superconductor is cooled below its T_c in a weak magnetic field, the magnetic flux is expelled from the material. In the superconducting state, the material exhibits perfect diamagnetic behavior.

It is crucial to note that superconductivity can be destroyed by an external magnetic field if that field exceeds a specific threshold value, defined as the Critical Magnetic Field H_c (sometimes denoted H^*).

Table 5.1 Critical temperature (T) and critical magnetic field (H) of selected superconductors.

Material	Type	T_c (K)	H_c (T)	Practical applications
Elemental (low-T_c)				
Aluminum (Al)	I	1.19	0.01	Classic Type-I superconductor.
Indium (In)	I	3.41	0.029	Type-I, soft superconductor.
Tin (Sn)	I	3.72	0.032	Well-studied Type-I example.
Lead (Pb)	I	7.18	0.082	Historically significant.
Vanadium (V)	I	5.30	0.132	Transitional to Type-II behavior.
Niobium (Nb)	II	9.46	0.196	Highest T_c among pure elements.
Alloys and compounds (high-T_c)				
Nb _{0.44} Ti _{0.56}	II	10	~12	Workhorse of superconducting magnets (Magnetic Resonance Imaging (MRI), accelerators).
Nb ₃ Sn	II	18	~22	A15 compound; used in high-field magnets.
Nb _{0.75} Zr _{0.25}	II	11	~8	Early high-field alloy.
V ₃ Ga	II	15	~25	A15 compound with high H_c .
Nb ₃ (Al _{0.8} Ge _{0.2})	II	20.7	~40	High-performance A15 variant.
MgB ₂	II	39	>50 (estimated)	Simple binary compound, highest T_c of conventional superconductors.

These materials are explicitly labeled Type I (soft superconductors, low B_c) and Type II (hard superconductors, high B_c), which is the key distinction for applications.

5.1.2 History and milestones

This historical journey showcases the relentless pursuit of higher T_c , from the foundational discovery by Onnes, through the theoretical breakthrough of the Bardeen–Cooper–Schrieffer

(BCS) theory, culminating in the High Temperature Superconductor (HTS) revolution ignited by Müller and Bednorz.

- In 1911, Gilles Holst, a physics student under the direction of Dutch physicist Heike Kamerlingh Onnes, discovered that mercury, when cooled to -268.8°C (4.2 K), abruptly loses all electrical resistance. It was soon understood that every superconductor has a T_c : below T_c , it is superconducting; above it, it is not.
- In 1933, German physicists Walter Meissner and Robert Ochsenfeld discovered that a superconducting sample placed in an external magnetic field expels that field, this is the Meissner effect.
- Over the following decade, other superconducting metals, including alloys and compounds, were discovered.
- In 1941, Niobium Nitride was found to superconduct at 16 K.
- In 1953, Vanadium Silicide showed superconducting properties at 17.5 K.
- In 1957, American physicists John Bardeen, Leon Cooper, and John Schrieffer developed the BCS theory (derived from their surnames' first letters, earning them a Nobel Prize in 1972), which for the first time explained the origin of superconductivity. It took nearly 40 years to find a satisfactory explanation for the phenomenon, which is essentially a quantum effect of electron pairing.
- In 1962, scientists at Westinghouse developed the first commercial superconducting wire, an alloy of Niobium and Titanium. Its first high-energy application was in electromagnets for particle accelerators, though it wasn't until 1987 that it was used in Fermilab's Tevatron.
- In 1964, Bill Little of Stanford University suggested the possibility of organic (carbon-based) superconductors. The first such theoretical superconductor was successfully synthesized in 1980 by Danish researcher Klaus Bechgaard of the University of Copenhagen and three French team members (TMTSF (Tetramethyl Tetra Seleno Fulvalene)).
- By March 1986, after 75 years of research, the superconductor with the highest T_c was Niobium-Germanide (Nb_3Ge), with a T_c of -250°C (23.3 K). Reaching such low temperatures required expensive and demanding liquid helium, significantly hindering industrial applications.
- In April 1986, Swiss physicist Karl Müller and German physicist Johannes Georg Bednorz developed a new lanthanum-based alloy with a T_c of 35 K. This marked the beginning of a new era: less than a year later, the -196°C (77 K) threshold was surpassed. This is the temperature of liquid nitrogen, which is far cheaper to produce and easier to handle than liquid helium. Superconductors had entered the industrial age!

- In 1997, researchers discovered that at a temperature very close to absolute zero, a gold and indium alloy was both a superconductor and a natural magnet. More recently, discoveries include the first HTS without copper and the first plastic superconductor.

5.2 Fundamental properties of superconductors

5.2.1 Zero electrical resistance

Upon cooling below a T_c , a superconducting material undergoes a phase transition where its electrical DC resistivity abruptly drops to zero. This is not merely an extremely small resistance, but a complete disappearance. A current induced in a closed loop of superconducting wire can persist indefinitely without any decaying voltage, as demonstrated in famous experiments. This zero-resistance state allows for lossless transmission of electrical power and enables the generation of extremely high magnetic fields in superconducting electromagnets. The transition is sharp and characteristic of the material, as shown in the resistivity vs. temperature graph below.

The phenomenological description of the energy gap (Δ) associated with this transition is given by the BCS theory :

$$\Delta(T) \approx 1.76 \times k_B \times T_c \text{ (at } T = 0 \text{)}$$

Where k_B is Boltzmann's constant.

Metals and conductors have low resistivity, insulators have high resistivity, and superconductors exhibit nearly zero resistivity below a T_c . This behavior of resistivity versus temperature for metals and superconductors is shown in Fig. 5.1, where superconductors display an abrupt drop to zero at T_c .

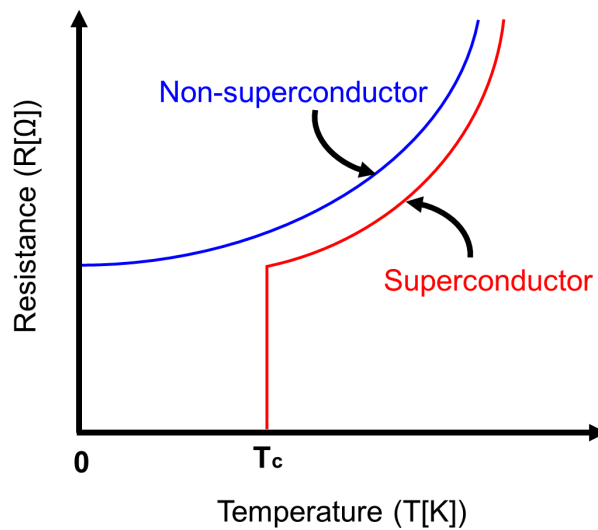


Fig. 5.1. Resistivity vs. temperature for metals and superconductors.

Superconducting materials can transport electrons with no resistance, and hence release no heat, sound, or other energy forms. Superconductivity occurs at a specific material's T_c .

As temperature decreases, a superconducting material's resistance gradually decreases until it reaches T_c . At this point resistance drops off, often to zero, as shown in Fig.5.2.

5.2.2 The Meissner-Ochsenfeld effect (perfect diamagnetism)

Discovered in 1933, the Meissner–Ochsenfeld effect is a defining property of superconductors. When cooled below their T_c in a weak magnetic field ($H < H_c$), superconductors completely expel magnetic flux from their interior; a phenomenon known as perfect diamagnetism. This is not simply a consequence of zero resistance; it is a fundamental thermodynamic signature of the superconducting state.

In the superconducting phase:

- The internal magnetic field $B = 0$
- Magnetization $M = -H$
- Volume susceptibility $\chi = -1$

The effect is described by the London equations, which predict that an external magnetic field decays exponentially within a superconductor over a characteristic distance called the London penetration depth λ_L . However, if the applied field exceeds the critical value H_c , superconductivity is destroyed.

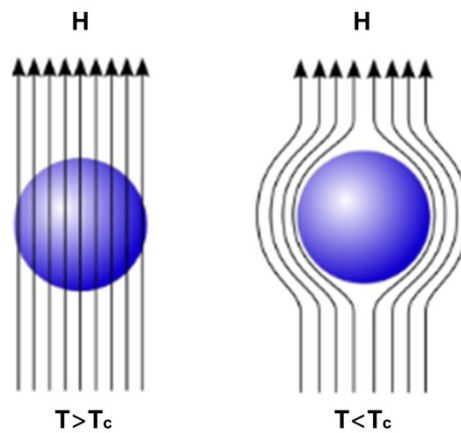


Fig. 5.2. The Meissner effect: a superconductor's magnetic flux above and below T_c .

5.2.3 Thermal properties

Thermal properties of superconductors change below T_c , revealing key microscopic features like the energy gap, unlike electrical resistance which simply vanishes.

5.2.3.1 Heat capacity (specific heat)

At the superconducting transition temperature T_c , the electronic specific heat C_e of a material exhibits a distinct discontinuity. In its normal state ($T > T_c$), C_e follows a linear dependence on temperature, given by $C_{e,n} = \gamma T$, where γ is the Sommerfeld constant. As the material is cooled through T_c , the specific heat jumps sharply due to the latent heat of the phase

transition. Below T_c , C_e falls off exponentially with decreasing temperature. This exponential decay is a fundamental signature of the opening of an energy gap Δ in the superconducting electron spectrum, which suppresses electronic excitations. At very low temperatures, the lattice (phonon) contribution to the specific heat becomes dominant.

5.2.3.2 Thermal conductivity

While ordinary metals exhibit high electrical and thermal conductivity, superconductors present a unique and opposite behavior. Upon transitioning to the superconducting state below the T_c , thermal conductivity plummets dramatically, becoming virtually negligible at very low temperatures.

This characteristic allows for the creation of a thermally activated switch. In such a device, thermal contact between two materials is gated by a superconducting link. The switch is off, providing thermal isolation, when the superconductor is in its zero-resistance state. A magnetic field exceeding the critical value can be applied to turn the switch on, as it drives the material back to its normal, thermally conductive state, re-establishing the thermal connection.

5.3 Critical parameters and limits

The superconducting state is defined by three very important factors: (T_c), (H_c), and (J_c). Each of these parameters is very dependent on the other two properties present.

5.3.1 Critical temperature (T_c)

The T_c is defined as the temperature below which a material transitions into the superconducting state, characterized by zero electrical resistance (infinite conductivity) and the expulsion of magnetic flux (Meissner effect), under conditions of zero external magnetic field and current. T_c is a fundamental property of a material, determined by its composition, crystal structure, and the strength of its electron-phonon coupling (or other pairing mechanisms). The transition is not always perfectly sharp; for many materials, particularly Type-II superconductors, it occurs over a narrow temperature range. When the temperature exceeds T_c , the material reverts to its normal, resistive state.

Superconductors are broadly categorized by their T_c :

- a) Low-Temperature Superconductors (LTS):** require cooling with liquid helium (4.2 K). Examples include metallic alloys like Niobium-Titanium (NbTi) and Niobium-Tin (Nb_3Sn).
- b) High-Temperature Superconductors (HTS):** ceramic materials, primarily cuprates, with T_c above the boiling point of liquid nitrogen (77 K). Their discovery in 1986 was revolutionary. Examples include $YBa_2Cu_3O_{7-x}$ (YBCO (Yttrium-Barium-Copper-Oxide)) and $Bi_2Sr_2Ca_2Cu_3O_{10-x}$ (BSCCO (Bismuth-Strontium-Calcium-Copper-Oxide)).

The value of T_c directly dictates the required cooling technology and associated operational costs, distinguishing between expensive liquid helium systems (for LTS) and the more accessible liquid nitrogen or cryocoolers (for HTS).

5.3.2 Critical magnetic field (H_c)

The H_c is the maximum external magnetic field strength that can be applied before superconductivity is destroyed at a given temperature. Its origin lies in the Meissner effect: upon magnetic field application, shielding supercurrents flow within a surface layer called the London penetration depth, generating a counteracting magnetization. H_c strength decreases with temperature, following an approximate parabolic dependence:

$$H_c(T) \approx H_c(T) \left[1 - \left(\frac{T}{T_c} \right)^2 \right]$$

The behavior, however, fundamentally distinguishes the two classes of superconductors: Type-I materials possess a single H_c , below which they are in a perfect Meissner state, while Type-II superconductors exhibit two critical fields, a lower H_{c1} and an upper H_{c2} , enabling a mixed (vortex) state between them where magnetic flux penetrates as quantized vortices, allowing them to carry high currents and making them technologically most important.

5.3.3 Critical current density (J_c)

While a superconductor carries current without Joule heating, the maximum achievable transport current is practically limited by the Critical Current Density (J_c), defined as the maximum electrical current per unit cross-sectional area:

$$J_c = \frac{I_c}{S_{\text{supra}}}$$

where I_c is the critical current, and S_{supra} is the superconducting cross-sectional area).

A superconductor can carry without dissipating energy. Crucially, J_c is not an intrinsic property like T_c but a microstructure-sensitive parameter that depends strongly on temperature and applied magnetic field. The primary limitation for Type-II superconductors is vortex motion in the mixed state; when the Lorentz force from the transport current overcomes the pinning forces, vortices move and generate electrical resistance (flux flow). Therefore, the central objective of superconductor materials engineering (e.g., for Nb-Ti, Nb₃Sn, and REBCO (Rare-Earth-Barium-Copper-Oxide) wires) is to optimize the defect microstructure to enhance flux pinning, thereby maximizing J_c at operational conditions, values that are nonetheless typically far superior to those of conventional conductors like copper.

5.3.4 The interdependent critical surface ($T_c - H_c - J_c$ diagram)

The superconducting state, however, only exists within a specific region bounded by three critical parameters: the T_c , the H_c , and the J_c (J_c sometimes referred to as the critical current I_c). This state can only persist if:

- ✓ $T < T_c$ (below the critical temperature);
- ✓ $J < J_c$ (below the critical current density);
- ✓ $H < H_c$ (below the critical magnetic field).

These three critical parameters define a three-dimensional volume, the superconducting state exists inside this volume, and the normal (resistive) state exists outside it. The boundary of this volume is known as the critical surface.

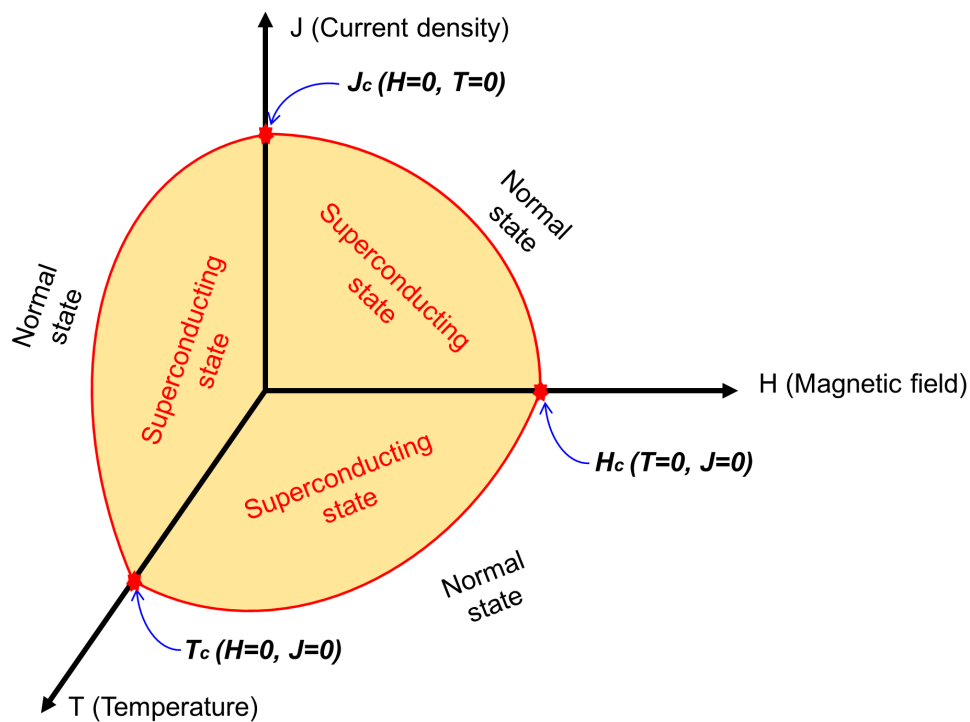


Fig. 5.3. The superconducting state and the critical surface.

5.4 Classification of Superconductors

Superconducting materials are classified according to magnetic response, transition temperature, pairing mechanism, and material composition.

5.4.1 Type I vs. Type II superconductors

In the presence of a magnetic field, two primary types of superconductors are defined: Type I and Type II.

5.4.1.1 Type I superconductors

Type I superconductors, historically the first to be discovered by Onnes in 1911 (in mercury), are characterized by a complete and abrupt transition to a state of perfect conductivity

and perfect diamagnetism, the full expulsion of magnetic flux known as the Meissner effect (see Fig. 5.4(a): Phase Diagram of a Type I Superconductor). These "soft" superconductors are defined by a single H_c ; below H_c , they exist in the superconducting Meissner state, and above it, they revert entirely to the normal resistive state. Nearly all pure elemental superconductors (e.g., Hg, Pb, Zn), with the notable exceptions of vanadium and niobium, are Type I. They are typically LTS, with T_c below ~ 30 K under ambient pressure, though extreme pressure can induce superconductivity in other elements like sulfur at higher T_c . Their properties are generally insensitive to impurities, but their low T_c and H_c limit their large-scale technological applications.

Table 5.2 Well-known elemental Type I superconductors and their critical temperatures.

Element	Symbol	Critical temperature (T_c)
Lead	Pb	7.20 K
Mercury	Hg	4.15 K
Tin	Sn	3.72 K
Indium	In	3.40 K
Aluminum	Al	1.175 K
Cadmium	Cd	0.517 K
Titanium	Ti	0.40 K
Tungsten	W	0.0154 K

5.4.1.2 Type II superconductors

Type II superconductors, often called "hard superconductors," are distinguished by the existence of two critical magnetic fields (H_{c1} (Lower Critical Magnetic Field) and H_{c2} (Upper Critical Magnetic Field)), defining three distinct states (see Fig. 5.4(b) b: Phase Diagram of a Type II Superconductor). Below the lower H_{c1} , they exhibit perfect diamagnetism, fully expelling magnetic flux like a Type I material. Between H_{c1} and the much higher H_{c2} , they enter a mixed (or vortex) state where quantized magnetic flux lines partially penetrate the material while the bulk remains superconducting. Above H_{c1} , superconductivity is entirely destroyed.

In this mixed state, magnetic flux penetrates in discrete filaments, or vortices, which arrange into a regular vortex lattice. The high J_c essential for applications is achieved by deliberately introducing microscopic defects and inhomogeneities into the material to trap or 'pin' these vortices, preventing their motion under the influence of an electrical current.

This mixed state, described by the BCS theory, is key to their technological importance, as it allows them to carry very high currents and withstand strong magnetic fields. Most high-field and high-current applications rely on Type II materials such as alloys (NbTi, Nb₃Sn) and ceramic cuprates; for example, Nb₃Sn has $H_{c1} \approx 0.035$ T and $H_{c2} \approx 23$ T. Their properties are highly sensitive to microstructure and defects, which can be engineered to pin vortices and enhance performance.

Table 5.3 Lower and upper critical fields (H_{c1} , H_{c2}) and critical temperatures (T_c) for selected Type II superconductors.

Material	T_c (K)	H_{c1} (T)	H_{c2} (T)
Nb	9.3	0.181	2
NbTi	9.5	0.035	13
Nb ₃ Sn	18.2	0.012	23
LaMo ₆ S ₈	11	—	44.5
Rb ₃ C ₆₀	29.6	—	57
YBaCuO	92	—	120–200

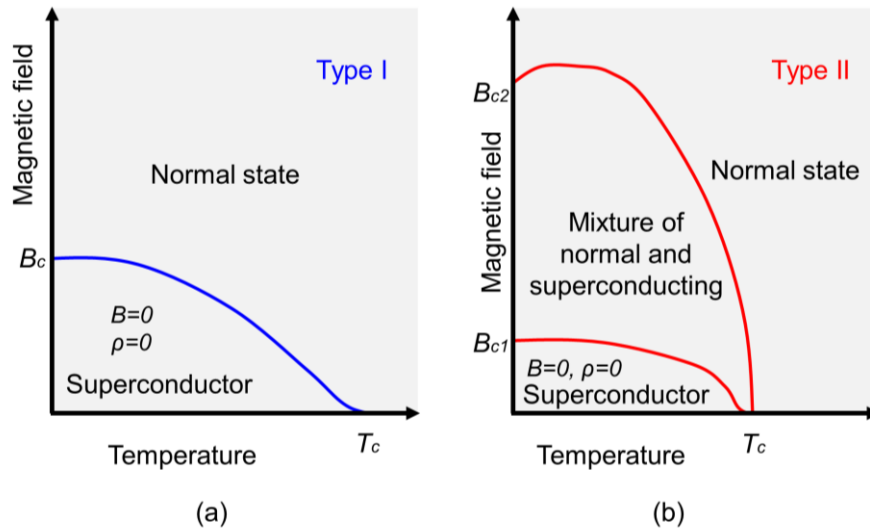


Fig. 5.4. Variation in critical magnetic field with temperature for both types: (a) Type I and (b) Type II.

5.4.2 Classification by critical temperature

The transition temperature of superconductors is the most fundamental and technologically defining characteristic. The primary divide is between LTS, which require costly and complex cooling (typically with liquid helium at ~ 4.2 K), and HTS, which can operate with simpler, cheaper cooling systems (using liquid nitrogen at 77 K or cryocoolers).

5.4.2.1 Low-Temperature Superconductors (LTS)

LTS materials are defined by a T_c typically below ~ 30 K (with a practical cutoff near 23 K) and are predominantly Type II materials, such as the industrially dominant NbTi ($T_c \approx 9$ K) and Nb₃Sn ($T_c \approx 18$ K). These conventional superconductors, well-described by BCS theory, are technologically mature and widely used in high-field magnets for applications like MRI and fusion reactors, due to their excellent performance, with critical current densities exceeding 2000 A/mm² at 3 T, and established large-scale manufacturing.

Their primary drawback is the need for costly and complex liquid helium (4.2 K) cooling systems, which constitute a significant operational expense despite their exceptional magnetic and transport properties.

5.4.2.2 High-Temperature Superconductors (HTS)

HTS materials are defined as Type II superconductors with a T_c above the boiling point of liquid nitrogen (77 K), a milestone first achieved with the discovery of cuprates by Müller and Bednorz in 1986 (e.g., BaLaCuO , $T_c = 35$ K). These materials feature perovskite-related layered structures, most notably YBCO and BSCCO, and their superconducting mechanism is considered unconventional, extending beyond the standard BCS theory. While inherently brittle and anisotropic, they have been engineered into practical second-generation (2G) coated conductors (e.g., REBCO tapes), which achieve high critical current densities (e.g., ~ 750 A/mm² at 30 K and 3 T). Their ability to operate with inexpensive liquid nitrogen cooling enables transformative applications, including compact fusion magnets, high-field MRI systems, and efficient power transmission, despite ongoing challenges related to granularity, weak links, and material synthesis.

5.4.3 Classification by underlying theory

This classification is based on the physical mechanism that creates the superconducting state, focusing on how electron pairs (Cooper pairs) are formed.

5.4.3.1 Conventional superconductors

These are fully described by the BCS theory, where electron-phonon interactions provide the "glue" for Cooper pair formation. They exhibit predictable properties, including an isotropic energy gap. Historically, this category includes all LTS, such as elemental metals (e.g., Nb, Pb) and alloys like NbTi. Recent discoveries of high- T_c materials under extreme pressure (e.g., H₂S) have shown that conventional, phonon-mediated pairing can persist at much higher temperatures.

5.4.3.2 Unconventional superconductors

These materials cannot be explained by standard BCS theory. Their pairing mechanism is different and not fully understood, often linked to magnetic or electronic interactions rather than phonons. This leads to complex properties, such as an anisotropic (e.g., d-wave) energy gap. Most HTS, including cuprates (e.g., YBCO) and iron-based pnictides, fall into this category. Developing a universal theory for them remains a major challenge in physics.

5.4.4 Material families and examples

5.4.4.1 Organic (plastic) superconductors

Organic superconductors, sometimes referred to as "plastic superconductors," are carbon-based molecular or polymeric materials that exhibit superconductivity at low temperatures. These unconventional materials, such as charge-transfer salts (e.g., $(\text{TMTSF})_2\text{PF}_6$) and fullerene-based compounds (e.g., K_3C_{60}), typically have T_c below ~ 30 K and are defined by their low-dimensional

structure and complex electronic interactions. Although early discoveries, like the first superconducting polymer reported at Bell Labs in 2001, demonstrated the potential for inexpensive, processable superconducting plastics, their technological use remains limited due to their low T_c and the challenges of material stability and processing.

5.4.4.2 Carbon Nanotubes

Carbon Nanotubes (CNTs) can exhibit superconductivity, particularly in Single-Wall Nanotubes (SWNTs) under specific doping and structural conditions. While superconductivity in bundled CNTs is typically observed at very low temperatures (<1 K), recent experiments have reported a T_c of ~ 15 K in individual, highly aligned nanotubes, suggesting that reduced inter-tube coupling and enhanced electronic coherence may significantly raise T_c . The superconducting mechanism in these quasi-one-dimensional systems remains a topic of active research, as their T_c and pairing behavior are highly sensitive to diameter, chirality, doping level, and structural alignment.

5.4.5 Practical superconducting conductors: wires and tapes

The translation of a superconducting material into a practical conductor for magnets and power cables involves complex materials engineering. The goal is to produce a flexible, mechanically robust, and electromagnetically stable wire or tape that can carry a high supercurrent and withstand the extreme operating conditions of high magnetic fields and cryogenic temperatures. Different conductor architectures have been developed for LTS and HTS materials.

5.4.5.1 LTS wire technology

The workhorse conductors for LTS are composite wires where fine filaments of superconducting alloy (e.g., NbTi or the brittle Nb₃Sn) are embedded within a high-purity copper matrix. This design serves three critical engineering functions: the copper stabilizes the conductor by providing a parallel current path during a quench, offers quench protection by safely dissipating heat and magnetic energy, and supplies essential mechanical support. Fabricated through processes like co-drawing (NbTi) or the "bronze route" (Nb₃Sn), these mature, reliable conductors are the foundation for high-field magnets in MRI scanners, particle accelerators, and fusion reactors.

5.4.5.2 HTS tape technology

Practical HTS wires employ a layered, thin-film architecture to overcome the material's brittleness. First-Generation (1G) conductors use a powder-in-tube method to form BSCCO filaments within a silver sheath. The superior Second-Generation (2G) coated conductors are the enabling technology for advanced applications; they are fabricated by depositing a thin film of

REBCO onto a flexible, textured metal substrate with engineered buffer layers. This architecture decouples superconducting performance from mechanical needs, producing a strong, flexible tape capable of carrying extremely high current densities in high magnetic fields. 2G conductors are critical for next-generation compact fusion magnets, high-field research systems, and efficient power grid devices.

5.5 Major technological applications of superconductivity

The zero resistance and high-current capacity of superconductors offer transformative advantages. Key implementations of these materials include generating intense magnetic fields for fusion reactors, particle accelerators, and MRI machines, as well as enabling magnetic levitation and lossless energy transmission/storage (Superconducting Magnetic Energy Storage (SMES)). While many advances remain in specialized R&D, these materials promise future compact, high-capacity electrical components that can carry immense currents without Joule heating losses.

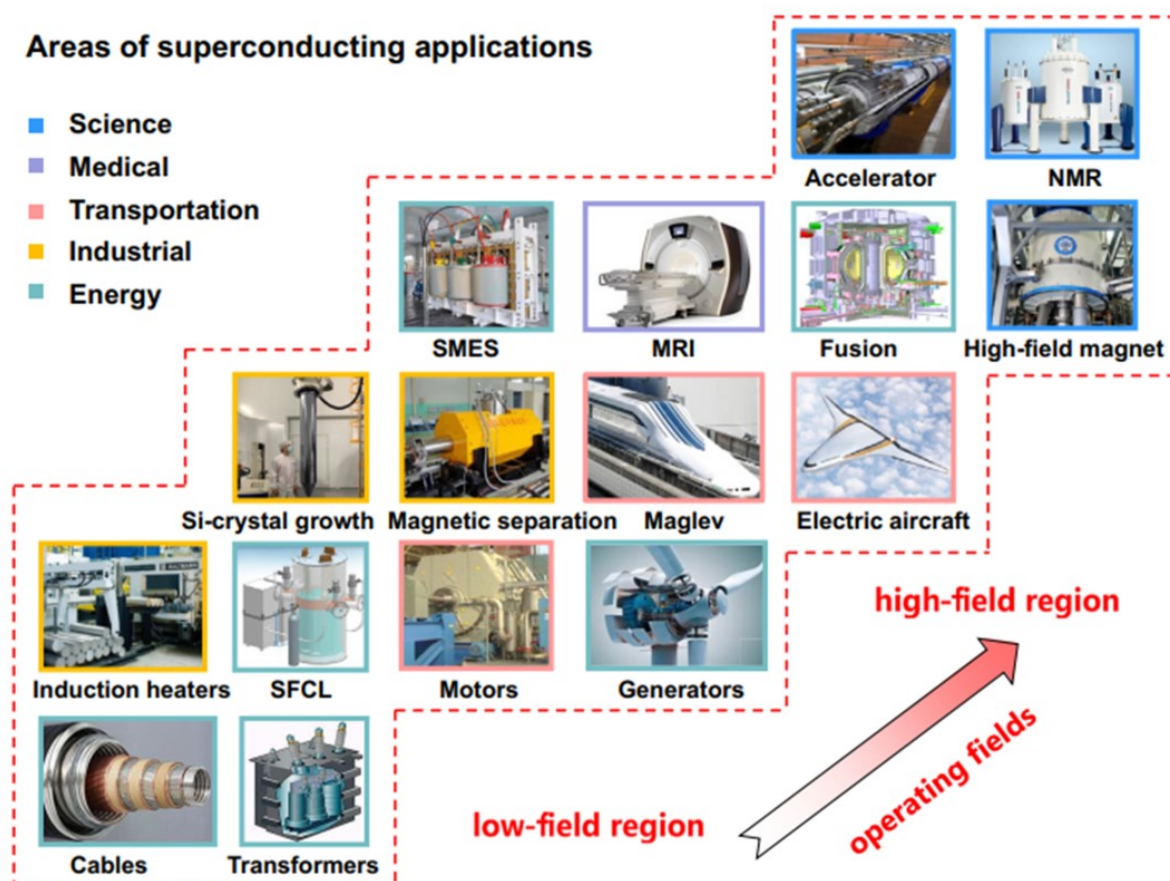


Fig. 5.5. Main applications of superconducting power and magnetic technologies with their typical operating magnetic fields.

5.5.1 Superconducting magnets

The most significant commercial application of superconductivity is the production of high-field electromagnets. Superconducting coils, typically made from alloys like NbTi, carry large persistent currents without resistive loss, generating powerful and stable magnetic fields unattainable with conventional technology. This capability is foundational for two major areas:

a) Scientific and medical instrumentation:

- **MRI:** relies on superconducting magnets to produce the intense, uniform fields (0.5–4 T) required for spatial encoding and signal generation in medical diagnostics.
- **Nuclear Magnetic Resonance (NMR) Spectroscopy:** requires even higher fields (>7 T) for precise analysis of molecular structure and composition, making superconducting magnets essential.

b) High-energy physics:

In particle accelerators like the Large Hadron Collider (LHC), networks of superconducting magnets are indispensable for guiding, focusing, and controlling particle beams, as well as for detecting collision products. These magnets also enable frontier research in superconductivity itself, having achieved record fields exceeding 30 T.

5.5.2 Large-scale science and engineering

Superconductivity provides the extreme magnetic fields and ultra-efficient energy systems required for humanity's most ambitious scientific projects, enabling breakthroughs in fundamental physics and energy generation.

5.5.2.1 Fusion reactors

International Thermonuclear Experimental Reactor (ITER), the flagship international fusion project, relies on massive superconducting magnets to generate the intense, stable magnetic fields required to confine a 100-million-degree plasma, a feat impossible with conventional magnets. The goal is to achieve a tenfold energy gain, producing 500 MW of fusion power from a 50 MW input.

5.5.2.2 Particle accelerators

Superconducting Radio Frequency (SRF) cavities, typically made of niobium, use superconductivity to achieve extremely efficient particle acceleration. Operating with near-zero resistive loss, they can generate very high electric fields (up to ~ 45 MV/m) to continuously accelerate particle beams, a capability essential for high-luminosity colliders and advanced light sources.

5.5.3 Energy and power applications

Superconductors enable lossless, high-efficiency electrical systems, essential for compact, powerful infrastructure and stable renewable-energy grids.

5.5.3.1 Power transmission cables

Superconducting power transmission is a transformative technology that enables loss reduction, increased capacity, and inherent fault current limiting capability in a compact footprint,

overcoming the thermal limits of conventional cables. Enabled by high-temperature superconducting materials, it is now moving toward commercial viability. Prototypes and pilot projects have successfully demonstrated both AC and DC configurations, each offering distinct advantages for grid stability and long-distance bulk power transfer. Key pilot projects demonstrate its capabilities, such as a 600-meter line in New York delivering 574 MW, four times the capacity of a comparable copper cable, and a planned 48-km line in South Korea. While cryogenic cooling remains a challenge, these systems offer a critical solution for urban power grids and efficient long-distance renewable energy integration.

5.5.3.2 Fault Current Limiters (FCL)

This is a revolutionary grid protection device that operates by leveraging a superconductor's ability to be lossless during normal operation and to automatically, rapidly transition to a highly resistive state during a fault. Superconducting Fault Current Limiters (SFCLs) provide a novel solution to a critical grid protection challenge. They leverage the superconductor's rapid, non-linear transition to a resistive state when a fault current exceeds a threshold. This instantaneously generates a counteracting electric field, automatically limiting the fault current to a safe, interruptible level without external triggering, thereby protecting downstream equipment from damage.

5.5.3.3 Transformers

Superconducting transformers are enabled by replacing conventional copper windings with superconducting tape, making them significantly smaller, lighter, and more efficient, offering particular advantages for niche applications such as dense urban substations or offshore wind farms. Superconducting Transformers eliminate copper losses. This results in dramatic improvements: demonstrated reductions of 30% in losses, 50% in volume, and 70% in weight, as exemplified by Siemens's 1 MVA prototype.

5.5.3.4 Energy storage

SMES uniquely stores electricity directly as magnetic energy within a superconducting coil. Unlike chemical or gravitational storage, SMES offers near-instantaneous charge/discharge cycles with exceptional efficiency (>95%). This enables critical grid support functions, such as sub-second frequency regulation, voltage stabilization, and uninterruptible power supply, addressing the fundamental challenge of instantaneous grid balancing.

5.5.4 Transportation : maglev trains

Superconducting Maglev systems, specifically Electro-dynamic Suspension (EDS), enable ultra-high-speed ground transport. This technology uses onboard superconducting magnets to induce repulsive forces in conductive track coils, producing both levitation and propulsion

without physical contact. This eliminates wheel friction, allowing for exceptionally quiet, efficient, and smooth travel at speeds exceeding 500 km/h. The record-setting Japanese ML-500 prototype demonstrated this principle in 1977, achieving 517 km/h.

5.5.5 Electronics : SQUIDs and RF filters

Superconducting electronics leverage quantum phenomena to achieve extreme sensitivity and speed, forming the basis for several key technologies:

- **Ultra-sensitive magnetometers:** superconducting Quantum Interference Devices (SQUIDs) are the world's most sensitive detectors of magnetic flux.
- **High-performance RF systems:** superconducting filters provide exceptional selectivity and low loss in critical telecommunications infrastructure, such as mobile phone base stations.
- **Advanced computing:** superconducting circuits are the leading platform for building the coherent qubits required for scalable quantum computers.
- **Surge protection and instrumentation:** these materials are also used in specialized electronic systems for circuit protection and ultra-sensitive measurement devices.

5.5.6 Advanced and future applications

5.5.6.1 Superconducting generators and motors

Superconducting generators and motors replace conventional copper windings with superconducting coils, enabling a dramatic leap in power density and efficiency. By operating with zero resistance, these machines can generate much stronger magnetic fields, leading to smaller, lighter, and significantly more powerful units for high-demand applications. This technology is particularly transformative for large-scale wind turbines, where reduced weight and size in the nacelle allow for higher power ratings and lower structural costs, and for all-electric ship propulsion systems, offering compact, high-torque motors that enable new naval and commercial vessel designs.

5.5.6.2 Magneto-Hydrodynamic (MHD)

MHD Propulsion leverages the principle of electromagnetic force on a conductive fluid (seawater). Superconducting electromagnets on a vessel create powerful magnetic fields (B). The interaction of these fields with electric currents (J) induced or directly applied in the water generates a Lorentz force ($F = J \times B$), providing silent, non-mechanical thrust with a minimal acoustic and radar signature, suitable for advanced maritime vessels.

5.6 Engineering challenges and system integration

While superconductors offer transformative performance, their integration into real-world systems is governed by overcoming several critical engineering barriers, primarily centered on

thermal management, electrical stability, and economic feasibility. These barriers manifest in four core technical areas:

- 1) **Cryogenics and cooling systems** : the main practical hurdle, requiring complex cooling to maintain superconducting temperatures. LTS uses expensive liquid helium (4.2 K), while HTS can use cheaper liquid nitrogen (77 K) or cryocoolers, supported by high-performance thermal insulation.
- 2) **AC losses and stability** : superconductors are not perfect under AC operation, experiencing hysteresis, coupling, and eddy current losses. Managing these losses is crucial for the efficiency and stability of AC power applications.
- 3) **Quench protection and reliability** : if a superconducting section transitions to the normal state, it can cause thermal runaway. Systems require detection methods, protection circuits, and a stabilizing copper matrix to prevent damage.
- 4) **Economic viability and future outlook** : adoption depends on balancing high initial costs (materials and cooling) against long-term benefits like loss reduction, compactness, and enhanced functionality. The future relies on reducing HTS production costs and proving reliability in large-scale grid and energy applications.

Part II

Introduction to High Voltage

Chapter 1

High Voltages Basics

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1.1 Definition and classifications (voltage domains)

The HV is an electrical potential sufficient to generate intense electric fields that fundamentally alter the state of insulating materials, invoking phenomena like air ionization. It establishes that voltage is classified into standardized domains based on operational, safety, and engineering criteria set by international bodies. These domains, including Extra-Low Voltage (ELV, <50 V), Low Voltage (LV, <1 kV), Medium Voltage (MV, 1 kV-33 kV), High Voltage (HV, 33 kV-230 kV), Extra-High Voltage (EHV, 230 kV-800 kV), and Ultra-High Voltage (UHV, >800 kV), are each characterized by specific numerical thresholds, distinct applications, and unique design requirements for power transmission and distribution systems.

Table 1.1 Voltage Classification According to Standard NF C18-510 (2009).

Voltage class	Alternating Current (AC)	Direct Current (DC)
ELV	$V_n \leq 50 \text{ V}$	$V_n \leq 120 \text{ V}$
LV	$50 \text{ V} < V_n \leq 10^3 \text{ V}$	$120 \text{ V} < V_n \leq 1.5 \times 10^3 \text{ V}$
HVA	$10^3 \text{ V} < V_n \leq 50 \times 10^3 \text{ V}$	$1.05 \times 10^3 \text{ V} < V_n \leq 75 \times 10^3 \text{ V}$
HVB	$V_n > 50 \times 10^3 \text{ V}$	$V_n > 75 \times 10^3 \text{ V}$

V_n : Stands for "nominal voltage" or "rated voltage."

In AC systems, HV transmission operates at standardized power frequencies, predominantly 50 Hz or 60 Hz, transporting currents typically ranging from 400 to 3,000 amperes. Global

implementation of the voltage domains varies by regional grid requirements and technological development. While most national grids operate within the 220 to 500 kV range (encompassing HV and EHV domains), maximum operational voltages differ: 765 kV in the United States, 735 kV in Canada, and 400 kV across Western Europe represent regional EHV benchmarks. Japan has progressed into the UHV domain with a commissioned 1,000 kV line, and ongoing international research projects target practical systems up to 1,200 kV to enable more efficient long-distance power transfer.

1.2 Standardization bodies

Standardization bodies establish the fundamental "rules of the road" for electrical engineering, ensuring safety, compatibility, and reliability across systems, materials, and technologies.

1.2.1 International

Key international bodies govern HV engineering. The International Electrotechnical Commission (IEC) provides the core standards, such as IEC 60038 for voltage classification, establishing universal frameworks for safety, terminology, testing, and equipment performance. Related entities include the International Special Committee on Radio Interference (CISPR), which sets limits for electromagnetic interference, and the International Organization for Standardization (ISO). Together, these organizations harmonize technical practices, ensure interoperability, and facilitate global trade in electrical systems.

1.2.2 Regional

International standards are implemented regionally by organizations such as the European Committee for Electrotechnical Standardization (CENELEC), which converts IEC standards into mandatory European Norms (EN). This ensures regulatory harmonization and market unification for electrical equipment across Europe under directives like the Low Voltage Directive. Prominent national institutes, including Germany's DIN (Deutsches Institut für Normung) and France's AFNOR (NF standards), align their national frameworks with these regional and international norms.

1.2.3 National

National bodies establish enforceable codes that adapt international and regional norms to local contexts, such as American Society for Testing and Materials (ASTM), the Swiss Association for Standardization (SNV), and its sectoral committees like the Swiss Electrotechnical Committee (CES) and Electrosuisse. In Algeria, this role is primarily fulfilled by the *Institut Algérien de Normalisation* (IANOR), which develops and publishes Algerian national standards (*normes algériennes*). These standards are tailored to national grid infrastructure,

legislation, and enforcement bodies. Specialized domains, such as the U.S. Department of Defense's Military Standards series (MIL-STD) or the Swiss Telecommunications Association (ASUT), provide stringent technical specifications for military and telecommunications applications, respectively.

1.3 Utility of HV in power transmission

HV transmission is essential for efficiently delivering electricity from power plants to distant load centers. The primary advantage lies in reducing resistive (Joule) losses over long distances.

For a simplified single-phase line model (neglecting shunt capacitance and conductance), the transmitted power is:

$$P_2 = U_2 \cdot I_2 \cdot \cos \Phi \text{ with } I_1 = I_2 = I$$

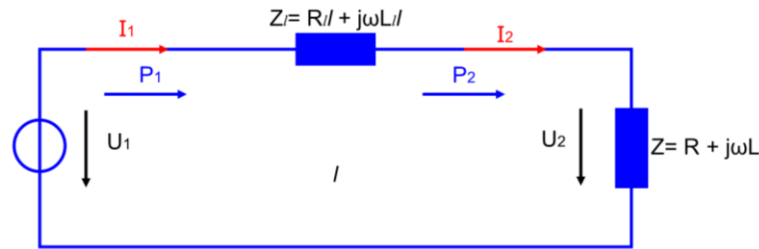


Fig. 1.1. Simplified single-phase transmission line model.

where I is the line current, Φ is the phase angle between voltage and current, and R_l and L_l are the per-unit length resistance and inductance.

To increase the transmitted power P , two main variables can be adjusted:

- Increasing the current:
 - ✓ Raises conductor heating (max. $\sim 60^\circ\text{C}$ allowed).
 - ✓ Requires larger cross-sections and increases weight.
- Increasing the voltage:
 - ✓ Increases the electric field strength.
 - ✓ Requires greater insulation distances.
 - ✓ May introduce disruptive phenomena.

Therefore, the choice is guided by transmission efficiency η :

$$\eta = \frac{P_2}{P_2 + P_J} \text{ where } P_J = R_l I^2 \text{ (Power lost due to the Joule effect)}$$

Substituting yields:

$$\eta = \frac{1}{1 + \frac{R_l I P_2}{\cos^2 \Phi U_2^2}}$$

For a three-phase example with $R_l = 0.1 \text{ m}\Omega/\text{m}$, $l=100 \text{ km}$, $\cos \Phi = 0.8$, and $P_2 = 300 \text{ MVA}$, the efficiency improves dramatically with voltage (Table 1.2):

Table 1.2 Variation of the efficiency as a function of the HV.

U (kV)	132	220	380	750
η	0.79	0.91	0.97	0.99

This clearly demonstrates that increasing voltage is the most effective way to enhance efficiency, making HV the standard for bulk power transmission.

The behavior of insulation and materials under HV is determined by intense electric fields at the atomic level. Such fields can alter material properties by ionizing atoms or distorting molecular bonds.

For instance, the intrinsic electric field within a hydrogen atom is ~ 100 GV/mm. Comparable fields exist in solid crystals. Meaningful changes only occur under similarly strong fields.

A high field results from:

- ✓ HV across a standard material.
- ✓ LV across an extremely thin layer.

Thus, core HV effects are fundamentally caused by high electric fields.

1.4 Power line types

1.4.1 Alternating Current (AC) lines

High Voltage Alternating Current (HVAC) lines constitute the core infrastructure for electrical power grids, based on a three-phase system where voltage and current oscillate at a fixed frequency (50/60 Hz). This alternating nature enables efficient voltage transformation via transformers, allowing power to be stepped up to HVs (typically 115 kV to 765 kV) for efficient long-distance bulk transmission with minimized losses, and then stepped down for local distribution and end use.

1.4.2 Direct Current (DC) lines

High Voltage Direct Current (HVDC) lines transmit power with constant voltage polarity, requiring conversion stations to interface with standard AC grids. While not used for general distribution, HVDC is specialized for specific applications where it provides critical advantages. These include connecting asynchronous AC grids (e.g., between different countries or regions), transmitting bulk power over very long distances (above approximately 600-800 km) with lower losses than AC, and powering long submarine or underground cables without reactive power issues. Key real-world examples include the ± 270 kV France-UK IFA 2000 interconnector and the ± 450 kV DC crossing in Quebec. HVDC technology is also central to major projects like the proposed DESERTEC network for renewable energy transmission.

1.5 Overhead lines vs. underground cables

The physical implementation choices, which represent a fundamental design trade-off comparing cost, capacity, reliability, visual/environmental impact, and fault location/repair.

- **Dielectric medium and capacitance:** the primary distinction lies in the insulation. Overhead lines use air, while cables employ solid/liquid dielectrics (e.g., XLPE, oil). This results in much higher capacitance per unit length for cables.
- **Technical limitations (cables):** a cable's high capacitance generates significant charging current, inherently limiting feasible AC transmission distance and maximum transmissible power due to reactive power constraints.
- **Technical limitations (general):** cables face challenges in achieving UHV, dissipating heat, and can be difficult to connect directly to overhead networks.
- **Operational and economic trade-off:** overhead lines are favored for cost-effective long-distance transmission. Cables, while having higher capital costs (often $\sim 10\times$), are essential in urban areas, sensitive environments, and for submarine routes, despite higher maintenance complexity.

1.6 Operating procedures and system management

A HV system integrates several essential components: generators produce power, which step-up and step-down transformers adjust to optimal transmission and distribution voltages. Switchgear (including circuit breakers, disconnectors, and earthing switches) controls, isolates, and protects the circuit. Live conductors are supported and insulated from structures by insulators (porcelain or composite). Safety is ensured by protection systems (relays and surge arresters), and accurate monitoring is provided by instrument transformers.

Operating any HV system requires integrated technical management and strict safety procedures to ensure reliability and protection. This operational framework extends to real-time grid control functions (such as load flow management, voltage control, and frequency control) which are enabled by Supervisory Control and Data Acquisition (SCADA) and Energy Management Systems (EMS).

- ✓ Continuous operational focus in any HV installation must ensure service continuity and protect personnel, property, and the installation itself.
- ✓ The substation design must proactively incorporate planning for specific operational responses.
- ✓ The design must specify the precise switching operations to be executed following an incident.
- ✓ It must clearly identify the personnel authorized and qualified to perform these critical operations.

- ✓ It must establish the specific procedures and instructions to be applied during these operations.

1.7 Power quality and system performance

Consistently, significant disturbances affect the quality of the power supply. The distribution utility is obligated to ensure a quality service, particularly concerning:

- The maintenance of frequency and voltage;
- The continuity of the energy supply.

1.7.1 Quality in normal operation

Power quality under normal grid conditions is defined by maintaining specific critical parameters within strict statutory limits. These key parameters include voltage magnitude, frequency, harmonic distortion, and flicker (e.g., $V_n \pm 5\%$, $f_n \pm 0.5$ Hz). This standard requires a continuous real-time balance between total power generation (P_G) and total load demand plus losses ($P_L + P_{\text{losses}}$) to stabilize the system frequency. Simultaneously, voltage levels, particularly in medium-voltage (MV) distribution networks, must be controlled by managing reactive power. This involves minimizing voltage drops and reactive power transport through compensation and power factor correction (targeting $\cos \varphi \approx 1$), which reduces losses. Broader quality management also involves actively limiting Total Harmonic Distortion (THD) and ensuring three-phase balance.

1.7.2 Quality under disturbed conditions

Power quality during disturbed regimes is defined by deviations from the ideal sinusoidal waveform, including primary disturbances such as sags (dips), swells, interruptions, and transients. It concerns the system's performance during faults and transient events. These disturbances are categorized by their nature and impact:

- **Temporary electrical phenomena:** These interfere with users without causing a complete outage. They primarily include voltage sags/dips (momentary drops of 10–100% due to faults or inrush currents) and harmonic distortions (waveform deformation from power electronics like drives), both characterized by magnitude ($\Delta V/V$) and duration against standards like the ITIC curve.
- **Brief interruptions:** Typically caused by atmospheric events, these lead to the automatic, protocol-driven opening and reclosing of HV circuit breakers to clear transient faults.
- **Long interruptions:** More severe outages result from causes such as major equipment failure, switching errors, severe weather, or external damage. While network design, supply redundancy, and live-line working practices can mitigate them, such interruptions critically affect reliability indices: System Average Interruption Duration Index/System Average Interruption Frequency Index (SAIDI/SAIFI). The system's response is quantified by metrics like fault level (short-circuit power (S_{sc})) and restoration time.

The overarching goal is to ensure rapid fault detection, clearing, and service restoration to minimize customer impact.

1.8 Perturbations and constraints introduced by HV

The intense electric fields inherent to HV systems introduce specific disturbances and impose critical design and safety constraints. These can be considered the inevitable "side effects" of operating at high potential.

1.8.1 Perturbations

- **Corona discharge:** a partial discharge in air occurring when the local electric field exceeds the dielectric strength of air ($\approx 3 \text{ kV/mm}$). This results in power loss (P_{corona}) and several environmental effects, including audible noise, radio interference (RI), TV interference (TVI), and ozone (O_3) production.
- **Electromagnetic Interference (EMI):** the rapid switching of HVs generates electromagnetic fields, contributing to Electric and Magnetic Fields (EMF) that can induce disruptive voltages in nearby communication lines and sensitive electronic equipment.
- **Partial Discharges (PD):** localized electrical discharges within or on the surface of solid or liquid insulation, which cause progressive, cumulative degradation of the insulating material over time.
- **Dielectric breakdown:** the catastrophic and sudden failure of insulation when the applied electric field exceeds its withstand capability, leading to a temporary or permanent loss of insulating properties.

1.8.2 Constraints

HV imposes specific engineering challenges, including insulation coordination, managing clearance distances, mitigating corona loss, and meeting increased material and safety requirements.

- **Insulation coordination:** the systematic selection of insulation strength to withstand continuous operating voltage and transient overvoltages (e.g., Switching Surges (V_{sw}) and Lightning Impulses V_{imp}) with a defined safety margin, quantified by the Basic Insulation Level (BIL).
- **Clearance and creepage distances:** mandatory minimum physical distances in air (clearance) and along insulating surfaces (creepage) that must be maintained to prevent electrical flashover, with dimensions that increase with system voltage.
- **Environmental and safety impact:** HV infrastructure imposes land-use restrictions, visual impact concerns, and necessitates strict safety protocols to protect personnel and the public from the risks of electric shock and exposure to intense electric fields.

1.9 Specialized industrial and technological applications

HV is indispensable for the bulk transmission of electrical energy, and it also serves as a critical enabling technology in a diverse range of other scientific, industrial, and technical fields. These applications demonstrate the essential role of HV far beyond traditional power networks.

Table 1.3 Technological and industrial applications of HV.

Domain	Applications
Power networks	Overhead lines, underground cables, insulators, voltage measurement transformers (potential transformers), current measurement transformers (current transformers), disconnectors / isolators, circuit breakers, surge arresters, grounding / earthing systems, generators / alternators, electromagnetic compatibility.
Static electricity	Electrostatic motors, electrostatic precipitators (for pollution control), electrostatic printers / photocopiers, electrostatic painting / coating, interference with sensitive electronics.
Physics	electron microscopes, particle accelerators.
Medicine	Biological effects of electric fields, x-ray diagnostics (radiography, Computed Tomography (CT) scans), x-ray therapy (radiotherapy), dielectrophoresis (cell manipulation), electrosurgery..
Electronics	Cathode ray tubes, piezoelectric generators / transformers, electrical ignition systems (e.g., in vehicles), electronic camera flash, discharge lamps (e.g., neon, sodium vapor), Ultraviolet (UV) bactericidal lamps / purification.
Lightning	Lightning capture / study, lightning protection (lightning rods, air terminals, spark gaps, surge protection devices), aviation (aircraft static discharge & protection).
Nuclear Electro-Magnetic Pulse (NEMP)	Transmission line protection, antenna protection, electronic equipment hardening / protection, shielded enclosures / faraday cages.

1.10 Future trends and developments in HV technology

Current development in HV technology is driven by the economic and reliability demands of modern power systems, focusing on intelligent asset management and advanced material science.

The core strategy employs predictive analytics, combining computer-aided modeling of equipment physics, continuous condition monitoring, and sophisticated data analysis (e.g., machine learning, neural networks) to forecast failures and optimize maintenance in liberalized markets.

This is enabled by progress in advanced dielectrics, such as novel insulating polymers and superconductors, which permit higher operational stresses, increased power density, and greater reliability in demanding applications like aerospace. These trends converge with broader grid modernization efforts, including key technologies such as Ultra-High Voltage Alternating Current (UHVAC), Ultra-High Voltage Direct Current (UHVDC), HVDC Grids (multi-terminal), superconducting power links, solid-state transformers, and digital substations for the integration of renewables. This aims to enhance system capacity, efficiency, and resilience.

Chapter 2

Overview of Constraints Due to High Voltage

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2.1 Introduction

The operation of High Voltage (HV) systems introduces severe electrical, thermal, and environmental stresses with potential failure modes. The core role of HV engineering is to manage these risks through deliberate design, rigorous testing, and comprehensive protection schemes. The core objective of HV engineering is to ensure the safe, reliable, and economical transmission, distribution, and application of electrical energy at elevated potentials. This involves a fundamental methodological approach based on insulation coordination and rigorous testing.

The methodology systematically applies HV testing techniques (such as dielectric withstand tests, partial discharge measurement, and impulse testing) to materials, components, and systems. This process verifies their ability to withstand both steady-state operating stresses and transient overvoltages, thereby defining the design parameters and safety margins required to prevent electrical failure and ensure operational integrity.

2.2 Constraints related to voltage

The primary stress in HV systems is the high electric field. This imposes limitations and risks that dictate design, material selection, and operational procedures.

2.2.1 Insulation stress and breakdown

The fundamental challenge in HV engineering is managing intense electric field stress, which must be kept below a material's dielectric strength to prevent failure mechanisms such as flashover across surfaces or puncture through bulk insulation. This principle is central to the concept of insulation coordination.

The HV creates intense electric fields that can exceed the dielectric strength of insulating materials (solid insulation, air, oil, SF₆), leading to partial discharges, corona, or complete breakdown (flashover/arc).

2.2.1.1 General mechanisms of dielectric breakdown

Dielectric breakdown in solid materials often leads to permanent physical damage, such as melting, burning, or perforation of both the insulator and adjacent electrodes. This damage leaves a visible trace, a channel of weakened material, that creates a permanent weakness. If voltage is reapplied, subsequent breakdowns will typically follow this pre-existing path, often at a lower voltage threshold. As a result, once a solid insulator experiences an arc, it usually must be replaced.

In contrast, liquid and gaseous dielectrics can recover after a breakdown, provided the event was brief and did not alter the material's fundamental properties. The high mobility of particles allows the breakdown path to dissipate, effectively regenerating the insulator's integrity.

The ability of any material to withstand breakdown (its dielectric strength) varies by substance and is influenced by several factors. Key among these are:

- **Frequency:** dielectric strength generally decreases as frequency increases.
- **Temperature:** higher temperatures reduce dielectric strength.
- **Exposure time:** longer durations of applied voltage lower breakdown resistance.

Different breakdown mechanisms:

Despite nearly a century of research into the breakdown of solid insulators, and despite numerous theoretical models proposed to quantify these processes, our understanding of the

phenomenon remains incomplete. A key practical consideration is that both the breakdown mechanism and the dielectric strength vary significantly with the duration of the applied voltage. As a result, it is standard practice to categorize different breakdown mechanisms based on this timescale, a classification commonly illustrated in diagrams such as Fig. 2.1.

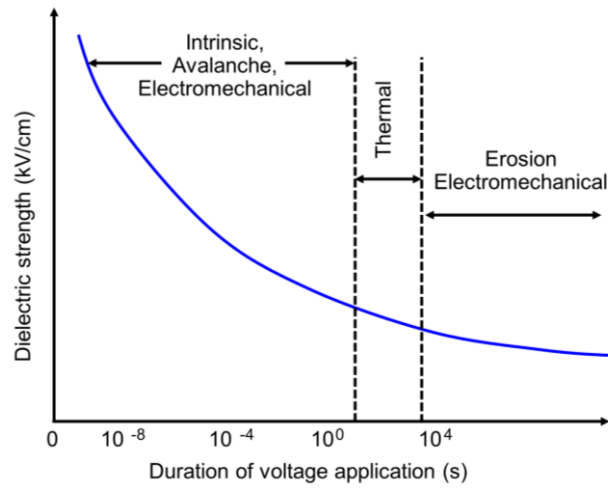


Fig. 2.1. Different types of breakdown in solid insulators.

a) Intrinsic breakdown

This type of failure, often termed "pure electrical breakdown" to separate it from other field-influenced mechanisms, is essentially the insulator's destruction by direct electrical forces. Contributing factors like heating or chemical reactions are excluded from this definition.

Pure electrical breakdown results when electrons and ions, accelerated by the electric field, collide with the insulator's atoms. The process occurs extremely rapidly, within about 10^{-8} seconds, and is considered electronic in nature. It requires very high field strengths, typically exceeding 10^6 V/cm, and is triggered when electrons gain enough energy from the field to jump from the valence band to the conduction band.

The key characteristics of the breakdown are:

1. **Fast development:** It occurs within microseconds or less. If the dielectric is not perforated very shortly after voltage application, a pure electrical breakdown will not occur.
2. **Voltage stability:** The critical breakdown voltage (V_c) is largely independent of both frequency and temperature.
3. **Experimental challenge:** In practice, reaching the true intrinsic breakdown voltage is rare. While many attempts have been made to measure it for various materials, there remains no definitive experimental proof to confirm an intrinsic breakdown, except in certain plastics like polyethylene. This makes the mechanism largely conceptual, representing an ideal maximum strength achievable if all secondary effects were eliminated.

b) Avalanche breakdown

Under controlled, uniform-field conditions with embedded electrodes, breakdown can result from just a single electron avalanche, analogous to the process in gases. If the electron's mean

free path (λ) is sufficient, its kinetic energy can surpass the ionization threshold, freeing another electron. This repeated process forms a growing electron avalanche. Breakdown occurs when this avalanche reaches a critical size, a concept that parallels the "streamer" theory of Raether, Meek, and Loeb developed for gaseous breakdown.

Electron avalanche

Consider two plane electrodes placed in a gas and subjected to a HV (Fig. 2.2).

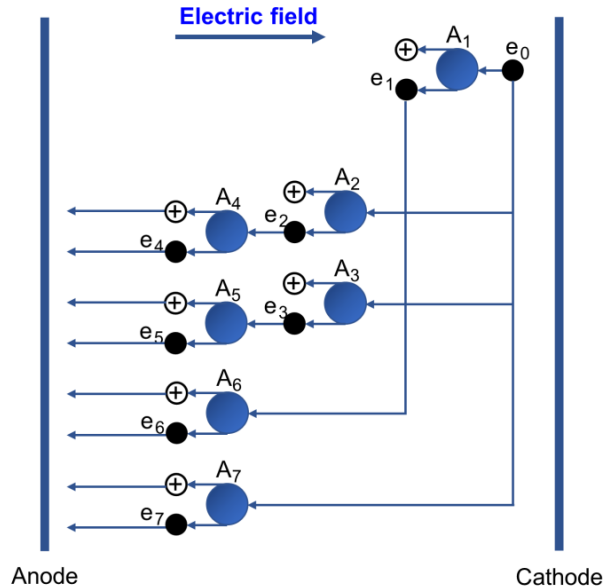


Fig. 2.2. Electron avalanche.

Primary electron (e_0): Created by ionization due to natural agents such as cosmic radiation and the Earth's radioactivity.

Avalanche Description:

The primary electron e_0 , accelerated by the electric field E , collides with an atom A_1 and ionizes it. A_1 releases an electron and itself becomes a positive ion.

Electrons e_0 and e_1 then collide and ionize two atoms A_2 and A_3 , which release two electrons e_2 and e_3 . These four electrons collide with 4 other atoms and ionize them, leading to an electron avalanche.

The multiplication of electrons continues according to this process until the avalanche reaches the anode.

c) Electro-thermal breakdown

Electro-thermal breakdown is a progressive process where an insulator subjected to HV begins to generate heat. As its temperature rises, the dielectric losses increase, causing further heating. This unstable thermal feedback loop intensifies until the accumulated heat damages the material (through melting, burning, cracking, or perforation) leading to failure at relatively low voltage levels. This breakdown becomes unlikely if the material has low initial loss ($\tan\delta$ in AC or

conductivity in DC) and a weak temperature dependence of these properties, combined with high thermal conductivity, which allows heat dissipation and stabilizes temperature.

Key considerations:

- Generally, thermal breakdown occurs in the region at the center of the electrodes where cooling is difficult, while electrical breakdown occurs at the sharp parts of the electrodes in regions with concentrated electric field E (edges, manufacturing defects of the dielectric...). It is also possible to observe a transition from electrical breakdown to thermal breakdown and vice versa.
- As a rule, increasing the thickness of the dielectric does not proportionally increase the critical voltage V_c . In the case of thermal breakdown, this is explained by the difficulty of dissipating heat for large thicknesses.
- When an insulator is heated, initially its resistance increases due to the elimination of any trace of moisture. After the insulator is completely dry, the resistivity then begins to drop.
- It is not necessary for the entire volume to be heated; it is sufficient that a small part where the heating is intense is altered.

d) Electro-mechanical breakdown

Substances that can deform significantly without breaking may rupture when the compressive electrostatic forces applied to the insulator under test exceed its mechanical compressive strength. The compressive forces result from the electrostatic attraction between the external charges that appear when the voltage is applied.

The pressure exerted when the field reaches about 10^6 V/cm can be several kilo-Newtons per square meter (kN/m²).

For an insulator with initial thickness d_0 and Young's modulus Y , which decreases to a thickness $d(m)$ under an applied voltage V , the electrically developed compressive force is in equilibrium with the mechanical compressive resistance if:

$$\epsilon_0 \epsilon_r = \frac{V^2}{2d^2} = Y \ln\left(\frac{d_0}{d}\right)$$

or equivalently

$$V^2 = d^2 \frac{2Y}{\epsilon_0 \epsilon_r} \ln\left(\frac{d_0}{d}\right)$$

where ϵ_0 and ϵ_r are the permittivity of free space and the relative permittivity of the dielectric, respectively.

By differentiating with respect to d , we find that the expression has a maximum when $\frac{d}{d_0} = e^{[-1/2]} = 0.6$. Therefore, no real value of V can produce a stable value of $\frac{d}{d_0}$ below 0.6. If

breakdown does not occur at this value, any further increase in V makes the thickness unstable and causes the insulator to rupture. The maximum apparent dielectric strength is then given by:

$$E_c = \frac{V}{d_0} = 0.6 \sqrt{\frac{Y}{\epsilon_0 \epsilon_r}}$$

e) Breakdown at the triple point

In practical insulation systems, the solid insulator is subjected to the conjunction with one or more other materials. If one of the materials is, for example, a gas or a liquid, then the measured breakdown voltage will be more influenced by the medium with the lower dielectric strength than by the solid itself.

A cross-section of a simple example is shown in the figure below, which represents the testing of a dielectric disk between sphere-plane electrodes. Ignoring the field distribution, i.e., assuming a homogeneous electric field, if we consider an elementary cylindrical volume of cross-section dS crossing the electrodes at a distance X as shown in the figure, a fraction V_1 of the voltage appears in the air, given by:

$$V_1 = \frac{V \cdot d_1}{d_1 + \frac{\epsilon_1}{\epsilon_2} d_2}$$

where d_1 and d_2 represent the thicknesses of media 1 and 2 in the figure, and ϵ_1 and ϵ_2 are their respective dielectric constants.

As shown in the Fig. 2.3, the field strength in the gaseous part increases more as X decreases and reaches very high values when d_1 becomes very small (point B). Consequently, the gas breaks down at a relatively low applied voltage. The concentration of electric charge estimated at the end of a local discharge channel is sufficient to produce a local field on the order of 10 MV/cm, which is higher than the intrinsic breakdown value. The breakdown develops, and complete breakdown is the result of a succession of many small breakdowns produced within the insulator, advancing step by step through the entire thickness of the insulator.

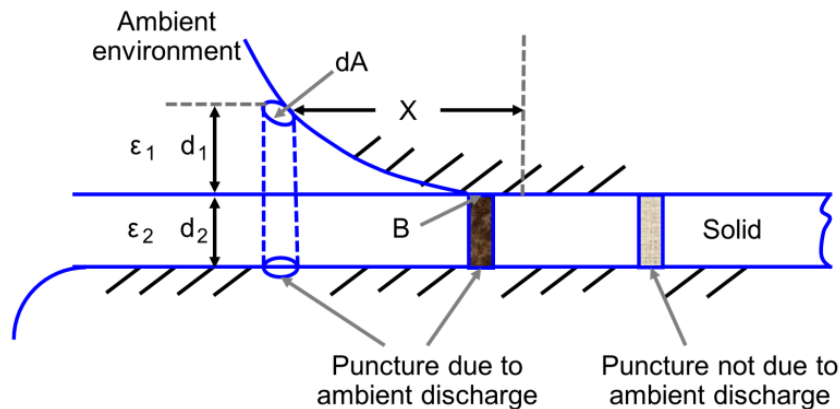


Fig. 2.3. Schematic representation of breakdown at triple point.

f) Partial Discharge (PD) breakdown

Insulators commonly used in HV applications are never perfectly homogeneous. The material contains cavities of various shapes and sizes. These are the main cause of aging and the long-term degradation of solid insulation. Measuring partial discharges is considered a very important tool for improving the reliability of HV insulation systems. The interpretation and analysis of the measured quantities constitute the key to estimating the risk of insulation failure.

Regardless of the deterioration mechanism, it results in the slow erosion of the insulator and a considerable reduction in the V_c .

Consider a solid insulator containing a gaseous inclusion. This can be modeled by the circuit shown in the Fig. 2.4.

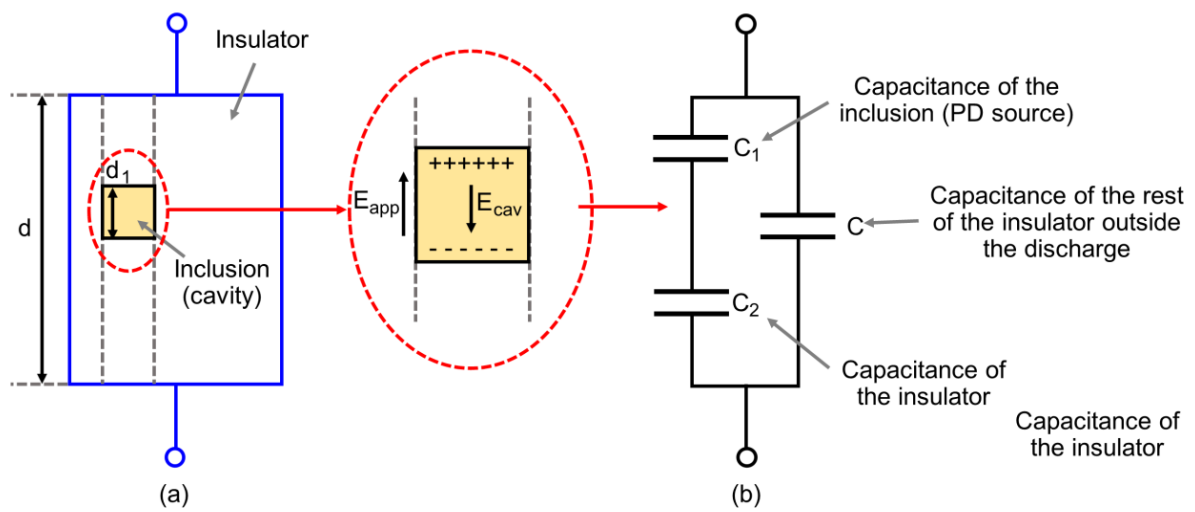


Fig. 2.4. Equivalent diagram (a) and equivalent electrical circuit (b) a solid insulator containing a gaseous cavity.

Let us consider a dielectric plate of thickness d , inside which there is a flat disk-shaped cavity of height d_1 and area S .

The capacitance of the cavity is:

$$C_1 = \epsilon_0 \epsilon_{r1} \frac{S}{d_1}$$

With $\epsilon_{r1} = 1$, the relative permittivity of the gaseous cavity.

The capacitance of the adjacent dielectric (assumed lossless), with area S and height $d - d_1$, is:

$$C_2 = \epsilon_0 \epsilon_{r2} \frac{S}{(d - d_1)}$$

With ϵ_{r2} being the relative permittivity of the dielectric.

The voltage V_{c1} across the cavity is therefore:

$$V_{c1} = \frac{C_2}{(C_1 + C_2)} \cdot V$$

Where V is the total applied voltage.

Substituting the expressions for the capacitances, we find:

$$V_{c1} = \frac{V}{1 + \frac{1}{\epsilon_{r2}} \left(\frac{d}{d_1} - 1 \right)}$$

2.2.1.2 Breakdown in gaseous insulation

During the electron avalanche, the fast electrons are absorbed by the anode, while the slower positive ions form a space charge within the gas. The size of the space charge depends on the gas pressure.

I. INFLUENCE OF PRESSURE

a) Low pressure: Since the atomic density is low, the space charge is such that it generates a weak and negligible electric field $E_c \Rightarrow$ TOWNSEND MECHANISM.

b) High pressure: The atomic density is high, and the space charge is substantial; it creates a considerable electric field E_c , which plays a major role in breakdown $\Rightarrow$ STREAMER MECHANISM.

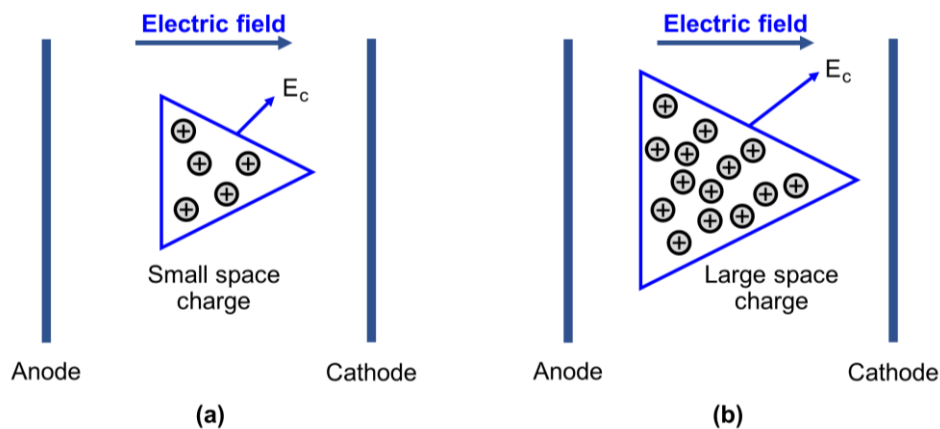


Fig. 2.5. Electron avalanche: (a) low pressure and (b) high pressure.

II. TOWNSEND MECHANISM (Low pressure)

For short distances (max. 1 m), Townsend's theory is valid for pressures below 0.1 to 1 atmosphere, while the Streamer theory is valid for high pressures (≥ 1 atm).

Phase 1: A primary electron located near the cathode causes a primary electron avalanche.

Phase 2: The electrons are absorbed by the anode, while the positive ions bombard the cathode with their kinetic energy to extract secondary electrons.

Phase 3: The (secondary) electrons emitted from the cathode due to bombardment create new secondary avalanches and cause the gas to break down.

Notes:

- In the Townsend mechanism, the discharge spark occurs as soon as the cathode emits secondary electrons.

- The Townsend discharge ranges from 10^{-8} to 10^{-6} A and is therefore not very luminous. The luminosity is fairly uniform throughout the space between the electrodes.

Influence of the Cathode:

The V_c depends on the type of cathode used. Assume 3 cathodes made of different materials: Aluminum, Nickel, and an Al-Ni Alloy.

The electron extraction energies are:

- Nickel $W_{\text{ext}} = 0.075$ eV;
 - Aluminum $W_{\text{ext}} = 0.1$ eV;
 - Al-Ni Alloy $W_{\text{ext}} = 0.15$ eV.
- Consequently, $V_c(\text{Al-Ni}) > V_c(\text{Al}) > V_c(\text{Ni})$.

Coefficients α and γ

- **Ionization coefficient α :** The number of electrons created by ionization by one electron over a distance of 1 cm.
- **Coefficient γ :** The number of secondary electrons emitted from the cathode due to bombardment by one positive ion.

The first Townsend coefficient, also called the ionization coefficient, is higher in noble gases due to their ease of ionization (neon, argon, metal vapor...). This coefficient, however, is smaller in the case of electronegative gases.

III. PASCHEN'S LAW

Consider a chamber filled with a gas, in which the pressure can be varied (Fig. 2.6). Paschen's Law describes the variation of the critical voltage as a function of the product $p * d$ (Fig. 2.7).

- V_c : Critical breakdown voltage
- P : Gas pressure
- d : Inter-electrode distance
- $V_{c_{\min}}$: Minimum critical breakdown voltage (If $V < V_{c_{\min}} \Rightarrow$ No breakdown occurs).

Paschen's Law is studied in a homogeneous electric field.

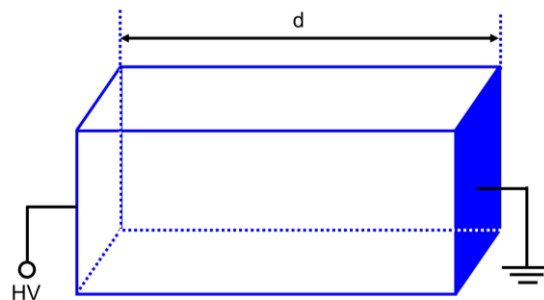


Fig. 2.6. Chamber filled with gas.

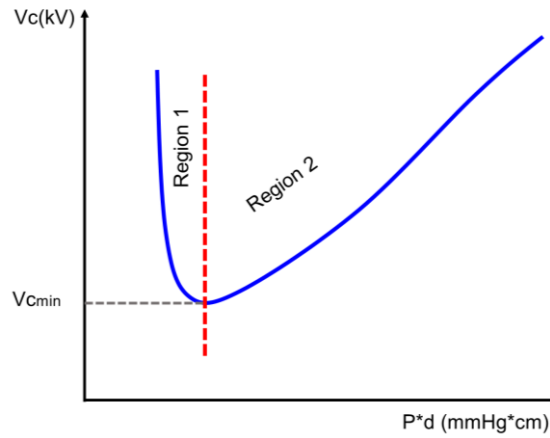


Fig. 2.7. Paschen's curve.

Paschen's minimum

From the Paschen's curve, it can be observed that there is a minimum voltage value V_{cmin} . When the voltage is below this value, the gaseous gap cannot break down at any length or under any pressure.

The Paschen's curve shows a minimum, which corresponds to 300–400 V in air at atmospheric pressure. This minimum is not very sharply defined and depends on the condition of the electrodes and the gas. This means that below this voltage, no ignition is possible. Thus, at 220 V, we can only have inductive voltage-breaking sparks and never sparks caused by the voltage itself.

Interpretation of the curve: (d constant)

- **Region 1: V_c decreases with pressure P :** When pressure increases, the atomic density increases; there are more particles and thus more ionization by collision. The gas becomes more conductive, and breakdown becomes easier $\Rightarrow V_c$ decreases.
- **Region 2: V_c increases with pressure P :** When pressure increases further, despite the increased probability of ionization by collision, λ becomes so small that the electron energy $W = \int q \cdot E \cdot dr = q \cdot E \cdot \lambda$ required to ionize atoms becomes insufficient. There is little ionization, and breakdown becomes difficult $\Rightarrow V_c$ increases.

According to Paschen's Law, it is more advisable to use gases at high pressure (and sometimes at very low pressure) in HV equipment, capacitors, cables, etc. The experimental validity of Paschen's Law is verified at short distances up to 0.1 mm and pressures up to 10 atmospheres.

IV. STREAMER MECHANISM (High Pressure)

The mechanism proceeds as follows:

Phase 1: A primary electron located near the cathode triggers a primary electron avalanche. Since the speed of electrons is approximately 100 times greater than that of ions, the avalanche develops like a cloud of electrons, leaving behind a positive space charge (Fig. 2.8.a). The

electrons are absorbed by the anode, while the positive ions form a positive space charge within the gas. The electric field E_c of this space charge is maximum at the head of the avalanche (Fig. 2.8.a).

Phase 2: Secondary electrons are created by photo-ionization around the space charge. These electrons trigger small secondary avalanches at the head of the primary avalanche (Fig. 2.8.b). The field of the space charge reinforces the field between the head of the avalanche and the cathode and also creates a radial component.

Origin of secondary electrons: The head of the avalanche is the site of intense activity (collisions between electrons and positive ions), which is a source of photons that are absorbed by the surrounding gas. In particular, excited nitrogen molecules can emit photons with energy exceeding 13 eV, which is sufficient to ionize oxygen molecules whose ionization energy is only 12.2 eV.

Phase 3: The space charge increases in volume and becomes a "Streamer." New secondary avalanches join the primary avalanche, and the streamer advances (Fig. 2.8.c(I)). When it reaches the cathode, breakdown occurs at that moment (Fig. 2.8.c(II)).

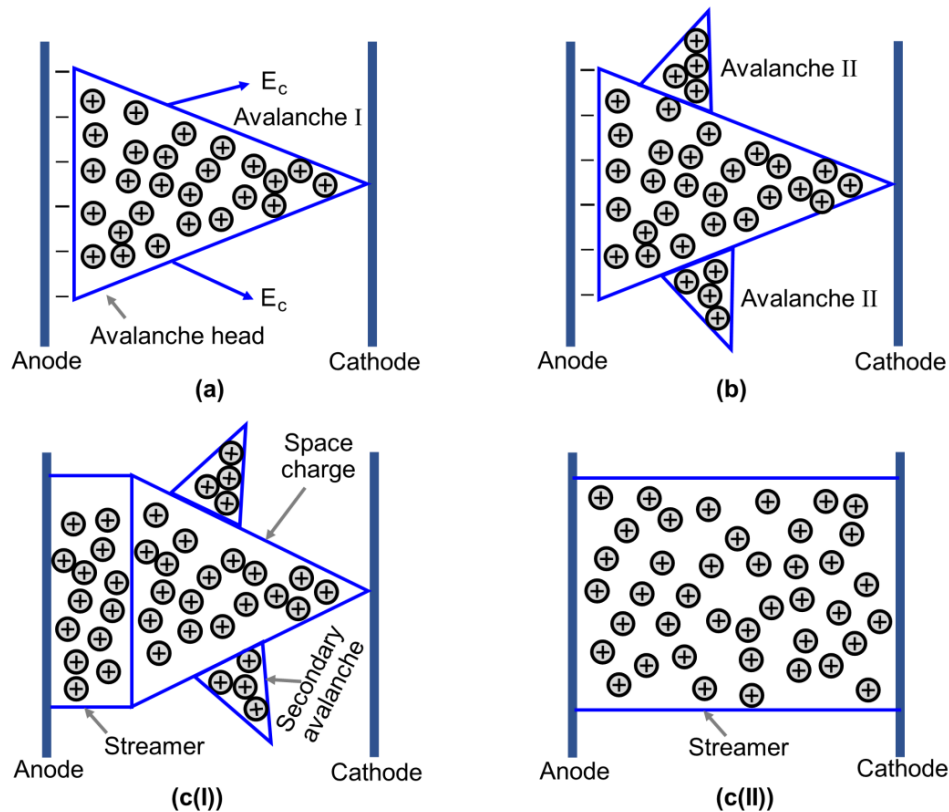


Fig. 2.8. Streamer mechanism: (a) phase 1, (b) phase 2 and (c) phase 3.

2.2.1.3 Electric fields in geometric configurations

A comprehensive understanding of electric field behavior is critical in HV system design. This importance stems from the fact that the intensity and distribution of the electric field directly dictate insulation stress. Managing this stress is paramount because excessive fields

necessitate large, bulky equipment to prevent dielectric breakdown and also cause rapid insulation aging, thereby shortening the lifespan of devices. Consequently, optimizing insulation systems requires a precise analysis of how these fields are calculated and behave in practical geometries (such as coaxial cables, sphere-to-sphere gaps, or conductor-to-ground configurations) to reduce equipment size without compromising quality or durability.

1) Two parallel plane conductors

Consider two infinite parallel plane electrodes separated by a distance d and an insulating material with charge density $\rho = 0$. One electrode is raised to a continuous potential U and the other is grounded, as shown in Fig. 2.9 below.

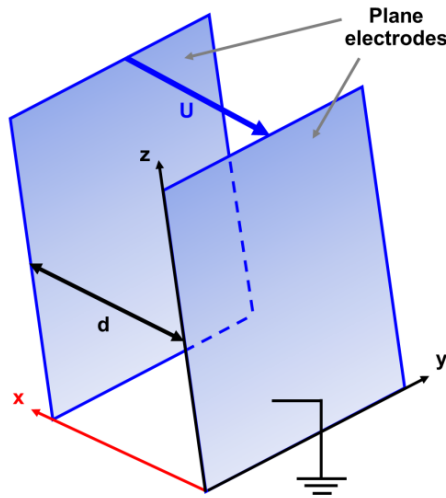


Fig. 2.9. Parallel plate capacitor.

If the electrodes are infinite along the y and z axes, the electric potential V depends only on the x coordinate, and Laplace's equation reduces to:

$$\frac{\partial^2 V}{\partial x^2} = 0$$

Integrating this equation yields:

$$V(x) = K_1 x + K_2$$

Applying the boundary conditions: at $x = 0$, $V = 0$; and at $x = d$, $V = U$, we obtain:

$$V(x) = \frac{U}{d} x$$

Hence, the absolute value of the electric field is:

$$E = -\frac{dV}{dx} = \frac{U}{d}$$

In a parallel-plane electrode configuration, the electric field between the electrodes is uniform.

2) Two coaxial cylindrical conductors (case of a unipolar coaxial cable)

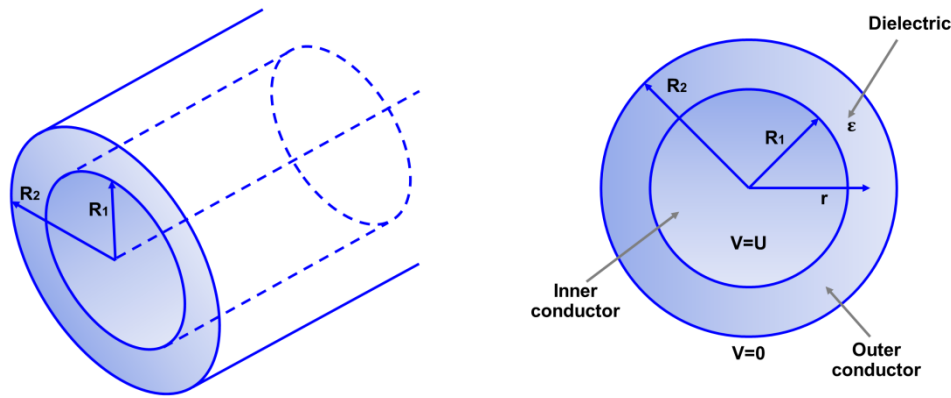


Fig. 2.10. Cylindrical capacitor.

This electrode configuration, shown in Fig. 2.10 above, presents perfect rotational symmetry if considered of infinite length along its axis of revolution O_z . These electrodes form a cylindrical capacitor. Furthermore, if the dielectric is devoid of charges ($\rho = 0$), the medium is governed by Laplace's equation. In cylindrical coordinates we obtain:

$$\frac{1}{r} \frac{\partial}{\partial r} \left(r \frac{\partial V}{\partial r} \right) = 0$$

After integrating for the electric potential V and applying the boundary conditions (for $r = R_1$, $V = U$ and for $r = R_2$, $V = 0$) and the relation $\vec{E} = -\nabla V$, we obtain the electric field between the conductors:

$$E(r) = \frac{U}{r \ln \frac{R_2}{R_1}}$$

Contrary to the plane electrode system, the coaxial cylindrical configuration presents a non-homogeneous electric field distribution. The distribution is radial, with the electric field being maximum at the surface of the inner electrode (with a small radius of curvature) and minimum at the surface of the outer electrode:

$$E_{\max} = E(R_1) = \frac{U}{R_1 \ln \frac{R_2}{R_1}} \text{ and } E_{\min} = E(R_2) = \frac{U}{R_2 \ln \frac{R_2}{R_1}}$$

We can easily deduce the linear capacitance C_l , linear inductance L_l , characteristic impedance Z , and insulation resistance R of the cable:

$$C_l = \frac{2\pi\epsilon}{\ln \frac{R_2}{R_1}} \text{ and } L_l = \frac{\mu}{2\pi} \ln \frac{R_2}{R_1}$$

$$Z = \sqrt{\frac{L_l}{C_l}} = \frac{1}{2\pi} \sqrt{\frac{\mu}{\epsilon}} \ln \frac{R_2}{R_1} \text{ and } R = \frac{1}{2\pi\sigma} \ln \frac{R_2}{R_1}$$

In insulation techniques, the maximum electric field must be less than the dielectric strength of the insulator.

3) Two concentric conducting spheres

We adopt the same calculation procedure as before. In spherical coordinates, Laplace's equation reduces to:

$$\frac{1}{r^2} \frac{\partial}{\partial r} \left(r^2 \frac{\partial V}{\partial r} \right) = 0$$

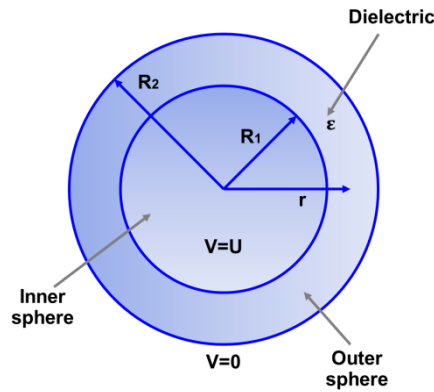


Fig. 2.11. Spherical capacitor.

After integrating for the electric potential V and applying the boundary conditions (for $r = R_1$, $V = U$ and for $r = R_2$, $V = 0$, Fig. 2.11 above) and the relation $E = -\frac{dV}{dr}$, we obtain the electric field between the conductors:

$$E(r) = \frac{U}{r^2} \frac{R_1 R_2}{R_2 - R_1}$$

We again find that the electric field is non-homogeneous between the conductors. It is maximum at the surface of the inner sphere and minimum at the surface of the outer sphere:

$$E_{\max} = E(R_1) = \frac{U}{R_1} \frac{R_2}{R_2 - R_1} \text{ and } E_{\min} = E(R_2) = \frac{U}{R_2} \frac{R_1}{R_2 - R_1}$$

4) Two parallel cylindrical conductors (case of an overhead line)

Two conductors of radius r are separated by a distance d and are subjected to a potential difference U , Fig. 2.12. One carries a positive charge $+Q$ and the other a negative charge $-Q$.

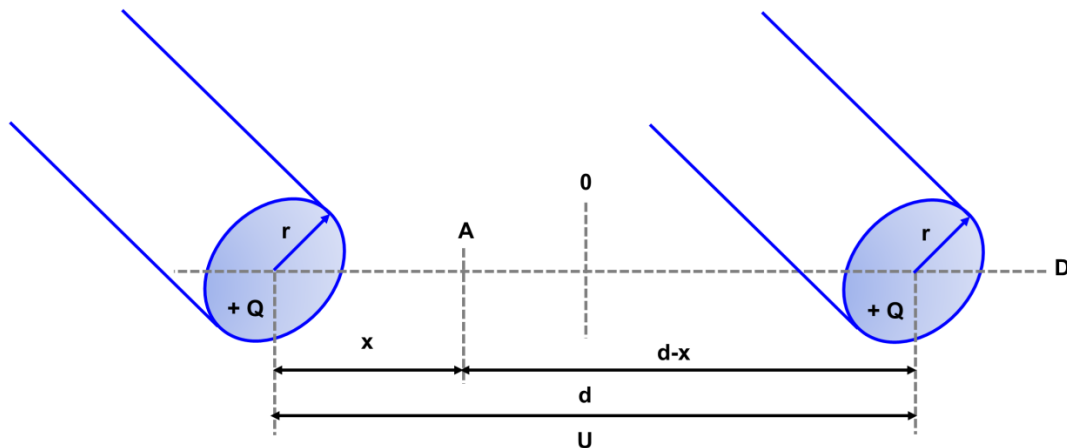


Fig. 2.12. Parallel cylindrical conductors (single-phase line).

Solving Laplace's equation in the medium between the conductors is complex. However, applying Gauss's theorem and the superposition principle allows us to obtain the electric field E along axis D . At point A with coordinate x , the electric field is:

$$E(x) = \frac{Q}{2\pi\epsilon} \left(\frac{1}{x} + \frac{1}{d-x} \right)$$

The electric potential is obtained by integrating $E(x)$:

$$V = \int_r^{d-r} E(x) dx = \frac{Q}{2\pi\epsilon} \ln \frac{(d-r)^2}{r^2} \approx \frac{Q}{\pi\epsilon} \ln \frac{d}{r}$$

Hence the expression for the charge Q :

$$Q = \frac{\pi\epsilon U}{\ln \frac{d}{r}}$$

The electric field is expressed as a function of the potential in the form:

$$E(x) = \frac{U}{2} \left(\frac{1}{x} + \frac{1}{d-x} \right) \frac{1}{\ln \frac{d}{r}}$$

We again find that the field is non-homogeneous and maximum at the surface of the conductors (at $x = r$).

$$E_{\max} = \frac{1}{2} \left(\frac{1}{r} + \frac{1}{d-r} \right) \frac{U}{\ln \frac{d}{r}} = \frac{1}{2} \frac{d-r+r}{r(d-r)} \frac{U}{\ln \frac{d}{r}} \approx \frac{U}{2r \ln \frac{d}{r}}$$

Schwaiger factor

Consider two electrodes of any geometric shape, separated by a distance d and subjected to a potential difference U , as shown in Fig. 2.13 below.

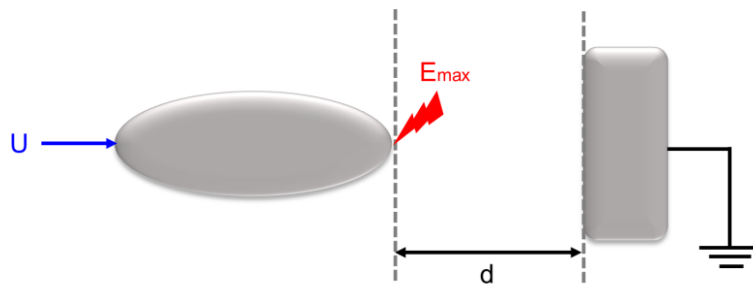


Fig. 2.13. Schwaiger factor for an arbitrary electrode system.

The equivalent homogeneous electric field is $E_h = \frac{U}{d}$. The ratio $\eta = \frac{E_h}{E_{\max}} = \frac{U}{(E_{\max} \times d)}$ is called the Schwaiger factor. It defines the maximum acuity of an electric field between two electrodes.

Application to previously studied electrode systems

- a) Two parallel plane electrodes: $\eta = 1$
- b) Two coaxial cylindrical conductors: $\eta = \frac{R_1}{R_2 - R_1} \ln \frac{R_2}{R_1}$
- c) Two parallel cylindrical conductors: $\eta = \frac{2r}{d} \ln \frac{d}{r}$
- d) Two concentric spheres: $\eta = \frac{R_1}{R_2}$

2.2.2 Overvoltage phenomena

These are voltages exceeding the system's maximum permissible operating voltage, posing severe threats to insulation:

- **External overvoltages (lightning surges):** high magnitude, short duration impulses (1.2/50 μ s wave) induced by direct or indirect lightning strikes on or near lines.
- **Internal overvoltages (switching surges):** generated by system operations like switching inductive/capacitive loads, fault initiation/clearing, or transformer energization. They have lower magnitude but longer duration (e.g., 250/2500 μ s wave) and can be particularly dangerous for equipment insulation.
- **Temporary Overvoltages:** sustained power-frequency overvoltages (seconds to minutes) caused by ground faults, Ferranti effect (on lightly loaded long lines), or load rejection.

Fig. 2.14 illustrates the relationship between surge voltage and pulse duration for the three primary overvoltage threats: direct lightning strikes, characterized by extremely HV and very short duration, resulting in high-energy impulses that are destructive despite their rarity; induced lightning surges, with moderate voltage and duration, posing a significant risk to electronics; and switching surges, which have lower voltage but much longer duration, delivering substantial energy over time and presenting a distinct challenge to system insulation.

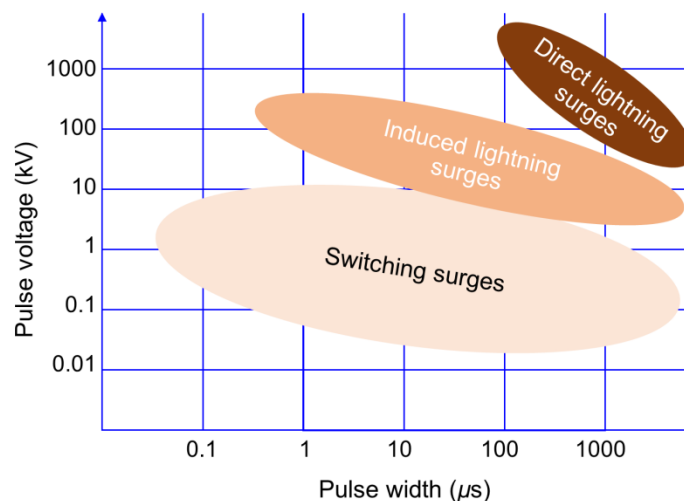


Fig. 2.14. Types of surge.

The chart (Fig. 2.14) underscores that effective protection design must consider both the peak magnitude and the duration of a transient, as these parameters define its energy content and potential for damage.

2.2.3 Corona and Radio Interference (RI) / Audible Noise (AN)

Corona discharge is a direct consequence of high electric fields on conductors, leading to local air ionization, energy loss, and various forms of electromagnetic emissions.

When the electric field strength exceeds the critical breakdown strength of air (~ 30 kV/cm) near conductors, it ionizes the air, causing corona discharge. This results in:

- Power loss: energy dissipation, especially in humid/bad weather.
- Electromagnetic interference: RI.
- AN: a crackling or humming sound, an environmental concern near lines.
- Chemical degradation: production of ozone (O_3) and nitrogen oxides.

2.2.4 Electrostatic induction and safety

HV lines create strong electrostatic fields. This can induce voltages on nearby ungrounded objects (fences, vehicles, parallel conductors), a direct safety hazard that poses a serious shock risk to personnel, and can interfere with secondary systems.

2.3 Constraints related to electric current

This section examines the limitations imposed by the flow of electric current in HV systems. Current-related constraints are primarily concerned with the thermal and mechanical stresses on conductors, cables, and equipment like transformers and circuit breakers. Exceeding design current limits can lead to overheating, insulation degradation, accelerated aging, and in extreme cases, catastrophic failure. The fundamental constraint is that the operational current I must not exceed the equipment's continuous thermal rating (I_{rated}), while also withstanding higher, temporary fault currents (FCs). Proper current management is essential for system security and equipment longevity.

2.3.1 Overcurrent

Overcurrent is a general condition where the current in a circuit exceeds its designated normal operating value. It is a key design and operational constraint, as it directly dictates the required capacity and protection settings for all system components. Overcurrent conditions are broadly categorized into two types based on their magnitude and duration: overloads and short circuits. The primary design parameter is the equipment's short-circuit withstand rating, which ensures it can survive the immense electromagnetic forces and thermal energy generated during a fault until protective devices clear it.

2.3.1.1 Overload

An overload is a sustained overcurrent confined to normal conductive paths, typically between 1 and 10 times the rated current (I_n). It results from increased power demand, such as motor start-up, blocked motors, or excessive connected load. The primary effect is a temperature rise in conductors governed by the I^2t heating effect, leading to insulation degradation and premature aging.

The allowable overload is often defined by thermal limits, such as those for an overhead conductor:

$$T_{\max} = \sqrt{\frac{(T_{\max} - T_{\text{amb}}) \cdot A \cdot \alpha}{R_{\text{dc}}(1 + \beta(T_{\max} - 20))}}$$

where $T_{\max}$ is max conductor temperature, T_{amb} is ambient temperature, A is cross-sectional area, α is heat dissipation coefficient, β is the temperature coefficient of resistance, and R_{dc} is DC resistance.

Overloads are categorized as :

- Temporary overload: e.g., increase in current of a hoisting motor during ascent.
- Prolonged overload: e.g., motor stalled / multiple heaters on the same outlet.

Protection relies on thermal devices like relays, fuses, or circuit breaker thermal trips, which operate with a time delay to permit harmless temporary surges.

Table 2.1. Common causes of overloads.

Cause category	Specific examples
Insufficient maintenance	Buildup of dust, dirt, or foreign particles.
Equipment aging	Worn mechanical parts, insufficient lubrication.
Thermal issues	Degraded insulation, failing components due to heat.
Improper application/use	Undersized capacity for the load, excessive or continuous operation beyond rating.
Power quality issues	Transient voltage surges and sags.
Low-level ground faults	Metallic debris, water damage leading to minor leakage currents.

2.3.1.2 Short-circuit (fault current)

A short circuit is an overcurrent resulting from an abnormal low-impedance connection (e.g., phase-to-phase or phase-to-ground). Fault magnitudes typically range from 10 to 1000 times the I_n and last for cycles to seconds until cleared by protection. The maximum prospective current at a point is governed by the system's Thévenin equivalent impedance:

$$I_{\text{sc}} = \frac{V_n}{\sqrt{3}Z_{\text{th}}}$$

This current produces severe electrodynamic stress (force proportional to I_{sc}^2) and thermal stress (energy proportional to $I_{sc}^2 t$). Equipment must withstand these stresses, as defined by the condition:

$$I_{sc}^2 \cdot t_{oper} \leq I_{cw}^2 t_{cw}$$

Where :

I_{sc} : Short-circuit current (in kA or A) — The actual maximum FC that can flow at the equipment's location.

t_{oper} : Operating time (in seconds) — The total time the I_{sc} actually flows until the protective device (circuit breaker, fuse) clears the fault. This includes the relay's detection time plus the breaker's opening time.

I_{cw} : Short-circuit withstand current (in kA or A) — A manufacturer's rating. The maximum RMS current the equipment can withstand for a specified time without damage.

t_{cw} : Withstand time (in seconds) — The manufacturer's rated time (e.g., 1s, 3s) for which the equipment is designed to carry the I_{cw} current.

Common causes include foreign conductive objects, component failure, overvoltages, and external influences (Table 2.2).

Table 2.2. Common causes of short-circuits.

Primary cause	Specific examples and mechanisms
Foreign conductive objects	Accidental contact with tools (e.g., screwdrivers), loose hardware (e.g., bolts, washers).
Internal component failure	Insulation breakdown, semiconductor junction failure, aging/deterioration of materials.
Transient overvoltages	Lightning strikes, switching surges, sudden interruption of inductive loads.
Severe insulation to ground fault	Direct phase-to-ground contact due to damaged cable insulation or equipment enclosure breach.
External environmental hazards	Flooding (causing tracking/breakdown), fires (damaging insulation), excessive vibration (leading to fatigue and contact).

Fault types are categorized as:

- Single-phase-to-ground (most common): this is a fault between one phase and ground.
- Three-phase (highest current): this involves the connection of all three phases; it results in the highest I_{sc} .
- Phase-to-phase: this is a fault between two phases. The resulting current is lower than in a three-phase fault, except when it occurs very close to a generator.
- Two-phase-to-ground: this is a fault involving two phases and ground.

Rapid clearing by protection systems is critical to prevent cable/equipment destruction and significant economic damage.

2.3.2 Constraints related to protection

The protection system must be designed to fulfill specific functional constraints without compromising normal network operation, while also adhering to fundamental operational principles. Its core functional constraints are:

- ✓ It must isolate only the faulted section, maintaining system continuity, particularly complex in meshed networks.
- ✓ It must clear faults within a critical time (often <100 ms) to prevent the fault energy (I^2t) from exceeding the thermal and mechanical withstand ratings ($I_{cw}^2 t_{cw}$) of the protected equipment.
- ✓ It must not restrict permissible network configurations (e.g., looped or meshed operation).
- ✓ It must remain inoperative (secure) during normal system events, including switching maneuvers, voltage/frequency variations, transitory overloads, and electromechanical oscillations from generator transients.

2.4 Protection system constraints

In HV environments, protection systems face significant challenges, including managing the extremely high magnitude of FCs, ensuring the fast transient response of instrument transformers (CTs, VTs), and mitigating communication delays in wide-area protection and tripping schemes.

Protection against overcurrents is a fundamental requirement for safeguarding equipment, maintaining system stability, and ensuring personnel safety. Its core function is to detect abnormal current conditions (overloads and short circuits) and initiate the timely isolation of the faulty section from the healthy network. The function of protective devices is to protect:

- Sources (transformers, generators) and conductors/cables (wires, cables, busbars) from overloads and short circuits.
- Loads/receivers (motors, appliances) from overloads (as a short circuit typically results in immediate and severe damage to the load).

2.4.1 Principles of protection

Protective devices perform the dual function of detecting disturbances and interrupting the faulted circuit. This capability (detection and interruption) classifies overcurrent protection devices into three protective scopes: specific overload protection, specific short-circuit protection, or comprehensive protection covering both conditions.

2.4.2 Principle of overload protection

Effective overload protection is achieved through protection coordination, which aligns the thermal withstand characteristic of the equipment (cable, motor, transformer) with the time-current tripping characteristic of the protective device. The principle is based on preventing

thermal damage by allowing temporary, harmless overloads (e.g., motor starting) while ensuring timely disconnection before sustained overheating causes insulation degradation. This is implemented using devices with inverse-time tripping curves, where the t_{oper} decreases as the overcurrent magnitude increases, thereby mimicking the I^2t heating behavior of the protected component.

2.4.3 Principle of short-circuit protection

Short-circuit protection requires the rapid interruption of high-magnitude FCs to prevent thermal and mechanical damage. Its operation must ensure that the fault energy I^2t does not exceed the equipment's short-time thermal withstand rating and that the peak current I_p remains below the electrodynamic withstand capability of conductors and structures.

A key design parameter is the breaking capacity of the protective device, which must be coordinated with the thermal limit of the protected conductor. This limit is defined by the relationship between cross-section S , fault current I_{sc} , and duration t , expressed as:

$$S = \frac{I_{\text{sc}}\sqrt{t}}{K}$$

where the coefficient K depends on the conductor material and insulation (e.g., 115 for PVC-insulated copper, 74 for PVC-insulated aluminum). Devices such as fuses, instantaneous relays, or differential protection must operate within this calculated time to prevent insulation failure or mechanical rupture, while maintaining selectivity with other protective devices in the system.

2.5 Key qualities of a protection system

The design and operation of any protection scheme are governed by four essential, often competing, principles:

2.5.1 Selectivity

Selectivity (discrimination) is the coordinated design principle ensuring that only the faulted section of an electrical network is isolated, maintaining continuity of service and providing backup protection. Its implementation, dependent on network structure and neutral grounding, employs three fundamental methods:

- ✓ Current-based (Amperometric) Selectivity
- ✓ Time-based (Chronometric) Selectivity
- ✓ Logic-based (Communication-aided) Selectivity

These methods create a hierarchical coordination of protection settings, enabling rapid fault isolation while minimizing supply disruption.

2.5.2 Speed

The total fault clearing time, critical for limiting damage and maintaining system stability, comprises two sequential components: the protection relay t_{oper} (typically tens of milliseconds) and the circuit breaker opening time. Combined, these must achieve a total clearing time within the equipment's withstand capability, often 100–200 milliseconds for primary protection.

2.5.3 Sensitivity

Protection sensitivity is defined by its operational range, bounded by a well-defined maximum FC (set by installation design) and a more challenging minimum detectable current. This lower limit, often corresponding to high-resistance or distant faults under exceptional network conditions, is critical for ensuring reliable operation across the entire required spectrum.

2.5.4 Reliability

Correct protection operation is defined by two fundamental reliability criteria: dependability (operating when required for all faults) and security (not operating unnecessarily). Incorrect operation manifests as either a failure to operate (loss of dependability) or an unwanted operation (loss of security). Achieving both often requires redundant schemes such as main and backup protection.

2.5.5 Simplicity and economy

While optimal performance in selectivity, speed, sensitivity, and reliability is the design goal, practical engineering imposes two critical constraints: simplicity and economy. A protection scheme must be as simple as possible to ensure ease of maintenance, testing, and commissioning while minimizing the risk of misoperation or misunderstanding. This simplicity must be balanced against economic feasibility, considering the total cost of ownership, including initial investment, installation, and long-term operation. The design must therefore avoid unnecessary complexity, using the most straightforward and cost-effective architecture that adequately fulfills the required protection functions and reliability standards.

2.6 Protection devices

Protection devices are components that detect abnormal conditions, mainly overcurrents, and trigger circuit disconnection based on predefined settings. They vary from simple to programmable units and are coordinated to ensure system selectivity, speed, and reliability.

2.6.1 Fuse

A fuse is a calibrated, sacrificial protective device that acts as the deliberate weak link in an electrical circuit, providing simple, sacrificial overcurrent protection, commonly used in MV

systems and for HV instrument transformer protection.. It operates by melting its element to interrupt the circuit when current exceeds its rated value for a sufficient duration.

Key characteristics include non-resetability, cost-effectiveness, and very fast short-circuit interruption. Selection is based on application-specific types:

- **gG** (General Purpose): Full-range protection (overload and short circuit).
- **aM** (Motor Protection): Withstands motor-starting currents; requires separate thermal overload protection.
- **AD** (Circuit-Breaker Backup): Used for backup protection in utility service connections.
- **UR** (Ultra-Rapid): Protects power semiconductors and DC circuits with extremely fast clearing times.

a) Fuse Selection

A fuse can protect either a circuit (line) or a load. Its selection criteria include:

- Class: gG (general purpose) or aM (motor protection)
- Rated current (I_n)
- Operating voltage (U): must not exceed the fuse's rated voltage (U_n)
- Breaking capacity (P_{dc})
- Form factor (cylindrical or blade type) and size
- Thermal coordination: the let-through energy of the fuse must be less than the withstand of the protected line: I^2t of fuse $< I^2t$ of line.

b) Advantages and Disadvantages

Advantages:

- Low cost and simple installation
- Maintenance-free operation
- Very high breaking capacity
- High reliability
- Ultra-fast interruption (UR types)

Disadvantages:

- Single-use (requires replacement after operation)
- Non-adjustable settings
- Can cause phase unbalance in three-phase systems
- May generate voltage surges during interruption

2.6.2 Thermal Relay

A thermal relay provides inverse-time overload and phase-loss protection for downstream equipment (e.g., motors), representing a basic sensing principle for overload protection. It continuously monitors load current, typically using a bimetallic strip whose heating replicates that of the protected load. After a time delay proportional to the overload magnitude, it actuates an auxiliary contact to open the control circuit of a contactor, which then disconnects power. Key characteristics include:

- **Trip class:** defined by the tripping time at 7.2 times the set current from a cold state (e.g., Class 10A: 2–10 s, Class 20A: 6–20 s).
- **Selection criteria:** based on the load's nominal current and the required trip class, which must be coordinated with the thermal limits of the protected equipment.

2.6.3 Magnetic (electromagnetic) relay

A magnetic (instantaneous overcurrent) relay provides fixed-threshold short-circuit protection, forming the basic sensing principle for instantaneous fault detection. It operates when the magnetic force from the FC in its coil overcomes a spring's return force, instantly actuating an armature. This action triggers auxiliary contacts to signal a fault or trip a contactor, as the relay itself has no breaking capacity.

Its pickup setting is mechanically adjusted by varying the air gap (via a calibrated screw/knob) and must be set above the circuit's maximum continuous current and permissible peaks to avoid nuisance tripping during normal operation.

2.6.4 Thermal-magnetic relay

A thermal-magnetic release is a combined protection unit that integrates a thermal element for inverse-time overload protection and a magnetic element for instantaneous short-circuit tripping. By merging these dual functions into a single device, it forms the core tripping mechanism of common low-voltage molded-case circuit breakers (MCCBs), providing coordinated protection against both prolonged overcurrents and high-magnitude faults.

2.6.5 Overcurrent relay

In medium and HV systems, an overcurrent relay (a programmable, intelligent electronic device (IED) serving as the core protection unit) receives a scaled current signal from a current transformer (CT) and uses programmable time-current curves (e.g., IDMT, DT) for coordination. Its operation is defined by three key parameters:

- **Operating (pickup) current:** set to be selective (above maximum load) and sensitive (able to detect minimum FCs).
- **Instantaneous threshold:** set above the maximum FC at the remote end bus-bar, often with a safety factor (≈ 1.3), to protect the entire line without overreaching.
- **Time delay:** selects a time-current characteristic (e.g., IEC Inverse) to ensure a coordinated time interval (≈ 0.3 s) between primary and backup relays, achieving graded tripping.

2.6.6 Thermal-magnetic circuit breaker

A thermal-magnetic circuit breaker is an integrated electromechanical device that combines the functions of a manual switch, a fault protector (via an internal thermal-magnetic trip unit), and a safety dis-connector. It provides coordinated protection by using a thermal element for

inverse-time overload tripping and a magnetic element for instantaneous short-circuit interruption.

Key operational characteristics include:

- Rated current (I_n): maximum continuous load current.
- Breaking capacity (I_{cu}/I_{cn}): maximum I_{sc} it can safely interrupt.
- Current limitation: ability to restrict the peak let-through current during a fault.
- Isolation: ensures safe circuit separation when open.

Note:

- I_{cu} (ultimate breaking capacity): the maximum I_{sc} the breaker can interrupt once. It may be damaged afterward.
- I_{cn} (rated breaking capacity): the maximum I_{sc} the breaker can interrupt repeatedly and remain operational.

Both (I_{cu} and I_{cn}) must be higher than the prospective FC at the installation point. I_{cn} is the key rating for normal service.

Circuit breakers are classified by voltage level and construction, each serving a distinct role in the protection hierarchy:

- ✓ Miniature Circuit Breaker (MCB): used in final distribution for branch circuit protection (typical ratings: 10–32 A, $I_{cn} \sim 6$ kA).
- ✓ Molded Case Circuit Breaker (MCCB): provides protection for LV industrial circuits and feeders (32–1250 A).
- ✓ Air Circuit Breaker (ACB): serves as a main LV distribution breaker with high breaking capacity (up to 70 kA) and adjustable protection (800–6300 A).
- ✓ MV/HV Circuit Breaker: used for network and substation protection (3 kV and above), employing advanced interruption technologies such as SF_6 gas or vacuum.

This makes the circuit breaker a central protection and control device across all voltage levels.

2.6.7 Contactor-disconnector

A contactor-disconnector combination (or motor starter) integrates three key functions into a single assembly:

- Remote control and automation: an electrically operated contactor enables frequent remote switching and automated system control.
- Safe isolation: a disconnector provides a visible air gap to de-energize the circuit for maintenance.
- Overload protection: an integrated thermal relay protects the load (e.g., a motor) against sustained overcurrents.

This combination separates the control circuit from the power circuit, ensures electrical interlocking, and often includes under-voltage detection. Crucially, it requires additional short-

circuit protection (e.g., a fuse or circuit breaker) upstream, as the contactor itself is not designed to interrupt FCs.

2.6.8 Circuit breaker (HV types)

The primary fault-interrupting device in HV networks, designed to extinguish the high-energy arc. Key technologies are:

- SF6 breakers: use sulfur hexafluoride gas for superior arc quenching in EHV/UHV systems.
- Vacuum breakers: employ a vacuum interrupter for fast, reliable arc extinction in MV/lower HV.
- Air-blast breakers: use compressed air to elongate and cool the arc; common in legacy HV systems.

2.6.9 Protective relays (advanced functions)

Specialized relays for HV system protection:

- Distance (impedance) relays: protect transmission lines by measuring impedance (V/I) to locate faults within set zones.
- Differential relays: protect transformers, generators, and busbars by comparing incoming/outgoing currents for internal faults.
- Buchholz relay: a mechanical device for oil-filled transformers that detects gas from internal faults (alarm for minor, trip for major faults).

2.6.10 Surge arresters (lightning arresters)

Non-linear resistors connected phase-to-earth that protect insulation by "clamping" overvoltages. Under normal voltage, they are high-impedance; during a surge (lightning/switching), their impedance drops to divert current to earth, then resets automatically.

2.6.11 Earth (ground) fault protection

Critical schemes for detecting faults to earth, especially in impedance-grounded HV systems:

- Residual current relays: detect earth FC via zero-sequence or residual current measurement.
- Directional earth fault relays: determine fault direction for selective tripping in meshed networks.
- Sensitive earth fault protection: detects high-impedance faults with very low current, improving safety.

2.6.12 Modern trends in HV protection

Modern HV protection is defined by three key digital trends: the shift to IEC 61850-based substations, which uses Ethernet-based Sampled Values (SV) for sharing digitized measurements and GOOSE messaging for high-speed, peer-to-peer tripping commands, replacing traditional

hardwiring; the implementation of Wide-Area Protection and Control (WAMPAC), which employs synchronized phasor measurement units (PMUs) to monitor the entire grid's dynamic state in real-time, enabling system-wide stability control and blackout prevention; and the development of Adaptive Protection schemes, which dynamically adjust relay settings in response to changing grid conditions like bidirectional power flow from renewables, ensuring reliable and selective operation in modern, variable grids.

Chapter 3

High Voltage Measurement

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3.1 Introduction

High Voltage (HV) measurement is essential for verifying the performance and safety of electrical insulation, components, and complete systems. Its primary purposes are in quality control and type testing, research and development of new materials and designs, and diagnostic field testing of existing assets. This field is structured around the measurement of three key

standard voltage waveforms used in testing: Alternating Current (AC) at power frequency, Direct Current (DC), and Impulse voltages (including both lightning and switching impulses). This chapter details the principles, methods, and devices used to accurately measure these high-potential waveforms.

3.2 Alternating HV generators

Specialized devices that generate precise, high AC voltages (50/60 Hz or variable) for dielectric testing. They step up low input voltage V_{in} with minimal distortion, featuring key parameters of rated output voltage (V_{out}) and kVA capacity.

3.2.1 Step-up transformer

The step-up transformer is the most fundamental and common type of alternating HV generator, operating on the same principle as power transformers. It consists of primary and secondary windings on a magnetic core, where a low voltage applied to the primary is transformed to a HV on the secondary based on the turns ratio N ($N = \frac{N_{secondary}}{N_{primary}}$), given by $V_{out} = V_{in} \times N$. For HV testing, these transformers are designed with special insulation, low leakage inductance, and are often housed in oil-filled tanks to prevent partial discharge and handle the high electrical stress.

3.2.2 Resonant test systems

In HV testing, an explosion of the tested equipment sometimes occurs due to a severe overvoltage generated by electrical resonance.

Example: Consider an insulator of capacitance C supplied by a HV source delivered by a transformer.

$r_1 = j\omega L_1$: Impedance of the transformer primary winding.

$r_2 = j\omega L_2$: Impedance of the transformer secondary winding.

$L\omega$: Shunt (magnetizing) impedance of the transformer, generally neglected compared to ωL_1 and ωL_2 .

C : Capacitive load with impedance $\frac{1}{\omega C}$.

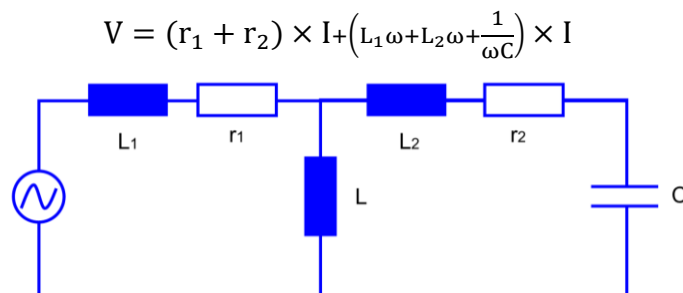


Fig. 3.1. Equivalent electrical circuit of the transformer and the tested insulator.

If, by chance, $\omega(L_1+L_2) \approx \left(\frac{1}{\omega C}\right)$, an accidental series resonance occurs. The current becomes so large that the overvoltage across the load can reach up to 20 to 50 times the applied voltage and can cause the load to explode.

The resonance phenomenon is utilized to produce very HVs. A variable tuning impedance (reactor), inserted in series with the transformer circuit, allows for adjustment and increase of the voltage to very high values (up to 600 kV).

The regulator, supplied by a low-voltage AC source, adjusts the V_{out} by varying the total reactive impedance value.

Note: If a higher voltage is needed, several resonant circuits are used in series.

This type of generator is particularly advantageous when the capacitance of the test object is high, such as with HV cables, for example. The specific advantages are that the delivered voltage is practically sinusoidal and that reactive power compensation follows (series resonance).

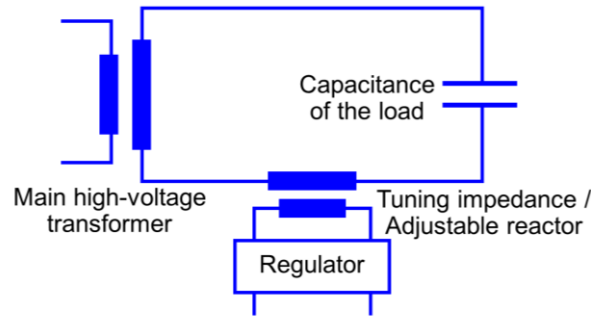


Fig. 3.2. Resonant circuit.

3.2.2.1 Series resonant circuit generator

Series resonant generators are mainly used for on-site cable testing. By adding an inductance in series on the secondary side of the transformer, tuned to the load, the voltage is multiplied by a factor roughly equal to its quality factor (Q).

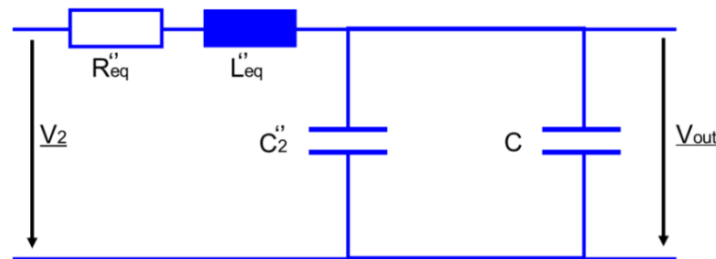


Fig. 3.3. Series resonant circuit.

a. Accidental resonance

Consider the 100 kV – 5 kVA test transformer, used to test a 100-meter-long HV cable. The equivalent circuit of the transformer is represented by R'_{eq} , L'_{eq} and the cable by its capacitance C .

$$R''_{eq} = 85 \Omega, L''_{eq} = 30 \text{ H}, C''_2 = 100 \text{ pF}, \text{ and } l = 100 \text{ m (Cable length)}.$$

$$C = 100 \text{ m} \times C', \text{ with } C' \text{ (Linear capacitance)} = 100 \text{ nF/km} \Rightarrow C = 100 \text{ nF}$$

In such a configuration, with $C_{tot} = C''_2 + C$, the resonance frequency of the system is given by:

$$f_r = \frac{1}{2\pi\sqrt{L''_{eq}C_{tot}}}$$

This resonance frequency proves to be dangerously close to the mains frequency. As for the magnitude V_{out} , it would under these conditions be:

$$V_{out} = \frac{1}{\sqrt{1 + (R''_{eq}C_{tot}\omega)^2}} \cdot \frac{1}{|1 - L''_{eq}C_{tot}\omega^2|} \approx 58V_2$$

We can therefore see that the voltage applied to the cable is significantly higher than V_{out} of the test transformer, which has indeed caused accidents in the past.

b. Intentional Resonance

This phenomenon can be exploited to apply a specified test voltage to the cable using a transformer that only generates a lower voltage. For this, a series inductance (R_L, L) is added to tune the test circuit so that its resonance frequency equals the supply frequency. With the previous values, we find:

$$L_{tot} = \frac{1}{\omega^2 C_{tot}} = 1013 \text{ H}, \text{ with } L_{tot} = L + L''_{eq} \Rightarrow L = 663 \text{ H}$$

In practice, Q of available inductors can range from 5 to 200. Assuming an average Q of 50, we would have:

$$R_L = \frac{\omega L}{Q} \approx 4167 \Omega \Rightarrow R_{tot} = R + R''_{eq} = 4252 \Omega$$

The voltage phasor diagram shows that the voltage amplification factor (α) is given by:

$$\alpha = \frac{V_s}{V_2} = \frac{V_{L_{tot}}}{V_{R_{tot}}} = \frac{\omega L_{tot}}{R_{tot}} \approx 75$$

We can therefore see that:

- α is equal to Q of the total inductance;
- The amplification factor can reach very high values.

The series resonant generator is particularly interesting for cable testing, as these tests generally need to be performed in situ; it is indeed not feasible to bring an installed underground cable back to a laboratory for testing. But it is also practically impossible to transport a large oil-insulated HV test transformer to the site.

The solution is therefore to use a relatively modest, dry-insulated test transformer combined with induction coils.

3.2.2.2 Parallel resonant circuit generator

The parallel resonant generator, whose principle diagram is illustrated in Fig. 3.4, presents similarities with the series circuit, as it is its dual. An inductance L is added in parallel with the capacitance C and must be calculated to be tuned with C for the frequency of the supply voltage. The whole is in series with the short-circuit inductance L''_{sc} referred to the secondary of the HV transformer.

$$f_r = \frac{1}{2\pi\sqrt{LC}}$$

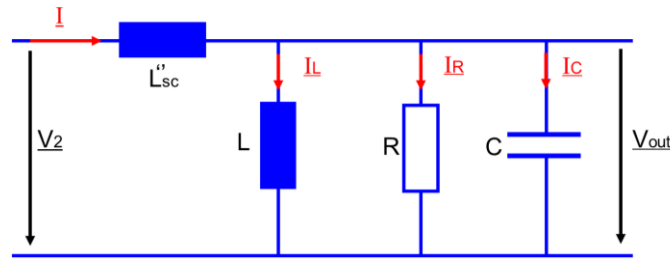


Fig. 3.4 Parallel resonant circuit.

The current reduction factor (β) is defined as:

$$\beta = \frac{I_C}{I} = \frac{I_L}{I} = \frac{R}{\omega L}$$

This circuit has the advantage of reducing the current drawn from the HV transformer since the latter does not supply the object C but only the active losses of the coil.

3.3 Direct HV generators

High Voltage Direct Current (HVDC) systems convert AC or mechanical energy into a smooth, high-potential DC output, essential for applications where AC becomes impractical or inefficient. They enable voltage multiplication to levels exceeding hundreds of kilovolts and are widely used in:

- HVDC transmission networks
- Insulation testing of cables, capacitors, and DC equipment
- Fundamental research where constant voltage simplifies analysis
- Applications requiring stable HV, such as radiology, electrostatic separation, and filtration
- Capacitive load testing, where DC offers economic advantages over AC.

3.3.1 AC voltage rectifier

a. Half-wave rectifier

This circuit employs a single diode to conduct during only one half-cycle of the AC input, charging a capacitor to approximately the peak AC voltage. The ideal DC output is:

$$V_{\text{out}} \approx V_{\text{peak}} - V_f = \sqrt{2} \cdot V_{\text{rms}} - V_f$$

where V_f is the diode forward voltage drop and V_{rms} is the root mean square voltage. However, this configuration produces significant ripple and is mainly suited for low-current, basic applications.

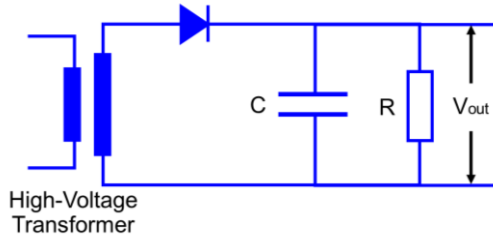


Fig. 3.5 Half-wave rectifier.

With:

C: smoothing capacitance of the rectifier + capacitance of the test object + stray capacitances.

R: resistance of the test object + leakage resistance of the smoothing capacitor.

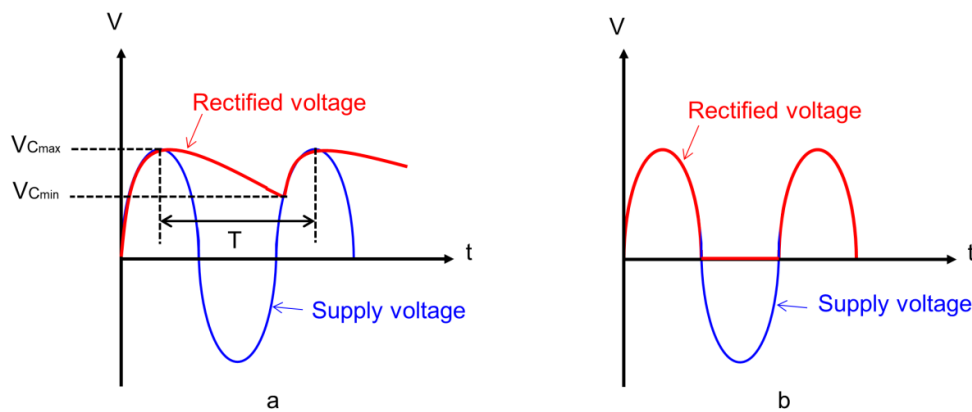


Fig. 3.6 Rectified voltage: a) with smoothing capacitor, and b) without smoothing capacitor.

b. Full-wave rectifier

A full-wave bridge rectifier uses four diodes to conduct during both half-cycles of the AC input, effectively doubling the pulse frequency. This reduces output ripple significantly and increases efficiency compared to the half-wave design, making it more suitable for higher-power and smoother DC voltage requirements. There is not a very significant difference between half-wave and full-wave rectifier circuits when a smoothing capacitor is used.

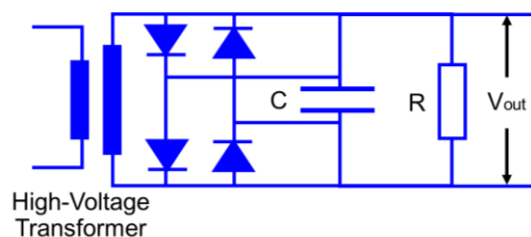


Fig. 3.7 Full-wave rectifier (Graetz bridge).

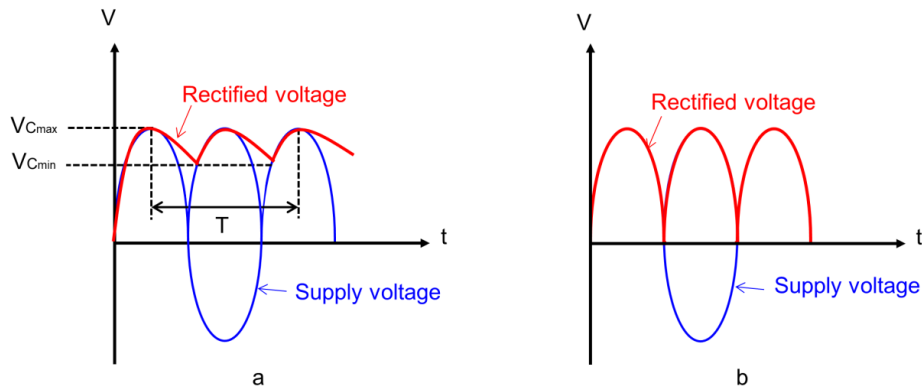


Fig. 3.8 Rectified voltage waveforms delivered by a Graetz bridge: a) with smoothing capacitor, and b) without smoothing capacitor.

3.3.2 Voltage doubler

A voltage doubler, most commonly implemented as a Schenkel or Greinacher circuit, is a two-stage rectifier that produces a DC output voltage theoretically twice the peak AC input. During the negative half-cycle, capacitor C_1 charges to V_{peak} . In the subsequent positive half-cycle, the transformer voltage adds to V_{C1} , charging C_2 to approximately $2 \cdot V_{\text{peak}}$. Under no-load conditions, the output is:

$$V_{\text{out}} = 2 \cdot \sqrt{2} \cdot V_{\text{rms}}$$

In practice, the voltage decreases under load due to ripple and internal losses.

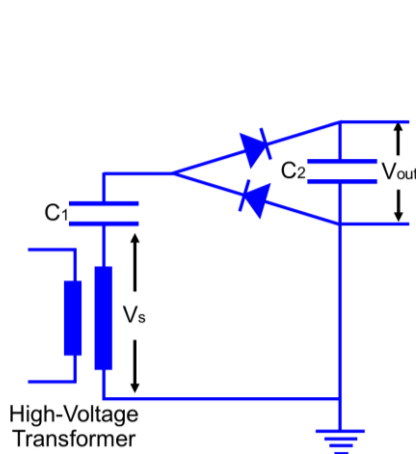


Fig. 3.9 Schenkel voltage doubler.

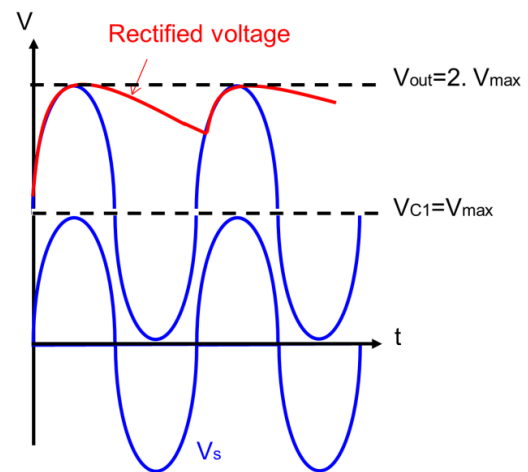


Fig. 3.10 Rectified voltage waveforms from a Schenkel voltage doubler.

3.3.3 Voltage multiplier

A voltage multiplier uses diodes and capacitors to produce a DC output greater than the input peak voltage (V_{peak}). In a half-wave design, the ideal output is $V_{\text{out}} \approx \pm n V_{\text{out}}$, where n is

the number of stages. Under load, voltage regulation is limited by ripple and drop, governed by load current I_{load} , frequency f , and stage capacitance C , often approximated by:

$$V_{\text{out}} \approx \frac{I_{\text{load}}}{fC} \times \frac{n(n+1)}{2}$$

An alternative switched-capacitor topology employs two phases: first charging capacitors in parallel via switches S_1 , then reconfiguring them in series via switches S_2 to deliver an output $V_{\text{out}} = n \cdot V_0$. This configuration acts as a single-use generator, with discharge duration determined by the stored energy $E = \frac{1}{2} C V_{\text{out}}^2$ and the load time constant $\tau = RC$. Once discharged, the output decays to zero.

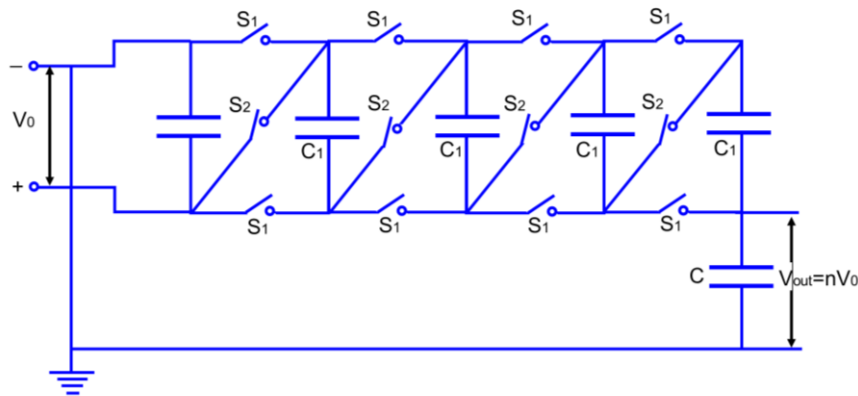


Fig. 3.11 Voltage multiplier.

3.3.4 Cascade rectifier

The Greinacher–Cockcroft–Walton (GCW) multiplier is a cascade of Schenkel-type voltage-doubler stages.

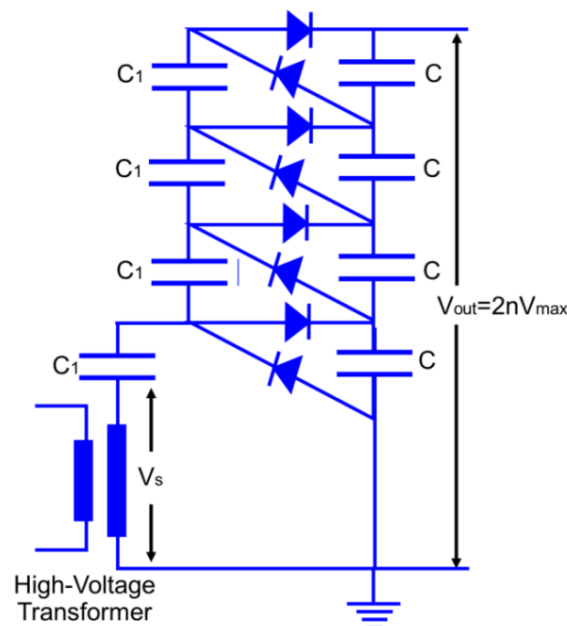


Fig. 3.12 Greinacher or Cockcroft-Walton cascade at no load.

Under no-load conditions, the ideal V_{out} is:

$$V_{\text{out}} = 2n \cdot V_{\text{max}}$$

where n is the number of stages and V_{max} is the peak V_{in} . Each diode must be rated for a reverse voltage of $2 \cdot V_{\text{max}}$.

Under load, the V_{out} is reduced by:

$$V_{\text{out}} = 2n \cdot V_{\text{max}} - \Delta V_{\text{out}}$$

with the voltage drop given by:

$$\Delta V_{\text{out}} = \frac{I_{\text{load}}}{fC} \left(\frac{2n^3}{3} + \frac{n^2}{2} - \frac{n}{6} \right)$$

or equivalently:

$$\Delta V_{\text{out}} \approx \frac{n(n^2 + 1)}{3fC} I_{\text{load}}$$

$$I_{\text{load}} = \frac{V_{\text{out}}}{R}$$

where I_{load} is the load current, f is the input frequency, and C is the stage capacitance.

Design Notes:

- The optimal stage count n is typically ≤ 10 , as beyond this ΔV_{out} grows significantly.
- GCW multipliers can achieve outputs up to 5MV, but deliver relatively low currents (~ 10 mA).

3.3.5 Electrostatic generators (Van de Graaff)

The Van de Graaff generator is an electrostatic device that produces high direct-current voltage through the mechanical transport of charge via an insulating belt. Charge is deposited onto the belt via corona discharge from a set of needle electrodes and transported to a hollow, spherical HV terminal, where it is collected. The accumulating charge raises the terminal's potential until limited by corona and electrical breakdown, governed approximately by the surface electric field $E_{\text{max}} \approx \frac{V_{\text{max}}}{r}$, where r is the sphere's radius.

The generator can achieve V_{out} in the range of hundreds of megavolts but delivers very low current (on the order of μA), limiting its power to a few kilowatts. Consequently, it is primarily used in low-intensity applications such as nuclear physics research, where a smooth, low-ripple HV source is required. Its operation includes a system of corona points to neutralize excess charge and maintain stability, with the entire assembly typically housed in a grounded metallic enclosure for safety and field control.

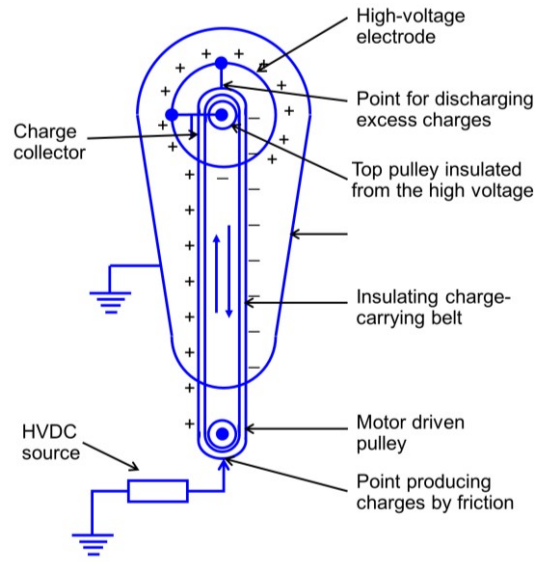


Fig. 3.13 The Van de Graaff generator.

3.4 Impulse voltage generators

Impulse voltage generators produce HV unidirectional pulses to simulate transient overvoltages like lightning strikes (1.2/50 μ s wave) and switching surges (250/2500 μ s wave). These pulses are essential for testing the insulation strength and resilience of HV equipment, such as transformers and surge protectors.

Each impulse waveform is defined by two key time constants:

- T_1 (Wavefront Time): Calculated as $1.67 \times (T_{90} - T_{30})$, representing the voltage rise.
- T_2 (Wavetail Time): Defined as T_{50} , representing the voltage decay.

The standard waves are used to replicate real-world overvoltage events, such as lightning-induced surges that can cause uneven voltage distribution and insulation failure in transformer windings.

The rise time to the peak value T_{peak} is not used, because on the oscillogram the peak is often flat and the maximum is difficult to distinguish. The rise time to the peak value T_{peak} is called the wavefront time, and the decay time T_{50} is called the wavetail time.

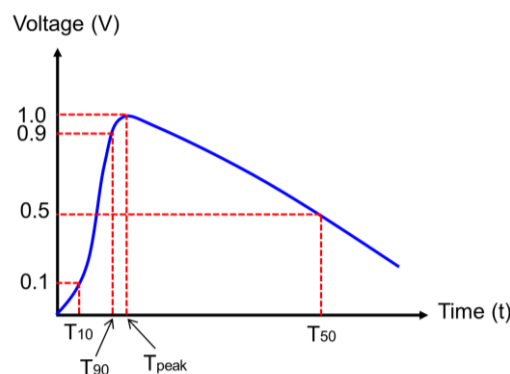


Fig. 3.14 Standard impulse wave.

3.4.1 Single-stage impulse generator

The single-stage generator forms the fundamental unit for impulse voltage generation. Its operation consists of a charging phase and a discharging phase that shapes the output waveform.

1. Charging phase

A HV DC source, typically comprising a transformer and rectifier diode (D), charges the main storage capacitor C_1 through a series damping resistor R_a . This resistor limits the charging current, resulting in a long charging time constant ($\tau = R_a C_1$) on the order of 10-20 seconds.

2. Discharge and waveform generation

When the voltage across the capacitor reaches the breakdown level V_0 of the triggered spark gap E, the discharge phase begins. Capacitor C_1 discharges abruptly into the circuit formed by the wavefront resistor R_1 , the wavetail resistor R_2 , and the load capacitance C_2 (which includes the test object).

Wave-Shaping Mechanism:

Wavefront (Rise Time T_1): Immediately after spark gap breakdown, and given $R_2 \gg R_1$, the initial discharge current charges C_2 primarily through R_1 . A short T_1 is achieved by minimizing the product $R_1 C_2$.

Wavetail (Decay Time T_2): Subsequently, the combined capacitances (C_1 and C_2) discharge more slowly through the much larger tail resistor R_2 , creating the long decay tail of the impulse.

The resulting standard double-exponential impulse waveform is characterized by its front time (T_1) and tail time (T_2), which are approximated by the circuit parameters:

- Front time: $T_1 \approx 3 \times R_1 \times \frac{C_1 C_2}{C_1 + C_2}$
- Tail time: $T_2 \approx 0.7 \times R_2 \times (C_1 + C_2)$.

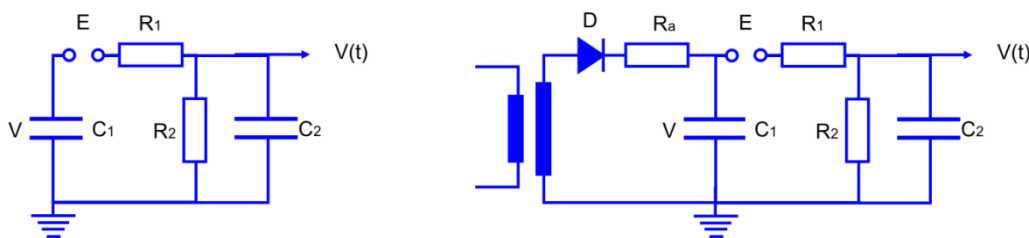


Fig. 3.15 Single-stage impulse (shock) generator.

3.4.2 Multi-stage impulse generator (Marx generator)

The Marx generator is a multi-stage circuit that significantly multiplies the V_{out} of a single-stage generator. Several capacitors (C) are charged in parallel via charging resistors to a moderate DC voltage V_0 . Upon simultaneous breakdown of the spark gaps, the capacitors effectively reconnect in series, discharging their combined energy through the wave-shaping circuit.

In an ideal lossless case with n stages, this generates an open-circuit output voltage of $V_{out} \approx nV_0$. This elegant principle allows for the generation of extremely high impulse voltages (in the MV range) using relatively lower-voltage DC charging supplies and components.

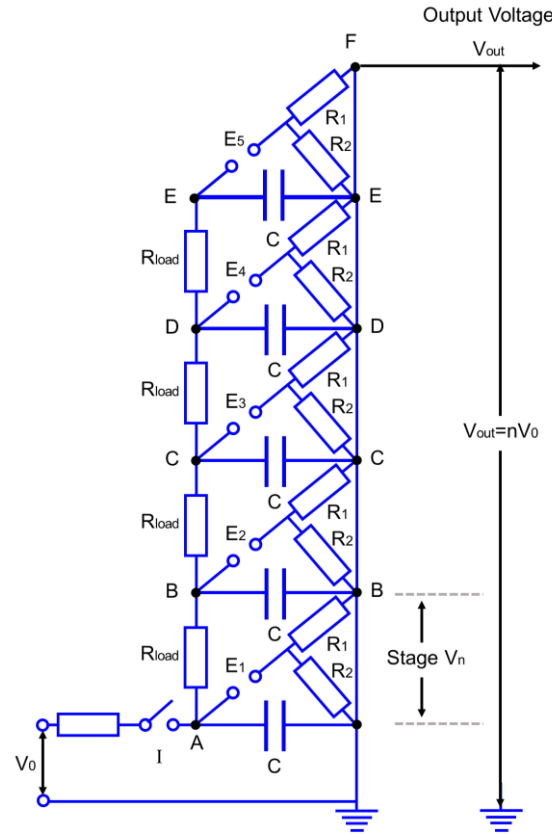


Fig. 3.16 Five-stage Marx generator.

3.4.3 Ruhmkorff coil generator

The induction coil (historically known as the Ruhmkorff coil) generates HV pulses through rapid interruption of a DC current in a primary circuit. Its operation is governed by the circuit equation:

$$V_{primary} = R_p i_p + L_p \frac{di_p}{dt} + M \frac{di_s}{dt}$$

where R_p and L_p are the primary winding's resistance and inductance, i_p and i_s are the primary and secondary currents, and M is the mutual inductance.

A mechanical interrupter creates extremely brief current interruptions ($dt \approx 0$), causing the derivatives $\frac{di_p}{dt}$ and $\frac{di_s}{dt}$ to become very large. This produces a high secondary voltage via electromagnetic induction ($V_{secondary} = M \frac{di_{primary}}{dt}$), specifically through the mutual inductance term $M \frac{di_s}{dt}$.

This principle of generating HV from rapid inductive current collapse is employed where brief, HV pulses are needed, such as in ignition systems for internal combustion engines (High voltage Transformer (HT) coils) and discharge lamps.

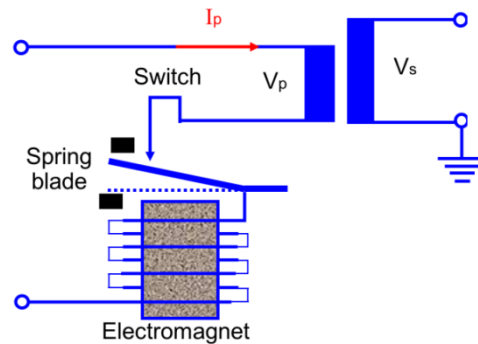


Fig. 3.17 Ruhmkorff generator.

3.4.4 Tesla coil generator

This device generates HV, High-Frequency (HF) oscillating current. The operational principle is as follows:

1. **Charging phase:** a HT, in conjunction with a rectifying diode D, charges the primary tank capacitor C_1 to a DC potential V_1 .
2. **Breakdown and primary oscillation:** when V_1 reaches a sufficient voltage, the spark gap E breaks down. This effectively closes the primary circuit, allowing the energy stored in C_1 to discharge rapidly. This discharge excites a coupled, resonant RLC circuit system (the primary and secondary coils with their associated capacitance and resistance).
3. **Resonant energy transfer and voltage magnification:** the discharge initiates a damped, HF oscillation in the primary circuit (L_1 , C_1). Through resonant inductive coupling with the secondary circuit—which is tuned to a similar frequency by the secondary coil inductance L_2 and its total effective capacitance C_2 , energy is transferred. This process results in a significant voltage gain, producing a very high oscillating output voltage V_2 across the secondary terminal.
4. **Damping and quenching:** resistors R_1 and R_2 serve to dampen the oscillations. The oscillatory cycle is terminated when the HV arc across the spark gap E is extinguished, typically by an air blast ("air blast quenching").
5. **Output specifications:** the generator produces HF outputs in the range of 10^4 to 10^5 Hz (10 kHz to 100 kHz), with V_2 capable of reaching values up to 1 Megavolt (1 MV).

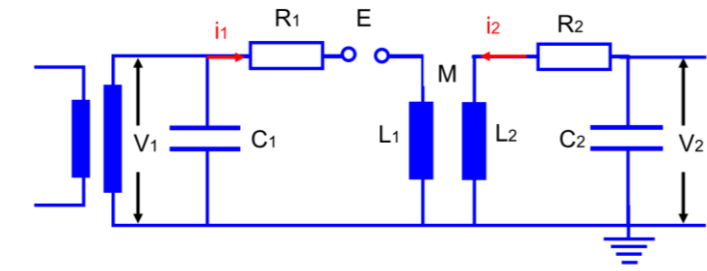


Fig. 3.18 Tesla generator.

3.5 General principles of HV measurement

A HV measurement system is a comprehensive set of devices used to perform measurements of alternating (AC), direct (DC), or impulse (impulse) HVs, as well as HF impulse currents and electric fields under HV conditions. The core challenge lies in achieving accurate measurement while ensuring galvanic isolation, minimizing field distortion, maintaining safety, and providing sufficient bandwidth for transient signals. This is addressed through two primary methodological approaches:

- Direct measurement, which utilizes a direct physical effect of the voltage (such as electrostatic force or spark length) on an isolated sensor.
- Divider methods, which reduce the HV to a safe, measurable low-voltage signal using precision resistive or capacitive voltage dividers.

It is employed during tests that involve the application of such HVs or currents.

3.6 AC HV measurement

There are many methods for measuring sinusoidal alternating voltages at power frequencies (e.g., 50/60 Hz). The key challenge is to accurately scale down the HV to a level safe for standard measuring instruments while preserving precision and phase accuracy.

3.6.1 Sphere-gap

The sphere-gap is a primary, absolute standard for measuring the peak value of AC and impulse voltages. It consists of two identical spherical electrodes of diameter D with an adjustable air gap distance d . The measurement is performed by determining the 50% disruptive discharge (sparkover) voltage for the given gap setting.

This measured voltage is compared to standardized reference tables (e.g., IEC 60052), which list V_{peak} as a function of sphere diameter D , gap distance d , and electrode connection (e.g., one sphere grounded). The tabulated values are valid for standard atmospheric conditions: 20 °C, 101.3 kPa (760 mmHg), and 11 g/m³ humidity.

The actual disruptive discharge voltage V under test conditions is obtained by applying correction factors for ambient air density and humidity to the tabulated voltage V_0 :

$$V = V_0 \times k_d \times k_h$$

Where:

k_d is the air density correction factor.

k_h is the humidity correction factor.

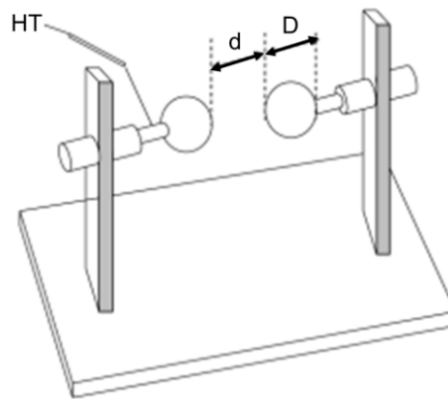


Fig. 3.19 Sphere gap (sphere discharge gap).

3.6.2 Capacitive voltage transformer/divider

The Capacitive Voltage Transformer (CVT) is a widely used device for metering and protection in HV transmission networks. It employs a capacitive divider (C_1 , C_2) to initially step down the line voltage. The intermediate voltage is then applied to the primary of a step-down inductive transformer, which further reduces it to a standard secondary level (e.g., 110 V).

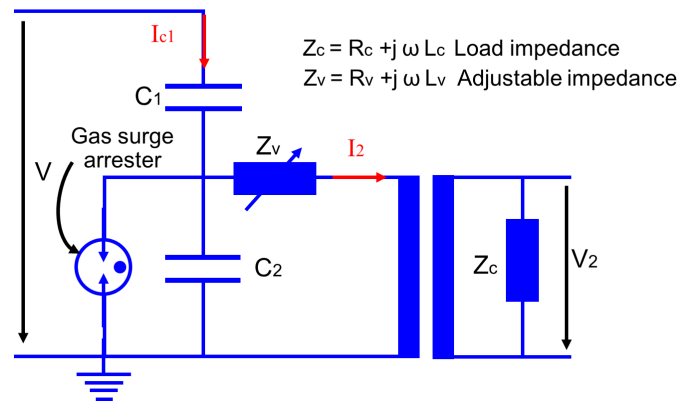


Fig. 3.20 Voltage transformer.

A key feature is the series inductor (L), which tunes the circuit to resonate at the system frequency. This resonance offers significant advantages: it amplifies the output current for robust long-distance signal transmission, and the tuned circuit inherently filters out harmonic and transient voltages. This design provides an economical solution for measurement at VHV.

3.6.2.1 Simplified capacitive divider

A capacitive voltage divider is a core scaling element for AC HV measurement. It consists of a HV capacitor (C_1) in series with a low-voltage capacitor (C_2). V_2 is a fraction of V_1 , determined by the capacitance ratio:

$$V_2 = V_1 \times \left(\frac{C_1}{(C_1 + C_2)} \right)$$

Since the transformation ratio (g) is high, the value of C_1 is typically much smaller than C_2 , which simplifies the relationship to $V_2 \approx V_1 \times \left(\frac{C_1}{C_2} \right)$.

In practical implementation, the effective capacitance of C_2 must account for parallel capacitances from the measurement cable, instrument input, and surge protection devices. This simple circuit offers high input impedance but its accuracy can be affected by stray capacitances.

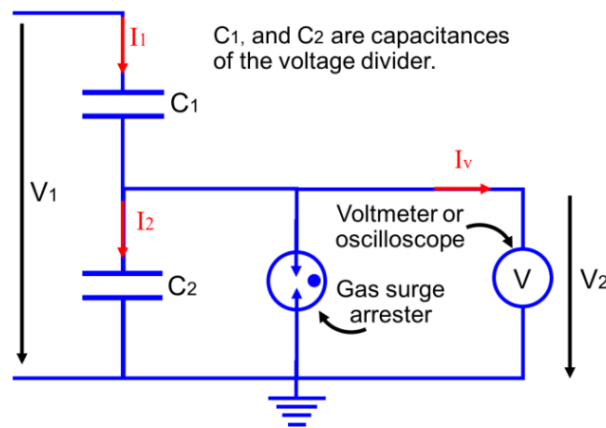


Fig. 3.21 Simplified capacitive divider.

3.6.2.2 Complete capacitive divider

The practical model of a capacitive divider must account for the influence of parasitic capacitance to ground (C_g), which becomes significant for accurate measurement.

The transformation ratio g of this complete divider is given by:

$$g = \frac{V_2}{V_1} = \frac{C_1}{C_1 + C_2} + \frac{C_1 \cdot C_2}{C_1 + C_2} \cdot \frac{1}{C_g}$$

This formula quantifies the error introduced by stray capacitances, showing that the actual division ratio deviates from the idealized value of $\frac{C_1}{C_1 + C_2}$. This necessitates careful design or calibration for high-precision applications.

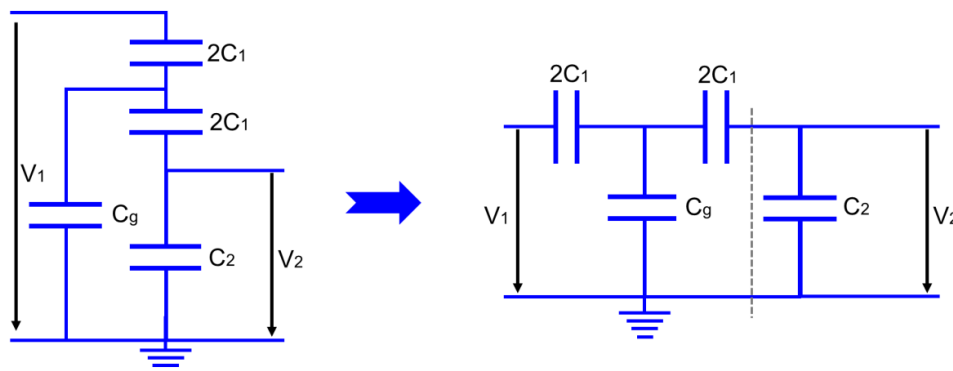


Fig. 3.22 Complete capacitive divider.

3.6.3 Measuring transformer

An Inductive Voltage Transformer (IVT) is the standard high-precision instrument for measuring AC power system voltages. It functions as a dedicated, low-power step-down transformer with a precisely defined turns ratio ($\frac{N_1}{N_2}$). The primary winding is connected across the HV line, and the secondary delivers an accurate, isolated low voltage (typically 110 V or 100 V/ $\sqrt{3}$).

The measured HV V_1 is determined by multiplying the secondary voltage V_2 by the transformation ratio ($V_1 = n \times V_2$). Accuracy is defined by metering classes (e.g., 0.2 or 0.5), which specify the maximum permissible ratio error and phase displacement.

While offering the highest precision for power frequency measurements, IVTs are less common in HV laboratories due to their size, cost, and limited voltage range compared to other methods like capacitive dividers.

3.6.4 Galvanometric measurement

This circuit measures the Root Mean Square (RMS) value of an AC HV using a capacitive divider. A capacitor C and a protective gas or semiconductor surge arrester form the HV arm. The voltage across a series inductor L is measured using a milliammeter (mA).

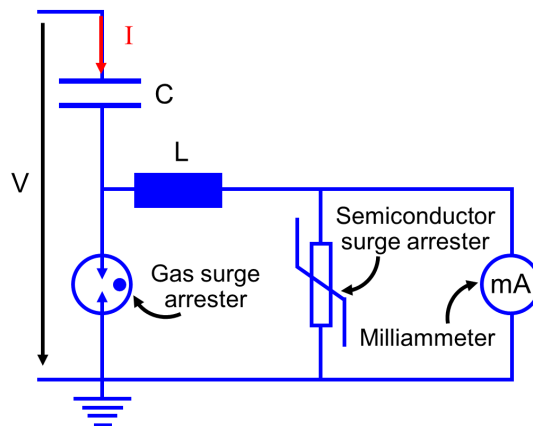


Fig. 3.23 Galvanometric measurement.

V_{rms} is calculated from the measured current I using the capacitive divider principle:

$$V_{\text{rms}} = \frac{I}{\omega C}$$

where ω is the angular frequency and C is the known capacitance. This galvanometric method provides a direct RMS reading suitable for high-impedance AC circuits.

3.7 DC HV measurement

Measuring DC HV avoids AC complexities but introduces challenges of leakage and insulation. Key methods address these through electrostatic force, current measurement, or resistive division.

3.7.1 Resistive voltage divider

The fundamental method for scaling a high DC voltage V_1 to a low, measurable voltage V_2 employs a series resistor network (R_1 , R_2). The division ratio g is governed by the voltage divider rule:

$$g = \frac{V_1}{V_2} = \frac{R_{eq} + R_1}{R_{eq}} = 1 + \frac{R_1}{R_{eq}}$$

With

$$\frac{1}{R_{eq}} = \frac{1}{R_2} + \frac{1}{R_f} + \frac{1}{R_v}$$

where R_{eq} is the equivalent resistance of the low-voltage arm in parallel with the measurement instrument's input impedance (R_v) and any filter or stray components (R_f).

Ensuring ratio accuracy requires managing the thermal stability of high-value resistors, controlling surface leakage currents, and mitigating corona discharge at HV terminals.

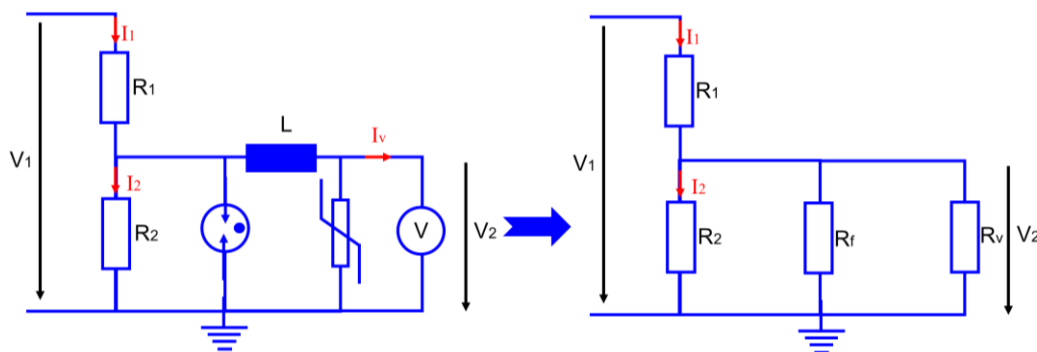


Fig. 3.24 Resistive voltage divider.

3.7.2 Electrostatic voltmeter

An electrostatic voltmeter operates as a variable capacitor with one movable plate. It measures HVs (50 V to 1 MV) by converting the electrostatic attraction force, described by $F = \frac{1}{2} \frac{dC}{dx} V^2$, into mechanical deflection. As illustrated, the mobile plate's movement is mechanically amplified and indicated on a scale. Because its response is proportional to the square of voltage, the instrument inherently measures RMS values for AC waveforms and is equally effective for DC. With an extremely high input impedance (up to $10^{12} \Omega$), it draws negligible current after initial charging, allowing accurate HV measurement with minimal loading of the circuit.

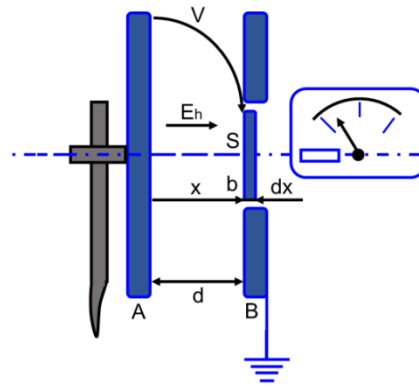


Fig. 3.27 Electrostatic voltmeter.

3.7.3 Electrometer

An electrometer measures electric charge or voltage using electrostatic principles. Historically, gold-leaf electrometers provided a qualitative voltage reading via the angular deflection α of repelling leaves, based on Coulomb's law. Modern electronic electrometers, such as the one illustrated, employ ultra-high-input-impedance amplifiers ($>10^{14} \Omega$) to enable precise quantitative measurements with minimal circuit loading, typically utilizing the relationship $Q = C \times V$. This evolution transformed the instrument from a delicate qualitative tool into a sensitive device for accurate low-current and charge measurements.

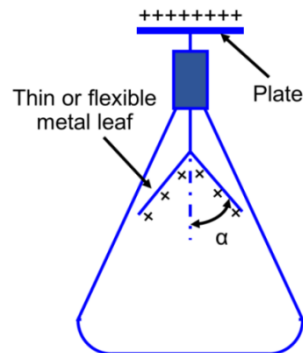


Fig. 3.26 Electrometer.

3.7.4 Galvanometric measurement

This technique directly applies Ohm's law. A known high-value standard resistor (R_{std}) is placed in series with the HV source, and the resulting DC current I is measured using a sensitive galvanometer or milliammeter. The voltage V is then calculated as $V = I \times R_{std}$.

The principal advantage of this DC measurement technique is its robustness against electromagnetic interference, as the measured current is sufficiently large to yield a reliable signal. However, its main drawback is the significant continuous power dissipation in the high-value R_{std} , typically on the order of $1 \text{ M}\Omega$ per kV, which necessitates the use of large, stable, and often externally protected components (such as gas or semiconductor surge limiters). The overall

accuracy of the method depends critically on the precision, stability, and power rating of this R_{std} , as well as on the sensitivity and proper calibration of the ammeter or galvanometer used.

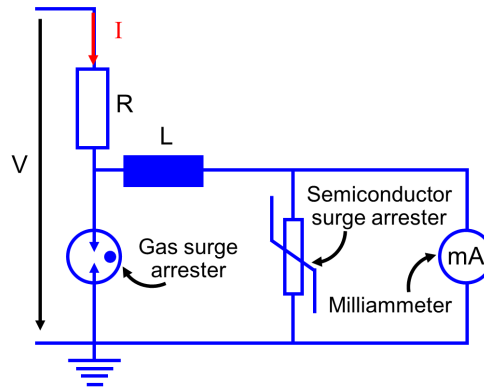


Fig. 3.25 Galvanometric measurement.

3.8 Impulse HV measurement

Measuring HV impulses (e.g., lightning) requires specialized systems due to their microsecond duration and high peaks. A voltage divider scales the impulse to a safe level for an oscilloscope, minimizing waveform distortion and preserving accurate peak values. Critical performance depends on the divider's response time being much shorter than the impulse's rise time.

3.8.1 Purely resistive impulse divider

A purely resistive impulse divider, as shown in the Fig. 3.28, consists of a HV resistor R_1 and a low-voltage arm formed by R_2 in parallel with a cable termination resistor R . To accurately measure fast impulses, the coaxial output cable must be terminated with $R = Z$, where Z is the cable's characteristic impedance (typically 10–100Ω), in order to avoid parasitic reflections. Ideally, R_2 is also set equal to Z for optimal impedance matching at the divider's output.

The divider's transformation ratio is:

$$g = \frac{R_{eq}}{R_1 + R_{eq}}$$

$$\text{where } R_{eq} = R_2 \parallel R = \frac{R_2 Z}{R_2 + Z}$$

If $R_2 = Z$ and $R = Z$, this simplifies to:

$$g = \frac{Z/2}{R_1 + Z/2} \approx \frac{Z}{2R_1} \text{ (since } R_1 \gg Z \text{)}$$

However, stray capacitances can distort very fast impulse waveforms, making purely resistive dividers better suited for slower impulses or DC unless specially compensated.

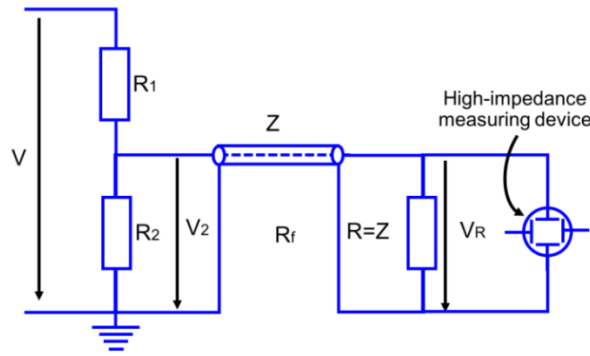


Fig. 3.28 Purely resistive impulse divider.

3.8.2 Purely capacitive impulse divider

A purely capacitive impulse divider consists of a HV capacitor C_1 and a low-voltage capacitor C_2 . Its ideal transformation ratio is given by:

$$g = \frac{C_1}{C_1 + C_2}$$

In practice, for fast impulses, the coaxial cable capacitance C_c must be accounted for, modifying the effective ratio to:

$$g(\tau) = \frac{C_1}{C_1 + C_2 + C_c}$$

Where τ is the coaxial cable propagation time.

To improve frequency response, Burch proposed adding a series $R_b C_b$ circuit at the cable output. For impedance matching, if $R_b = Z$ (cable characteristic impedance), then $C_b = C_1 + C_2$; otherwise $C_b = C_1 + C_2 + C_c$.

Unlike resistive dividers, capacitive dividers are less affected by stray capacitances to ground and are well-suited for fast AC impulses, such as lightning waveforms, but cannot measure DC components and may be sensitive to lead inductance.

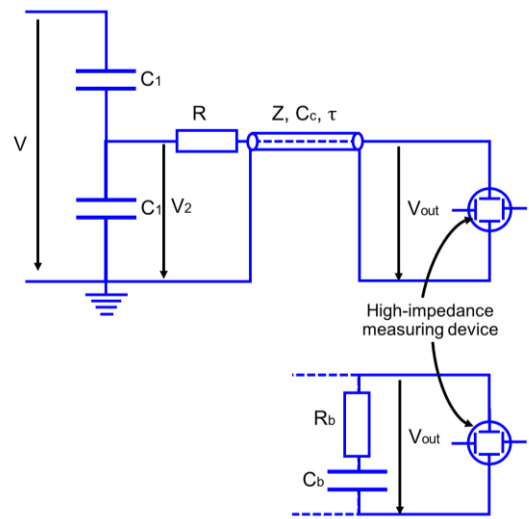


Fig. 3.29 Purely capacitive impulse divider.

3.9 High-current measurement under HV

Measuring high currents in HV circuits requires safe galvanic isolation. Unlike low-voltage shunts, HV systems use non-contact sensors that detect the magnetic field around the conductor. This ensures operator safety and signal integrity without introducing dangerous ground potentials.

3.9.1 Current transformer (CT)

A CT is the standard device for measuring high ACs in HV systems (e.g., up to 170 kV). It provides galvanic isolation and steps down the primary current I_1 to a proportional, low-level secondary current I_2 according to its turns ratio $\frac{N_1}{N_2}$. In an ideal case, $I_2 \approx I_1 \cdot \left(\frac{N_1}{N_2}\right)$ with negligible phase shift.

The practical equivalent circuit (referred to the secondary, as shown in the Fig. 3.30) includes magnetizing inductance L_m , core loss resistance R_h , and burden impedance Z , leading to the relationship:

$$I_2 = I_1 \frac{N_1}{N_2} - \frac{N_1}{N_2} \left(\frac{R_h + Z}{j\omega L_m} \right) I_\mu$$

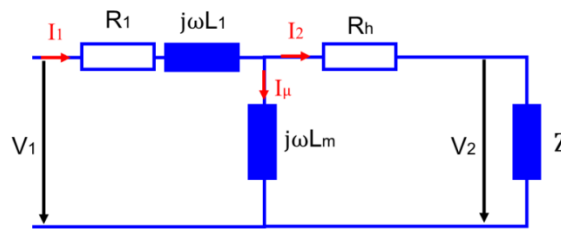


Fig. 3.30 Current transformer.

This construction ensures safety and accuracy for AC measurements but cannot measure DC and is subject to saturation under transient or DC-offset conditions.

3.9.2 Hall effect sensor

A Hall effect sensor measures AC, DC, and impulse currents by utilizing the magnetic field around a conductor. It consists of a thin semiconductor wafer placed in the air gap of a magnetic core, which concentrates the flux. A control current I_c passes through the wafer; when the magnetic flux density B from the measured current acts on it, a proportional Hall voltage V_H appears across the wafer, given by:

$$V_H = \frac{K_H \cdot B \cdot I_c}{d}$$

where K_H is the Hall constant and d is the wafer thickness (on the order of micrometers). This principle enables galvanically isolated measurement of HV and fast-impulse currents with wide bandwidth and excellent linearity for complex waveforms.

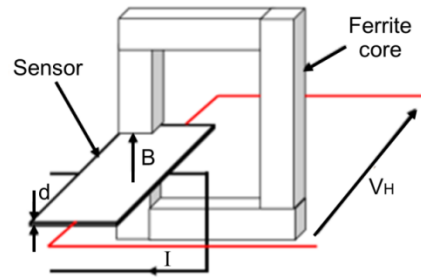


Fig. 3.31 Hall effect sensor.

3.9.3 DC current converter

A DC current converter is specifically designed to measure medium- to HV direct currents, such as in HVDC systems. Unlike AC current transformers, the magnetic flux in its core is fixed by the circuit under load, making the magnetizing current I_0 constant.

The fundamental relation is:

$$N_1 \cdot I_1 + N_2 \cdot I_2 = N_1 \cdot I_0$$

For an ideal transformer ($I_0 = 0$), this simplifies to:

$$I_2 = \frac{N_1}{N_2} \cdot I_1$$

In modern implementations, a Hall sensor in a closed-loop configuration is often used to generate a compensating current in a feedback winding, ensuring precise measurement with high galvanic isolation and minimal drift. This makes DC current converters accurate and reliable for steady-state DC measurements in HV applications.

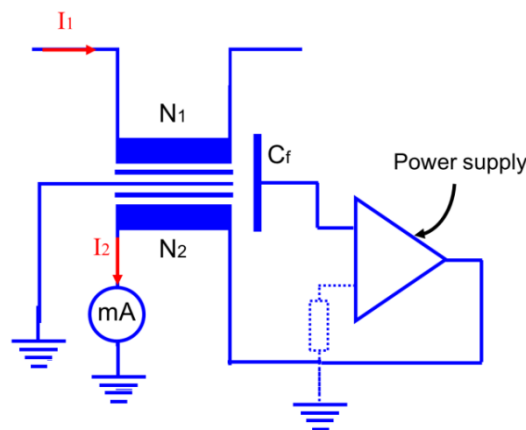


Fig. 3.32 DC current converter

3.9.4 Rogowski coil

A Rogowski coil is an air-cored, toroidal winding that measures current without galvanic contact. The induced V_{out} is proportional to the rate of change of the primary current:

$$V(t) = \mu_0 \cdot N \cdot A \cdot \frac{di}{dt}$$

where N is the number of turns, A is the area of a single turn, and μ_0 is the permeability of free space.

To recover the original current waveform, the coil's output is fed into an active integrator circuit (typically using an op-amp, an integration capacitor C , and resistors R_g and R_f). This integrator performs the mathematical inverse of differentiation, producing an output signal that is directly proportional to the instantaneous current $i(t)$. This setup enables galvanically isolated, wide-bandwidth current measurement ideal for AC and fast transients, though it cannot measure pure DC.

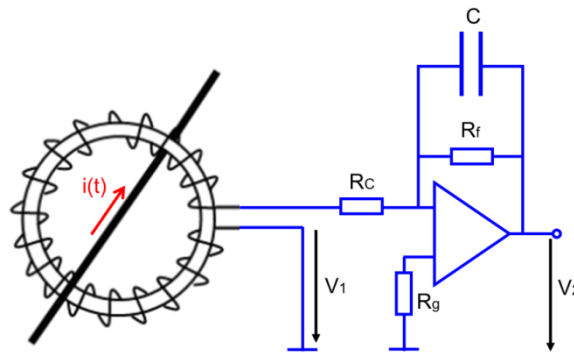


Fig. 3.33 Principle of Rogowski coil (Rogowski coil fitted around a current-carrying conductor).

3.10 Measurement accuracy, traceability, and standards

Reliable HV measurements require a defined traceability chain to international standards. National Metrology Institutes (NMIs) maintain primary references (e.g., precision voltage dividers) to calibrate the working dividers used in test labs. Each measurement includes an uncertainty budget, quantifying all error sources to give a confidence interval, ensuring results are accurate, legally valid, and technically comparable.

3.11 Safety in HV testing

Safety in HV testing is governed by a strict, multi-layered protocol to eliminate risk of electric shock and arc flash. It is enforced through clear, documented procedures and physical measures, including permanent barriers and interlock systems that prevent access to live circuits. Robust earthing (grounding) practices are critical, using visible, portable earths to discharge and short-circuit equipment before any approach. Operational rules like the two-man rule (requiring a qualified observer) and strict adherence to safety clearances (Minimum Approach Distances (MAD)) provide essential human redundancy and spatial protection, creating a comprehensive safety culture that is as vital as the technical measurements themselves.

Fig. 3.34 shows the MAD of the worker's body in relationship to an exposed energized part.

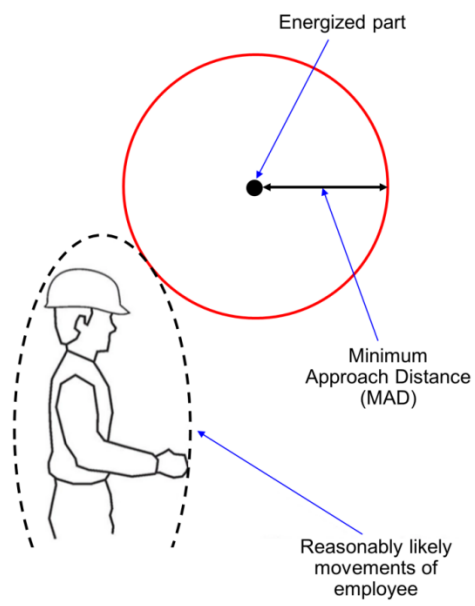


Fig. 3.34 The MAD of the worker's body in relationship to an exposed energized part.

Chapter 4

Transient Phenomena in High Voltage

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4.1 Introduction

Transient overvoltages are high-amplitude, short-duration voltage surges that are a primary cause of electrical insulation stress, posing a direct threat to system reliability and operational safety. Their analysis is therefore critical for robust system design. Overvoltages are transient voltage surges exceeding a system's permissible operating level, quantified by their per-unit (p.u.) value. They are classified by mode, differential (between phases) or common (conductor to earth), and by origin, as internal (e.g., switching) or external (e.g., lightning). These traveling wave phenomena, often modeled by functions like the double-exponential $v(t) = V_0(e^{-\alpha t} - e^{-\beta t})$, can manifest as transverse (between conductors or to ground) or longitudinal (along a conductor)

stresses, posing risks from brief interruptions to permanent equipment damage (α and β are time constants that define the shape of the impulse waveform, specifically its rise time and decay time).

The analysis of transient phenomena, including its frequency spectrum and wave propagation characteristics, is fundamentally directed toward the engineering discipline of insulation coordination. This systematic process involves designing a system's insulation to withstand expected overvoltages with a defined safety margin, while optimizing for both cost and reliability. Its core principle is strategically selecting the most economical point of failure, such as a surge arrester, to protect critical and expensive equipment like transformers, thereby providing the essential framework for designing protective systems and mitigating transient threats in electrical networks.

4.2 Different types of overvoltage in electrical networks

Electrical systems are susceptible to four primary types of overvoltages, categorized by origin and duration. These events are fundamentally classified as internal, generated by network operations like switching or faults, or external, originating from outside sources like lightning. Their severity is quantified by the temporary overvoltage factor, $k = \frac{V_{\max}}{V_n}$, which compares the peak overvoltage ($V_{\max}$) to the nominal system voltage (V_n). This classification is essential for analyzing transient behavior and designing appropriate insulation and protection.

4.2.1 Switching overvoltages

Switching overvoltages are transient surges of high magnitude and frequency, generated by the abrupt change in a network's state during operations like energizing or de-energizing lines, transformers, or capacitor banks. These transients are oscillatory in nature and are particularly severe when interrupting small inductive currents or closing onto a line with trapped charge. Their amplitude, frequency, and duration (ranging from microseconds to milliseconds) are determined by the network's characteristics and the switching device's properties, with peaks typically reaching 2.0 to 3.0 per unit of the system voltage.

4.2.2 Power frequency overvoltages

Power-frequency overvoltages are sustained or temporary increases in voltage at the system's fundamental frequency (e.g., 50/60 Hz), typically lasting from seconds to minutes. Their primary causes include load rejection, ground faults leading to neutral displacement, and ferroresonance. Other causes involve faults in voltage regulation, broken neutrals, or reactive power overcompensation. While their amplitude is generally lower than switching surges, their extended duration imposes significant thermal stress on insulation and poses a risk to system integrity.

4.2.3 Overvoltages caused by electrostatic discharges

Electrostatic Discharge (ESD) overvoltages are nanosecond-duration transients caused by the sudden release of accumulated charge, typically from triboelectric charging (e.g., human friction on carpets). The discharge releases energy defined by $W = \frac{1}{2}CV^2$, where C is the capacitance between objects and V is the pre-discharge potential (often tens of kilovolts). Though the total energy is low, the extreme rate of change (nanosecond rise times) generates high peak voltages and currents (tens of amperes), capable of perforating semiconductor junctions and igniting flammable atmospheres. ESD is a critical risk in dry environments and for unprotected electronics.

4.2.4 Overvoltages of atmospheric origin

Atmospheric overvoltages result from lightning discharges that maintain the Earth's electrical equilibrium within the global atmospheric capacitor. Lightning is modeled as a high-current impulse $i(t) = I_0(e^{-\alpha t} - e^{-\beta t})$, where I_0 is the peak current (tens to hundreds of kA), and α and β define the tail (tens of μs) and front ($\sim \mu s$) time constants, respectively. Overvoltages arise from direct strikes to conductors ($V \approx \frac{I \times Z}{2}$, where Z is the surge impedance) or induced voltages from nearby strikes. These events represent the most severe transient threat to HV insulation, characterized by extreme magnitude and rapid rise times.

4.3 Classes of overvoltages in electrical networks

The International Electrotechnical Commission (IEC) classifies overvoltages into two classes for insulation coordination: low-frequency (temporary) overvoltages at or near power frequency, and transient overvoltages, subdivided into slow-front (e.g., switching) and fast-front (e.g., lightning) surges. This framework standardizes equipment withstand tests in standards like IEC 60071.

4.3.1 Transient overvoltages

Transient overvoltages are short-duration, high-amplitude surges categorized by their rise time. According to the IEC, they include:

- **Slow-front (switching) transients:** time to peak: 20–5000 μs , time to half-value < 20 ms.
- **Fast-front (lightning) transients:** front time: 0.1–20 μs , time to half-value < 300 μs .
- **Very fast-front transients:** front time < 0.1 μs , time to half-value < 3 ms.

Originating from events like switching, lightning, and GIS (Gas-Insulated Switchgear) operations, these transients impose high dielectric stress on insulation, testing its ability to withstand extreme electric fields over microseconds to milliseconds.

4.3.2 Low-frequency voltages

Low-frequency overvoltages are characterized by prolonged duration (seconds to hours) and operate at or near the system's fundamental frequency (50/60 Hz) or its harmonics. They encompass continuous power-frequency voltage (the nominal operating voltage) and temporary overvoltages, which are sustained increases above nominal levels due to conditions like load rejection (Ferranti effect), ground faults, or ferroresonance. While their amplitude is moderate (typically 1.1–1.5 p.u.), their extended duration imposes significant thermal stress on insulation. The waveform is generally sinusoidal, $v(t) = V_{\text{peak}} \sin(2\pi ft + \varphi)$, with the overvoltage defined by an elevated V_{peak} .

4.4 Atmospheric overvoltages (lightning)

The overvoltages caused by lightning are the most severe and unpredictable natural transient threat to electrical systems. Understanding them is essential for designing effective lightning protection and insulation coordination.

4.4.1 Nature and behavior of lightning

Lightning is a massive ESD, typically a negative cloud-to-ground strike (90% of cases), resulting from charge separation within a thundercloud. The discharge process involves a propagating stepped leader connecting with a grounded upward streamer, followed by the main return stroke, a powerful current wave traveling at $\sim 1/3$ the speed of light. It produces high-frequency, impulsive energy characterized by a cloud potential of 10^8 – 10^{10} V, a ground-level electric field of 5–10 kV/m, and peak currents typically between 20–60 kA (with extremes up to 200 kA). This results in short-duration (μs – ms), high-magnitude transients that stress all conductive elements, especially electrical networks and tall, grounded structures.

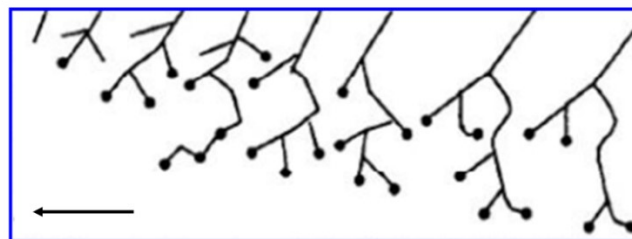


Fig. 4.1. Propagation of a stepped leader from a thundercloud to the ground.

4.4.2 Characteristics of the lightning strokes

Atmospheric overvoltages, originating from lightning, are characterized by extreme magnitude and fast rise times, imposing severe dielectric stress. Their key parameters include peak currents in the tens to hundreds of kilo-amperes (with 50% > 33 kA and 5% > 65 kA), microsecond-scale rise times, and durations of tens to hundreds of microseconds. The standard test waveform is the 1.2/50 μs impulse (1.2 μs virtual front time, 50 μs time to half-value),

modeling the threat for insulation coordination. As a global phenomenon (occurring 30–100 times per second), lightning's high energy also poses significant fire and structural damage risks, particularly to tall structures.

Lightning strikes are classified based on:

1. **Discharge origin:** descending (cloud-to-ground) in flat terrain or Ascending (ground-to-cloud) from tall/mountainous structures.
2. **Polarity:** negative (~80% of cases in temperate regions) or Positive, with the latter often having higher peak currents.
3. **Point of impact:** direct strikes (to conductors or structures), shielding failures, or induced overvoltages from nearby strikes.

The critical electrical parameters are the peak current (I_{peak}), which follows a statistical distribution, and the rate of rise $\left(\frac{di}{dt}\right)$, which determines induced voltages via $V = M \cdot \left(\frac{di}{dt}\right)$, where M is mutual inductance. This classification is essential for risk assessment and protection design.

4.4.3 Characterization of the lightning surge

Lightning surges are characterized by standardized impulse waveforms for engineering analysis. The current is modeled by a double-exponential function $i(t) = I_0(e^{-\alpha t} - e^{-\beta t})$, where α and β define the tail and front. The IEC standardizes two key current waveforms: the 10/350 μs wave for direct strikes and the 8/20 μs wave for indirect effects. The resulting voltage surge on a struck conductor is determined by the surge impedance Z as $V = \frac{I \times Z}{2}$. For equipment testing, the standardized 1.2/50 μs voltage impulse (per IEC 61000-4-5) verifies withstand capability against these extreme transients.

4.5 Mode of action of lightning on lines

Lightning affects power lines through three principal coupling mechanisms:

1. **Direct strike to phase conductor (shielding failure):** injects the full lightning current (50% > 25 kA, 1% > 180 kA) directly into the line, with a high rate of rise (up to ~100 kA/ μs). This is the most severe overvoltage source.
2. **Direct strike to shield wire or tower:** the current raises the local ground potential, which can cause back-flashover across line insulators if the tower-to-conductor voltage exceeds the insulation withstand level.
3. **Induced overvoltage:** the intense, rapidly changing electromagnetic field (via electromagnetic induction) from a nearby ground strike induces significant voltages (hundreds of kV) on line conductors without physical contact. Electrostatic induction also contributes, charging the line-to-earth capacitor to 150–500 kV under

strong pre-strike fields (~ 30 kV/m). These induced surges are a critical threat, particularly to lower-voltage networks.

4.6 Effects of lightning on electrical installations

Lightning overvoltages inflict severe, multi-faceted damage on electrical systems. The primary effect is insulation breakdown, causing flashover across air gaps or puncture within solid/liquid insulation (e.g., transformers, cables), leading to short circuits and outages. The surge's steep wavefront $\left(\frac{di}{dt}\right)$ also induces destructive transferred overvoltages in secondary circuits via electromagnetic coupling and generates damaging thermal and magnetic forces. Beyond direct hardware destruction (transformers, meters, appliances), consequences include hard-to-quantify operational disruptions in automation, regulation systems, computers, and networks. The total cost, often dominated by operational and downtime losses, typically far exceeds the direct cost of equipment repair or replacement.

4.7 Switching overvoltages

Switching overvoltages are internally generated transients resulting from a sudden change in the network's operating state. Unlike lightning, these events are deterministic and primarily governed by the system's topology and switching device characteristics. They are a key design factor for insulation coordination in HV systems, particularly for EHV and UHV networks, where their magnitude can be a limiting constraint. Understanding and mitigating these transients is crucial for ensuring reliable and cost-effective grid operation.

4.7.1 Mechanisms

Switching overvoltages are generated by several key mechanisms. The most common is the energization or re-energization of unloaded transmission lines, leading to traveling wave phenomena and standing wave effects that can double the voltage at the open line end. Another critical mechanism is current chopping during the interruption of small inductive currents (e.g., in shunt reactors or transformer magnetizing currents), where premature arc extinction forces the magnetic energy into the system capacitance, causing a high-frequency voltage surge. A third mechanism is the re-ignition or pre-strike in circuit breakers, where a breakdown across the contacts during opening or closing generates a series of high-frequency voltage oscillations. The interaction between system inductance (L) and capacitance (C) often governs these oscillations, with a natural frequency of $f_0 = \frac{1}{2\pi\sqrt{LC}}$.

4.7.2 Influencing factors

The magnitude and shape of a switching overvoltage are influenced by a combination of system and operational factors. Key system factors include the source impedance, the surge impedance and length of the line, the presence of trapped charge on a line before re-closing, and

the damping provided by resistive losses and corona effect. The characteristics of the switching device are equally critical, such as the point-on-wave (synchronized or unsynchronized switching), the speed of contact separation, and the dielectric recovery strength of the interrupting medium. For example, closing at the peak of the source voltage on a line with opposite polarity trapped charge can lead to the most severe overvoltage conditions.

4.7.3 Calculation methods

The calculation of switching overvoltages typically requires sophisticated simulation tools due to the complexity of the networks and the non-linear behavior of components. The primary method is digital simulation using Electromagnetic Transients Programs (EMTP), which models the system with distributed parameters and detailed component models (non-linear inductances, frequency-dependent lines, arc models). For simplified preliminary estimates, lumped-parameter equivalent circuits can be used, representing the system as a series $R - L - C$ network to calculate the transient's peak using formulas like the two-times rule for an un-damped LC circuit: $V_{\max} \approx 2 \times V_{\text{source-peak}}$. However, statistical methods are often applied to EMTP results to determine the statistical switching overvoltage (U_2) used in insulation coordination.

4.8 Modeling and analysis of switching transients

Accurate modeling is essential (a systematic approach to studying switching transients), representing system components with appropriate fidelity: distributed-parameter models for transmission lines (using Bergeron's method or frequency-dependent models), non-linear models for transformers (hysteresis, saturation), and dynamic arc models for circuit breakers. Analysis involves time-domain simulation to obtain overvoltage waveforms at critical nodes. The results are then processed through statistical analysis (e.g., using the Monte Carlo method for varying switching instants) to determine the probability distribution of overvoltage peaks. This data directly feeds into the insulation coordination process, defining the required insulation withstand levels (V_w) and the protective level (V_p) of surge arresters using the safety margin formula:

$$K_p = \frac{V_w}{V_p} > 1.$$

4.9 Different propagation modes

The propagation mode of a transient overvoltages, common mode (conductor-to-ground) or differential mode (between conductors), determines the voltage stress on insulation and dictates the design of protection devices (like surge arresters and filters) and electromagnetic compatibility measures to protect equipment.

4.9.1 Common mode

Common Mode (CM) propagation occurs when a transient overvoltage appears with the same phase and amplitude between all live conductors and the earth (ground) reference. In this mode, the overvoltage is impressed between the entire power or signal system and the ground plane. A simplified representation for two conductors (L1, L2) and earth (E) is $V_{CM} = \frac{(V_{L1-E} + V_{L2-E})}{2}$, where the voltages to earth are in phase. This mode is particularly hazardous for equipment insulation and human safety, as it stresses the insulation between conductors and ground, and is often associated with direct lightning strikes or ground potential rise.

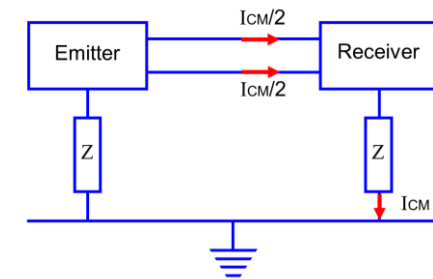


Fig. 4.2. Common mode.

4.9.2 Differential mode

Differential Mode (DM) propagation, also known as Normal or Symmetrical Mode, occurs when a transient overvoltage appears between the live conductors themselves (e.g., phase-to-phase or line-to-neutral), with little or no involvement of the earth reference. In this mode, the voltages on the conductors are equal in magnitude but opposite in polarity relative to a common reference. For a simple two-conductor system, it is defined as $V_{DM} = V_{L1} - V_{L2}$. This mode primarily stresses the insulation between conductors and is commonly excited by internal switching operations or by the conversion of common-mode surges due to imbalances in the system's impedance to ground.

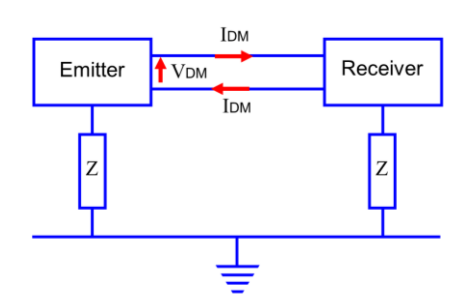


Fig. 4.3. Differential mode.

4.10 Consequences of overvoltages

Overvoltages generate critical risks across equipment integrity, operational reliability, and human safety, primarily through:

- Insulation failure, including immediate dielectric breakdown and accelerated aging from repeated exposure.
- Extended outages and operational disruption due to equipment damage and interference with control and communication systems.
- Structural and thermal damage caused by high electrodynamic forces and heat, which can lead to fire or explosion.
- Personnel hazards from ground potential rise, resulting in dangerous step and touch voltages.

4.11 Lightning protection devices

Lightning Protection Systems (LPS) are designed to intercept, conduct, and safely dissipate lightning energy to earth, preventing damage to structures and electrical systems. They consist of external protection (air terminals, down conductors, grounding) and internal protection (Surge Protective Devices (SPDs)).

External lightning protection uses air-termination systems (rods, wires) to capture strikes, down conductors to route current, and a low-impedance grounding system to disperse energy. The rolling sphere method (see Fig. 4.4) is a geometric model used to determine the placement of air terminals based on the desired protection level (Class I–IV).

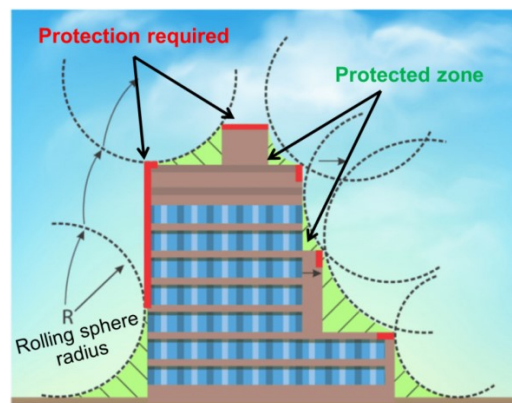


Fig. 4.4. Rolling sphere method for lightning protection.

Internal protection relies on spark gaps (see Section 4.12) and surge arresters (see Section 4.13) installed at strategic points to limit overvoltages entering electrical installations.

Table 4.1 summarizes the rolling sphere radius and corresponding minimum peak current for different protection classes.

Table 4.1 Max. values of rolling sphere radius corresponding to the Class of LPS.

Class of LPS	Rolling sphere radius R (m)	Minimum peak current I (kA)
I	20	3
II	30	5
II	45	10
IV	60	16

4.12 Spark gaps

A spark gap is a simple SPD consisting of electrodes separated by an adjustable air gap (e.g., 40 mm for 20 kV systems) connected between the conductor and ground, as shown in the basic three-phase configuration in Fig. 4.5. It operates on dielectric breakdown, creating a controlled short-circuit to divert surges. Its breakdown voltage is defined by a volt-time characteristic, $V_{\text{spark}}(t)$, but exhibits significant dispersion due to dependency on atmospheric conditions (humidity, pressure, temperature) and surge amplitude, resulting in variable response times.

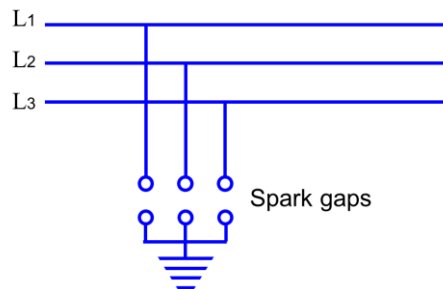


Fig. 4.5. Basic three-phase spark gap installation for surge protection.

While low-cost, robust, and adjustable, key drawbacks include: a sustained power-follow current that can cause system faults; a chopped voltage wave with a steep front that risks damaging nearby equipment windings; and a potential loss of protection coordination due to its variable delay. Although still used in some MV/HV applications, modern designs include features such as an anti-bird rod to prevent accidental short circuits and electrocution, as illustrated in Fig. 4.6. However, due to their limitations, spark gaps are largely being replaced by modern surge arresters.

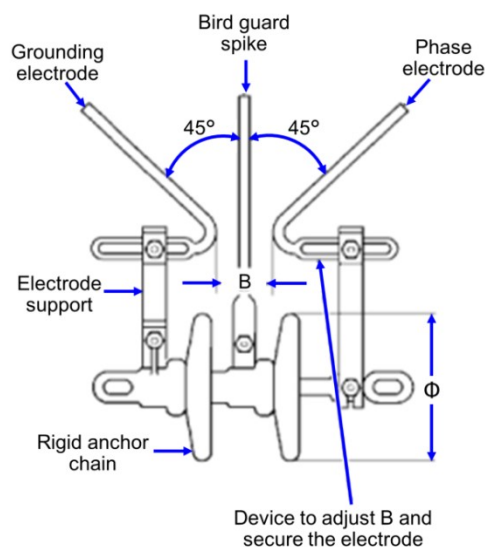


Fig. 4.6. MV spark gap with anti-bird rod to prevent short circuits.

4.13 Surge arresters

A surge arrester is an advanced protective device connected in parallel with equipment. It functions as a voltage-dependent nonlinear resistor, presenting high impedance under normal voltage and rapidly switching to low impedance when the voltage exceeds its continuous operating voltage (V_c). This action clamps the surge to a safe V_p , diverting the current to ground and protecting the insulation.

It mitigates both common-mode (phase-to-earth/neutral) and differential-mode (phase-to-neutral) overvoltages. Optimal placement is as close as possible to protected equipment or at aerial/cable junctions, with multiple arresters often used on critical busbars in large substations. After the surge, it recovers to a blocking state, interrupting the power-follow current, making it the cornerstone of modern insulation coordination.

4.13.1 Types of surge arresters

Surge arresters are classified both by technology and by application/performance level according to IEC standards.

a) By technology:

The modern standard is the Metal-Oxide (ZnO) Arrester (MOA), which uses gapless zinc oxide varistors with a highly nonlinear characteristic $I = k \cdot V^\alpha$ (where $\alpha \approx 25-50$), enabling fast response and no follow-current interruption. This has largely superseded older Silicon Carbide (SiC) Arresters, which required series spark gaps.

b) By IEC application class (low voltage / SPD classes):

- **Type 1 (Class I):** designed to handle partial direct lightning currents (10/350 μ s impulse), used at service entrances of buildings with external lightning protection (lightning rods, cages).
- **Type 2 (Class II):** the primary protection for electrical installations, installed in distribution boards to limit overvoltages and protect loads (8/20 μ s impulse).
- **Type 3 (Class III):** supplementary protection with lower discharge capacity, installed near sensitive equipment in combination with Type 2 arresters (tested with a combined 1.2/50 μ s voltage and 8/20 μ s current wave).

Further engineering classifications (station, line, distribution-class) define voltage ratings and energy capabilities for specific network applications.

4.13.2 Characteristics

Surge arrester performance is defined by key parameters:

1. **Rated voltage (V_r):** the maximum permissible continuous power-frequency RMS voltage (e.g., 24 kV). Related is the continuous operating voltage (V_c), the maximum RMS voltage for stable long-term operation (e.g., 12.7 kV).

2. **Residual voltage (V_{res}):** the maximum voltage across the arrester terminals during discharge, determined by the non-linear protective characteristic $V = f(I)$. For a standard 8/20 μs impulse, a typical value is $< 75 \text{ kV}$ for a 5 kA discharge.
3. **Protective level:** the maximum V_{res} (e.g., for a 10 kA lightning current) must be below the equipment's Basic Insulation Level (BIL).
4. **Energy handling capability:** the total transient energy (in kJ) the arrester can absorb, related to its discharge capability (e.g., rated 5 kA 8/20 μs) and impulse withstand (e.g., 65 kA 4/10 μs).
5. **Follow current interruption:** the device must interrupt the network's power-follow current within a half-cycle after the surge.
6. **Response time:** must operate in $< 0.1 \mu\text{s}$, with stable characteristics independent of polarity, wave shape, and climatic conditions.

The ZnO (metal oxide) varistor is the standard nonlinear element, enabling these characteristics in designs like the porcelain-housed unit shown in Fig. 4.7.

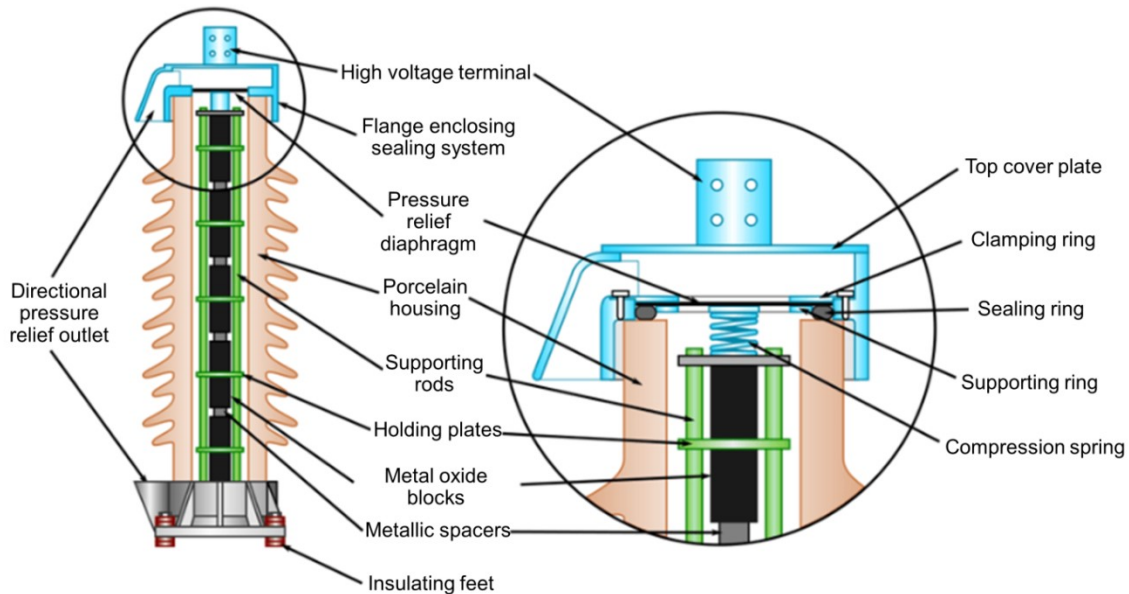


Fig. 4.7. Cross section view of a porcelain housed metal oxide surge arrester.

4.13.3 Installation of HV and MV surge arresters

For effective protection in HV/MV networks, surge arresters must be installed following critical rules. They should be placed as close as possible to the protected equipment (e.g., transformer bushings) to minimize the separation distance, preventing harmful voltage reflections and oscillations that can exceed the equipment's insulation strength.

Key installation requirements include:

- ✓ Short, straight, low-inductance connections with a large cross-section to minimize the inductive voltage drop $L \cdot \frac{di}{dt}$ during discharge.

- ✓ A common, low-impedance ground shared with the protected equipment to ensure they experience the same residual voltage.
- ✓ Adherence to the specific protection distance, which defines the maximum effective cable length between the arrester and the equipment.
- ✓ Consideration of environmental factors like mounting position, pollution, and UV exposure for long-term stability.

Respecting these rules is essential for the arrester to maintain a V_p below the equipment's withstand capability.

4.13.4 Main applications

Surge arresters are strategically installed to protect critical equipment by ensuring their V_p is sufficiently below the equipment's insulation withstand level (V_w), maintaining a safety margin $K_p = \frac{V_w}{V_p} > 1$.

Key applications include:

- **HV equipment:** protecting power transformers, shunt reactors, and switchgear at substation entrances from lightning and switching surges.
- **Line performance:** improving transmission line reliability by reducing back-flashover rates.
- **Low-voltage (LV) installations:** modular LV arresters are installed in distribution panels, while compact types are used for outlet-level protection (with lower discharge capacity).
- **Low-current/data circuits:** specialized SPDs protect telecommunications, automation buses (e.g., fieldbus), and control networks from external (lightning) and internal (switching) overvoltages, often installed in cabinets or integrated into loads.

4.14 Coordination of protections (insulation coordination)

The systematic process of insulation coordination defines the dielectric strength of equipment and the V_p of devices to ensure reliable and economical network operation. The core principle is to ensure that V_w of system insulation (e.g., the BIL) is always higher than the highest transient overvoltage that can appear at its terminals, with a deliberate safety margin. This is achieved by strategically placing surge arresters to "clamp" transient voltages and by using the protective ratio K_p , which must be greater than 1.

The goal is to force any insulation failure to occur only at predetermined, non-critical points, like external spark gaps, thereby protecting expensive apparatus like transformers.

4.15 Protection against internal overvoltages

Mitigation of internally generated overvoltages, particularly switching surges, employs several key strategies. Protection begins at the source with controlled (synchronized) switching, where point-on-wave control energizes circuits at the voltage instant that minimizes transient intensity.

The primary network protection device is the metal-oxide surge arrester, strategically installed at line terminals and near sensitive equipment to clamp surge magnitudes.

On transmission lines, shunt reactors compensate for the line's capacitive charging current, thereby mitigating sustained temporary overvoltages such as those from the Ferranti effect.

Furthermore, pre-insertion resistors in circuit breakers provide critical damping during line energization. Temporarily inserted into the circuit, they modify the transient response to approximately $V(t) = V_0(1 - e^{-t/\tau})$, where the increased time constant τ due to the resistor reduces the initial surge peak.

4.16 Case studies and system-level protection

Protection principles are applied to the key power system assets through :

- **Protection of a HV substation:**

A substation is protected by a coordinated system: differential relays for busbars and transformers, distance and overcurrent relays for feeders, and surge arresters at all terminals. The goal is selectivity (isolating only the faulted component) using time-graded settings and communication-aided tripping to maintain service continuity.

- **Protection of an overhead transmission line:**

The primary scheme uses distance relays with multiple zones for instantaneous and backup protection, backed by overcurrent relays. Communication-aided schemes (e.g., current differential) allow ultra-fast, unit protection. Auto-reclosing restores service after transient faults, while shield wires and surge arresters defend against lightning.

- **Protection of underground cable networks:**

Cables primarily use differential relays (via pilot-wire or fiber) for fast, selective internal fault protection. Sensitive earth fault protection detects insulation failures, while surge arresters protect at terminations. Key challenges include managing high charging currents, accurate fault location, and coordination at overhead-to-cable transitions.

4.17 Monitoring and diagnostics of transient phenomena

Monitoring and diagnostics are essential for understanding real-world transient events and validating system protection. This is achieved using specialized equipment installed at key points in the network:

- **Transient recorders / disturbance recorders:**

These high-speed, multi-channel instruments capture the detailed waveform of voltage and current during a transient event (lightning strike, switching operation). The data is used to analyze event magnitude, shape, origin, and the performance of protective devices.

- **Surge counters and discharge recorders:**

Physically attached to surge arresters, these devices log the number and often the approximate energy of discharge events. This data is crucial for predictive maintenance, indicating arrester aging and helping to schedule replacements before failure.

- **Integrated monitoring systems:**

These systems combine data from recorders, Supervisory Control and Data Acquisition (SCADA), and protection relays to provide a comprehensive view of system disturbances, supporting root cause analysis, insulation condition assessment, and the refinement of insulation coordination strategies.

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