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# GENERATION, TRANSMISSION AND DISTRIBUTION OF THE ELECTRICITY

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ELECTRICITY**

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The textbook is written based on a modern new program for analyzing international curricula and higher education programs. The textbook “Generation, transmission and distribution of the electricity” provides a comprehensive overview of modern electric power systems, covering the fundamental principles, technologies, and operational aspects involved in the production, transmission, and delivery of electrical energy to consumers. The course begins with the basic structure of power systems, including conventional and renewable power plants, operating principles of generators, and performance characteristics of different energy conversion technologies. Special attention is given to renewable power generation technologies, along with their efficiency, environmental impact, and operational constraints. The textbook further examines the design and analysis of high-voltage transmission systems, including transmission lines, substations, transformers, and power flow control. Electrical parameters such as impedance, voltage regulation, power factor, and system stability are analyzed using engineering models and practical calculations. The distribution section focuses on medium- and low-voltage networks, load characteristics, reliability indices, protection systems, and smart grid technologies. Topics such as power quality, fault analysis, relay protection, and system automation are also discussed to provide a modern perspective on power system management.

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## Introduction

Global economic growth and the continuous development of societies largely depend on the level of access to energy resources. At the end of the 20th century and the beginning of the 21st century, humanity is facing environmental, economic, and technical challenges that have never been encountered before. The depletion of reserves of traditional energy sources such as oil, gas, and coal, along with the harmful gases emitted during their usage negatively impacting the environment, and the increasing risks associated with climate change, have necessitated the shift towards alternative energy sources. As a result, fundamental changes are taking place in the processes of electricity generation, transmission, and distribution.

One of the key reforms in the energy sector is the active integration of renewable energy sources into the power generation process and their effective incorporation into existing power grids. The entire process—from generating electricity to transmitting and distributing it to consumers—is technically, technologically, and economically interconnected. Therefore, it is essential to analyze this system as a whole, improve its efficiency, identify existing issues, and develop solutions to address them.

Electricity generation serves as the foundation of modern industry and technology. Alongside conventional thermal power plants, stations operating on hydropower, wind, solar, biogas, geothermal, and other alternative energy sources are becoming increasingly widespread. Each of these sources is characterized by its unique production technology, environmental impact, operational stability, and transmission capabilities.

Moreover, the electricity transmission and distribution system is a complex and multi-stage engineering network. The main components of this system include high-voltage transmission lines, transformers, distribution substations, switching equipment, and consumer devices. Along the path from the power source to the end user, various technical losses, voltage fluctuations, and frequency deviations can occur. These challenges become even more complex in systems that incorporate renewable energy sources.

Renewable energy sources are energy resources that are environmentally friendly, sustainable, and capable of long-term utilization. These include solar energy (via photovoltaic panels and thermal power plants), wind energy (through wind turbines), hydropower (micro and mini hydroelectric stations), biogas and biomass, as well as geothermal energy sources. Each type possesses specific principles of energy generation, methods of converting energy into electricity, mechanisms of grid integration, and control technologies. Their integration is influenced not only by technical aspects but also by economic and regulatory frameworks.

Solar power plants (SPPs) are among the most widespread renewable energy sources. These primarily consist of photovoltaic panels that directly convert solar radiation into electricity. However, due to the intermittency of solar energy, which depends heavily on weather conditions, the amount of power generated is variable. This variability introduces challenges in maintaining voltage and frequency stability within the power grid. Additionally, solar power plants are often located in remote

areas requiring off-grid operation, which in turn necessitates technical and economic solutions for integration into the centralized energy system.

Wind power plants (WPPs) are also key contributors to the renewable energy mix. They convert the kinetic energy of wind into electrical energy using wind turbines. However, the inherent variability and unpredictability of wind speed result in significant fluctuations in power output. Such systems require synchronized operation and balancing of grid loads. Although WPPs are composed of relatively small units that can be distributed across various locations, their simultaneous connection to the grid may introduce challenges related to electromagnetic compatibility.

Hydropower, particularly in the form of micro and mini hydroelectric power stations, is considered highly effective for providing stable energy in rural areas. These systems, which operate by harnessing the force of flowing water, perform well even under fluctuating load conditions. Nevertheless, their performance is subject to seasonal variations in water flow, which can limit full-capacity operation at times. Furthermore, issues such as hydraulic transients and synchronization of turbines remain pressing technical concerns that need to be addressed.

Bioenergy from biogas and biomass is based on the utilization of agricultural waste and other organic materials to generate energy. These sources play a crucial role in ensuring continuous energy production capacity. However, to efficiently transmit and synchronize the generated electricity with the grid, advanced inverters and power amplification systems are required.

Geothermal energy sources, on the other hand, utilize subterranean heat and can become a stable source of energy. However, they involve technically complex systems and require substantial capital investments.

Beyond energy generation, energy storage and control are integral components of a modern energy system. Devices such as batteries, flywheel generators, and supercapacitors are essential in systems integrated with renewable sources. Given that these sources cannot ensure continuous and stable production, the ability to temporarily store the generated energy and deliver it when needed becomes critically important.

The maintenance of electric power quality indicators, reactive power management, voltage fluctuation mitigation, and the prevention of harmonic distortions are increasingly being addressed through the development of modern inverters and power electronics. In particular, the introduction of smart-grid technologies has created opportunities for real-time monitoring, automated control systems, and energy flow optimization.

Electric power transmission networks serve as the nervous system of the entire energy infrastructure, and their reliability determines the overall system stability. Transformers, switching devices, distribution substations, and other components perform vital functions such as adjusting voltage levels, directing energy flow to the appropriate destinations, and managing system overloads. At the same time, minimizing energy losses and voltage drops, and implementing energy-saving technologies in these networks has become a modern necessity.

Each stage of electric energy generation, transmission, and distribution demands thorough scientific and technical approaches. Especially in systems based on

renewable energy sources, integration requires complex technological solutions, innovative management methods, and the use of modern electronic tools. Scientific research and technological advancements in this field are expected to play a key role in establishing stable, environmentally friendly, and economically efficient energy systems in the near future.

# CHAPTER 1: PROCESSES OF ELECTRICITY GENERATION, TRANSMISSION, AND DISTRIBUTION, AND RENEWABLE ENERGY SOURCES

## 1.1. The processes of generation, transmission and distribution of electricity.

**Power Generation Stations:** Electric energy is the primary source of energy in today's modern society. The demand for electricity is steadily increasing in various sectors, including industry, transportation, households, information technologies, and many others. The process of generating electricity is based on various technologies that depend on the specific characteristics of natural resources. The main task of power generation stations is to convert one form of energy (thermal, mechanical, nuclear, solar, or hydro energy) into electrical energy. All power plants are equipped with generators that operate based on the law of electromagnetic induction, converting mechanical energy into electrical energy.

**The main types of power generation stations include:**

1. Thermal Power Stations (TPS) – utilize organic fuels such as coal, gas, fuel oil, or biogas, as well as waste heat.
2. Hydroelectric Power Stations (HPS) – use the potential energy of flowing water.
3. Wind Power Stations (WPS) – harness the kinetic energy of wind movement.
4. Solar Power Stations (SPS) – convert solar radiation directly into electricity.
5. Nuclear Power Stations (NPS) – generate electricity by utilizing nuclear reactions.

### Thermal power stations

Thermal power stations are among the most widely used types of power plants in the world. These stations utilize organic fuels such as coal, natural gas, or fuel oil, as well as biofuels. The fundamental process in thermal power plants involves burning fuel to convert water into steam, which in turn drives a turbine.

### Operating principle

1. Fuel (coal, gas, or fuel oil) is burned in a boiler unit, generating thermal energy.
2. The generated heat transforms water into steam.
3. The steam rotates a turbine.
4. The turbine drives a generator, producing electrical energy.
5. The steam is then condensed back into liquid form in a condenser and recirculated into the system.

The processes occurring in thermal power stations operate based on the **Rankine cycle**, which is a thermodynamic cycle used to convert heat into mechanical energy and then into electricity.

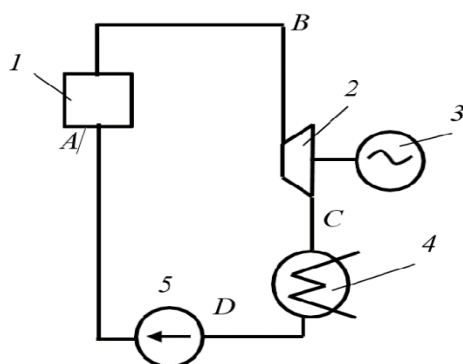
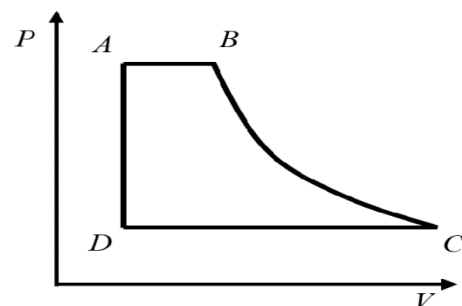


**Figure 1.** A – Technological diagram of a TPS operating on the Rankine cycle,  
B – Schematic of the ideal Rankine cycle [1].

In the turbine, the expansion process of the steam takes place along the **adiabatic line BC** in accordance with the **ideal Rankine cycle**. The steam exiting the turbine is condensed in a **condenser**, where it is cooled using cooling water and removed. The condensation process corresponds to the **segment CD**. The resulting condensate is pumped back to the boiler using a **feedwater pump**. This process corresponds to **segment DA**, where the pressure of the liquid increases at a **constant volume**, since the volume of the liquid does not change significantly during compression due to its incompressible nature. The **thermal efficiency** of the ideal Rankine cycle, like that of any heat engine, is determined by the ratio of the useful work done to the total heat input supplied to the boiler:

$$K = \frac{Q_1 - Q_2}{Q_1}$$

Here,  $Q_1$  represents the amount of heat transferred to the working fluid in the

| №  | Station Type                              | Fuel                       | Efficiency (%) | Advantages                                        | Disadvantages                                            |
|----|-------------------------------------------|----------------------------|----------------|---------------------------------------------------|----------------------------------------------------------|
| 1. | Thermal Power Plants (IES)                | Coal, Gas, and Oil (Mazut) | 30-40 %        | The possibility of building a high-capacity power | Low efficiency, high water consumption                   |
| 2. | Gas turbine power plants                  | Gas, diesel                | 35-45 %        | Occupies less space, starts quickly               | Lower efficiency compared to modern thermal power plants |
| 3. | Combined cycle gas and steam power plants | Gas                        | 55-60 %        | High efficiency, low emissions                    | Expensive technology                                     |

steam generator, while  $Q_2$  denotes the amount of heat rejected through the cooling water in the condenser.

The efficiency of a thermal power plant (useful work coefficient, UWC) is determined by the following formula:

$$\eta = \frac{P_{out}}{P_{in}} \times 100\%$$

For the ideal steam cycle, the efficiency is determined through the Rankine cycle and is given by the following formula:

For the ideal Rankine cycle, the efficiency can also be expressed as:

$$\eta_{\text{Rankine}} = \frac{W_{\text{net}}}{Q_{\text{in}}} = \frac{Q_{\text{in}} - Q_{\text{out}}}{Q_{\text{in}}} = 1 - \frac{Q_{\text{out}}}{Q_{\text{in}}}$$

This formula is used to assess the performance of the ideal Rankine cycle, which forms the basis of most thermal power plants.

**Hydroelectric Power Plants:** Hydroelectric power plants (HPPs) are facilities that convert the potential and kinetic energy of flowing or falling water into electrical energy using hydropower resources. HPPs are considered renewable energy sources and are known for generating clean electricity with minimal environmental impact.

**Working Principle:** The basic working principle of an HPP involves transforming the mechanical energy of water flow into rotational energy in a hydroturbine, which then drives a generator to produce electricity. The main stages are as follows:

- Water is stored in a dam or reservoir.
- The stored water is channeled towards the hydroturbine under high pressure.
- The turbine rotates due to the force of the water flow.
- The rotation drives a generator that produces electrical energy.
- Transformers adjust the voltage for efficient transmission and deliver the electricity to consumers.

**Types of HPPs:** Hydroelectric power plants can be classified based on their structural design and water source characteristics into the following types:

1. Storage (Reservoir) HPPs – Utilize large dams and reservoirs to control water flow and supply consistent power.
  2. Run-of-River HPPs – Use natural river flow with minimal or no water storage; suitable for consistent water streams.
  3. Pumped Storage HPPs – Work like energy storage systems: during low demand, water is pumped to an upper reservoir, and during high demand, it is released to generate electricity.
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### **Advantages and disadvantages of hydroelectric power plants (hpps)**

#### **Advantages:**

- Renewable and environmentally friendly energy source.
- Long operational lifespan with low maintenance costs.
- Reservoirs can also be used for irrigation and drinking water supply.

**Disadvantages:**

- High construction costs.
- Potential environmental issues, including impact on aquatic ecosystems.
- In some cases, may require the relocation of local populations.

**Environmental impact of HPPs:** Hydroelectric power plants can have various environmental impacts:

- Disruption of the natural river ecosystem.
- Changes to habitats of fish and aquatic species.
- Increase in thermal emissions and water evaporation rates.
- Hydroelectric power plants are a crucial part of the global energy system and play a significant role in sustainable development. Their efficient operation ensures energy supply stability and contributes to environmental protection.

**Hydroelectric power output Formula**

The output capacity of a hydroelectric power plant is calculated using the following formula:

$$P = \eta \cdot \rho \cdot g \cdot H \cdot Q$$

Where:

- P – Power output (Watts)
- $\eta$  – Efficiency of the turbine-generator system
- $\rho$  – Water density (typically 1000 kg/m<sup>3</sup>)
- g – Gravitational acceleration (9.81 m/s<sup>2</sup>)
- H – Net head or effective water height (meters)
- Q – Flow rate (cubic meters per second)

**Wind power plants (WPPs)**

Wind Power Plants (WPPs) are one of the renewable energy sources that convert wind energy into electrical energy. This technology enables the generation of sustainable electricity without causing harm to the environment.

The operating principle of WPPs includes the following stages:

- The kinetic energy of wind motion rotates the blades of the turbine.
- The rotational motion is transferred to the electric generator.
- As a result of the generator's operation, electrical energy is produced.
- The generated electricity is transmitted to consumers via a transformer [2].

**Types of wind power plants:** Wind power plants (WPPs) are generally classified into the following main categories:

- **Onshore WPPs** – Installed on land, these systems are effective in regions with favorable wind resources.
- **Offshore WPPs** – Located over seas or oceans, these plants benefit from strong and consistent wind currents.
- **Hybrid Systems** – Power plants that operate in combination with solar panels or other renewable energy sources.

**Advantages and disadvantages of wind energy****Advantages:**

- A clean and renewable energy source.
- Does not emit harmful pollutants into the atmosphere.
- Requires no fuel for electricity generation.
- Economically viable with long-term operational potential.

**Disadvantages:**

- Wind variability can cause fluctuations in power output.
- High capital costs associated with construction and installation of wind turbines.
- May cause noise and visual disturbances in residential areas.
- Can pose threats to birds and local wildlife.

Wind power plants are a crucial component of the future sustainable energy system, contributing to enhanced reliability in energy supply. Their widespread implementation plays a significant role in ensuring energy security and protecting the environment.

**The power output of a wind turbine is determined using the following formula:**

$$P = \frac{1}{2} C_p \rho A v^3$$

Where:

- P – Power output of the wind turbine (Watts)
- $C_p$  – Power coefficient (dimensionless), represents the efficiency of the turbine in capturing wind energy
- $\rho$  – Air density ( $\text{kg/m}^3$ ), typically around  $1.225 \text{ kg/m}^3$  at sea level
- A – Swept area of the turbine blades ( $\text{m}^2$ ), calculated as  $A = \pi r^2$
- v – Wind speed (m/s)

This equation indicates that the power output is proportional to the cube of the wind speed, highlighting the importance of site selection for wind energy projects. Even small increases in wind speed can result in significantly higher energy output.

**Solar power plants (SPPs) :** Solar power plants (SPPs) are renewable energy systems that convert solar energy into electricity. This technology is environmentally friendly and economically efficient, playing a crucial role in enhancing energy independence.

**Solar power plants operate through the following key components:**

1. **Photovoltaic (PV) panels** – Convert sunlight directly into electrical energy.
2. **Inverters** – Convert the direct current (DC) generated by the PV panels into alternating current (AC).
3. **Batteries (energy storage systems)** – Store the generated energy and supply it when needed.
4. **Electrical grid** – Distributes the produced energy to consumers.

SPPs are classified into the following main types:

1. **Photovoltaic (PV) plants** – Convert sunlight directly into electrical power using semiconductor technology.
2. **Concentrated solar power (CSP) plants** – Utilize solar thermal energy to generate steam, which drives a turbine to produce electricity.
3. **Hybrid systems** – Combine solar energy with wind or other renewable energy sources for enhanced reliability and performance.

**Advantages and disadvantages of solar energy****Advantages:**

- Clean and inexhaustible source of energy.
- Does not emit harmful pollutants into the atmosphere.
- Low operational costs in electricity generation.
- Enables independent and long-term energy supply.

**Disadvantages:**

- Solar irradiance is dependent on weather conditions.
- High initial cost of photovoltaic panels.
- Requires large installation areas.
- Batteries and storage systems incur additional expenses.

Solar power plants are an integral part of the global energy system, contributing to sustainable energy supply. The widespread deployment of this technology plays a significant role in mitigating environmental challenges and supporting economic development [3].

**Power output of a solar panel**

$$P = \eta * A * S * P$$

The power output of a solar panel is calculated using the following expression:  
Where:

- $\eta$  – Efficiency of the solar panel (dimensionless)
- $A$  – Surface area of the solar panel ( $m^2$ )
- $S$  – Solar irradiance ( $W/m^2$ )

This formula reflects the direct relationship between the panel's efficiency, its surface area, and the intensity of solar radiation, which collectively determine the electric power output.

**Electricity transmission line.**

Electricity generation, transmission, and distribution are the core components of a modern energy system. Once electrical energy is generated at power plants, it must be delivered to consumers through specialized transmission networks.

Electricity transmission networks consist of high-voltage transmission lines (Transmission Lines - TLs) and low-voltage distribution networks, which together facilitate the reliable delivery of electric power to end users. These systems are designed to minimize energy losses and ensure stable, uninterrupted power supply across various geographic regions.



**Figure 1. Thermal power plant.**

Electricity transmission consists of the following key components:

1. **Power Plants** – Where electricity is generated.

2. **High-voltage Transmission Lines** – Used to carry electricity over long distances with minimal energy loss.
3. **Substations** – Facilities that transform high-voltage electricity from transmission lines to a lower voltage suitable for distribution.
4. **Transformers** – Devices that step up or step down the voltage of electricity.
5. **Switchgear and protection systems** – Ensures the safe operation of the transmission network by isolating faults and preventing damage.



**Figure 2. Transformer substation**



**Figure 3. Transmission lines**

**High-voltage transmission lines (HVTL)** are designed to efficiently deliver electrical energy over long distances from generation sources to remote consumers. Due to their high voltage levels, they minimize power losses and enhance the reliability of the electrical grid.

Consumers – Users of electrical energy (households, factories, industrial facilities). The transmission networks of electrical energy must be robust, reliable, and efficient, as any disruptions in the power grid can have a negative impact on the entire industry and economy. The electrical transmission system is classified by power capacity and transmission distance into the following types:

#### **High-voltage transmission networks**

These operate at voltage levels of 110 kV, 220 kV, 330 kV, 500 kV, 750 kV, 1150 kV, and 1500 kV.

They are primarily used for transmitting electricity over long distances from power plants.

The use of high voltage reduces energy losses because the current is lower, thereby minimizing power dissipation.

### **Medium-voltage transmission networks**

These operate at voltage levels of 6 kV, 10 kV, 35 kV, and 110 kV. They are used for transmitting electrical energy between cities, districts, and industrial facilities.

### **Low-voltage transmission networks**

These operate at voltage levels of 220 V, 380 V, 400 V, and 660 V. They deliver electrical energy to households, shops, and small enterprises. These networks are present in urban, rural, and industrial areas [3–4].

### **Distribution of Electric Energy**

Electricity distribution is carried out across all voltage levels. The main goal of distribution is to separate overhead lines depending on the location of consumers, and this process is implemented at both high and low voltage levels. Moreover, the distribution process is carried out based on variations in the energy consumption voltage and the nature of the energy demand. In an energy system, distribution processes are executed through precise calculations. Kirchhoff's laws are primarily used in distribution. Kirchhoff's laws are fundamental principles in the distribution of electrical energy. The distribution of power flow through electrical networks is described based on nodes and loops. Kirchhoff's laws are used to calculate currents and voltages in networks based on the law of conservation of electric energy and Ohm's law.

### **Kirchhoff's two fundamental laws:**

**1. The Junction Rule** – The algebraic sum of currents at a junction is equal to zero. A junction is a point in a network where multiple conductors meet. Kirchhoff's first law is based on the law of conservation of charge, meaning that the sum of all currents arriving at a junction is equal to the sum of all currents leaving that junction.

Mathematical expression:

$$\sum I_{in} = \sum I_{out} \quad (1)$$

That is:

$$I_1 + I_2 = I_3 + I_4 + I_5 \quad (2)$$

where:

$I_1, I_2$  – currents entering the junction,

$I_3, I_4, I_5$  – currents leaving the junction.

Energy distribution calculation in transformer substations, balancing currents in electrical networks

Example:

If 100 A of current enters a junction in an electrical substation, and 40 A and 30 A exit, the remaining outgoing current is:

$$\begin{aligned} 100A &= 40A + 30A + I_x \\ I_x &= 100 - 40 - 30 = 30A \end{aligned}$$

Thus, the current in the final network must be 30 A.

**Kirchhoff's second law** is based on the law of conservation of energy, meaning that the algebraic sum of voltages around a loop is zero.

$$\sum U = 0$$

or:

$$U_1 - U_2 - U_3 = 0$$

where:

$U_1$  – voltage source (e.g., generator or transformer output),

$U_2, U_3$  – voltages dropped across resistances and loads along the loop [5].

**Concept:** In any closed electrical loop, the source voltages and the consumed voltages must be equal.

**Application:** Calculating voltage losses in electricity distribution, maintaining energy balance.

**Example:**

If there is a 3 kV voltage loss in the line during the distribution of power from a 10 kV substation, the voltage reaching the consumers will be:

$$10kV - 3kV = 7kV$$

This voltage should be normalized based on the operating conditions of the consumer lines

### **Stability and efficiency of the electric power system**

The electric power system is one of the most critical infrastructures of modern society, and its stability and efficiency are of decisive importance for ensuring a reliable power supply.

**Stability** refers to the system's ability to maintain operation under various conditions, to self-recover, and to operate without interruptions.

**Efficiency** is the ability of the electric power system to deliver maximum output with minimal losses.

The stability of an electric power system is generally classified into three main types:

1. **Dynamic stability** – The ability of the power system to adapt quickly to small disturbances and return to normal operating conditions.
2. **Static stability** – The ability to maintain system equilibrium under gradually changing load conditions.
3. **Transient (or transmission) stability** – The system's ability to recover from major faults or disturbances.
4. **Factors ensuring the stability of electric current include:**
5. **Voltage stability** – The ability to withstand sharp voltage fluctuations.
6. **Frequency stability** – Maintaining operation within the 50 Hz frequency range.
7. **Network redundancy level** – The activation of backup power sources in case of system failure.

### **Measures to ensure power system stability:**

1. **Optimization of energy distribution** – Delivering electric energy to consumers in the most efficient way possible.
2. **Modernization of transformer and generation equipment** – Introducing equipment with reduced power losses.

## 1.2. General overview of renewable energy sources

The energy system is currently one of the fundamental pillars of human development. Due to the limitations of conventional energy sources and their contribution to environmental problems, the demand for alternative energy sources is steadily increasing. Renewable energy sources refer to energy derived from naturally replenished resources. These include solar energy, wind energy, hydropower, biomass, geothermal energy, and hydrogen power. Compared to traditional fossil fuels, these sources are environmentally safer and more suitable for long-term use [6]. The significance of renewable energy sources is associated with the following factors:

1. **Resource sustainability** – Solar, wind, water, and geothermal energy are continuously replenished by natural processes and are virtually inexhaustible.
2. **Minimal environmental impact** – In comparison with conventional fuels, renewable energy sources emit fewer pollutants into the atmosphere and aquatic environments.
3. **Energy security** – Many countries rely on imported fossil fuels to meet their energy needs. Renewable energy sources contribute to enhancing energy independence.
4. **Economic efficiency** – Although they require substantial initial investment, renewable energy technologies are cost-effective in the long term and help stabilize energy prices.

The rapid development and deployment of renewable energy sources is one of the key directions in 21st-century energy strategies. In particular, the international community is fulfilling strict commitments within the framework of the **Paris Agreement** to reduce carbon emissions and combat climate change. Numerous countries, including Germany, China, and the United States, are making significant investments in renewable energy technologies. Given the global increase in energy consumption, it is evident that renewable energy sources will play a crucial role in ensuring sustainable energy supply in the future. Therefore, the development and application of these technologies will continue to expand [7].

### **Technological development and application of renewable energy sources**

Today, renewable energy sources are undergoing significant technological advancement. Their widespread application contributes to ensuring the sustainability of global energy supply. As a result of scientific research and innovation, new technologies are being introduced, improving efficiency and strengthening economic competitiveness. The development of renewable energy sources can be analyzed through the following main directions:

#### **1. Development of solar energy technologies**

Solar energy represents one of the most crucial sectors of renewable energy, and its technological development has progressed rapidly in recent years. Photovoltaic (PV) panels and concentrated solar power (CSP) systems are extensively utilized in this domain.

1. **Photovoltaic panels** – Modern-generation solar panels possess high efficiency, with conversion rates reaching 20–25%. Additionally, new-generation tandem panels are being developed to maximize the utilization of solar radiation.

**2. Concentrated solar power (CSP)** – This technology is used primarily for supplying large industrial facilities with energy. CSP systems enable the storage of thermal energy in specialized materials, allowing for electricity generation even during nighttime hours [8].

### **2. *Development of wind energy technologies***

Wind energy technologies have advanced considerably in recent years due to improvements in aerodynamic design and increased turbine capacity. Wind turbines are used not only in large-scale power plants but also as independent energy sources in smaller-scale applications.

**1. Offshore wind power plants** – Due to the greater stability of wind over the sea compared to land, many countries are investing in offshore wind farm development.

**2. Efficiency improvements in wind turbines** – New-generation turbines are being manufactured with blades made of lightweight and durable materials, thereby enhancing overall performance [9].

### **3. *Hydropower and ocean energy***

Hydroelectric power plants (HPPs) constitute a major portion of renewable energy. In addition to traditional hydropower, small and micro HPP technologies are also evolving.

**1. Micro HPPs** – These systems utilize the flow of small rivers and canals to supply energy to local areas.

**2. Tidal and wave energy** – New technologies are being developed to harness energy from ocean waves. For instance, underwater turbines can convert ocean currents into usable energy [10].

### **4. *Biomass and geothermal energy***

Biomass energy—derived from organic waste—is being developed to ensure environmental sustainability. Biomass fuel is widely used in both industrial and agricultural sectors.

**1. Biogas technologies** – These are evolving to extract biogas from agricultural waste, domestic refuse, and sewage water.

**2. Geothermal power plants (GPPs)** – Technologies that generate electricity by utilizing geothermal heat are improving. In particular, advancements in deep drilling methods and new heat exchange systems are increasing overall efficiency [11].

### **5. *Hydrogen energy technologies***

In recent years, hydrogen energy has gained attention as a stable and environmentally friendly energy source. Technologies for producing "green hydrogen" are being developed and are becoming increasingly economically viable. Hydrogen is now being applied in vehicles, industrial enterprises, and energy systems. The technological advancement of renewable energy sources contributes to improving energy efficiency, protecting the environment, and ensuring energy security. In the future, these technologies are expected to develop further and constitute a core element of the global energy system [12].

### **Prospects and development trends of renewable energy sources**

Renewable energy sources represent one of the most steadily developing sectors on a global scale. In the future, they are expected to play a key role in reducing dependence on conventional energy resources and minimizing environmental impacts. The prospects for their development are closely linked to scientific research,

economic factors, national policies, and international agreements. By the mid-21st century, it is anticipated that renewable energy sources will constitute the primary share of global energy supply [13].

The future development of renewable energy can be analyzed in the following key areas:

**1. Prospects for solar energy** Solar energy remains one of the fastest-growing alternative energy sources worldwide. According to data from the International Energy Agency (IEA), solar energy may account for 30–40% of global electricity generation by 2050 [14].

- **Next-generation solar panels** – Organic solar panels, tandem photovoltaic (PV) technologies, and perovskite-based solar cells are expected to surpass current silicon-based panels in both efficiency and cost-effectiveness.

- **Energy storage systems** – To ensure the reliable supply of solar energy, advanced battery technologies (e.g., lithium-ion, sodium-ion, hydrogen storage systems) are being developed [15].

- **Artificial intelligence and smart grids** – AI technologies are increasingly used to optimize solar energy production and manage energy distribution networks effectively.

**2. Prospects for wind energy** With the continuous improvement of wind power technologies, the capacity and efficiency of wind turbines are increasing. Innovations such as large-diameter rotors, aerodynamic blades, and advanced generators are driving progress in this field.

- **Offshore wind farms** – Offshore installations offer more consistent wind resources compared to onshore sites, and many countries are investing heavily in this area. The cost of offshore wind energy is expected to decrease significantly in the near future [16].

- **High-altitude wind turbines** – Airborne wind energy systems, operating in the stratosphere, are being explored as a novel method for power generation.

- **Wind-to-hydrogen conversion** – Technologies are being developed to produce green hydrogen using surplus wind energy, supporting the growth of hydrogen-based energy systems.

**3. Prospects for hydropower** Hydropower remains one of the most reliable and sustainable energy sources today. Future developments are likely to focus on the following areas:

- **Small and micro hydropower plants** – Compared to large hydroelectric stations, small-scale systems are more environmentally friendly and suitable for supplying electricity to rural and remote areas.

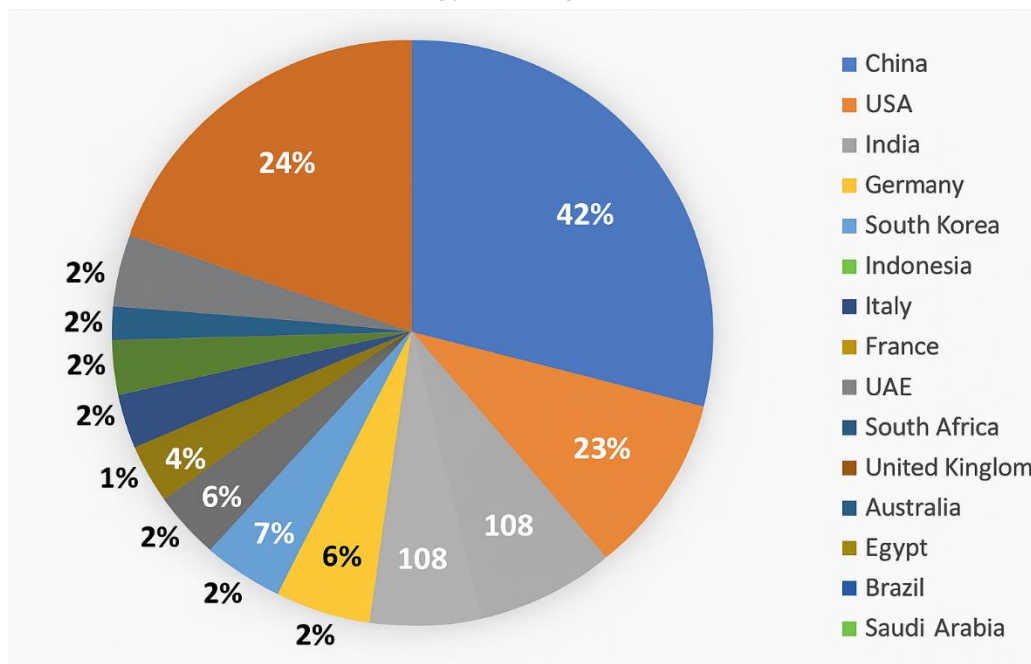
- **Ocean energy** – New technologies are being developed to harness energy from ocean waves and currents. For example, underwater turbines are being designed to generate electricity from marine flows on a continuous basis [17].

**4. Development of biomass and geothermal energy** Biomass and geothermal sources provide environmentally friendly means of energy generation. Their development contributes to the production of clean energy without harming the environment.

- **Biogas and biofuels** – It is anticipated that the technologies for biogas production from agricultural waste will be further refined and widely adopted in the transport sector.

- **High-temperature geothermal power plants** – Advancements in deep-drilling technology are enhancing the efficiency of geothermal energy systems. Ongoing research aims to increase the utilization of subterranean heat for electricity generation [18].

**5. Development of the hydrogen economy** Hydrogen energy has the potential to become a viable alternative to traditional fossil fuels in the near future. The production of "green hydrogen" supports a stable and clean energy supply, positioning hydrogen as a cornerstone of sustainable energy strategies.



**Projected Solar Photovoltaic Capacity by Country in 2030 (GW)**

**Hydrogen storage and transmission technologies** – Next-generation catalysts and high-density hydrogen storage systems are being developed. The development of alternative energy sources is expected to become a key part of the future energy system. Scientific research in solar, wind, hydro, biomass, and hydrogen energy is increasing their efficiency and strengthening their economic competitiveness. These sectors are receiving significant investments from both governments and the private sector. In the future, the further advancement of alternative energy technologies will help reduce global greenhouse gas emissions and contribute to the creation of a sustainable energy system [19].

**Utilization and significance of solar energy** - Solar energy is a clean and renewable source of energy derived from sunlight. This form of energy originates from thermonuclear reactions occurring in the core of the Sun and reaches the Earth in the form of electromagnetic waves. The following theoretical aspects are of great importance in the study of solar energy:

**Photovoltaic effect** – This is the process of directly converting sunlight into electrical energy using semiconductor materials (e.g., silicon). This phenomenon was discovered in 1839 by Alexandre-Edmond Becquerel [20]. Photovoltaic panels absorb

sunlight and convert the energy of photons into electric current. This process can be expressed by the following formula:

$$\eta = \frac{P_{out}}{P_{in}} \times 100\%$$

In the utilization of solar thermal energy, the first and second laws of thermodynamics are applied. Solar radiation is used to heat water or generate steam, which in turn is used to produce electrical energy. This process can be described by the following formula:

$$Q = mc\Delta T$$

To increase the efficiency of solar panels, new materials such as *perovskites* are being researched. Perovskite materials offer high photovoltaic efficiency, with potential conversion rates exceeding 25% [21].

Photovoltaic (PV) systems are used to convert solar radiation into electrical energy. These systems typically consist of the following components:

1. **Solar panels** – Convert solar radiation into electrical energy.
2. **Inverter** – Converts direct current (DC) into alternating current (AC).
3. **Batteries** – Store energy for later use.

For example, the PV systems utilized in Germany demonstrate an average efficiency of around 20–22% [22].

**Concentrated solar power (csp) systems** - focus sunlight to heat water or generate steam, which is then used to produce electricity. These systems are classified into the following types:

- **Parabolic troughs** – Concentrate sunlight onto receiver tubes to heat fluid.
- **Solar power towers** – Use a central receiver to collect focused sunlight and generate electricity.

In Spain, CSP systems have a combined capacity exceeding 2.3 GW.

**Smart grids** play a vital role in the management and distribution of solar energy. These systems enable the optimization of energy consumption and help prevent power outages.

**Example:**

If a solar panel has an efficiency of 20% and the incident solar power is 1000 W/m<sup>2</sup>, how much electrical energy will be produced by a panel with an area of 10 m<sup>2</sup>?

**Solution:**

$$P_{out} = \eta \times P_{in} \times A$$

$$P_{out} = 0.20 \times 1000 \times 10 = 2000W$$

### 1.3. Photovoltaic panels: operating principle and technological features

Photovoltaic (PV) panels convert sunlight directly into electrical energy using semiconductor materials. These panels generate an electric current when photons from sunlight excite electrons within the semiconductors. This process is known as the photovoltaic effect.

**Key factors influencing PV efficiency:**

- **Type of material:** Monocrystalline panels typically offer higher efficiency compared to polycrystalline and thin-film technologies.

- **Temperature effects:** The performance of PV panels can degrade at high temperatures.
- **Installation angle:** Optimal orientation relative to the sun maximizes energy capture.
- **Panel design:** Innovations such as half-cut cells and multi-busbar structures can significantly enhance panel efficiency

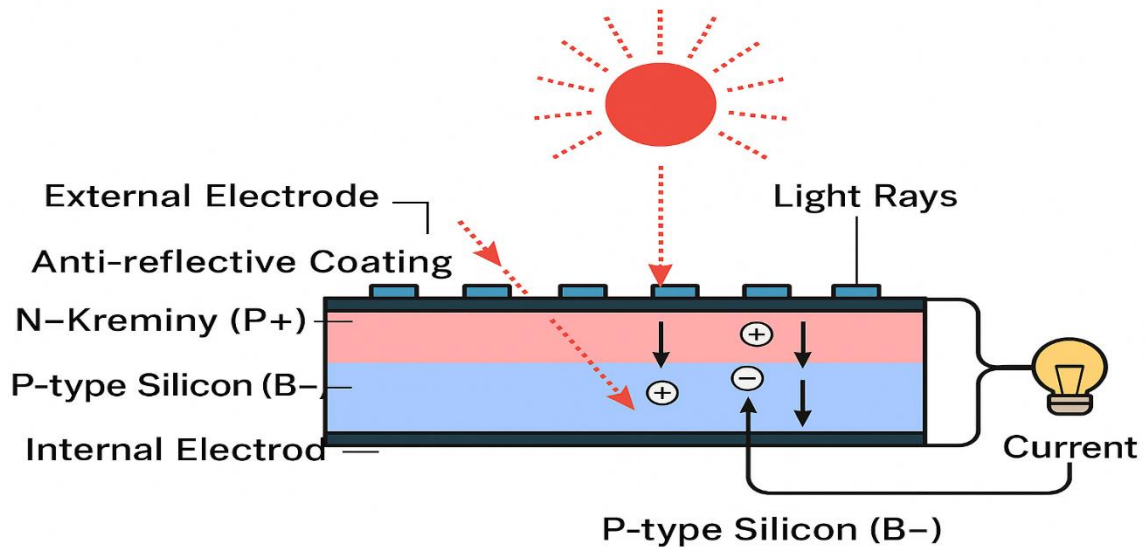


**Figure 7. Design of photovoltaic elements.**

**Advantages of photovoltaic panels:** Photovoltaic panels convert sunlight directly into electrical energy through the photovoltaic effect. This process is highly efficient and often delivers more energy per square meter compared to conventional solar thermal systems. They can be installed on various surfaces, including rooftops and facades, making them highly versatile in urban environments. Once installed, photovoltaic technology requires minimal maintenance. Most systems come with warranties of 20 to 25 years, ensuring long-term performance. Furthermore, many regions offer incentives and rebates, which make the initial investments more financially accessible.

These panels can also be integrated with battery storage systems. This feature allows users to store excess energy generated during the day for use at night or during cloudy weather, thereby increasing energy independence.

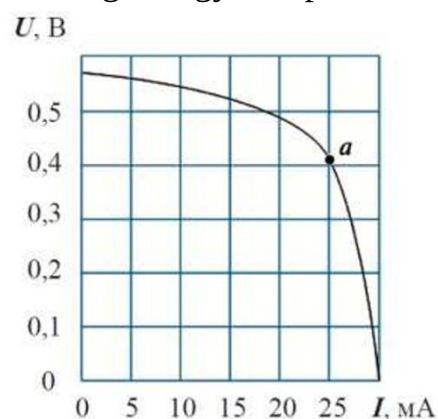


**Figure 8. Energy band diagrams of the p-n junction under various illumination modes:**

**Disadvantages of photovoltaic panels:** Although photovoltaic panels are efficient, their initial installation cost can be relatively high. Despite long-term financial benefits, this can deter some users from investing in the technology. The energy output of solar systems can fluctuate due to weather conditions and day-night cycles. Without proper battery storage, users may rely on the grid during periods of low solar irradiation, which reduces the attractiveness of off-grid solutions. Additionally, although many panels are designed to last 25 years or more, performance degradation may occur over time. The gradual loss in efficiency may require users to invest in replacement or repairs earlier than expected.

**Solar thermal power plants: types and applications:** If only 1% of the area of the Sahara Desert were covered with solar power plants, it could meet the global electricity demand. Solar thermal power plants offer one of the lowest-cost options for energy generation, especially in tropical regions. Unlike photovoltaic systems, parabolic collector-based solar plants utilize thermal processes instead of the photoelectric effect. Currently, there are three main types of solar thermal power plants: parabolic trough systems, solar tower systems, and Stirling engine-based systems. In parabolic trough systems, sunlight is concentrated using specially designed parabolic reflectors to heat a working fluid. These collectors consist of a parabolic-shaped mirror and a heat-absorbing tube placed along the focal line of the parabola. To maximize efficiency, the collectors track the movement of the sun throughout the day.

**Parabolic trough systems:** This system uses curved or flat mirror reflectors to direct solar radiation onto a receiver tube containing heat transfer fluid. The thermal energy collected is then used to convert water into steam for electricity generation.

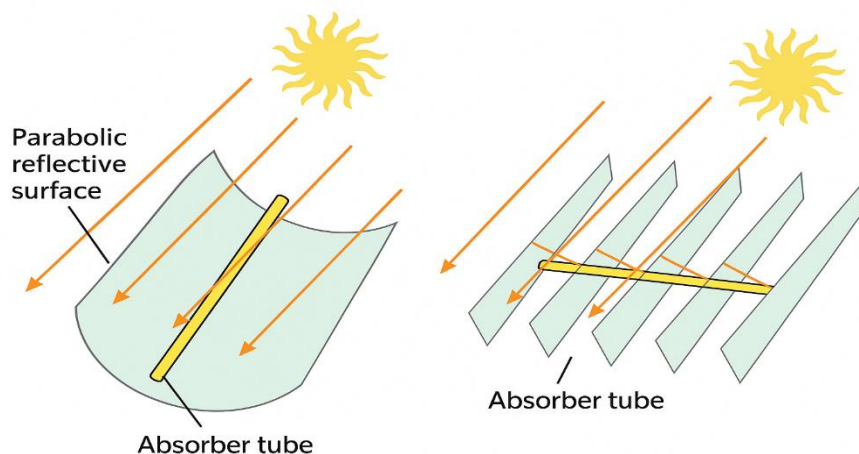


**Figure 10.** Schematic Structure of a Parabolic Collector [1]

**Disadvantages:**

- High construction and maintenance costs
- Reduced efficiency during cloudy weather conditions

- *Example:* The SEGS (Solar Energy Generating Systems) plant in California (USA) is one of the world's largest parabolic trough systems, with a capacity of 354 MW [23].



**Figure 11-12.** Arrangement of parabolic collectors at a solar thermal power plant in California, USA: a) general view; b) relative positioning of the collectors

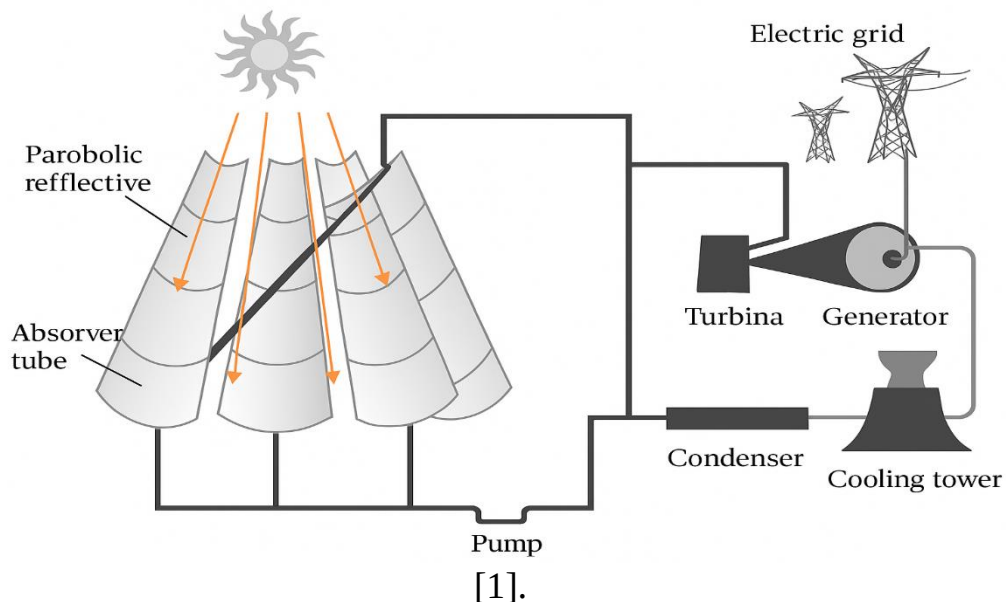


**Figure 13. Schematic Diagram of a Solar Thermal Power Plant Where Solar Radiation Directly Converts Water into High-Pressure Steam**

Modern technologies aim to utilize solar energy more efficiently and reduce the cost of electricity. In Almería, Southern Spain, a system is being tested in which solar radiation directly converts water into steam. In this system, parabolic collectors heat the water up to  $400^{\circ}\text{C}$ , driving a steam turbine. In the future, such systems may replace those that use heat transfer fluids. Between 2007 and 2009, three large solar thermal power plants with a capacity of 50 MW each were constructed in Spain. Today, the country is building plants with a total capacity exceeding 1.5 GW, some of which are equipped with thermal storage units. In the United States, the largest planned solar thermal plant will have a capacity of 950 MW, bringing the total planned capacity to 4.5 GW.

### Solar power tower systems

In solar power tower systems, solar energy is converted into electricity using a different approach. In this system, thousands of mirrors known as heliostats are

arranged around a central tower. These heliostats are controlled by a computer-based tracking system that directs the sunlight toward a receiver located at the top of the tower. The receiver is positioned at the focal point of the reflected sunlight and is heated to temperatures exceeding  $1000^{\circ}\text{C}$ . A working fluid (typically air or molten salt) absorbs this thermal energy and transfers it into a gas or steam cycle for electricity generation. In this configuration, hundreds or even thousands of heliostats concentrate solar radiation onto a single receiver mounted on a central tower. The fluid in the receiver—commonly molten salt—is heated and then used to generate steam in a steam generator, which in turn produces electricity.



**Figure 14. General view of a solar power tower plant**

Alongside parabolic trough solar plants, solar power tower plants have also been operational in several countries for years. Pilot plants of this type are in operation in Almería (Spain), Barstow (USA), and Rehovot (Israel), where they are used to optimize system configurations and test new components [1].

**Dish-stirling systems:** In this system, parabolic dish reflectors concentrate sunlight onto a central receiver. At this point, a Stirling engine converts thermal energy into mechanical energy, which is then converted into electrical energy.



**Figure 15. solar thermal electricity generation system**

**Smart energy grids** – Solar thermal power plants enhance grid stability by integrating with the energy network. Solar thermal power plants are one of the key directions in modern energy development, offering high efficiency and reliable energy production. In the future, these technologies are expected to evolve, becoming more efficient and cost-effective sources of energy.

## 1.4 Sources and importance of wind energy

Among natural energy sources, wind energy holds a prominent position. It is renewable, environmentally friendly, and economically efficient, playing a crucial role in electricity generation. Today, wind energy is one of the fastest-growing sectors in the field of alternative energy. According to the International Energy Agency (IEA), a significant share of the world's electricity production comes from wind turbines, and this share continues to grow annually [26]. The primary source of wind energy is the atmospheric pressure differences caused by solar radiation. The uneven distribution of temperature by the sun creates airflows. The main factors generating wind energy include:

- **Atmospheric pressure differences** – Different areas of the Earth's surface heat and cool at different rates, resulting in wind flows.
- **Earth's rotation** – Due to the Coriolis force, air masses move in different directions.
- **Geographical location** – Wind speed and stability vary in coastal, desert, and mountainous regions.

Ocean and sea coasts are rich in wind resources and are considered the most effective locations for installing wind turbines [27]. Wind energy plays a key role in sustainable development and the transition to eco-friendly energy systems on a global scale. Its primary importance lies in the following aspects:

- **Environmental friendliness** – Wind energy reduces greenhouse gas emissions and mitigates the effects of global warming [28].
- **Renewability** – Wind is a naturally occurring, inexhaustible energy source, making it a sustainable solution.
- **Economic efficiency** – Wind turbines have a long service life and help lower the cost of electricity production [29].
- **Energy independence** – Wind energy allows countries to reduce their dependence on imported fuels.

Wind energy is a renewable energy source with significant potential and relatively low conversion costs. The structure and operating principle of a wind power system are relatively simple. Figure 17 shows a schematic diagram of a wind turbine converting wind energy into electricity. Wind's kinetic energy strikes the turbine blades, causing them to rotate. The resulting rotational energy is transferred via the main shaft, gearbox, and high-speed shaft to an electric generator. The generator converts the rotor's mechanical (kinetic) energy into electricity. If a DC generator is used, the produced electricity can supply DC consumers or charge batteries. To supply AC consumers or feed into an AC grid, the generated DC is first converted into AC of nominal frequency using an inverter. If an AC generator is installed, the frequency of the generated AC varies with the wind speed and corresponding rotor speed. In such cases, the variable-frequency AC is first converted into DC via a rectifier. The resulting DC can then power DC consumers or charge batteries. Again, to supply AC consumers or integrate with the grid, this DC is converted into nominal-frequency sinusoidal AC using an inverter [1]. By the end of 2009, the total installed capacity of wind power systems worldwide reached 157,900 MW, representing an annual growth

of 31%. During the same year, wind power contributed 1.3% of global electricity production.

Currently, wind turbines are widely used in European countries and to a lesser extent in the USA and parts of Asia. Wind power's share in electricity generation stands at 19% in Denmark, 11% in Spain and Portugal, and 9% in Ireland. Figure 4.16 shows the global trend of installed wind power capacity from 1996 to 2008. The diagram illustrates the rapid and accelerating growth in wind turbine deployment and electricity production [1].

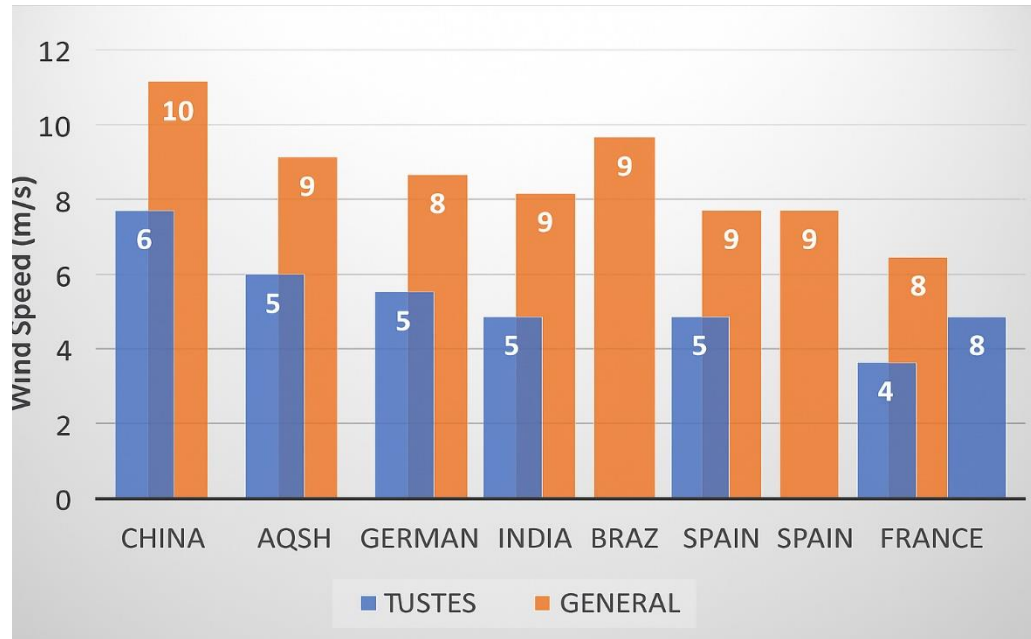


Figure 16. Global dynamics of total installed wind power capacity.

$$E_k = \frac{1}{2}mv^2$$

**Wind turbines: structure and operating principle** - Wind turbines operate based on the physical process of converting the kinetic energy of wind into mechanical energy, which is subsequently transformed into electrical energy. The kinetic energy of wind is calculated using the following formula:

The air mass  $m$  is determined as:

$$m = \rho A v t$$

Thus, the theoretical power extractable by a wind turbine is:

As seen from this equation, even a small increase in wind speed significantly increases the power output — for example, doubling the wind speed results in an eightfold increase in power.

$$P = \frac{1}{2}\rho A v^3$$

However, wind turbines cannot convert 100% of wind energy into useful power. According to **Betz's Limit**, the maximum theoretical efficiency of a wind turbine does not exceed 59.3%:

This physical limit indicates that only a portion of wind energy can be converted into useful energy [30, 31].

$$P_{\max} = \frac{16}{27} \cdot \frac{1}{2} \rho A v^3$$

**Main components of a wind turbine** - Wind turbines typically consist of the following main components:

1. **Blades (Rotor)** – capture wind energy and convert it into mechanical rotation.
2. **Main Shaft** – transfers the rotational motion from the blades to the gearbox.
3. **Gearbox** – increases the rotation speed to match the generator's requirements.
4. **Generator** – converts mechanical energy into electrical energy.
5. **Control System** – monitors wind speed and direction and adjusts the rotor speed accordingly.
6. **Tower** – supports the rotor and generator at an optimal height [32]

**Operating principle of wind turbines** - When wind hits the turbine blades, it causes them to rotate. The blades are shaped based on Bernoulli's principle, where differences in air pressure on each side create lift and induce rotation. This rotational motion transfers kinetic energy to the main shaft, which is then geared up by the gearbox to higher speeds. Electricity generation occurs in the generator based on

$$E = -N \frac{d\Phi}{dt}$$

**Faraday's law of electromagnetic induction:**

**Improving wind turbine efficiency**

To improve efficiency, the following methods are applied:

1. **Aerodynamic design** – optimizing the shape of the blades.
2. **Increased tower height** – higher altitude generally provides stronger winds.
3. **Electronic control systems** – optimize turbine performance based on real-time wind data [35, 36].

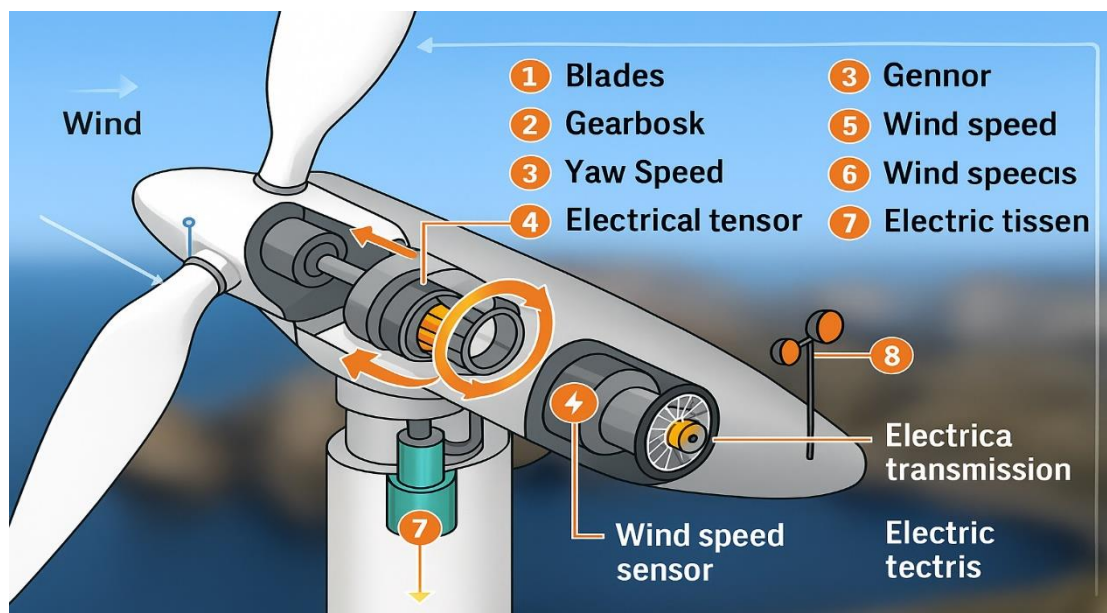


**Figure 19. Schematic diagram and structural layout of a wind turbine.**

May cause aesthetic and noise concerns [37, 38]. Wind turbines are devices designed to convert wind energy into electricity. Their operation is based on

aerodynamic principles and electromagnetic induction. Enhancing their efficiency involves optimizing blade design and employing advanced control systems

### **Prospects for the development of wind energy and methods to improve efficiency**

Wind energy is currently one of the fastest-growing sectors among renewable energy sources. The increasing global demand for energy and the need to address environmental issues have accelerated the expansion of wind power plants. According to the International Energy Agency (IEA), by 2050, wind energy is expected to account for 30–35% of global electricity production [39].

In recent years, innovations in wind turbine technologies have significantly increased the efficiency of power generation. In particular, high-capacity and aerodynamically enhanced rotor blades are being developed. Moreover, the construction of **offshore wind farms** is expanding, enabling the utilization of higher and more stable wind speeds [40].

The following technological solutions play a key role in the development of wind power plants:

1. **High-efficiency wind turbines** – new-generation turbines with capacities of 5–15 MW are being deployed.
2. **Offshore wind farms** – offer more efficient energy generation due to higher wind speeds over water.
3. **Artificial intelligence and automation** – improve turbine efficiency through real-time operational control [41].
4. **Innovations in materials science** – modern lightweight and durable materials extend turbine lifespan.

The economic attractiveness of wind power is driven by decreasing production costs. The construction and operation costs of modern turbines can be summarized as follows:

- **Average wind turbine cost:** \$1.2–2 million per MW.
- **Levelized cost of electricity (LCOE):** 2–5 cents per kWh.
- **Operational lifetime:** 20–30 years [42].

**From an environmental perspective, wind energy offers the following advantages:**

1. **Zero emissions** – no harmful gases are released into the atmosphere.
2. **No water consumption** – saves water compared to conventional power plants.
3. **Renewable energy source** – wind is considered an inexhaustible resource.

**To improve the efficiency of wind power plants, the following strategies are employed:**

- **Blade aerodynamics optimization** – new designs reduce air resistance and increase power output.
- **Generator optimization** – use of high-efficiency permanent magnet generators.
- **Increased tower height** – wind speeds are generally higher at greater elevations.
- **Artificial intelligence and data analysis** – ensures optimal operating conditions.

**In the future, wind energy is expected to develop in the following directions:**

1. **Wind-hybrid systems** – integrated with solar panels and energy storage technologies for enhanced performance.

**2. Next-generation offshore wind farms** – more efficient than onshore wind farms due to higher and more stable wind speeds.

**3. Superconductor-based generators** – improve efficiency by minimizing energy losses.

**4. Integration of energy storage systems** – enhances supply stability through advancements in battery technologies [43].

Wind energy is playing an increasingly significant role in the global energy market. Thanks to emerging technologies and innovations, the efficiency of wind power plants continues to improve. In the future, the sector is expected to expand further and become one of the core pillars of global energy systems.

### **1.5. General concept and development of hydropower**

Hydropower refers to the set of technologies that convert hydraulic energy into electrical energy, using the potential energy of naturally or artificially accumulated water flows. As one of the primary renewable energy sources, hydropower offers environmentally clean and sustainable electricity generation. The basic working principle of hydropower systems is the conversion of the potential or kinetic energy of water into mechanical energy, which is then converted into electrical energy. Water flows drive turbines, which in turn rotate generators to produce electricity.

#### **Hydropower systems are typically categorized as follows:**

**1. Large Hydropower Plants** – with a capacity of 100 MW or more, supplying major power grids.

**2. Medium Hydropower Plants** – with capacities ranging from 10 MW to 100 MW.

**3. Mini Hydropower Plants** – with capacities from 100 kW to 10 MW.

**4. Micro Hydropower Plants** – with capacities below 100 kW, usually intended for small villages or agricultural operations.

**Historical Development of Hydropower** - Hydropower has a long history. The earliest hydraulic structures were built in ancient Egypt and China, primarily for irrigation. Modern hydropower development began in the 19th century with the invention of electric generators. In 1882, the first industrial hydropower plant was launched in Wisconsin, USA. Throughout the 20th century, large-scale hydropower projects were implemented globally. Today, hydropower plays a significant role in global electricity production. According to the International Energy Agency (IEA), approximately 16–17% of the world's electricity is generated from hydropower plants. The advancement of technologies, especially in mini and micro hydropower, is making hydropower more accessible and efficient.

#### **International examples of hydropower development**

- **Norway:** Over 90% of Norway's electricity comes from hydropower. The country operates a wide range of micro and mini hydropower plants that ensure energy stability. Tonstad HPP is a major facility, complemented by numerous smaller plants across the nation.

- **Switzerland:** In Switzerland, many mini hydropower plants are located in mountainous regions. These plants harness mountain rivers and streams to produce electricity. The Grimsel hydropower system is one of the key contributors to renewable energy generation in the country.

- **India:** To electrify remote regions, India has implemented numerous micro hydropower plants, particularly in Arunachal Pradesh and Uttarakhand. Due to their low cost and eco-friendliness, these systems play a vital role in rural electrification.

### **Stages of hydropower development in Uzbekistan**

#### **Stage 1: 1923–1941**

Before 1923, the only hydropower plant in Uzbekistan was the Murgab HPP with a capacity of 1350 kW. Development began in 1923, with the establishment of “Gidroproekt” in 1930. Notable constructions include:

1. Bozsut HPP (4 MW, 1926)
2. Qodiriya HPP (13 MW, 1933)
3. Burijar HPP (6.4 MW, 1936)
4. Tovoqsoy and Komsomol HPPs (73.6 MW and 86.4 MW, 1938–1941)

#### **Stage 2: 1941–1960**

This period involved gaining experience in hydropower construction. New engineering methods were developed, and the focus shifted to larger plants. Major projects include:

5. Chirchiq-Bozsut cascade
6. Farhod HPP (126 MW)
7. Namangan HPPs (1–4), Aqsuv, Oqqovok, Shahrixon (6,7), Hisorav, and Qumqurgon HPPs

#### **Stage 3: 1961–1984**

Hydropower construction reached international standards. High dams and large-scale HPPs were built:

8. Chorvoq, Hojickent, Ghazalkent HPPs
9. Tuyamuyin HPP (150 MW)
10. Andijan HPP (140 MW)

#### **Stage 4: 1984–1990**

First units of the unique Chorvoq HPP were commissioned. Key developments include:

11. Ghazalkent (120 MW)
12. Uchqurghon (180 MW)

Design and construction of hydropower infrastructure reached world-class levels, considering agricultural (especially irrigation) demands.

#### **Stage 5: 1990–Present**

By 2005, agriculture’s energy demand reached approximately 11.7 billion kWh, rising to around 20 billion kWh by 2010, risking an energy shortage.

### **Theoretical basis of hydropower systems**

The science that studies hydropower plant operations is called **hydraulics**, consisting of:

- **Hydrostatics** – study of fluid balance
- **Hydrodynamics** – study of fluid motion

The power of water flowing through any cross-section depends on its **discharge (Q)** and the difference between upstream and downstream water levels, known as **head (H)**. The power of falling water (in kW) is calculated using its discharge (m<sup>3</sup>/s) and head (m):

$$P = \eta \cdot \rho \cdot g \cdot Q \cdot H$$

Due to losses occurring in hydraulic structures, turbines, and generators of hydropower plants (HPPs), only a portion of the water flow's total potential power can be effectively utilized. These losses arise from several factors, including friction in penstocks, turbulence at bends and valves, cavitation in turbine blades, and electrical losses in generators and transformers. As a result, the overall efficiency of a hydropower plant is typically less than 100%, often ranging between 80% and 92%, depending on design quality, maintenance practices, and operating conditions.

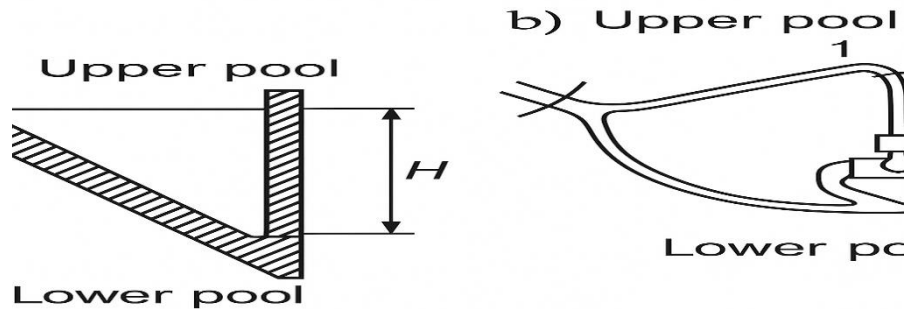


**Figure 20.** Schemes of head (hydraulic head) generation: a) head created by a dam; b) head created using a diversion channel: 1 – channel; 2 – forebay; 3 – penstocks to turbines; 4 – powerhouse; 5 – riverbed; 6 – dam [1].

**Operating principle of micro and mini hydropower plants** - Micro and mini hydropower plants are small-scale power generation systems with capacities ranging from 100 kW to 10 MW. These plants are designed to harness energy from small water streams and are ideal for supplying electricity to remote areas, small enterprises, and rural communities. Their main advantages include:

- **Environmentally friendly** – require no fuel and emit no harmful gases.
- **Low operational costs** – maintenance and servicing expenses are minimal.
- **Energy independence** – suitable for locations not connected to centralized power grids.

Micro and mini hydropower systems are simple yet efficient and generally consist of the following main components:

- **Intake structure** – collects water from rivers, streams, or canals and directs it to the turbine with the required pressure.
- **Turbine** – the core component of hydropower, converting the kinetic energy of flowing water into rotational mechanical energy. Common types include:
  - *Pelton turbines* – used for high-head, low-flow conditions.
  - *Kaplan and Francis turbines* – suitable for medium-head flows.
- **Generator** – converts mechanical energy from the turbine into electrical energy.
- **Transformer and control system** – adjusts the generated electricity to the required voltage and distributes it to end users.
- **Discharge system** – returns the used water back to the river or natural waterway.

#### **Basic operation stages of micro and mini hydropower plants**

##### **1. Water intake and direction**

- Water is collected through a specialized intake system and transported via pipes or canals to the turbine.

- If needed, small dams or reservoirs are constructed to increase water pressure.

## **2. Turbine rotation**

- The pressure of the water flow causes the turbine blades to rotate.
- The turbine rotation drives the generator.

## **3. Electricity generation**

- As the generator rotates, electromagnetic induction occurs, producing electricity.
- The generated electricity is transmitted directly to consumers or integrated into the grid.

## **4. Water discharge**

- The water used in the process is safely returned to the river or natural reservoir.

### **International examples**

#### **1. Micro HPPs in nepal**

Due to the energy supply challenges in Nepal's mountainous regions, numerous micro hydropower plants have been installed. For instance, the *Pharping Micro HPP* is a small but efficient station supplying electricity to local villages.

#### **2. Mini HPPs in switzerland**

Switzerland has constructed many mini hydropower plants to effectively harness mountain rivers. The *Gornerli Mini HPP* is considered one of the most efficient small-scale hydropower stations in the country.



**Figure 21.** View of a micro hydropower plant with a windmill-type water turbine

### **Waterwheel-type hydroturbines are mainly designed for low-head and slow-flowing rivers**

These turbines have a simple mechanical structure, where the water flow directly strikes the paddles, causing them to rotate. Such turbines are usually used in micro hydropower plants, as they require low costs and are easy to operate. Although waterwheel-type hydroturbines are small and economically efficient solutions, they can only be used in low-head and slow-flowing water sources. Their main advantage is simplicity, low cost, and environmental safety. However, low efficiency, sensitivity to water level changes, and difficulties in ensuring stable electricity supply are their main disadvantages. Therefore, before installation, it is essential to thoroughly

analyze the hydrological conditions, energy demand, and operational environment. To improve their performance and adaptability, modern waterwheel-type hydroturbines are sometimes integrated with optimized blade designs and adjustable flow control mechanisms. These improvements aim to slightly increase efficiency and allow the turbines to operate under a broader range of flow conditions. Despite their limitations, such turbines play a crucial role in off-grid applications, particularly in remote or rural areas where conventional infrastructure is either unavailable or economically unfeasible.



**Figure 22.** General view of a Pelton hydroturbine.

**Pelton turbines are designed to operate in high-head and low-flow water sources.**

They are equipped with cup-shaped buckets, and the water flow is directed through a special nozzle onto the turbine wheel. As a result, torque is applied to the turbine shaft, which drives the generator.

**Advantages:**

1. High efficiency – up to 90%;
2. Performs effectively under high-pressure water flow conditions;
3. Ideal for small-scale hydropower plants with capacities ranging from 1 to 100 kW.

**Disadvantages:**

1. Not suitable for low-head water sources;
2. Structurally complex and may involve higher installation costs.



**Figure 23.** General view of a Francis hydroturbine.

**Francis turbines are suitable for medium to high-head water sources.**

Water enters the turbine runner from the side, flows through its interior, and rotates the blades to generate energy.

**Advantages:**

- Can operate under a wide range of water head conditions;
- Suitable for both large and small hydropower plants;

- Provides stable and consistent electricity generation.

**Disadvantages:**

- Installation and maintenance can be expensive;
- Sand and solid particles in the water may cause rapid wear of turbine components.

**Application:**

Used in micro hydropower plants with medium to high capacity.



**Figure 24.** General view of a Kaplan hydroturbine.

**Kaplan turbines are designed for low-head but high-flow water sources.**

They feature propeller-like blades, where the pressure of flowing water rotates the turbine shaft.

**Advantages:**

- Ideal for low-head rivers and canals;
- High efficiency due to adjustable blade angles;
- Can operate effectively even with fluctuating water levels.

**Disadvantages:**

- High initial installation costs;
- Mechanically more complex compared to other turbine types.

**Application:**

Used in micro hydropower plants located on low-head rivers and canals.



**Figure 25.** General view of a Banki (cross-flow) hydroturbine

Banki turbines (also known as cross-flow turbines) are used for medium- and low-head water flows. Water enters the turbine from the side and passes through the blades twice: the first pass extracts the majority of the energy, while the second pass recovers additional energy.

**Advantages:**

- Simple construction and easy maintenance;
- Effective in small to medium head water flows;
- Resistant to sand and solid particles.

**Disadvantages:**

- Lower efficiency compared to Francis and Pelton turbines;
- Not suitable for high-head water sources.

**Application:**

Used in micro hydropower plants located on small water flows.

**Environmental impact and future prospects**

Micro and mini hydroelectric power plants (HPPs) are among the renewable energy sources that are typically installed on small rivers and canals to generate electricity. While these stations are considered to be more environmentally friendly compared to conventional large-scale HPPs, they still present certain ecological impacts. However, ongoing technological advancements in micro and mini HPPs are expected to enhance their efficiency and environmental safety in the future.

**Positive environmental impacts**

- 1.Reduction of harmful atmospheric emissions.** Unlike thermal power plants, micro and mini HPPs do not emit carbon dioxide (CO<sub>2</sub>) or other harmful gases during operation. This contributes to the mitigation of global warming issues [44].
- 2.Utilization of local energy resources.** These types of HPPs are often installed in remote areas, thereby reducing dependency on centralized energy systems. This improves electricity access for populations living in isolated regions.
- 3.Relatively low impact on ecosystems.** Micro and mini HPPs exert minimal influence on the natural flow of rivers and typically do not require the creation of large water reservoirs or basins, which are common for large-scale hydropower plants.

**Negative environmental impacts**

- 1. Impact on river ecosystems.** By regulating water flow, micro and mini HPPs can alter the natural hydrological regime of rivers. This may hinder fish migration and change the living environment of aquatic organisms [45].
- 2. Changes in water quality and temperature.** In some cases, micro HPPs can alter water temperature, which negatively affects the hydrobiological environment. For fish and other aquatic fauna, water temperature is a critical ecological factor.
- 3. Landscape alteration during construction.** As with any infrastructure project, the installation of micro and mini HPPs imposes a certain ecological burden on the surrounding environment.

Although micro and mini HPPs are more environmentally favorable than conventional energy sources, they are not without ecological challenges. In the future, implementing advanced technologies and monitoring systems will be essential to minimize their environmental impact. The development of these stations contributes to ensuring an environmentally sustainable energy supply.

### 1.6. General concept of biogas and biomass energy

**Biomass** is a renewable energy source that includes biological materials such as wood, household waste, hydrogen gas, and alcohol-based fuels. Biomass is primarily associated with plant-based materials used for generating electricity or thermal energy. This source has long been utilized as a traditional fuel and continues to be recognized today as an environmentally friendly energy resource.

There are natural and artificial sources of biomass. Natural biomass includes fallen trees, branches, tree bark, wood chips, and other organic residues. Artificial biomass, on the other hand, consists of various industrial and agricultural wastes, residues from the sugar industry, paper production waste, and animal and plant remains. Additionally, organic substances produced during biogas and biodiesel production processes are also considered biomass.

#### Types of Biomass

1. **Wood and wood residues** – This type of biomass originates from the forestry, furniture manufacturing, and paper industries. It is used as fuel for energy production.
2. **Agricultural residues** – Corn stalks, sugarcane residues, cotton residues, and other plant waste fall into this category.
3. **Animal waste** – Manure and other biological wastes are utilized for biogas production.
4. **Organic household waste** – Food scraps and other organic wastes are used in anaerobic digestion processes to produce biogas.
5. **Industrial waste** – Organic residues from the food industry and other production processes.

#### The role of biomass in energy production

Today, biomass is employed in energy production through various methods, including:

- **Direct combustion** – The most traditional method, where wood and agricultural residues are burned in stoves and boilers.
- **Pyrolysis** – Biomass is heated at high temperatures without the presence of oxygen, resulting in the production of liquid, gas, and solid fuels.
- **Gasification** – Biomass is converted into gaseous fuel under high temperatures with a limited amount of oxygen.
- **Biogas production** – Animal waste and organic household waste are converted into methane gas through anaerobic digestion.

#### Environmental advantages of biomass

One of the significant environmental advantages of biomass is that it does not disrupt the natural carbon cycle. The combustion of fossil fuels releases large amounts of carbon dioxide into the atmosphere, contributing to climate change. Biomass, however, operates within the natural cycle of carbon renewal. For example, trees and plants absorb carbon dioxide from the atmosphere during photosynthesis to produce biomass. When this biomass is burned, the amount of carbon dioxide released is approximately equal to the amount previously absorbed, thus maintaining the natural balance.

Biomass is an environmentally clean and renewable energy source, obtainable from a variety of materials such as wood residues, agricultural waste, animal manure, and organic household waste. It is utilized for energy generation through direct

combustion, pyrolysis, gasification, and biogas production methods. Compared to fossil fuels, biomass is more environmentally friendly, helping to preserve the carbon cycle and mitigate climate change.

### **Biogas production technology and operating principle**

The production of biogas is based on the principle of anaerobic decomposition. In this process, organic waste is decomposed by bacteria, resulting in the formation of methane ( $\text{CH}_4$ ) and carbon dioxide ( $\text{CO}_2$ ) gases. Biogas is produced using bioreactors, where waste materials are fermented under specific conditions [46].

Biogas production occurs in three main stages:

1. **Hydrolysis** – Organic materials (plant residues, manure, food waste) are broken down from polymer forms into monomers with the help of enzymes [47].
2. **Acidogenesis** – Monomers are converted into organic acids and alcohols.
3. **Methanogenesis** – Specialized bacteria transform organic acids into methane and carbon dioxide gases [48].

### **Main components of a biogas system**

A typical biogas production system consists of the following elements [47]:

- **Fermentation chamber (bioreactor)** – the area where organic waste is processed.
- **Gas collection system** – collects and stores the generated gas.
- **Gas purification system** – removes moisture, sulfur compounds, and other harmful substances from the gas.
- **Energy production unit** – utilizes the biogas to generate electricity or thermal energy.

### **Operating principle and efficiency**

The general operating steps of a biogas system are as follows:

1. Organic waste is loaded into the bioreactor.
2. Anaerobic microorganisms decompose the material, producing biogas.
3. The generated gas is collected and purified.
4. The purified biogas is then used as a fuel or to generate electricity [48].

### **The efficiency of biogas production depends on several factors:**

1. **Waste composition** – The higher the organic content, the better the biogas yield.
2. **Temperature** – The optimal temperature range is 35–40°C, as bacteria are most active under these conditions.
3. **pH balance** – The ideal pH range is between 6.8 and 7.5 [49].
4. **Moisture content** – Moisture levels should be maintained at 80–90%.

### **Advantages of Biogas**

1. **Environmentally friendly** – Produces significantly less carbon emissions compared to fossil fuels.
2. **Waste recycling** – Effectively utilizes organic waste materials.
3. **Energy independence** – Enables local production of energy.

**4. Fertilizer production** – The residual digestate can be used as an organic fertilizer.



**Figure 26.** General view of a 1000 kW biomass-powered heating plant (Austria) [1].

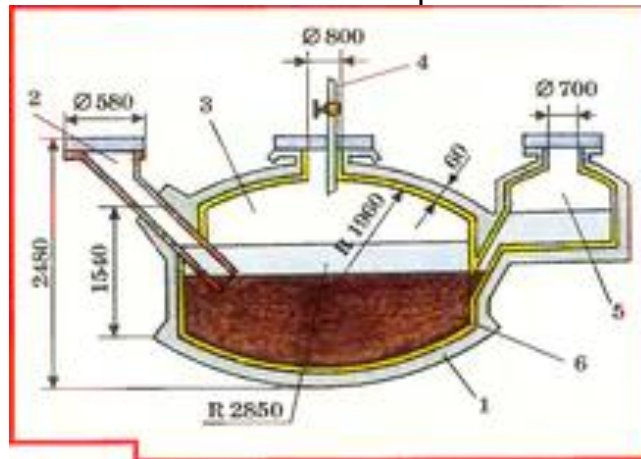


**Figure 27.** General view of the biogas production technology.

#### **Prospects and future of biogas and biomass energy**

Research and technological developments in the field of biogas and biomass energy are further enhancing the prospects and future significance of these energy sources. The use of biomass and biogas plays a vital role in combating global climate change, as they are considered much more environmentally friendly and sustainable compared to fossil fuels.

One of the main advantages of biogas and biomass energy is their environmental cleanliness and economic efficiency. During the biogas production process, methane emissions are significantly reduced, helping to mitigate the greenhouse effect. In addition, the residues from biogas production can be utilized as natural fertilizers in agriculture.

Biomass fuel, being a renewable energy source, can be continuously replenished. Agricultural residues and wood waste, in particular, can be effectively used as sources of biomass. Biomass fuel emits less carbon dioxide compared to coal and oil, thus contributing to the reduction of global warming.

In recent years, significant advancements have been made in biogas and biomass production technologies. Advanced fermentation systems for biogas production, efficient waste recycling technologies, and gas purification equipment are being developed. Similarly, high-efficiency steam generators, gasification systems, and

biochemical methods are being created for converting biomass fuel into electrical energy [50].

All these technologies enable a broader application of biogas and biomass energy. For instance, small-capacity biogas plants can be installed in rural areas to meet local energy needs. In the future, the scope of biogas and biomass energy utilization is expected to expand further, particularly in the following areas:

- **Biogas production from municipal waste:** Increasing energy generation through the recycling of residential waste.
- **Use of industrial waste:** Efficient conversion of food and agricultural waste into biogas and biomass fuels.
- **High-efficiency biogas generators:** Advancing technologies for generating electricity from biogas.
- **Biomass gasification:** Achieving higher energy efficiency by converting solid biomass fuels into gas form.

The significance of biogas and biomass energy will continue to grow in the future, as these sources provide sustainable, environmentally friendly, and affordable energy solutions [51].

### General reaction of biogas formation

Biogas mainly consists of methane (CH<sub>4</sub>) and carbon dioxide (CO<sub>2</sub>).

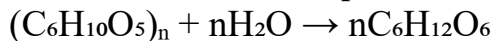
During the anaerobic fermentation process, organic matter decomposes, resulting in the following general reaction:



#### 1. Stages of Anaerobic Decomposition

##### a) Hydrolysis stage (polymer decomposition)

Complex organic compounds are broken down into monomeric forms. For example, when cellulose decomposes:



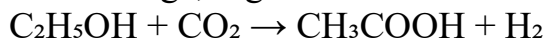
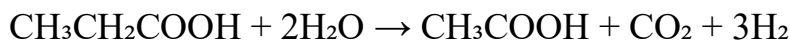
##### b) Acidogenic fermentation (formation of organic acids)

Sugars and amino acids are converted into organic acids and alcohols:



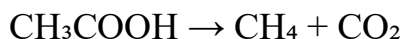
##### c) Acetogenesis stage (formation of acetic acid)

At this stage, organic substances are transformed into acetic acid (CH<sub>3</sub>COOH):

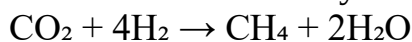


##### d) Methanogenesis stage (formation of methane)

Methane is formed from acetic acid and hydrogen:



Methane can also be synthesized from carbon dioxide and hydrogen:



#### 2. Composition of Biogas and Gas Production Efficiency

Biogas typically consists of the following gases:

- **Methane (CH<sub>4</sub>):** 50–75%
- **Carbon dioxide (CO<sub>2</sub>):** 25–50%
- **Hydrogen (H<sub>2</sub>):** 0–1%
- **Nitrogen (N<sub>2</sub>):** 0–10%

- **Hydrogen sulfide (H<sub>2</sub>S):** 0–3%

**Energy value of biogas:** 1 m<sup>3</sup> of biogas  $\approx$  20–25 MJ (equivalent to 80–90% of the energy content of natural gas).

If the methane content in biogas is  $x$  (in percent), the energy value can be calculated as:

$$E = x \times 0.36 \text{ (MJ/m}^3\text{)}$$

where:

- $x$  – methane percentage (between 50–75%),
- **0.36** – energy value corresponding to 1% of pure methane (MJ/m<sup>3</sup>).

For example, if the biogas contains 60% methane:

$$E = 60 \times 0.36 = 21.6 \text{ MJ/m}^3$$

This is approximately equivalent to the energy content of 0.6 liters of diesel fuel.

### **1.7. Geothermal energy and its conversion into electrical energy**

Geothermal energy is the energy obtained from the Earth's internal heat sources, and geothermal electrical energy is produced by converting it into electricity. Currently, technologies that convert geothermal energy into electricity operate based on dry steam, flash steam, and binary cycle methods.

Globally, geothermal energy is utilized as a source of heat in 70 countries; however, electricity generation from geothermal sources is carried out only in 24 countries. The potential for electricity generation using these technologies is estimated to range between 35 and 2000 GW [52]. The United States leads in terms of installed geothermal power plant capacity (3086 MW), followed by the Philippines and Indonesia [53].

The efficiency of geothermal power plants is relatively low, ranging from 10% to 23%. This is mainly due to the lower temperature of geothermal fluids compared to the steam obtained from conventional boilers. According to the first law of thermodynamics, losses occur during the conversion of geothermal heat energy into electrical energy:

$$\eta = W_{\text{out}} / Q_{\text{in}} \times 100\%$$

Geothermal energy is a reliable and renewable resource, with a capacity factor that can reach up to 96%. In 2005, the annual average capacity factor of geothermal power plants was recorded at 73% [54].

Geothermal power plants offer environmental advantages compared to conventional fossil-fuel-based thermal power stations. The amount of carbon dioxide emitted per megawatt-hour of electricity produced is 122 kg, which is significantly lower than that of fossil-fuel-based plants [55]. For comparison, the CO<sub>2</sub> emissions from coal-fired power plants are 820 kg/MWh, from oil-fired plants 650 kg/MWh, and from natural gas plants 490 kg/MWh.

Additionally, due to the natural thermal conductivity of geothermal energy, approximately 44.2 TW of heat power is transmitted to the Earth's surface, of which about 30 TW is renewable. This heat flow is determined by the following formula:

$$Q = k \times A \times dT/dx$$

Geothermal energy is extracted from underground heat sources through the following methods:

1. By fluid flow (hydrothermal systems),
2. Through magma flows (volcanic areas),

3. Through hydrothermal deposits (by drilling wells),
4. By drilling and circulation (deep geothermal wells).

Currently, the depth of wells used to extract geothermal energy typically reaches up to 3 km. Estimates suggest that in order to achieve more efficient utilization, well depths of several tens of kilometers may be required [56]. With the development of technologies for drilling and exploiting geothermal resources located in areas with large underground heat reservoirs, the possibilities for utilizing geothermal energy are expanding.

According to a 2006 study conducted by the Massachusetts Institute of Technology (MIT), if \$1 billion were invested in the research and development of Enhanced Geothermal Systems (EGS), the geothermal electricity generation capacity in the United States could reach 100 GW by 2050. Projections by the International Energy Agency (IEA) and the World Geothermal Congress (WGC) indicate that global geothermal energy production could significantly increase, reaching a total generation capacity of 200 GW by 2040. This confirms the growing importance of geothermal energy as a sustainable and strategic energy resource.

Technological advancements are enhancing the ability to effectively exploit the Earth's natural heat resources. In particular, the use of modern binary cycle technologies and advanced drilling techniques is significantly increasing the potential of geothermal energy sources. Geothermal energy is considered a long-term and sustainable energy source and is expected to play a crucial role in reducing carbon emissions and ensuring sustainable electricity production in the future.

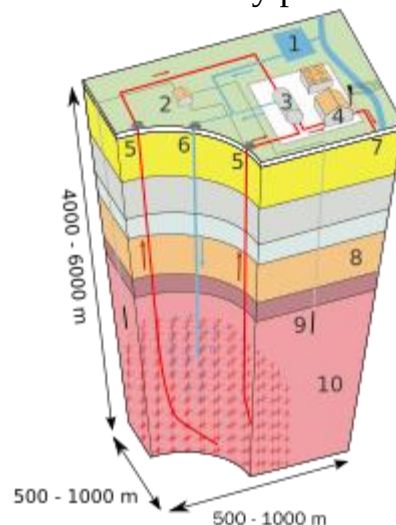


**Figure 28. General view of a geothermal system:** 1 – Reservoir; 2 – Pumping unit; 3 – Heat exchanger; 4 – Turbine hall; 5 – Production well; 6 – Injection well; 7 – Hot water for centralized heating; 8 – Porous sedimentary rocks; 9 – Observation well; 10 – Crystalline basement rocks.

### **Types of geothermal power plants**

Geothermal power plants are facilities that generate electricity by utilizing natural underground heat sources, with the operational principle based on the use of geothermal water or steam. Technologically, they are classified into the following main types:

- **Dry Steam Plants**
- **Flash Steam Plants**

- **Binary Cycle Power Plants**

We will analyze these plants based on their operational mechanisms, efficiency, and environmental impact.

**Dry steam plants**

Dry steam geothermal power plants directly extract high-temperature (150–300°C) natural steam from underground to rotate turbines and generate electricity.

**Advantages:**

- One of the simplest and most efficient geothermal technologies.
- No intermediate working fluid (such as water or other substances) is required during electricity production.
- Very low emissions of harmful substances into the atmosphere.

**Disadvantages:**

- Applicable only in geothermal fields with very high temperatures.
- Geothermal steam may contain sulfur dioxide (SO<sub>2</sub>) or other corrosive gases, leading to rapid equipment degradation.

**Practical Use:** Dry steam technology is one of the oldest geothermal energy production methods in the world, with the Larderello geothermal plant in Italy (built in 1904) being a prime example.

**Flash steam plants**

These types of power plants utilize high-pressure geothermal fluids at temperatures of 180–350°C. When the hot water reaches the surface, the sudden pressure drop causes it to flash into steam. The produced steam drives turbines to generate electricity.

**Advantages:**

- Enables the use of moderately lower temperature sources.
- After utilization, water can be re-injected into the well, helping to maintain water balance.
- The natural steam generation process is energetically efficient.

**Disadvantages:**

- Geothermal water may contain minerals and dissolved gases, potentially damaging equipment.
- Requires deep drilling, increasing capital costs.

**Practical Use:** Flash steam power plants are the most widely used type of geothermal power plants worldwide, especially in the United States, Indonesia, the Philippines, and Japan.

**Binary cycle power plants**

In this type of plant, geothermal fluid (at temperatures of 80–180°C) is not used directly. Instead, it transfers heat through a heat exchanger to a secondary working fluid with a low boiling point (such as isobutane or isopentane). The working fluid vaporizes and drives the turbines.

**Advantages:**

- Allows the use of low-temperature geothermal sources.
- Almost no harmful emissions are released into the environment because the geothermal fluid operates in a closed system.
- Efficient utilization of water resources.

**Disadvantages:**

- Requires additional investment in heat exchanger systems.
- Efficiency is lower compared to dry steam and flash steam technologies (10–13%).

**Practical Use:** Binary cycle geothermal power plants are widely used in areas with low-temperature geothermal sources, including the United States, Germany, and Iceland.

### **Criteria for selecting the type of geothermal power plant**

The choice of geothermal power plant depends significantly on the temperature of the geothermal field, the physical properties of the available fluid, and technological efficiency:

- If the geothermal source has a high temperature (above 150°C), dry steam or flash steam power plants are most effective.
- If the geothermal source has a lower temperature (80–180°C), binary cycle power plants are the most suitable technology.

In the future, new technologies, particularly Enhanced Geothermal Systems (EGS), are expected to expand electricity production possibilities even in areas without traditional geothermal resources.

Geothermal energy is a stable, environmentally safe, and continuous energy source, playing an important role in reducing carbon emissions and ensuring sustainable electricity production.



**Figure 29. General view of a geothermal power plant.**

**Environmental Impact of Geothermal Energy Utilization** - Since geothermal energy is the method of producing electricity or thermal energy by utilizing the heat energy from within the Earth's crust, it is a renewable energy source and plays an important role in reducing environmental pollution. However, the use of geothermal energy can still have certain impacts on the environment.

**Positive Environmental Impacts** - One of the main advantages of geothermal energy is that it significantly reduces atmospheric pollution. Geothermal power plants emit 90% less carbon dioxide (CO<sub>2</sub>) compared to traditional coal-fired power plants [57]. This helps mitigate climate change and the problem of global warming. Additionally, geothermal energy production uses water resources efficiently, as geothermal fluids can be reused. For example, Flash and Binary Cycle plants have water recycling systems [58].

Several measures must be taken to minimize the environmental impacts:

1. Installing purification systems to remove harmful substances from geothermal fluids and steam before release,
2. Recycling water to conserve water resources,
3. Maintaining underground pressure to prevent subsidence,

Geothermal energy plays a crucial role in environmental conservation and supporting sustainable development. However, effective measures must be taken to minimize its negative impacts on the environment. Properly managed geothermal energy allows for the preservation of the environment and the conservation of energy resources.

## **CHAPTER 2: ENERGY STORAGE AND TRANSMISSION IN ALTERNATIVE ENERGY SYSTEMS**

### **2.1 Methods of Energy Storage in Alternative Energy Systems** **Energy Storage Systems Used in the Power Sector**

Modern energy systems use various energy storage technologies to ensure reliable electricity delivery and to balance consumption demands. Energy Storage Systems (ESS) perform critical functions such as balancing the variability of renewable energy sources, energy backup, ensuring grid stability, and reducing peak loads. ESSs can vary depending on their operating mechanisms, capacities, and areas of application.

Currently, energy storage systems are divided into the following main categories:

- Mechanical Energy Storage Systems
- Chemical and Electrochemical Energy Storage Systems
- Thermal Energy Storage Systems
- Superconducting Magnetic Energy Storage Systems

#### **Mechanical energy storage systems**

Mechanical energy storage systems store energy in the form of mechanical motion, which is later converted into electrical energy. These systems typically offer high reliability and long-term use.

#### **Pumped hydro storage (PHS)**

In these systems, excess electricity is used to pump water from a lower reservoir to an upper reservoir. When needed, the water is released back down to generate electricity.

*Advantages:* Ability to store large amounts of energy for extended periods.

*Disadvantages:* Geographic limitations, requires large infrastructure.

### **Flywheel energy storage (FES)**

These systems store electricity as kinetic energy in a rapidly spinning rotor, which can later be converted back into electrical energy.

*Advantages:* Fast charging and discharging, long lifespan.

*Disadvantages:* Relatively low energy capacity.

### **Chemical and electrochemical energy storage systems**

Chemical energy storage systems store electricity in chemical bonds, which can be released as electrical energy when needed.

#### **Battery energy storage systems (BESS)**

Batteries are one of the most common energy storage technologies. They store electrical energy in chemical form and convert it back into electricity when needed.

*Advantages:* Flexible, available in various sizes and capacities.

*Disadvantages:* Degradation over time, limited lifespan.

#### **Types:**

- *Lithium-ion (Li-ion) batteries* – High energy density, long life.
- *Lead-acid batteries* – Low cost, but short cycle life.
- *Sodium-sulfur (NaS) batteries* – Operate at high temperatures, suitable for long-term use.

### **Hydrogen energy storage (HES)**

This technology uses electricity to electrolyze water, producing hydrogen which is stored. When needed, the hydrogen is converted back into electricity via combustion or fuel cells.

*Advantages:* Long-term storage capability, environmentally friendly.

*Disadvantages:* Low efficiency, high infrastructure requirements.

### **Thermal energy storage systems (TES)**

Thermal energy storage systems store energy by maintaining heat or cold for later use.

#### **Sensible heat Storage (SHS)**

This system stores heat in specific materials (e.g., water, sand, or solids).

*Advantages:* Simple technology, long-term storage.

*Disadvantages:* Low energy density.

#### **Latent heat storage (LHS)**

This system uses phase change materials (PCM) to store energy.

*Advantages:* High energy density.

*Disadvantages:* Emerging technology, high cost.

### **Thermochemical energy storage (TCES)**

Based on chemical reactions for storing and releasing energy when needed.

*Advantages:* Long-term storage, high efficiency.

*Disadvantages:* Complex technology.

### **Superconducting magnetic energy storage systems (SMES)**

This technology stores electricity in the form of a magnetic field within superconducting loops.

*Advantages:* High efficiency, rapid charging and discharging.

*Disadvantages:* Requires extremely low temperatures, expensive technology.

Energy storage systems are essential components of modern electric grids. They help optimize energy transmission, enable efficient use of renewable energy sources, and

improve the reliability of energy supply. In the future, the efficiency of these systems is expected to increase further with the development of new materials and technologies.

## **2. Application of energy storage systems in solar photovoltaic power plants**

Since electricity generation in solar photovoltaic (PV) power plants depends on the availability of sunlight, it is crucial to use energy storage systems to ensure an uninterrupted power supply. This section analyzes the main energy storage technologies that are integrated with PV systems.

### **Battery energy storage systems (BESS)**

Batteries are the most commonly used energy storage technology in PV systems. They store excess electricity produced by solar panels in the form of chemical energy and convert it back into electrical energy during periods of high demand or low sunlight.

- **Lithium-ion (Li-ion) batteries:** Most widely used in PV systems due to their high energy density and efficiency.
- **Lead-acid batteries:** Inexpensive, but characterized by low efficiency and shorter lifespan.
- **Sodium-ion batteries:** A promising technology for the future, known for their environmental safety and long lifespan.

### **Thermal energy storage (TES)**

TES technologies store solar energy in the form of heat and later use it to generate electricity. They are especially compatible with Concentrated Solar Power (CSP) systems.

- **Molten salt technology:** Enables long-term energy storage and stands out for its high efficiency.
- **Phase change materials (PCM):** Used for high-temperature energy storage.

### **Hydrogen energy storage systems**

Producing hydrogen through electrolysis using solar energy and storing it is another promising technology used alongside PV systems.

- **Fuel cells:** Convert hydrogen into electricity.
- **Hydrogen storage tanks:** Allow storage of large volumes of energy and are suitable for long-term storage.

### **Supercapacitors**

Supercapacitors are used for short-term energy storage and rapid discharge. They are typically used in conjunction with batteries and play an essential role in balancing fast power fluctuations.

The use of energy storage systems in solar PV power plants is critical for enhancing the stability and reliability of energy supply. Each technology has its own advantages and disadvantages, and choosing among them requires considering economic efficiency, lifespan, and environmental factors.

## **3. Energy storage method in hydropower systems**

### **Pumped storage hydroelectric power plants (PSHPP)**

PSHPPs are specialized hydro-technical facilities designed to store electricity and reuse it according to the system's needs. These stations accept excess electricity from other power plants, convert it into potential energy by pumping water to an elevated reservoir, and then regenerate electricity through hydropower when required.

These types of plants are mainly used to balance energy system loads, supply electricity during peak loads, and efficiently utilize renewable energy sources. Compared to thermal power plants, PSHPPs are more efficient, with the advantage of quick start-up and flexible power control.

### **3.1 Principle of operation and technological structure of PSHPP**

A PSHPP generally consists of two water reservoirs located at different elevations, connected by pipelines. The upper reservoir can be natural or artificial, while the lower reservoir is usually a river or a water storage basin. The main operating principle of the plant functions under two modes:

- **Pumping mode:** During periods of low electricity demand (typically at night or during low-load periods), the PSHPP operates in pumping mode. In this process, electricity is used to pump water from the lower to the upper reservoir, storing it as potential energy.
- **Hydroelectric mode:** During high demand hours (peak load times), the PSHPP operates as a conventional hydroelectric plant. Water from the upper reservoir flows down, driving turbines and generating electricity through hydrogenerators.

The PSHPP building is located at the lower end of the pipeline system and includes hydroturbines, electric generators, and pumps. Modern PSHPPs use reversible hydroelectric units, which combine both pump and generator functions in a single device.

### **3.2 Role of PSHPP in the energy system**

The uneven distribution of electric loads in energy systems increases the importance of PSHPPs. Storing excess electricity generated during low-demand periods and reusing it during peak times plays a vital role in maintaining grid stability.

#### **Main functions of PSHPP in energy systems:**

- **Load leveling:** When the electricity generated does not match consumption, the system can become unbalanced. PSHPPs help smooth out these load fluctuations.
- **Reliable reserve capacity:** PSHPPs can supply large amounts of power to the grid in a short time, enhancing power supply stability.
- **Renewable energy integration:** PSHPPs serve as important auxiliary technology for the stable operation of solar and wind power plants.

### **3.3 Efficiency and Limitations of PSHPP**

PSHPPs have an efficiency (round-trip efficiency) of around 70–85%, meaning some energy is lost during storage and retrieval. Despite this, PSHPPs offer several advantages:

#### **Advantages:**

- Efficient storage and timely supply of electricity.
- Ensures stable power delivery.
- Facilitates effective use of renewable energy sources.
- High flexibility and rapid start-up capability.

**Disadvantages:**

- High construction and operation costs.
- Geographical dependency on mountainous regions.
- Dependence on water resources.

PSHPPs are a key component of modern energy systems. Their primary function is to maintain energy balance and increase the reliability of electricity supply. Their high maneuverability and synergy with renewable energy sources make them an integral part of future energy infrastructure. With advancing technologies, the efficiency of PSHPPs can be improved, making them even more environmentally and economically beneficial.

Moreover, PSHPPs play a strategic role in grid stabilization, particularly in systems with high penetration of variable renewable energy sources such as solar and wind. Their capability to act as both a load and a generator allows them to perform frequency regulation, voltage support, spinning reserve, and black start functions, thereby enhancing the resilience and reliability of national power grids. As energy systems transition toward decarbonization, PSHPPs provide a proven long-duration storage solution that complements the intermittency of renewables. Technological innovations—such as variable-speed pump-turbines, advanced control algorithms, and digital SCADA integration—are significantly improving the operational flexibility and energy conversion efficiency of modern PSHPPs. Hybridization with battery storage systems and integration into smart grid architectures further expand their functional scope, allowing for optimized energy dispatch and reduced curtailment of renewable generation.



**Figure 30. View of the PSHPP reservoir**  
**Calculation of energy stored by PSHPP**

The PSHPP system utilizes the potential energy of water. When water is pumped to the upper reservoir, it is stored as potential energy and converted into electrical energy when needed.

**Stored Energy (E)**

The stored energy is calculated using the following formula:

$$E = mgh\eta$$

Where:

E – stored energy (in joules, J)

m – mass of the water (kg)

g – acceleration due to gravity (9.81 m/s<sup>2</sup>)

h – height of water elevation (m)

η – overall efficiency of the system (typically 70–85%)

**Alternative formula (based on water volume):**

If water mass **m** = **ρV** (where **ρ** is the density of water, 1000 kg/m<sup>3</sup>, and **V** is the water volume in m<sup>3</sup>), the formula becomes:

$$E = \rho Vgh\eta$$

Where:

- **ρ** – density of water (1000 kg/m<sup>3</sup>)
- **V** – volume of water (m<sup>3</sup>)

### **Power output calculation of PSHPP**

To calculate the rate of electricity generation (power), the following formula is used:

$$P = \frac{E}{t}$$

Where:

- **P** – power output of the PSHPP (watts, W)
- **E** – stored energy (J)
- **t** – duration of operation (seconds)

PSHPP power is typically measured in megawatts (MW). To convert watts to megawatts, divide by 1,000,000:

$$P(MW) = \frac{\rho Vgh\eta}{t \times 10^6}$$

### **Efficiency calculation of PSHPP**

The efficiency of PSHPP is defined by the overall system efficiency:

$$\eta = \eta_{\text{pump}} \times \eta_{\text{generator}} \times \eta_{\text{turbine}}$$

Where:

- $\eta_{\text{pump}}$  – pump efficiency (approximately 85%)
- $\eta_{\text{generator}}$  – generator efficiency (around 90–95%)
- $\eta_{\text{turbine}}$  – turbine efficiency (approximately 90%)

The total efficiency typically ranges between 70–85%.

### **Practical example – given:**

- Volume of water in the upper reservoir: **500,000 m<sup>3</sup>**
- Water elevation height: **150 m**
- Efficiency: **75% (0.75)**
- Time: **4 hours (14,400 seconds)**

### **Stored energy calculation:**

$$E = (1000 \times 500,000) \times 9.81 \times 150 \times 0.75 = 551.8 \times 10^9 \text{ J}$$

Stored energy ≈ **552 GJ (gigajoules)**

**Power output calculation:**

$$P = (551.8 \times 10^9) / (14,400 \times 10^6) = 38.32 \text{ MW}$$

**Power output  $\approx$  38.3 MW**

PSHPP is an effective method for storing and generating electricity on demand. These calculations show that the system's capacity and efficiency depend on pump and turbine performance, water elevation, and storage volume.

**Review questions**

1. What are the main functions of Energy Storage Systems (ESS)?
2. What types of mechanical energy storage systems exist, and how do they operate?
3. What types of batteries are used in chemical and electrochemical energy storage systems?
4. What are the advantages and disadvantages of hydrogen energy storage systems?
5. How do thermal energy storage systems work, and what are their main types?
6. What is the working mechanism of superconducting magnetic energy storage, and what is its main drawback?
7. Why are energy storage systems needed in solar photovoltaic power plants, and which technologies are most widely used?
8. How do pumped storage hydroelectric power plants (PSHPP) operate, and what are their modes of operation?
9. What is the main role of PSHPP in the power grid?
10. List the main advantages and disadvantages of the PSHPP system.

## **2.2 Power Quality Indicators and Their Management in Alternative Energy Systems**

**Outline:**

1. Power quality indicators
2. Power quality in alternative energy systems
3. Methods of power quality management

**1. Power quality indicators**

Power quality refers to how well the delivered electrical energy conforms to required standards. If the quality indicators are insufficient, various problems may arise in electrical networks such as equipment malfunctions, reduced efficiency, excessive heat generation, and energy losses.

Power quality is closely related to the reliability and efficiency of an energy system and is determined by the following main factors:

- Voltage and frequency stability
- Degree of harmonic distortion
- Voltage ripple and oscillations

**Main power quality indicators include:**

- Voltage level
- Frequency
- Harmonic distortion
- Voltage ripple

### Voltage level

In power supply systems, the voltage may vary within certain limits from the nominal value. These variations are regulated by international standards such as GOST 32144-2013 and IEC 60038. According to the standard, the voltage level should be:

$$U = U_{nom} \times (1 \pm \delta)$$

Where:

$U_{nom}$  — Nominal voltage (220V, 380V, 10kV, etc.),

$\delta$  — Allowed deviation coefficient.

### Frequency

The standard power frequency is 50 Hz (Europe, Asia) or 60 Hz (USA and some other regions). Frequency deviation is calculated as:

$$\Delta f = f_{nom} - f_{act}$$

Where:

$\Delta f$  — Frequency deviation,

$f_{nom}$  — Nominal frequency,

$f_{act}$  — Actual frequency.

### Harmonic distortion

High-frequency components present in the power network are called harmonics, which can cause equipment malfunction and reduce efficiency. The level of harmonic distortion is evaluated using Total Harmonic Distortion (THD):

$$THD = \frac{\sqrt{\sum_{n=2}^{\infty} U_n^2}}{U_1} \times 100\%$$

Where:

$U_n$  — n-th order harmonic voltage,

$U_1$  — Fundamental frequency voltage.

### Voltage ripple and oscillations

Voltage ripple refers to short-term fluctuations in voltage. The ripple level is calculated as:

$$P = \frac{U_{max} - U_{min}}{U_{nom}} \times 100\%$$

Where:

- $U_{max}$  – Maximum voltage
- $U_{min}$  – Minimum voltage
- $U_{nom}$  – Nominal voltage

### Factors affecting power quality:

- **Network load:** Excessive load causes voltage drops
- **Transmission line length:** Longer lines cause more energy loss
- **Harmonic distortions:** Caused by asynchronous motors, inverters, and electronic stabilizers
- **Operating mode of power stations:** Imbalances in generation and transmission lead to frequency and voltage fluctuations

### International standards for power quality:

- **IEC 61000** – Electromagnetic compatibility and harmonic distortion requirements

- **GOST 32144-2013** – Voltage and frequency requirements
- **IEEE 519-2014** – Limits for harmonic distortion
- **EN 50160** – European standard for assessing power quality

Adhering to these standards is crucial to ensure supply stability and high-quality energy delivery. Maintaining stable voltage, frequency, and minimizing harmonics and ripple enhances the reliability of the grid and protects consumer equipment.

## 2. Power quality in alternative energy systems

Alternative energy sources, particularly solar and wind, significantly affect power quality due to their variable and asymmetrical nature.

**Solar photovoltaic panels** generate direct current (DC), which must be converted to alternating current (AC) using **inverters**. However, this process introduces challenges:

- **Frequency variation:** Caused by uneven solar irradiance, leading to unstable inverter output
- **Harmonic distortion:** High-order harmonics may arise in voltage and current

Total harmonic distortion in such systems is expressed as:

$$THD = \frac{\sqrt{V_2^2 + V_3^2 + \dots + V_n^2}}{V_1} \times 100\%$$

Where:

$V_1$  – Fundamental frequency voltage

$V_n$  – n-th order harmonic voltage.

**Wind turbines** can also cause quality issues due to:

- **Variable wind speed** affecting voltage and frequency
- **Asymmetry and harmonics** from synchronous or asynchronous generators
- **Network oscillations** during connection/disconnection

### Frequency and Voltage Stabilization in Alternative Energy Systems

Maintaining stable voltage and frequency is one of the main challenges in renewable systems. Solutions include:

- **Inverter-based control:** Using MPPT (Maximum Power Point Tracking) algorithms to optimize output
- **Energy storage systems** (batteries, supercapacitors): To buffer sudden load changes
- **Grid synchronization devices:** Ensure smooth phase matching during connection

**Voltage stability assessment is calculated as:**

$$\Delta U = \frac{U_{max} - U_{min}}{U_{nom}} \times 100\%$$

### Impact of renewable sources on power grids

Renewable energy sources impact power grids in the following ways:

- **Changing network load:** Due to variability in solar/wind output
- **Increase in harmonic distortion:** Additional frequencies generated by inverters
- **Complexity in voltage control:** Due to distributed generation sources

To address these issues, the following approaches are used:

- **Smart Grid technologies**

- **Harmonic filters and compensation systems**
- **Synchronization algorithms for frequency matching**

#### **4. Inverter and filtering technologies for power quality improvement**

Inverters and filtering technologies are critical for improving power quality. Key methods include:

- **Harmonic filters** – Active and passive filters reduce high-frequency distortions
- **PWM (Pulse Width Modulation) inverters** – Enhance signal quality by reducing harmonics
- **Synchronous switching technologies** – Ensure inverter phase alignment during grid connection

**Formula for reducing voltage distortion using filters:**

$$X_f = \frac{1}{2\pi fC}$$

Where:

- $X_f$  – Filter's reactive impedance
- $f$  – Grid frequency
- $C$  – Capacitance

Conclusion:

Alternative energy sources like solar and wind can significantly affect power quality indicators. Frequency and voltage control in these systems is critical, and technologies such as inverters and filters play a central role in maintaining grid quality and stability.

### **3. Methods of managing power quality**

Managing power quality is crucial to ensure the efficient operation of the power system and to avoid damage to devices and systems. The methods for managing power quality differ between high and low voltage systems due to their varying requirements and needs. Below are some methods for managing power quality in high and low voltage systems.

#### **1. Power quality management in high voltage systems**

High voltage networks are typically used in transmission systems and require stable voltage levels. In this context, the following methods are applied:

##### **a. Voltage regulation and balancing**

One of the main methods for managing power quality in high voltage systems is voltage control. This involves maintaining voltage within maximum and minimum permissible limits.

Tap-changing transformers and reactors are used to maintain voltage at the required levels.

##### **b. Reducing non-sinusoidal voltages in devices (THD)**

In high voltage systems, harmonics—deviations from the sinusoidal waveform—can occur. A high level of harmonics reduces power quality and can damage the system.

Filtering systems and reactors are used to reduce the effects of harmonics.

##### **c. Protection and safety systems for devices**

In high voltage networks, overvoltage or short circuit conditions may arise. To prevent this, circuit protection devices, full-disconnection systems, and surge suppressors are installed.

**d. Ensuring phase balance**

Maintaining phase balance in high voltage systems ensures efficient operation. Each phase should have equal voltage; otherwise, imbalances can occur in the system.

**2. Power quality management in low voltage systems**

Low voltage networks are commonly used in manufacturing, industrial enterprises, and residential systems. Management methods here are more focused on individual devices and equipment:

**a. Voltage stabilization**

Voltage fluctuations and low voltage problems are common in low voltage systems. These can be addressed using stabilizers to balance and stabilize the voltage. Voltage stabilizers are typically used in small to medium voltage networks.

**b. Harmonic filtering**

Harmonics also exist in low voltage systems and can negatively affect the proper functioning of electrical devices. Passive and active harmonic filters are installed to address this issue.

Active harmonic filters are effective in reducing high levels of voltage harmonics.

**c. Device protection and overload prevention**

Overloads or short circuits in low voltage systems lead to decreased power quality. Short circuit protection devices and automatic disconnection systems are used. Overcurrent protection systems quickly protect the system in case of an overload or short circuit.

**d. Management of charging and battery systems**

In low voltage networks, proper operation of batteries and charging systems plays an important role in maintaining power quality. These systems help optimize energy storage and transmission processes.

**3. General methods for both high and low voltage systems**

**a. Power quality monitoring**

Regular monitoring of power quality is necessary in both types of voltage systems. This includes tracking voltage fluctuations, harmonics, frequencies, and other parameters.

**b. Safety and protection systems**

Installing protection systems against overvoltage and short circuits in both high and low voltage systems helps maintain power quality. Power quality management includes many methods. In high voltage systems, it mainly focuses on maintaining voltage stability and reducing harmonics. In low voltage systems, it is directed at minimizing voltage variations affecting devices, reducing harmonics, and ensuring protection and safety.



**Figure 31. voltage regulation device in 0.4 kv networks**

A **Voltage stabilizer** is a device used to reduce voltage fluctuations in the electrical grid and maintain a constant, stable voltage level. It is primarily used in low-voltage systems, where voltage variations tend to cause more problems.

This device automatically adjusts the voltage to the required level when it is too low or too high in the network. Voltage stabilizers are essential components in modern electrical systems, particularly in areas where grid voltage is unstable due to load imbalances, long transmission lines, or fluctuating power generation. These devices operate by continuously monitoring the input voltage and regulating the output through mechanisms such as tap-changing transformers, servo motors, solid-state relays, or buck-boost transformers. When the input voltage deviates from the nominal range, the stabilizer compensates by either boosting or bucking the voltage to deliver a near-constant output—typically within  $\pm 1\%$  to  $\pm 5\%$  of the rated value.

In residential, commercial, and industrial settings, voltage stabilizers protect sensitive electrical equipment such as computers, medical devices, laboratory instruments, refrigerators, and air conditioners from damage caused by undervoltage or overvoltage conditions.



**Figure 32. Harmonic filter**

Passive harmonic filters and active harmonic filters are used to reduce harmonics in voltage or current. A high level of harmonics lowers the quality of electrical energy, reduces the efficiency of devices, and puts the system at risk.

Passive filters consist of various resistors, inductors, and capacitors, and are used to filter specific harmonic frequencies present in the system.

Active filters, on the other hand, dynamically eliminate various harmonics in voltage and current, thereby improving power quality and eliminating system issues.



**Figure 33. Capacitor bank for reactive power compensation**

Capacitor banks are used in electrical networks to manage reactive power and improve power quality. This device combats voltage drops and excessive absorption of reactive power in the grid, ensuring efficient energy supply within the network.

#### **Review questions**

1. What are the power quality indicators of electrical energy?
2. What factors determine the quality of electrical energy?
3. How is the voltage level calculated?

### **2.3 The role of inverters and power electronics in renewable energy systems**

#### **theoretical foundations of inverters and power electronics**

**Inverters** are devices used to convert direct current (DC) into alternating current (AC). They play a fundamental role in energy generation and distribution systems because many renewable energy sources (such as solar panels and wind turbines) generate DC, while most electrical grids require AC. Inverters perform the necessary conversion for the grid and also enhance the energy efficiency and durability of the system.

There are various types of inverters:

- **Pure sine wave inverters:** These inverters provide the highest efficiency because they reproduce the standard sine wave shape of the grid. They are primarily used in places where high-quality power supply is required.
- **Modified sine wave inverters:** These inverters are cheaper but reduce energy quality. While they may be sufficient for some systems, they can be harmful to certain electronic devices.

- **Square wave inverters:** These are the least efficient and are rarely used in main power supply systems.

### **Working principle of inverters**

The principle is simple: they convert DC into AC using internal conversion mechanisms and a moving electric field. During operation, the efficiency of transmission, control, and output is monitored.

### **Factors affecting durability and efficiency**

The efficiency of inverters depends on several factors, including:

- **Speed control and multi-level operation:** Multi-level inverters improve efficiency by managing energy in multiple stages, which increases system stability and durability [63].
- **Heating and cooling systems:** Inverters may generate heat during operation, so effective cooling systems are essential for ensuring long-term operation [64].
- **High-efficiency components:** High-quality components such as diodes, transistors, and thyristors improve inverter efficiency, extend their service life, and reduce energy losses [63].

### **Key components of power electronics**

The main components of power electronics play a crucial role in ensuring the efficiency and operating life of inverters. Some key components include:

- **Diode:** Allows current to flow in only one direction. Diodes improve overall system efficiency and reduce energy losses.
- **Transistors:** Control the voltage of the current, which is essential for achieving high efficiency [64].
- **Thyristors:** Used for power control, especially in high-power inverters. They provide self-controlled and managed power gating [63].

### **Power management, transmission, and improving energy efficiency**

The main objective of power electronics is to efficiently manage energy flow.

Through effective inverters:

- **Power management:** Controlling voltage, frequency, and direction of power can enhance energy efficiency [64].
- **Energy transmission:** Inverters adapt voltage and current to match the grid, minimizing energy losses during transmission.
- **Energy storage and uninterrupted supply:** Power electronics also support the creation of energy storage systems and ensure uninterrupted energy supply. This is a crucial feature for improving the reliability and efficiency of renewable energy systems.

### **The role of inverters and power electronics in renewable energy systems**

Inverters and power electronics play a vital role in renewable energy systems. In solar and wind energy systems, inverters perform the following roles:

- **Inverters in solar energy systems:** They are necessary to convert the DC from solar panels into AC, enabling connection to the power grid.
- **Grid connection of wind energy:** Energy produced by wind turbines is also transmitted to the grid via inverters. These systems ensure stable and efficient energy generation [64].

- **Efficient grid integration:** Inverters optimize grid connection, reduce energy losses, and stabilize energy supply.

The practical importance of inverters and power electronics in renewable energy systems inverters play a crucial role in the efficient operation of renewable energy systems. The energy generated by solar panels and wind turbines is typically in the form of direct current (DC). However, alternating current (AC) is required for the power grid, making inverters essential. In renewable energy systems like solar and wind, inverters perform the following roles:

#### **Solar panels:**

Inverters convert the DC produced by solar panels into AC and ensure the frequency matches the grid requirements. Inverters improve the panels' performance and enhance the stability of energy supply.

#### **Wind turbines:**

The energy produced by wind turbines is also converted into AC via inverters. These systems operate efficiently in response to variable wind speeds and directions, and inverters help adapt the energy to grid demands.

#### **Enhancing efficiency in connecting ac and dc networks**

Inverters facilitate the conversion between AC and DC systems. In renewable energy systems—such as those producing solar and wind energy—DC must be converted to AC for grid connection. Inverters:

- **Improve energy transmission efficiency:** Inverters bridge DC and AC networks, increasing the efficiency of energy transmission. They also reduce energy losses between systems and ensure a stable energy supply to the grid.
- **Ensure proper synchronization:** Inverters operate in sync with the AC grid, boosting efficiency and reducing energy losses in the system.

#### **Efficiency of power electronics in renewable energy systems**

The efficiency of power electronics is critical in renewable energy systems. When inverters and power electronics function properly:

- **Energy consumption:** High-efficiency power electronics minimize energy consumption in systems. Efficient inverters prevent partial energy losses, improving overall system performance.
- **Monitoring:** Power electronics monitoring systems are necessary to observe and analyze the performance of renewable energy systems. These systems help optimize energy usage and system operation.

#### **Monitoring energy use and efficiency of systems**

To enhance the efficiency of inverters and power electronics, regular monitoring of energy use and system performance is essential. Through monitoring systems:

- **Efficiency improvement:** By tracking energy distribution, consumption, and performance across systems, it's possible to optimize operations. Balancing energy use and efficiency ensures uninterrupted system function.
- **Ensuring durability:** Monitoring systems track inverter performance and improve their efficiency, supporting long-term operation of the systems.

#### **Ensuring energy quality and continuity with power electronics**

The main objective of power electronics is to ensure energy quality and continuity. Inverters and other power electronics components:

- **Energy quality:** Inverters consistently maintain the quality of power supply. By improving energy quality, systems operate more stably and align with grid standards.
- **Continuity:** Power electronics ensure uninterrupted power supply within the network, which increases the operating life and reliability of energy generation and distribution systems.

### **Grid integration and adaptation of inverters**

The integration of inverters and power electronics into the grid enhances the performance of renewable energy systems. The adaptation of inverters to electric grids includes:

- **Grid connection:** Inverters are key components in integrating solar and wind energy systems into the grid. They adapt and transfer energy efficiently to the grid.
- **Digital control systems:** Digital inverters and control systems ease grid adaptation. These systems automatically manage operations, improving system stability and efficiency.

### **Digital inverters and their adaptation to grid systems**

Digital inverters play a vital role in optimizing renewable energy system performance. They facilitate grid adaptation and ensure effective control:

- **Flexible control systems:** Digital inverters enable efficient management between energy generation and transmission systems. They improve the quality of energy supply and enhance grid connection.
- **Rapid adaptation:** Digital inverters enable fast adaptation to the system and manage energy production and consumption in real-time.

### **3. Development and future of inverters and power electronics**

Inverter technologies have undergone significant changes in recent years. New inverter types focus especially on high efficiency and low energy losses. Some innovations include:

- **Hybrid inverters:** Developed to use solar and wind energy jointly, these inverters support dual energy sources and optimize energy usage.
- **Multiphase inverters:** New multiphase inverters help increase efficiency and stability in grid systems, while reducing energy losses.
- **Microinverters:** Tailored for individual solar panel segments, microinverters enhance efficiency by monitoring each panel's performance, thus boosting overall system output.

### **Recent advances in power electronics and cutting-edge technologies**

The latest developments in power electronics improve the efficiency of many energy systems. Notable examples include:

- **GaN (Gallium Nitride) technology:** GaN-based semiconductors operate at high speeds and with lower energy losses, significantly improving inverter efficiency.
- **SiC (Silicon Carbide) technology:** SiC-based transistors perform well at high temperatures and manage large currents efficiently, extending inverter lifespan and enhancing performance.
- **Digital control systems:** Inverters and other power electronics are now equipped with digital control systems, enabling real-time monitoring of power supply and system status.

In the future, renewable energy systems are expected to become a major portion of global energy sources. Inverters are anticipated to become core components of these systems. The following factors will increase the significance of inverters and renewable energy systems:

- **Green energy and reducing carbon footprint:** Through the development of renewable systems, carbon-free energy sources are generated. Inverters play a key role by adapting and optimizing energy systems to the grid.
- **Modular systems and multi-source energy production:** Inverters will be adapted to multi-source systems, such as combined solar and wind setups. These inverters allow full integration between energy sources.
- **Long-term energy storage systems (e.g., batteries, supercapacitors)** will integrate with inverters. This integration:
  - **Ensures uninterrupted power supply:** By using long-term storage, energy production disruptions can be minimized. Inverters then adjust and deliver consistent supply based on grid demands.
  - **Works efficiently with storage systems:** Integration between long-term storage and inverters ensures better energy retention and usage.

The development of inverters and power electronics is vital for improving the efficiency of renewable energy systems and integrating them into global energy networks. Key development points include:

- **Rapid advancement:** Technological innovation increases inverter efficiency, enabling cost-effective operation of renewable energy systems.
- **Technology integration:** Integration with advanced technologies simplifies energy distribution and control, supporting energy production optimization.

### **Global trends in the development of renewable energy systems and inverter market growth**

Globally, renewable energy systems and the inverter market continue to grow. Integration of digital inverters and energy storage systems, along with high-efficiency power electronics and stable energy supply, shapes global growth trends:

- **Market growth:** The inverter market is expected to grow between 2023 and 2028, contributing to the expansion of renewable energy systems. Market growth is closely tied to innovation and new technologies.
- **Global integration:** Renewable energy systems are being integrated across various countries and regions. This, in turn, supports the global development of inverters and power electronics.

### **Control Questions**

1. Explain the main types of inverters and their working principles?
2. List the key factors affecting inverter efficiency?
3. Describe the main components of power electronics and their functions?
4. Explain the role of inverters and power electronics in renewable energy systems?
5. What role do inverters play in solar energy systems, and how do they increase efficiency?
6. Compare the key differences between microinverters and hybrid inverters?
7. What are the benefits of integrating long-term energy storage systems with inverters?

8. Explain the role of GaN and SiC technologies in improving inverter efficiency?
9. How will future developments in inverters and power electronics impact renewable energy systems?
10. Analyze global trends in the development of renewable energy systems and inverter market growth?

## CHAPTER 3: INTEGRATION OF ELECTRICITY PRODUCED FROM ALTERNATIVE ENERGY SOURCES INTO ELECTRICAL NETWORKS AND ITS MANAGEMENT

### 3.1 Integration of alternative energy sources into power grids

#### Integration of solar power plants into power grids

The process of integrating solar power plants into power grids often involves transferring the electricity generated by solar panels in accordance with the voltage and power conditions of the network itself. Solar power plants are typically integrated into power grids of the following voltage levels:

##### Integration of solar power plants into 10 kV networks

Integration into 10 kV networks occurs rarely, as this voltage level is generally insufficient for medium-level consumers. However, small- and medium-capacity solar power plants, especially those located near the grid or in remote areas, can be integrated into 10 kV networks.

- **Parameters required for integration:** The power transmitted to the 10 kV grid should be low, since the network may have a high energy demand during operation.
- **Advantages:** Fast and inexpensive connection; suitable for small-scale systems.
- **Disadvantages:** Requires more precise control due to low power transmission.

##### Integration into 35 kV networks

35 kV networks are used in medium-level electricity supply systems and are typically effective for small- and medium-sized solar power plants. In this network, energy generation and transmission are easier because the voltage level meets average requirements.

- **Parameters required for integration:** Energy produced by solar panels can be transmitted in a balanced manner in the 35 kV grid. Since the energy output of solar plants is variable, the system must be optimized to regulate transmission.
- **Advantages:** Improved integration with medium-level grids, maintains balance during energy transmission.
- **Disadvantages:** Must address mismatches between production variability and demand.

##### Integration into 110 kV Networks

110 kV networks are used for high-capacity systems and are ideal for integrating large solar power plants. These networks enable efficient energy transmission over long distances.

- **Parameters required for integration:** The 110 kV grid is suitable for receiving energy from high-capacity solar power plants (e.g., 10–20 MW). Even with varying solar irradiance, system optimization is needed to balance production and transmission.
- **Advantages:** High efficiency in connecting large-scale solar plants; effective energy transfer across the network.
- **Disadvantages:** Requires optimization to minimize transmission losses.

##### Integration into 220 kV Networks

220 kV networks are high-capacity systems suitable for integrating large solar power plants. These networks are often used to supply industrial or large-scale consumers.

- **Parameters required for integration:** The energy distribution and management system must be optimized to integrate large-scale solar energy producers into the grid. Additional energy reserves or batteries may be necessary to compensate for solar irradiance fluctuations.
- **Advantages:** High efficiency in large-scale energy production and transmission.
- **Disadvantages:** Managing large energy-producing systems and the grid can be complex.

### **Integration into 500 kV networks**

500 kV networks are ultra-high-voltage systems used to transmit high-capacity energy over long distances. These are primarily used to connect large central solar power plants to the grid.

- **Parameters required for integration:** The energy from large solar power plants is transmitted through high-capacity systems. Effective grid operation requires extensive power control and energy storage.
- **Advantages:** Enables the transmission of large-scale solar energy over long distances, ensuring stable energy supply.
- **Disadvantages:** Complexities in high-volume energy transmission; energy loss minimization is necessary.

### **Efficiency and loss reduction:**

To ensure efficient solar energy transmission to the grid, it is necessary to develop effective transmission systems. Converters, inverters, and voltage control systems play a critical role in this process.

### **Energy reserves:**

Due to the variability of solar energy production, integrating energy storage systems or batteries may be necessary.

### **Grid management:**

An energy flow management system is essential to ensure the grid operates efficiently. This system helps balance the energy within the network and prevents any transmission losses.

Solar power plants can be integrated into 220 kV, 110 kV, 35 kV, and 10 kV electrical grids; however, in each case, system optimization is required to ensure efficient energy production and transmission. High-voltage networks (e.g., 220 kV and 500 kV) are best suited for large solar power stations, while lower voltage networks are ideal for small-capacity systems.

When integrating solar power plants into electric grids, it is essential to consider factors like **phase angle differences**, **power oscillations**, and other physical parameters, as these changes affect grid stability and energy transmission efficiency. The following formulas can be used to explain and calculate these aspects:

### **Phase angle between phases**

The transmission and reception of electrical energy are mainly associated with phase parameters. Managing and analyzing phase angle differences is crucial for efficient system operation.

### **Phase angle calculation**

The phase angle, typically observed in AC (alternating current) systems, can be determined using the following formula:

$$\phi = \arctan \left( \frac{V_L}{I_L} \right)$$

Where:

$\phi$  — phase angle (in degrees or radians),

$V_L$  — voltage (V),

$I_L$  — current (A).

The phase angle is crucial when integrating solar power plants into the grid, as changes in current and voltage—such as those caused by fluctuations in solar irradiance—necessitate active control of the phase difference within the system.

### **Phase angle and grid stability**

If the phase angle between phases exceeds the normal range (typically  $\pm 30^\circ$ ), it may lead to power oscillations, which reduce transmission efficiency and can even cause short circuits or loss of system stability.

The variability in the power output of a solar power plant can cause power oscillations (swings) in the system. These fluctuations depend on factors such as solar irradiance, weather conditions, and other environmental influences. Frequent power variations must be considered to ensure system stability.

### **Calculating frequency (power oscillations)**

The power transmitted from a solar power plant to the grid may sometimes result in energy oscillations within the system. These oscillations can be calculated using the following formula:

$$P_{\text{oscillation}} = P_{\text{max}} \cdot \sin(\omega t)$$

Where:

- $P_{\text{oscillation}}$  — oscillating power (kW)
- $P_{\text{max}}$  — maximum power (kW)
- $\omega$  — angular frequency ( $\omega = 2\pi f$ , where  $f$  is the frequency)
- $t$  — time (in seconds)

This formula represents the time-based fluctuations and oscillations in the power output of a solar power plant.

### **Oscillations relative to high and low power levels in the grid**

Based on the efficiency of power transmission in the network, it's necessary to calculate losses and energy oscillations that occur within the system. Power swings in relation to upper and lower limits are expressed as:

$$P_{\text{max}} = P_{\text{rated}} + \Delta P_{\text{oscillation}}$$

Where:

$P_{\text{max}}$  — maximum power,

$P_{\text{rated}}$  — rated power (nominal operating power)

$\Delta P_{\text{oscillation}}$  — variation representing power swings.

### **Frequent Fluctuations and System Control**

Due to the variable nature of solar energy production, temporary rises and falls (oscillations) may occur in the system. To manage this, the following formula can be used

$$P_{\text{network}}(t) = P_{\text{panel}} \cdot (1 + \alpha \cdot \sin(\omega t))$$

Where:

$P_{\text{network}}(t)$  — power transmitted to the network at time  $t$  (kW)

$P_{\text{panel}}$  — power generated by the solar panel (kW),

$\alpha$  — parameter representing the degree of power oscillation,

$\omega$  — frequency (rad/s).

### **Managing frequent fluctuations and power oscillations**

To ensure the stability of energy production and consumption in the grid, it is essential to maintain the balance when managing frequent fluctuations and power oscillations.

### **Control of phase and power oscillations in the grid**

To maintain the stability of solar energy transmission within the grid, the following actions are implemented:

- **Optimization of phase angle:** To reduce energy losses, a control system must manage the phase angle of the energy being transmitted to the grid.
- **Control of power oscillations:** To minimize power oscillations (swings), systems that respond to fluctuations—such as inverters and batteries—are installed.
- **Grid tuning:** It is necessary to install systems that regulate high and low power variations and phase angles within the grid. These systems help reduce energy oscillations and ensure the stability of the network.

During the integration of a solar power plant into the electrical grid, it is crucial to consider the phase angle between phases and power oscillations. These factors play a vital role in maintaining energy flow and system stability. By implementing systems to manage phase angle and power swings, the efficiency of energy production and transmission can be significantly improved

## **2. Integration of wind power plants into electrical grids**

The use of wind energy is widespread in modern power systems, and integrating wind power plants into electrical grids requires addressing specific technical challenges. These include the variability of wind energy generation, grid compatibility, and optimization strategies to ensure stable and efficient network operation. The following presents theoretical and mathematical concepts on the subject [73].

Wind energy has fluctuating and random characteristics, affecting the efficiency of energy production. The generation capacity of wind power plants depends on several factors:

- Wind speed
- Wind direction
- Geographical conditions
- Stability of the electrical system

The generation capacity of a wind power plant is given by the formula:

$$P_{\text{wind}} = \frac{1}{2} \cdot \rho \cdot A \cdot v^3 \cdot \eta$$

Where:

$P_{\text{wind}}$  — power output of the wind turbine (kW),

$\rho$  — air density (kg/m<sup>3</sup>),

$A$  — area of the turbine blades (m<sup>2</sup>)

$v$  —wind speed (m/s),

$\eta$  —efficiency coefficient of the turbine.

Because wind speed changes over time, the generated power also varies [74], potentially leading to fluctuations in the grid.

#### **Key considerations for integrating wind power into the grid:**

- **Power fluctuations:** Variations in wind speed may cause abrupt changes in generated power, affecting system stability.
- **Phase coordination and angles:** Maintaining the balance of power and phase angles in the system is essential [75].
- **Grid tuning:** To transmit wind-generated energy effectively, inverters and energy storage systems are required.

Despite the fluctuating nature of wind energy, several strategies exist for managing these variations:

The output power of a wind plant varies over time, causing oscillations. The power fluctuation over time can be modeled as:

$$P_{\text{oscillation}}(t) = P_{\text{max}} \cdot \sin(\omega t)$$

Where:

$P_{\text{oscillation}}(t)$  —oscillating power (kW),

$P_{\text{max}}$  —maximum power (kW),

$\omega$  —angular frequency ( $\omega = 2\pi f$ ,  $f$  —frequency),

$t$  —time (seconds).

To minimize high and low power fluctuations in the grid, inverters and batteries are employed [76]. The managed output to the grid can be modeled as:

$$P_{\text{network}}(t) = P_{\text{panel}} \cdot (1 + \alpha \cdot \sin(\omega t))$$

Where:

$P_{\text{network}}(t)$  — power transferred to the grid (kW),

$P_{\text{panel}}$  — power produced by the panel (kW),

$\alpha$  — parameter representing the degree of power fluctuation,

$\omega$  — frequency (rad/s).

#### **4. Grid calculations for wind power integration**

Due to the variable nature of wind power generation, grid optimization involves:

- **Inverter optimization:** Balancing generation and consumption through inverters
- **Energy storage systems:** Storing excess energy in batteries for later use

Measures taken during integration of wind power plants into the grid include:

- **Grid tuning:** Managing high and low power variations
- **Control system optimization:** Minimizing oscillations using inverters and storage systems [77]

Integrating wind power into the electrical grid plays a crucial role in ensuring energy system stability. Wind speed variability and generation fluctuations can cause power oscillations, necessitating system optimization and energy balancing. To enhance the efficiency of energy production and distribution, the use of inverters, energy storage, and control systems is essential.

### 3. Integration of micro hydropower plants into the electrical grid

Micro hydropower plants (MHPs) are small-scale hydroelectric facilities that primarily generate electricity by utilizing small rivers, canals, and other water sources. Their integration into the electrical grid requires addressing specific challenges. Below are the theoretical and practical aspects of integrating micro hydropower plants into the electrical grid, along with relevant literature references [78].

The energy production of a micro hydropower plant mainly depends on the following factors:

- **Water flow rate:** The speed of water flow determines the power capacity of the hydropower plant.
- **Water head (height):** The capacity of a hydropower plant depends on the height (or pressure) difference [79].
- **Turbine efficiency:** The power output efficiency of micro hydropower plants is related to the efficiency and design of the turbine [80].

The power output of a hydropower plant is calculated using the following formula:

$$P_{\text{hydro}} = \eta \cdot \rho \cdot g \cdot Q \cdot H$$

Where:

- **P<sub>hydro</sub>** — power output of the hydropower plant (kW)
- **η** — turbine efficiency coefficient
- **ρ** — water density (kg/m<sup>3</sup>)
- **g** — gravitational acceleration (9.81 m/s<sup>2</sup>)
- **Q** — water flow rate (m<sup>3</sup>/s)
- **H** — water head (m)

There are numerous technical challenges when connecting micro hydropower plants to the grid. Some of these include:

- **Variability of water flow:** The flow rate of water changes over time, which leads to fluctuations in the generated power. This affects grid stability.
- **Energy storage systems:** To manage rapidly changing power generation, it is necessary to use energy storage systems.
- **Grid management:** Inverters and control systems are required to optimize the grid and reduce power fluctuations.

The following optimization methods can be applied when integrating micro hydropower plants into the grid:

- **Inverters and voltage control systems:** Since the energy output from micro hydropower plants is variable, the grid must be optimized using inverters and control systems [81].
- **Energy storage systems:** Excess energy generated by micro hydropower plants can be stored in batteries or other storage systems and transmitted to the grid when needed.
- **Smart grid systems:** New technologies, such as smart grid systems, can be used to increase the efficiency of the grid.

#### Review Questions

1. How is the power output of a micro hydropower plant calculated?

2. What technical challenges arise when integrating solar energy into the electrical grid?
3. What role do inverters play in the integration of wind energy into the electrical grid?
4. What factors influence the power output of a hydropower plant?
5. What are the advantages of optimizing the grid using smart grid systems?
6. How does the variability of water flow affect the connection of micro hydropower plants to the grid?
7. What grid management challenges arise from the variability of solar and wind energy production?
8. What can be said about the role of energy storage systems?
9. What technologies are used for grid management and how do they work?
10. How can the combined operation of micro hydropower, solar, and wind energy systems be optimized?

### 3.2 Transmission of electricity generated from renewable energy sources

#### 1. Problems with connecting hydroelectric power plants (hpps) to the grid

Hydroelectric power plants convert the potential and kinetic energy of water into electrical energy. This process includes the following stages:

- **Water accumulation:** Water is accumulated at a height through a dam built over a river or water source, generating potential energy.
- **Water release:** The stored water is released through pipes under high pressure and directed toward turbines.
- **Conversion to mechanical energy:** The kinetic energy of water rotates the turbine blades, producing mechanical energy.
- **Conversion to electrical energy:** A generator connected to the turbine shaft converts the mechanical energy into electrical energy.

The following types of generators are mainly used in hydroelectric plants:

- **Synchronous generators:** These rotate synchronously with the turbine, ensuring stable frequency. They connect directly to the grid and allow precise frequency control.
- **Asynchronous generators:** These have simpler structures and are used in small and medium-sized hydro plants. However, they are less efficient in frequency regulation compared to synchronous generators.

The electricity generated is usually at low voltage (e.g., 11 kV). To transmit this power over long distances effectively, it must be stepped up to high voltage using transformers:

- **Main transformers:** These increase the output voltage of the generator to higher levels (e.g., 24 kV or more) to allow long-distance transmission with minimal loss.
- **Step-up power transformers:** These adjust the generator output to be compatible with high-voltage busbars and transmit power to step-down transformers.
- **Step-down transformers:** These reduce the voltage from high-voltage busbars to levels suitable for low-voltage single-phase or three-phase loads.

After voltage is increased by transformers, electricity is delivered to consumers via transmission lines. The transmission process involves:

- **Transmission lines:** High-voltage electricity is transmitted over long distances through power lines, minimizing losses and increasing efficiency.
- **Voltage reduction:** Voltage is reduced to appropriate levels (e.g., 220V or 380V) using transformers near the end-users.

Through this process, hydro energy is converted to electrical energy and transmitted to the grid and consumers via transformers.

Several problems may arise when connecting hydroelectric plants to power grids, including voltage fluctuations, frequency changes, and phase imbalances. These issues can negatively affect the stability and efficiency of the grid.

- **Voltage fluctuations:** Starting or stopping HPPs can cause voltage fluctuations, which may damage electrical equipment. Solutions include:
  - **Automatic Voltage Control Systems:** These continuously monitor and adjust voltage levels in the grid.
  - **Capacitor Banks:** These compensate reactive power, reduce voltage fluctuations, and improve grid stability.
- **Frequency changes:** Connecting or disconnecting HPPs can cause frequency variations, affecting grid stability and other power stations. Solutions include:
  - **Fast-response control systems:** Utilize the quick response of HPPs to adapt to frequency changes.
  - **Use of mechanical inertia:** Inertia of the HPP's mechanical components helps smooth frequency variations.
- **Phase imbalances:** The phase angle between the HPP and grid must match; otherwise, large currents may occur, damaging equipment. Solutions include:
  - **Synchrosopes:** Used to match the phase of the HPP with the grid before connection.
  - **Automatic synchronization systems:** Automatically align HPP and grid phases for safe connection.

The impact of an HPP on grid parameters depends on its power relative to the grid. If the grid capacity is significantly higher, the HPP will cause minimal disturbances. However, if the HPP contributes a large portion of the grid's capacity, disturbances may occur, potentially disrupting normal operations.

## 2. Problems with connecting solar power plants (SPPs) to the grid

Generating electricity from solar energy is environmentally clean and economically efficient. However, several technical, economic, and social challenges exist when integrating solar power plants into the grid:

- **Intermittent production:** Solar energy output depends on natural conditions like sunlight, weather, seasons, and time of day. This variability complicates maintaining voltage and frequency stability in the grid.

### Solutions:

- **Energy storage systems** (e.g., batteries): Store energy for use when production drops.
- **Advanced control systems** (e.g., AI-based production forecasting): Help manage variability.

- **Grid stability:** Variability in solar output affects overall grid stability. To ensure efficient power transfer and continuous operation of SPPs, support systems are needed. Voltage fluctuations and power control issues arise from solar energy's inconsistent nature.

**Solutions:**

- **Multilevel grid management systems:** Help stabilize voltage and power flow.
  - **Energy storage technologies:** Allow stored solar energy to be used as needed.
- **Infrastructure challenges:** SPPs are often located far from existing grid infrastructure, requiring costly and time-consuming transmission line construction and grid modernization.

**Solutions:**

- **Build new or expand existing grids.**
  - **Support microgrids and distributed generation** (e.g., smart grid systems) to reduce integration issues.
- **Control and monitoring:** Advanced control and monitoring systems are required to manage integration and ensure efficient use of solar energy.

**Solutions:**

- Implement **automated systems and AI-based technologies** to manage solar energy efficiently.
  - Adopt **smart grid** technologies to improve real-time energy management.
- **Economic challenges:** Integrating SPPs can be costly due to the need for grid expansion and infrastructure upgrades. Additionally, government policies and regulations significantly impact integration success.

**Solutions:**

- Encourage investment in solar energy through **subsidies, tax incentives, and favorable policies.**

Integrating solar power into the grid involves technical, economic, and social challenges. Addressing them requires advanced technologies, effective management systems, infrastructure modernization, and policy support. Energy storage systems and smart grid technologies play a vital role in realizing the full potential of solar energy.



## **Figure 34. Energy generation from renewable energy sources**

### **3. Challenges of integrating wind power plants into the grid**

**Wind energy** is growing globally as a renewable energy source. However, integrating Wind Power Plants (WPPs) into the grid presents several challenges. Although effective solutions are being developed, some technical and economic difficulties remain. Below, we outline the main issues in connecting wind power plants to the grid and the approaches being taken to address them.

#### **Key challenges:**

- **Intermittency of wind:** One of the main issues with wind energy is its intermittent nature. Wind speed and direction constantly change, leading to unpredictable energy generation. This variability complicates balancing energy supply and demand, as the output capacity of wind plants can be very low or even nonexistent at times [88].
- **Energy storage systems:** Technologies such as batteries, accumulators, hydroelectric plants, and other storage systems help balance energy in the grid by reducing the gap between production and demand.
- **Smart grid integration:** Smart grid technologies allow real-time management and optimization of both energy consumption and generation. These systems adapt to changing energy source availability.
- **Grid stability:** Ensuring grid stability is crucial when integrating wind power. Wind turbines may produce sudden fluctuations or pulses in energy, potentially destabilizing the grid. Voltage variation, frequency shifts, and phase imbalances can lead to grid issues.
- **Power electronics control systems:** Converters and variable-frequency controls help maintain voltage stability when transferring energy from wind turbines.
- **Static synchronous compensators (STATCOMs):** These are being developed alongside energy storage systems to manage energy flow and ensure grid stability.

#### **Transmission and location issues:**

- Wind power plants are often located in rural or remote areas, which increases energy loss during long-distance transmission. High-voltage transmission lines are needed to address this, but they also present challenges.
- **High-Voltage transmission systems:** Building these systems helps reduce transmission losses over long distances [89].
- **Multi-point networks:** These help efficiently manage energy production and transmission from multiple wind turbines.

#### **Technical complexity and design:**

- Wind power plants typically consist of multiple turbines, and integrating all of them into the grid poses technical and construction challenges. Each turbine must be compatible with the grid to ensure overall system efficiency.
- **Modular and Distributed Systems:** Modular and decentralized system designs ensure reliable and stable integration of turbines into the grid.
- **Grid Adaptation and Integration:** Technical and operational solutions are needed to optimize wind energy and integrate turbines into the network.

### **Environmental and maintenance factors:**

- Wind energy performance is heavily influenced by climate conditions such as wind speed and direction. These factors can challenge the stable operation of wind plants. Additionally, locating turbines in areas rich in natural ecosystems may cause environmental concerns.
- **Reducing environmental impact:** Carefully choosing installation sites and conducting environmental assessments help minimize ecological effects.
- **Optimizing wind networks:** Implementing efficient and environmentally friendly energy generation methods is essential.
- **Maintenance requirements:** Wind turbine systems require high maintenance and regular servicing throughout their operational life. This is especially difficult for large grids and remote installations.
- **Automated monitoring systems:** These enable real-time monitoring of turbine performance and energy quality.
- **Optimized maintenance systems:** Efficient systems for replacing and repairing turbine parts are needed to ensure reliability.

### **Conclusion:**

Integrating wind power plants into the grid comes with several technical and economic challenges. To effectively address these, solutions such as energy storage systems, smart grid technologies, high-voltage transmission networks, and eco-friendly approaches must be implemented. New technologies should be developed to manage the variability and uncertainty of wind energy.

### **Control questions:**

1. What are the main technical challenges in connecting a hydroelectric power station to the grid?
2. How does the variability in energy production affect the grid when a hydroelectric power station is connected?
3. What is the significance of hydrological and climate conditions in hydroelectric grid integration?
4. How can energy losses be reduced when integrating hydroelectric stations into the grid?
5. How does the intermittency of solar energy affect grid management?
6. How does the generation capacity of a solar power plant influence the energy balance in the grid?
7. What role do energy storage systems play in integrating solar power plants into the grid?
8. How does wind variability affect grid stability when integrating wind power plants?
9. What technical solutions exist to manage energy quality and protect the grid during solar energy integration?
10. How are fluctuations in frequency and voltage managed during the grid connection of wind power plants?

### 3.3 Smart Grid and alternative energy.

#### 1. 1. Smart Grids and Their Integration with Renewable Energy Sources

A **Smart Grid** is an advanced and efficient energy system that optimizes traditional electricity generation, distribution, and consumption by integrating digital technologies, automation, and information-communication technologies. The Smart Grid system enables real-time monitoring of electricity flow, grid management, and optimization of energy production and consumption.

Smart Grid systems consist of the following key components:

- **Sensors:** Monitor grid conditions and energy flows in real-time.
- **Automated systems:** Enhance efficiency by automating electricity distribution and control.
- **Communication networks:** Transmit real-time information to control systems and consumers.
- **Data and analytics:** Analyze big data and provide forecasting for efficient grid management.

#### **Importance of smart grids:**

- **Energy efficiency:** The Smart Grid allows for better management of energy flows within the grid, helping to conserve electricity and reduce losses.
- **Stability:** The grid's high level of stability is ensured through automated control systems that quickly detect and resolve disruptions in the energy supply.
- **Managing intermittency:** The variability of renewable energy sources (such as solar or wind) is managed by the Smart Grid, ensuring a continuous and stable energy supply.
- **Efficient use of resources:** Smart Grid systems improve the efficiency of energy generation, storage, and distribution, and provide opportunities for consumers to save energy.

#### **Automated control systems**

Automated control systems manage the processes of energy generation, distribution, and consumption without human intervention. They are primarily used in the following processes:

- **Energy generation:** Automating various processes at power plants, such as controlling generators, integrating renewable energy sources, and optimizing their output levels.
- **Energy distribution:** Automatically managing voltage levels and energy distribution across the grid. These systems ensure optimal distribution and automatically detect grid issues.
- **Energy storage:** Using batteries or other energy storage systems to store excess energy and deliver it to consumers when needed.
- **Fault detection and mitigation:** Automated control systems quickly identify faults within the energy grid, minimizing associated risks. These systems also enable rapid repair or grid restoration.

## Smart Grids and Their Advantages in Utilizing Renewable Energy Systems

Smart Grid systems enable the effective integration and management of renewable energy sources (such as solar, wind, and bioenergy) into the electricity grid. With Smart Grids, the intermittency of variable energy sources like solar and wind can be managed. These systems allow surplus energy to be stored and made available to consumers when needed.

Due to the fluctuating nature of solar and wind energy production, Smart Grid technologies allow excess energy to be transmitted to storage systems and returned to the grid when necessary. These systems help optimize energy distribution and maintain grid balance.

### **1. Advantages in efficient energy management and distribution**

Smart Grid systems provide the ability to manage energy flows within the network in real time. This enables maximum utilization of renewable energy sources, reduces energy consumption, and improves energy efficiency. Smart Grids automate the energy distribution process and ensure timely delivery of surplus energy to consumers.

Smart Meters are used to help consumers monitor their energy usage and plan their consumption. These systems display real-time energy flow information to users, encouraging them to conserve energy.

### **Enhancing grid stability**

Smart Grid systems can quickly detect and eliminate malfunctions in the grid. During the use of renewable energy sources, sudden changes in energy flow may occur. Smart Grids play a crucial role in identifying these fluctuations and restoring the grid.

When a wind turbine or solar panel stops generating power, the Smart Grid automatically redirects the energy supply to alternative sources (such as gas or nuclear power stations) and maintains the grid's energy distribution.

### **Energy storage and ensuring system stability**

Smart Grids manage energy storage systems (e.g., batteries or hydro-based storage), allowing surplus energy to be stored and supplied to the grid when needed. This helps manage the intermittency of energy sources and maintain energy balance in the network.

Solar energy production occurs mainly during the day, but peak energy demand may be in the evening. Smart Grids store the excess daytime energy in batteries and supply it to the grid in the evening to meet demand.

### **Optimizing energy and managing consumers**

Smart Grid technologies assist consumers in optimizing their energy usage. Consumers, in turn, can reduce their bills by lowering consumption or shifting energy usage away from peak periods.

Through dynamic pricing systems, Smart Grids allow consumers to choose the most cost-effective energy rates. For example, when energy prices are low (e.g., at night), consumers can increase their usage.

### **Reducing environmental impact**

Using renewable energy sources and managing them efficiently through Smart Grids reduces negative environmental impact. Smart Grids help decrease reliance on

coal or gas-based energy production and increase the use of renewable sources. This, in turn, reduces carbon dioxide emissions.

By increasing the use of renewable energy, Smart Grid systems play an important role in mitigating global warming and other environmental challenges.

### **Conclusion**

Smart Grids enable the management, optimization, and efficient use of renewable energy systems. These systems allow for the maximum utilization of renewable energy sources, help stabilize the grid, and optimize energy distribution. Through Smart Grid technologies, energy efficiency is improved, energy costs are reduced, and the environmental impact is minimized.

### **3. The future of smart grids and renewable energy sources**

**Smart Grid technologies** are digital systems that enable the automation, optimization, and management of modern energy networks. These systems are essential for efficiently managing energy production, distribution, and consumption. The future of Smart Grid systems plays a significant role in ensuring electricity supply, protecting the environment, and increasing economic efficiency.

#### **Future prospects of smart grid systems**

##### *Rapid Advancement of Digital Technologies and IoT Integration*

Smart Grid systems are evolving further through digital technologies and the Internet of Things (IoT). Using sensors, smart meters, and digital control systems, energy flows can be monitored, managed, and optimized in real time. IoT technologies help make the grid smarter and increase efficiency in energy consumption and distribution.

#### **1. High-efficiency energy storage systems**

The future of Smart Grid systems is closely linked to the development of energy storage technologies. Batteries, supercapacitors, and other storage systems allow excess energy to be stored and returned to the grid when needed. These technologies help manage the variability of renewable energy sources and optimize the grid.

#### **2. Decentralized energy systems and microgrids**

A greater decentralization of the grid is expected in the future. Distributed energy resources and microgrids help strengthen energy supply and management via Smart Grid systems. Microgrids, which use local energy production and storage, increase resilience against outages and ensure a stable energy supply.

#### **3. Artificial intelligence and data analysis**

The development of AI and data analytics technologies in Smart Grid systems significantly increases grid efficiency. With AI, real-time data analysis, accurate forecasting of energy demand and supply, and overall grid optimization become possible.

#### **The future of renewable energy sources**

The future of renewable energy sources, especially solar, wind, bioenergy, and other sustainable sources, is tied to innovations aimed at electricity generation. Today, these sources play a crucial role in energy production, but their importance is expected to increase even more in the future.

- **Solar energy** may become one of the most widespread and affordable energy sources. The efficiency of solar panels continues to increase while their

production cost decreases. Large solar farms and small residential systems may become key parts of the energy supply in many countries.

- **Wind energy** is also expected to grow, as wind turbine efficiency improves. Its role is predicted to be vital not only for large wind farms but also for urban and small-scale regions. Necessary infrastructure and technologies for wind energy development are progressing.
- **Bioenergy and other renewable sources** (such as geothermal) could achieve substantial growth in energy production. These sources cause less harm to the environment and ensure sustainable production. The advancement of biotechnology and biorefinery systems supports high-efficiency bioenergy generation.

### **1. Optimizing global energy distribution**

Integrating renewable energy sources with Smart Grid systems helps optimize global energy distribution. This improves system efficiency, enables the management of variability in renewable sources, and facilitates their integration into the grid. Smart Grids play a key role in enhancing global energy exchange and using resources efficiently in each region.

### **2. Hybrid energy systems**

The future of renewable energy lies in the development of hybrid systems. These combine multiple renewable sources — for example, using wind and solar energy together. Hybrid systems enhance the reliability and efficiency of energy supply.

### **Conclusion**

Smart Grids and renewable energy sources will become essential components of global energy systems. The advancement of Smart Grid systems and the broad use of renewable energy will make energy production and distribution more efficient, sustainable, and environmentally friendly. In the future, these technologies will significantly contribute to environmental protection, energy supply stability, and economic growth.

### **Review Questions**

1. What are Smart Grids and what role do they play in energy supply?
2. How are renewable energy sources (solar, wind, bioenergy) integrated with Smart Grids?
3. What are the main advantages of integrating renewable energy sources into Smart Grids?
4. What are the technical and economic challenges of integrating renewable energy systems into Smart Grids?
5. How does coordinated management of energy production and consumption work in Smart Grids?
6. What are the key advantages of applying Smart Grids to renewable energy systems?
7. What is the role of Smart Grids in improving energy efficiency?
8. How can Smart Grids ensure stability in energy production and consumption?
9. How can Smart Grids and renewable energy systems together enhance energy infrastructure?

### 3.4 Components and functions of power transmission networks

#### structural elements of overhead power transmission lines

Overhead power transmission lines (HLs) serve to transmit electrical energy over long distances via conductors. The main structural elements of HLs include **conductors**, **ground wires (shield wires)**, **supports (poles/towers)**, **insulators**, and **line fittings (hardware)**.

Conductors serve to **transmit electric energy**. Ground wires are installed at the top of supports to **protect the HL from atmospheric overvoltages** [1].

Supports keep the conductors and ground wires at a certain height above the ground and water surfaces. **Insulators** electrically isolate conductors from the support structures. With the help of **line fittings**, conductors are fastened to insulators, and insulators are attached to the supports. In some cases, conductors are mounted directly to engineering structures like brackets using insulators and fittings.

Single and double-circuit HLs are especially common in practice. A **three-phase HL circuit** consists of **three phase conductors**. A single support may carry two circuits.

The performance of HL components is affected by the **self-weight** of the conductors and ground wires, **ice accumulation**, **wind pressure**, and **temperature variations**. Wind can also cause **vibration** (high-frequency, low-amplitude oscillations) or **galloping** (low-frequency, high-amplitude oscillations) of conductors. These mechanical stresses, vibrations, and oscillations can result in **conductor breakage**, **support damage**, **entanglement of conductors**, or **insulation failure** due to reduced clearance, possibly causing arcing across insulators.

Overhead lines use **bare conductors**, meaning they are not covered with insulating material. Aluminum and **aluminum-steel reinforced (ACSR)** conductors are widely used. **Copper conductors** are no longer used in HLs unless justified by special technical-economic considerations. The use of **steel wires alone** is generally not recommended.

Ground wires used for overvoltage protection were previously made of steel. In recent years, ground wires have also been used to **carry high-frequency communication channels**, and in such cases, they are made from aluminum-steel composite materials. The structure and general view of bare conductors are shown in **Figure 35a**. A **single-wire conductor** (Figure 35b) consists of one round cross-sectional wire. These are **cheaper** than multi-wire conductors but have **lower flexibility** and therefore lower **mechanical strength**.

**Multi-wire conductors made from the same metal** (Figure 35d) are formed by twisting multiple wires together. Increasing the number of wires increases the cross-sectional area. In **composite multi-wire conductors** (Figure 35e), such as **aluminum-steel reinforced (ACSR)** conductors, the **inner wires (core)** are made of **steel**, while the **outer wires** are made of **aluminum**. The **steel core** provides **mechanical strength**, and the **aluminum** forms the **current-carrying part**.

**Hollow conductors** (Figure 35f) are made from flat wires connected via mechanical interlocking grooves. Due to their **large outer diameter**, they have **higher corona onset voltage**, reducing power loss due to corona discharge. These conductors are rarely

used in HLs and are mostly found in **busbars of substations** with voltages of **330 kV and above**.

In HLs rated at **330 kV and higher**, each phase may consist of **multiple conductors** (bundled conductors).

### Materials for conductors

The materials used for HL conductors must have **high electrical conductivity** and, if possible, **high mechanical strength**. In terms of conductivity, **copper** ranks first, followed by **aluminum**, while **steel** has significantly lower conductivity. Mechanically, **steel** ranks first, followed by **copper**.

Considering these characteristics, **availability**, and **relative cost**, **aluminum** and **aluminum-steel reinforced conductors** are most commonly used in HLs. In ACSR conductors, the **conductivity of the steel core is neglected**, and the **electrical resistance** of the conductor is calculated based only on the **aluminum part**.

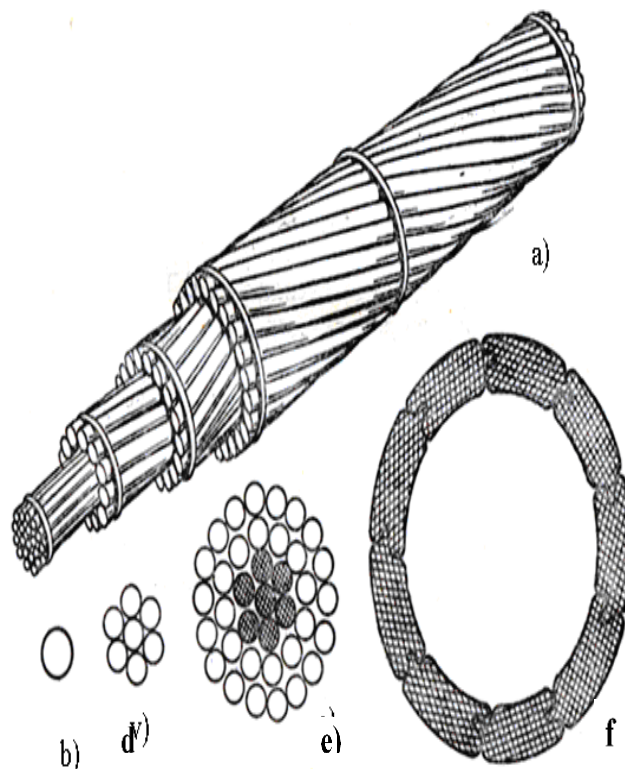


**Figure 35. Structure of HL (High-voltage Line) conductors:**

- a) general view of a multi-wire conductor;
- b) cross-section of a single-wire conductor;
- d), e) cross-sections of multi-wire conductors made from one or two types of metals;
- f) cross-section of a hollow conductor.

### 2. Supports of overhead power transmission lines

HL supports are divided into **anchor** and **intermediate** supports. These two main types of supports differ in the way conductors are suspended from them. On intermediate supports, conductors are hung using **suspension insulator strings** (Figure 36). Anchor-type supports serve to **tension and secure the conductors**. On such supports, conductors are suspended using **strain insulator strings**. The distance between intermediate supports is called the **span**, while the distance between anchor supports is referred to as the **anchor span**.



- **Branching supports** – used to split HLs into branches.
- **Crossing supports** – used to span across rivers, ravines, etc.

**Transposition** is applied in HLs with voltage over 110 kV and longer than 100 km to equalize the **capacitance and inductance** of all three phases. This is achieved by periodically changing the relative positions of the conductors on the supports (Figure 38).



**Figure 38. Transposition cycle of conductors in a single-circuit power transmission line.**

The most commonly used conductor arrangements on supports are shown in Figure 38.

- The **triangular arrangement** (Figure 39a) is used in single-circuit metal and reinforced concrete supported HLs with voltage up to 330 kV.
- The **horizontal arrangement** (Figure 39b) is used in wooden-supported HLs with voltages between 35–220 kV and also in 330 kV HLs. This configuration allows for **lower support height** and reduces the risk of conductor entanglement when ice layers form or during wind-induced swaying.
- In **double-circuit HLs**, the **inverted Christmas tree arrangement** (Figure 39d) is convenient for assembly but requires two cables to be suspended and therefore **increases the weight** of the support.
- The **barrel arrangement** (Figure 39g) is the most **economically efficient** and is widely used in practice for double-circuit HLs.

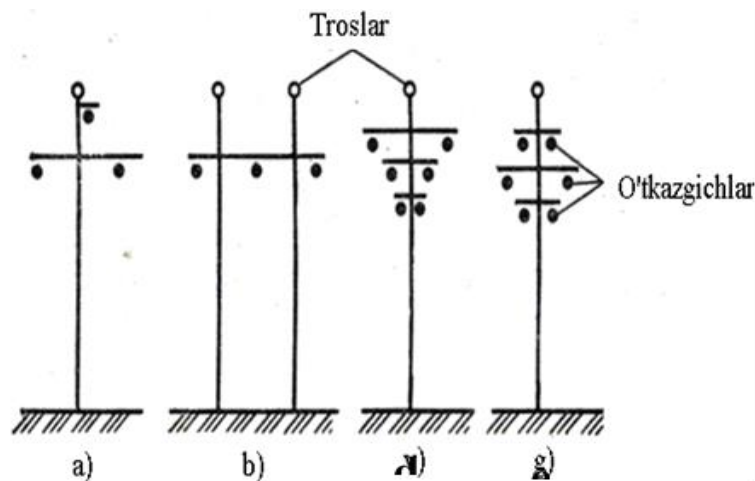


**Figure 39. Arrangement of conductors and cables on supports:**

- a - triangular arrangement;
- b - horizontal arrangement;
- d - inverted Christmas tree arrangement;
- e - barrel arrangement.

### 3. Types of supports used in overhead power transmission lines

In our country, wooden supports are used for high-voltage lines (HVL) with voltages up to 110 kV. Their advantages include low cost and ease of fabrication, while the disadvantage is their susceptibility to decay (especially in places where they are in contact with the ground).

Metal supports used in HVLs with voltages of 35 kV and above require a large amount of metal, and they must be painted regularly to protect against corrosion. Metal supports are installed on reinforced concrete foundations. According to their construction, such supports can be classified as **tower-type or single-pole** (Figure 40a), and **portal-type** (Figure 40b). Based on the method of attachment to the foundation, they are divided into **freestanding** (Figure 40a) and **guyed** supports (Figure 40).

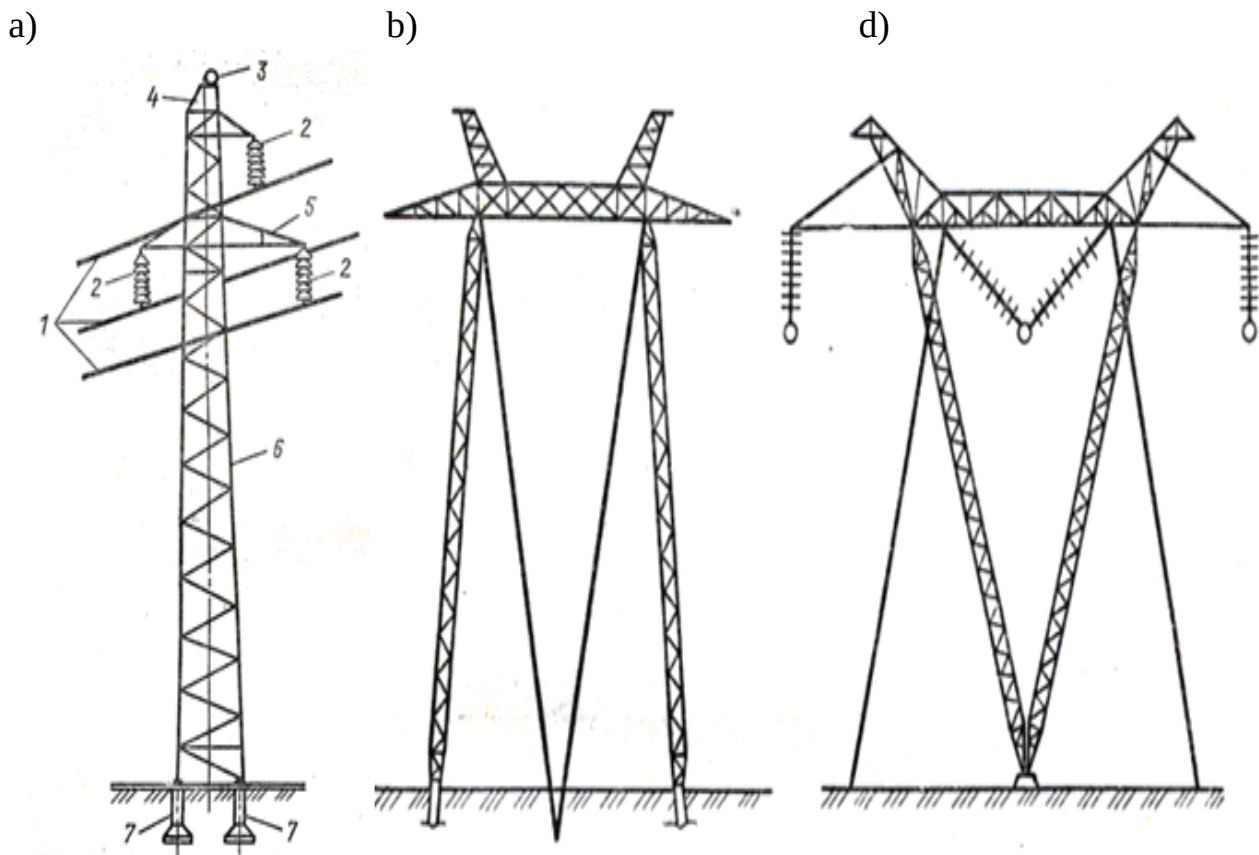


**Figure 40. External appearance of metal supports:**

- a) tower-type or single-pole;
- b) portal;
- d) guyed supports.

Anchor-type metal supports differ from intermediate supports in terms of strength and the length of their arms. **Figure 41a** shows an intermediate support used in a 220 kV HVL, and **Figure 41b** shows an anchor support used in a 110 kV HVL.

For HVLs with a voltage of 500 kV, the horizontal arrangement of conductors is typically used. The intermediate supports in 500 kV HVLs can be either freestanding or guyed .

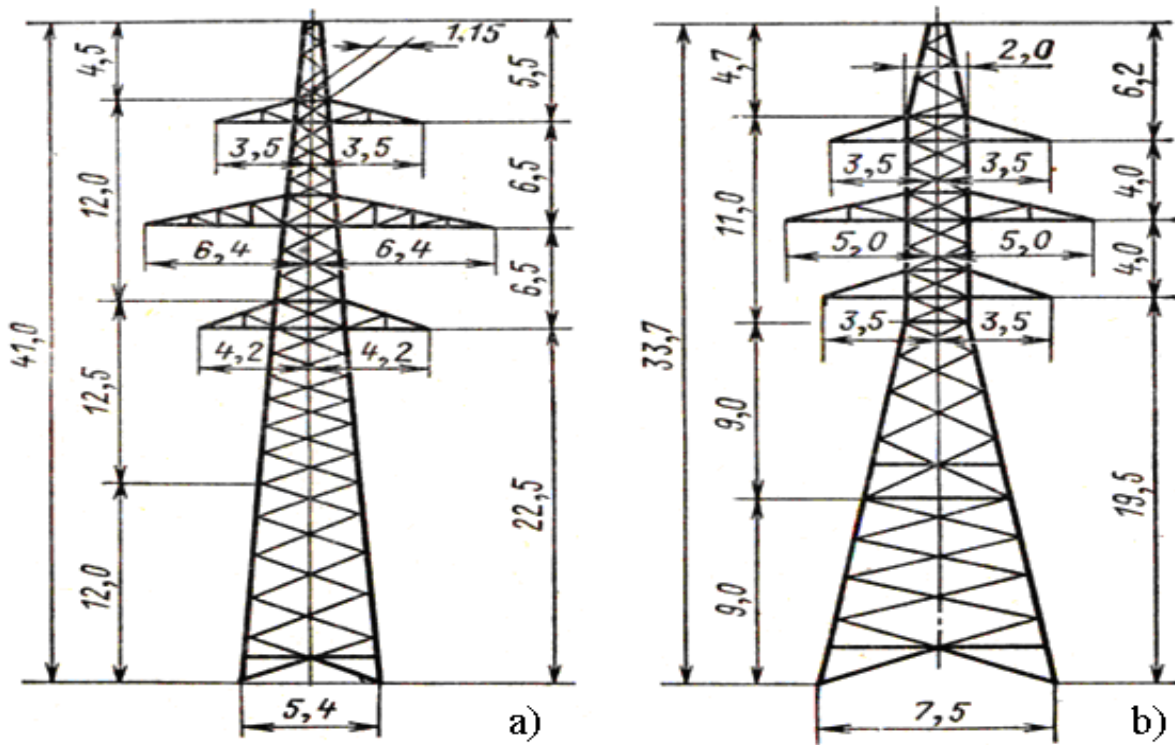


**Figure 41. Anchor-type metal supports:**

- a) Intermediate support;
- b) Anchor support.

**Reinforced concrete supports** are stronger and more durable than wooden supports, and simpler to maintain compared to metal supports. Therefore, they are widely used in overhead lines (OHLs) with voltages up to 500 kV.

**Figure 42** shows intermediate reinforced concrete supports used in OHLs of various voltage levels.

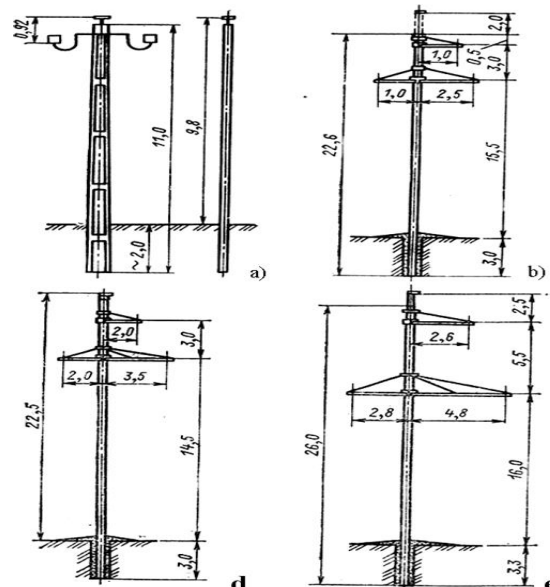


**Figure 42. Freely Placed Reinforced Concrete Intermediate Supports**

- a) For 6–10 kV with pin-type insulators;
- b) For 35 kV;
- c) For 110 kV;
- d) For 220 kV.

#### 4. Insulators and fittings of overhead transmission lines

Insulators are used to insulate and fasten overhead lines (OHLs), as well as distribution equipment of power stations and substations. They are made of porcelain or tempered glass. Structurally, insulators are divided into **pin-type** and **suspension** insulators.

**Pin-type insulators** are used in OHLs with voltage up to 10 kV (see Figure 43a). In the symbolic designation of insulators, letters and numbers represent the following:

- **Sh** – pin-type (in Uzbek: *shtirli*),
- **F** – made of porcelain (*farfor*),
- **S** – made of glass (*steklo*),
- A number – the nominal voltage in kV,
- The last letter (**A, B, V**) – structural class of the insulator.

**Disc-shaped suspension insulators** are widely used in OHLs with voltages of 35 kV and above. Suspension insulators (see Figure 7.9b) consist of:

1. An insulating part made of porcelain or glass,
2. A metal cap (2),
3. A metal pin or rod (3),
4. A cement joint connecting the insulating and metal parts.

The symbolic designation of this type of insulator includes:

- **P** – suspension (*podvesnoy*),
- **F/S** – made of porcelain or glass,
- **G** – for polluted or foggy environments,
- A number – the maximum mechanical load in kN that may lead to failure,
- Letters **A, B, V** – denote the structural class of the insulator.

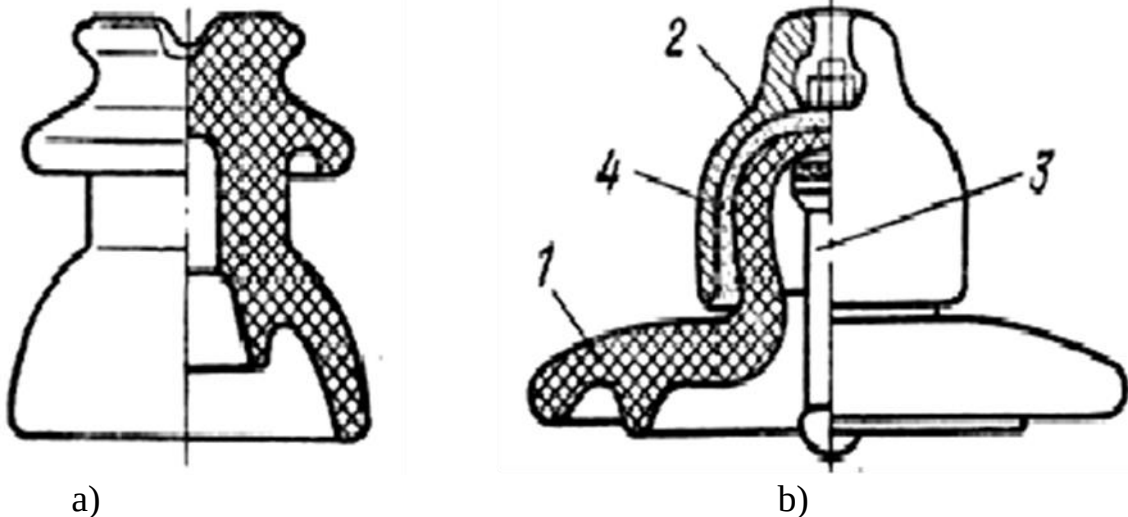


**Figure 43. Pin-type and Suspension Insulators**

a) Pin-type insulator designed for 6–10 kV;

b) Disc-shaped suspension insulator.

Suspension insulators are used in the form of strings: suspension-type at intermediate supports and tension-type at anchor supports. The number of insulators in a string is determined by the voltage level of the overhead line (OHL). For example, in suspension strings on metal and reinforced concrete supports:

- 3 insulators for 35 kV,
- 6–8 insulators for 110 kV,

- 10–14 insulators for 220 kV, and so on.

In OHLs, fittings are used to secure conductors to insulators and insulators to the supports. These fittings are classified into the following main types:

- Clamps for securing conductors to suspension insulator strings,
- Connecting fittings for attaching insulator strings to supports and to one another in series,
- Connectors for joining conductors and ground wires in span sections.

**Connecting fittings** consist of a clevis, link, and eye. The clevis connects strings to crossarms or to mounting components of the crossarm. The suspension insulator string (Figure 44a) is secured to the intermediate support's crossarm with a link (1). The link connects to the clevis or crossarm part on one side and to the cap of the upper insulator (2) on the other side. The lower insulator is connected to a clamp (4) via an eye (3), which holds the conductor (5) inside it.

Clamps for securing conductors and ground wires in the strings are divided into two types:

- **Suspension clamps** used at intermediate supports
- **Tension clamps** used at anchor supports

Suspension clamps are further divided by holding strength into:

- **Rigid clamps,**
- **Limited-strength clamps.**

In rigid clamps (Figure 44d), the tightening bolt (1) presses the conductor into the clamp body (3), or "saddle," using the strap (2). It holds the conductor firmly without movement when pulled from one side. These rigid clamps are the primary type used in OHLs operating at 35–500 kV.

Limited-strength clamps are used in 500 kV lines. When a conductor breaks, it can slip through the clamp to the other side, reducing the lateral force acting on the intermediate support.

At anchor supports, conductors are fully secured with **tension clamps**. A conductor in one span is connected to another span's conductor using a loop or tail. Tension clamps come in several types:

- **Bolted clamps** for conductors with cross-sections of 35–500 mm<sup>2</sup>,
- **Compressed (pressed) clamps** for conductors of 300 mm<sup>2</sup> and above,
- **Hook-type clamps** for securing steel wire ropes.

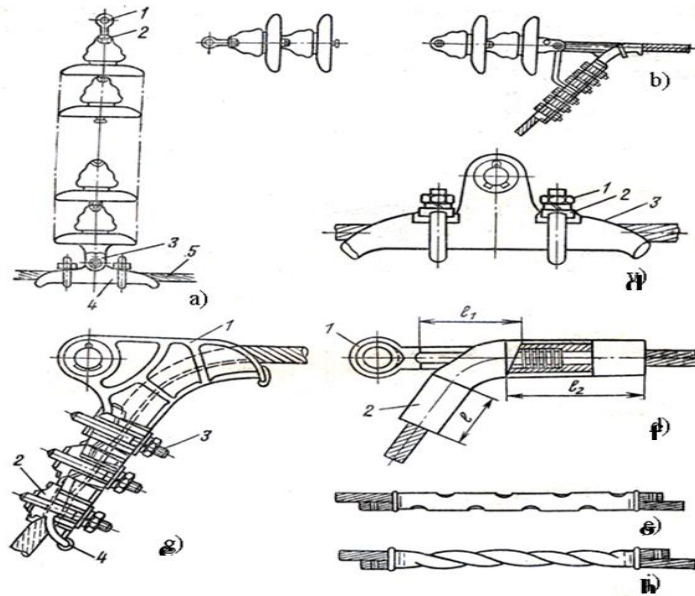


**Figure 44. Suspension and tension insulator strings and fittings:**

- a) Suspension insulator string with rigid clamp;
- b) Tension insulator string with bolted clamp;
- d) Rigid suspension clamp;
- e) Bolted tension clamp;
- f) Compressed (pressed) tension clamp;
- g, h) Compression and twisted oval connectors.

Bolted clamps (Figure 44e) consist of a body (1), strap (2), tightening bolts with nuts (3), and an aluminum wedge (4).

Compressed clamps (Figure 44f) are made up of a steel anchor (1) and an aluminum body (2). The steel core of the conductor (length  $l_1$ ) is pressed into the steel anchor, while the aluminum part of the conductor (length  $l_2$ ) and part of the loop (length  $l$ ) are pressed into the aluminum body.

In industry, conductors are manufactured in segments of specific lengths. In overhead lines (OHL), connectors are used to join these segments. They are divided into oval and compression-type connectors.

Oval connectors are used for connecting conductors with a cross-sectional area of  $185 \text{ mm}^2$  or less. In this type of connector, the conductors are overlapped and then compressed with special presses (Figure 44g).

Compression connectors, on the other hand, are used for connecting conductors with a cross-sectional area of  $240 \text{ mm}^2$  or more, as well as steel wire ropes. For connecting steel-aluminum conductors, these connectors consist of two tubes:

- The first tube is made of steel and is used to connect the inner steel strands of the conductors.
- The second tube is made of aluminum and is used to connect the outer aluminum strands of the conductors (see Figure 45a)

To ensure mechanical strength and electrical continuity in high-voltage transmission systems, the proper selection and installation of connectors are of paramount importance. Compression connectors, particularly those designed for steel-aluminum conductors (commonly referred to as ACSR – Aluminum Conductor Steel Reinforced), are engineered to withstand high mechanical loads, minimize electrical resistance at the joint, and prevent galvanic corrosion between dissimilar metals.

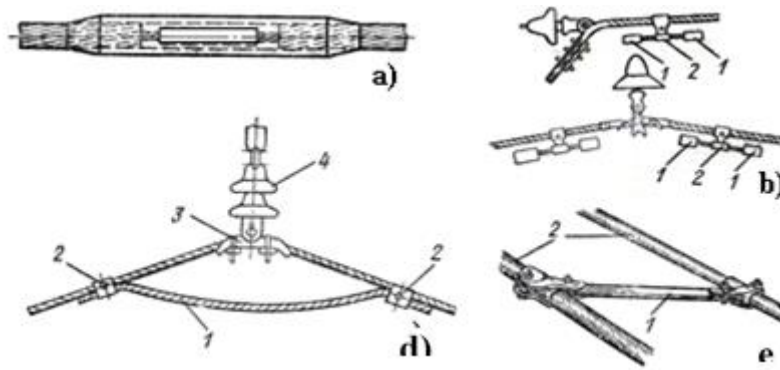


**Figure 45. Connectors and vibration dampers of overhead lines:**

- a) Compression connector;
- b) Vibration damper;
- d) Damping (stabilizing) loop;
- e) Spacer.

Vibration dampers or damping (stabilizing) loops are installed near the clamps of overhead lines. Vibration dampers suppress oscillations in overhead lines and help prevent conductor wire breakage. The damper consists of two cast iron weights (1) connected by steel cables (2) (see Figure 45b). Since the vibration frequency of the damper is significantly lower than that of the conductor, it reduces the vibration in the conductor.

For small cross-sectional aluminum and steel-aluminum conductors, vibration is damped using a damping (stabilizing) loop (see Figure 45d). The loop (1) is attached via bolted clamps (2) to the conductor that is secured to the clamp (3) in the string of suspension insulators (4).

In 330–750 kV conductors, spacers (1) are used to fix the positions of split-phase conductors (2) relative to one another (see Figure 45e). These spacers maintain the necessary distance between the split-phase conductors and prevent them from colliding or twisting together [1].

### **Control questions:**

1. What are the main structural elements of overhead power transmission lines?
2. What materials are used to construct power transmission lines and why?
3. What tools are used to secure wires in overhead lines?
4. What is the primary function of supports in overhead transmission lines?
5. What factors determine the distance between supports?
6. What types of supports are used in high-voltage power transmission lines?
7. What are the advantages and disadvantages of wooden, reinforced concrete, and metal supports?
8. Which material produces the most durable electrical support in terms of strength?
9. What is the main function of insulators in overhead power transmission lines?
10. What are the main types of hardware used in power transmission lines, and what are their functions?

### 3.5 Voltage and energy losses in power transmission networks

#### The concept of voltage and its types in power transmission networks

Electric voltage is the potential difference that arises as a result of the electric field's effect on a charge, and it is measured in volts (V). Mathematically, voltage is expressed as:

$$U = \int_A^B \mathbf{E} \cdot d\mathbf{l}$$

Where:

- $U$  — voltage between points A and B (V),
- $E$  — electric field intensity (V/m),
- $d\mathbf{l}$  — length of the path element (m).

The main function of voltage in power transmission networks is to transmit energy from one point to another with minimal losses. Different voltage levels help improve the efficiency of energy transmission.

In power transmission networks, both direct current (DC) and alternating current (AC) voltages are used. These voltages can be classified into the following types based on their levels:

**Low-voltage systems** are mainly used for delivering electric energy to consumers. These systems are used to distribute electric energy in both alternating and direct current forms.

**Voltage level:** up to 0.4 kV

Formula:

$$P = U \cdot I \cdot \cos \phi$$

Here:

$P$  — active power (W),  
 $U$  — phase or line voltage (V),  
 $I$  — current (A),  
 $\cos \phi$  — power factor.

Medium-voltage networks are used for distributing electrical energy to cities and industrial enterprises. These systems are designed to be efficient for transmitting energy over moderate distances.

**Voltage level:** 10-35 kV.

Formula:

$$\Delta U = \frac{P \cdot R + Q \cdot X}{U}$$

Here:

$\Delta U$  — voltage drop (V),  
 $P$  — active power (W),  
 $Q$  — reactive power (VAr),  
 $R$  — line resistance (ohms),  
 $X$  — line inductive reactance (ohms).

High-voltage systems are used for transmitting electrical energy over long distances. As the voltage level increases, energy losses decrease and efficiency improves.

**Voltage level:** 110-750 kV.

Formula:

$$S = U \cdot I^*$$

Here :

$S$  — complex power (VA),

$I^*$  — complex conjugate of current (A).

Ultra-high voltage systems are mainly used in intercountry (interstate) trunk power transmission lines. These systems help significantly reduce energy losses, but special attention must be paid to insulation and protection requirements.

Voltage level: 750 kV and above.

Model:

$$Z = R + jX, Y = G + jB$$

Here:

$Z$  — total resistance of the line (Ohm),

$Y$  — full line conductivity (S),

$R$  — active resistance (Ohm),

$X$  — inductiv reaktivlik (Ohm),

$G$  — electrical conductivity (S),

$B$  — capacitive reactance (S).

There are various voltage levels in power transmission networks, which help improve energy efficiency and minimize energy losses. High-voltage systems are efficient for transmitting energy over long distances, but they have higher safety and insulation requirements.

The amount of voltage drop in power transmission lines depends on the active and reactive power flowing through them, the resistance of the wire, and the voltage level, and it is determined by the following formula:

$$\Delta U_1 = \frac{P_x \cdot \ell \cdot r_0 + Q_x \ell \cdot X_0}{U_1 - \sum_{i=1}^{n_k} \Delta U_{\text{п.к.учму}}}; \text{ V}$$

Here:  $R_h$  — calculated active power (kVt);

$Q_h$  — calculated reactive power (kVar);

If the total calculated power -  $S_h$  is known, then:

$$R_h = S_h \cdot \cos \varphi, \text{ (kVt)}$$

$$Q_h = S_h \cdot \sin \varphi, \text{ (kVar)}$$

$L$ —liniyaning uzunligi, km;  $r_0, x_0$ —1 km uzunlikdagi liniyaning aktiv va reaktiv qarshiligi bo‘lib, ular simning markasiga ko‘ra ma‘lumotnoma kitobdan tanlab olinadi. 1—jadvalda turli markalardagi simlarning qarshiliklari ko‘rsatilgan.

1—jadval

| Qarshilik | Sim markasi |       |       |       |       |       |
|-----------|-------------|-------|-------|-------|-------|-------|
|           | AS-16       | A-25  | A-35  | A-50  | A-70  | A-95  |
| $r_0$     | 2.06        | 1.28  | 0.92  | 0.64  | 0.46  | 0.34  |
| $x_0$     | 0.405       | 0.391 | 0.380 | 0.369 | 0.355 | 0.346 |

Given for  $D_{0,rt}=1,25$  m.

If the loads are connected at different distances along the line, the distance between two load connection points is called a **line section**. The power flowing through each of

these line sections is calculated individually for each section, assuming it's consistent within that section.

To determine the **total voltage drop** across the entire line, the voltage drops in each consecutively connected line section must be added together.

- $U_1$  – is the voltage at the starting point of the line, in kV;
- $\sum \Delta U$  – is the sum of the voltage drops in the line sections up to the “K” line section, in kV;

As a result of the calculations, the actual **voltage drop** across the entire line must be **less than or equal to** the permissible voltage drop for that line:

$$\Delta U_l \leq \Delta U_{\text{rux.et.}}$$

Otherwise, the **cross-sectional area** of the conductor must be increased and  $\Delta U$  recalculated.

### Example:

For a 10 kV line, determine the voltage drop ( $\Delta U$ ) for both maximum and minimum load conditions according to the parameters shown in the diagram, assuming the **permissible voltage drop** ( $\Delta U_{\text{rux.et.}} = 2.5\%$ ) is 2.5%.

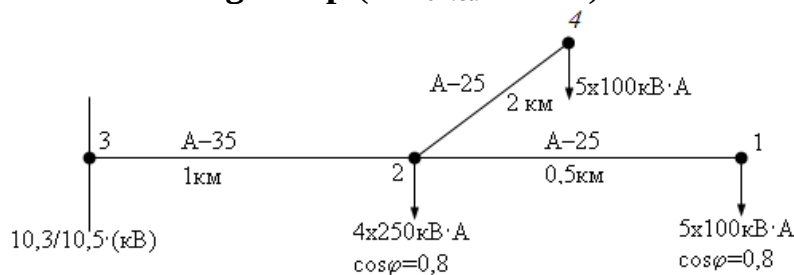


Figure 46. Calculation scheme for a 10 kV line

**Solution:** The voltage loss from the line sections for the maximum mode is determined from the formula above.

$$\Delta U_{2-3}^{100} = \frac{P_b \cdot l \cdot r_0 + Q_b \cdot l \cdot x_0}{U_{\text{HOM}}} = \frac{1600 \cdot 1 \cdot 0.92 + 1200 \cdot 1 \cdot 0.38}{10.3} = 187B$$

$$R_h = 2000 \cdot 0.8 = 1600 \text{ kVt};$$

$$Q_h = 2000 \cdot 0.6 = 1200 \text{ kVar}$$

$$\Delta U_{1-2}^{100} = \frac{400 \cdot 0.5 \cdot 1.28 + 300 \cdot 0.5 \cdot 0.391}{10.3 - 0.14} = 35B$$

$$R_h = 500 \cdot 0.8 = 400 \text{ kW};$$

$$Q_h = 500 \cdot 0.6 = 300 \text{ kVar}$$

$$\Delta U_l^{100} = 187 + 35 = 222B;$$

$$2,22\% < 2.5\% \text{ dan}$$

The voltage loss in the line sections for the minimum mode is determined from the above formula:

$$\Delta U_{1-2}^{25} = \frac{\frac{400}{4} \cdot 1 \cdot 1.28 + \frac{300}{4} \cdot 0.5 \cdot 0.391}{10.3 - 0.36} = 9B$$

$$\Delta U_{2-3}^{25} = \frac{\frac{1600}{4} \cdot 1 \cdot 0.92 + \frac{1200}{4} \cdot 1 \cdot 0.38}{10.3} = 46B$$

$$\Delta U_k^{25} = 46 + 9 = 54 B;$$

$$\Delta U_{\%} = \frac{54}{10000} \cdot 100 = 0,54\%;$$

$$\Delta U_{2-4}^{100} = \frac{400 \cdot 2 \cdot 1,28 + 300 \cdot 2 \cdot 0,391}{10,3 - 0,14} = 128 B;$$

$$\Delta U_{\%}^{100} = 40 + 128 = 268 B;$$

$$3,15\% > 2,5\%$$

$$A - 35(r_o = 0,92; X_o = 0,38)$$

$$\Delta U_{2-4}^{100} = \frac{770 + 240}{10,3 - 0,14} = 96 B;$$

$$\Delta U_{2-4}^{25} = \frac{100 \cdot 2 \cdot 1,28 + 75 \cdot 2 \cdot 0,391}{10,3 - 0,036} = 30 B;$$

$$\Delta U_{\%}^{25} = 46 + 30 = 76 B;$$

$$\frac{76}{10000} \cdot 100\% = 0,76\%.$$

## 2. Energy losses in the process of power transmission and their main causes

During the transmission of electrical energy from power plants to consumers, a portion of the power and energy is lost due to conductor heating, the formation of electromagnetic fields, and other effects. These types of losses occur in overhead and cable lines, as well as in the transformers and autotransformers of step-up and step-down substations.

In a three-phase electrical network, the active power loss in a segment with resistance R is calculated as follows:

$$\Delta P = 3I^2 R$$

Where:

- I – is the load current.

This current is determined based on the transmission of total power:

$$S = \sqrt{P^2 + Q^2}$$

Where:

- P – active power converted into mechanical, thermal, or light energy by the consumers,
- Q – reactive power used to generate electromagnetic fields in electric motors, transformers, and lines.

If we substitute the expression of current in terms of power and voltage into the formula for power loss, we get:

$$I = \frac{S}{\sqrt{3}U}$$

Where:

- U – line voltage.

$$\Delta P = 3 \left( \frac{S}{\sqrt{3}U} \right)^2 R = \frac{S^2}{U^2} R = \frac{P^2 + Q^2}{U^2} R$$

$$\Delta Q = \frac{P^2 + Q^2}{U^2} X$$

According to this formula, a similar expression can also be written for **reactive power losses** in the line.

In any element of an electrical network, including the line itself, active energy losses depend on the nature of the load and how it changes over time. If the line operates under a constant load with an active power loss of  $P\Delta$ , the energy lost over a time period  $t$  is calculated as:

$$\Delta W = \Delta P t$$

If the load changes throughout the year, then electrical energy loss in the line can be calculated using several different methods. All available methods can be divided into two major groups depending on the mathematical model used:

**deterministic and probabilistic-statistical methods.**

The most accurate method for calculating energy losses is determining them based on **branch load graphs**. This method involves calculating power losses for each step of the load graph and summing them. This method is sometimes referred to as the **graphical interpolation method**.

Load graphs are divided into **daily** and **annual** graphs. Daily graphs show how load power changes throughout the day, while annual graphs represent changes throughout the year. Annual graphs are built based on characteristic daily graphs for spring-summer and autumn-winter periods. To calculate annual energy losses, **duration-based load graphs** are used.

To build such a graph, the process is as follows:

- The initial ordinate of the graph is set equal to the maximum load.
- Using daily graphs and accounting for different types of days (e.g., Saturdays, Sundays, Mondays, workdays), the number of hours in a year corresponding to each load power value is determined.
- First, the time when the maximum load occurs is identified, followed by the time intervals for other (decreasing) load levels.

Based on the annual load graph, the **annual energy loss** can be determined. For this, power and energy losses are calculated for each condition, and their sum gives the total annual electric energy loss.

As an example, consider a **three-step load graph** (Figure 47b). For the load condition  $P_1$ , the power loss in the line (Figure 47a) is calculated as:

$$\Delta P_1 = \frac{S_1^2}{U_1^2} R$$

The energy loss for this condition is then:

$$\Delta W_1 = \Delta P_1 \Delta t_1$$

The same approach is used for the remaining load conditions:

For  $P_2$ :

$$\Delta P_2 = \frac{S_2^2}{U_2^2} R$$

$$\Delta W_2 = \Delta P_2 \Delta t_2$$

For  $P_3$

$$\Delta P_3 = \frac{S_3^2}{U_3^2} R$$

$$\Delta W_3 = \Delta P_3 \Delta t_3$$

Based on the above, the power and annual energy losses for the  $i$ -th step of a multi-step load graph with  $N$  steps are determined by the following formulas:

$$\Delta P_i = \frac{S_i^2}{U_i^2} R \quad i=1, \dots, N$$

$$\Delta W_i = \sum_i^N \Delta P_i \Delta t_i$$

Here,  $\Delta t_i$  is the duration of the  $i$ -th page of the loading graph

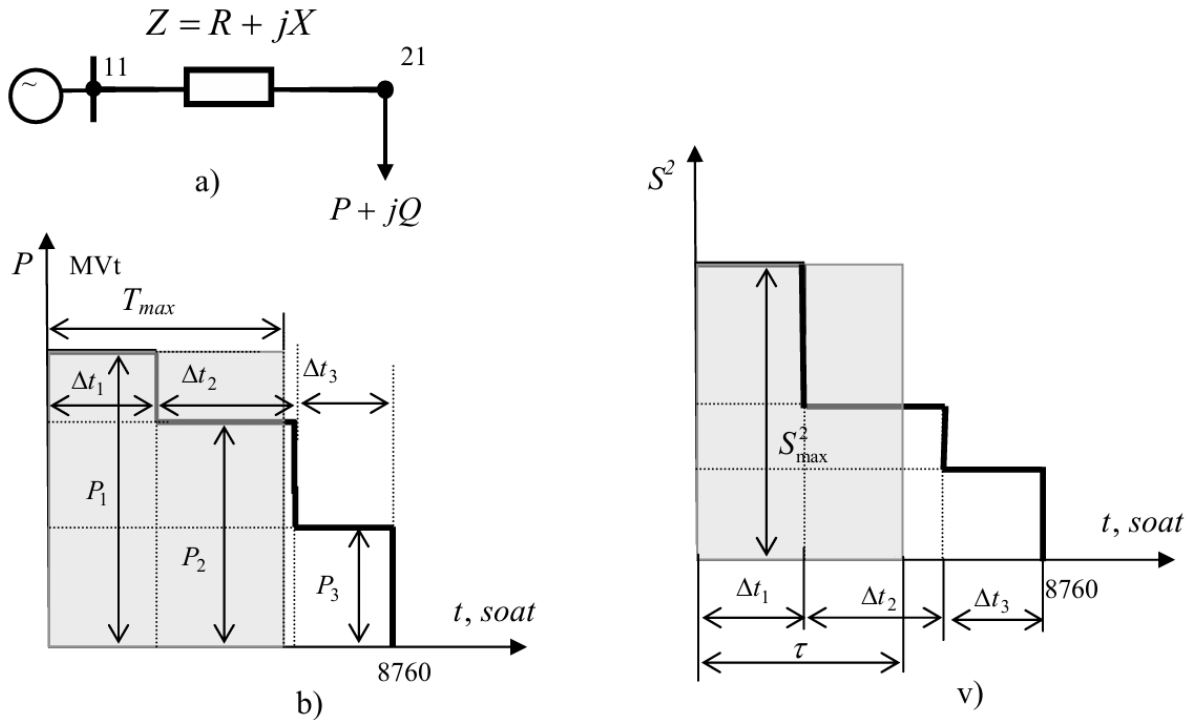


**Figure 47. Determining electric energy losses based on load graph and time of maximum losses:**

a) – Line substitution scheme; b) – Three-step load graph; v) – Three-step  $S^2$  graph.

The advantage of the method for determining losses based on the load graph is its **high accuracy**. However, the **limited availability of information** about the loads on all sections restricts the application of this method.

### 3. Methods to reduce voltage drop and energy losses

In the current situation, reducing energy losses in electrical networks is considered one of the important sources of fuel saving. When analyzing electrical energy losses, total losses should be categorized as follows:

- **Calculated energy losses in the power system** – the difference between the amount of electrical energy supplied from all power stations to the network and the amount recorded and paid for by all consumers.
- **Technical and calculated losses** – determined based on known operational parameters and design parameters of network elements. These losses are due to conductor heating and the formation of electromagnetic fields.

- **Commercial losses** – defined as the difference between calculated and technical losses. These occur due to underdeveloped metering systems, inconsistencies and inaccuracies in meter readings, errors in measuring devices, and the presence of unregistered consumers;
- Losses also include theft and other related issues.

Currently, the measures to reduce energy losses in electrical networks are divided into three groups: organizational, technical, and improvements in the technical and metering systems of electrical energy.

**Organizational measures** generally do not require any additional funding. **Technical measures**, on the other hand, require additional capital investment.

**Improving the technical and metering systems** of electrical energy allows for more accurate calculations in selecting the appropriate loss reduction strategies.

In 35 kV voltage networks, 35% of energy loss occurs, while the remaining 65% corresponds to 0.22–10 kV electrical networks. Despite the high energy losses in 0.22–10 kV networks, their construction requires four times more non-ferrous metals compared to 35 kV and higher-voltage networks. This shows that in order to reduce energy losses, the length of lines below 1000 V should be decreased. To achieve this, more substations need to be built closer to consumers.

It is also possible to significantly reduce losses in the network by increasing the **power factor** of electrical equipment. This is because... *(text appears to be cut off here)*

$$\Delta P = 3J^2 R_n = \frac{P^2 R_n}{U^2 \cdot \cos^2 \varphi}, \text{ kW}$$

power factor from this

$$\cos \varphi = \frac{P}{S} = \frac{P}{\sqrt{P^2 + Q^2}}$$

and at time t

$$\cos \varphi_{cs} = \frac{w_a}{\sqrt{w_a^2 + w_p^2}}$$

$w_a$  va  $w_p$  – are the active and reactive energy consumed during time **t** (within 30 minutes).

**Natural measures to increase power factor  $\cos \varphi$**  include:

- Correct selection of the power rating of asynchronous motors. The power factor of asynchronous motors during idle running is  **$\cos \varphi = 0.2–0.3$** , while under nominal load it reaches  **$\cos \varphi = 0.83–0.86$** . In underloaded asynchronous motors,  **$\cos \varphi$**  drops significantly. This situation is also observed in power transformers and heating devices. Therefore, replacing asynchronous motors that operate at less than 40% load with smaller power-rated motors is advisable.
- If the technological process allows, it is appropriate to replace asynchronous motors with synchronous motors.
- Ensuring quality maintenance of electrical equipment, and so on.

**Artificial methods to increase  $\cos \varphi$**  are primarily carried out by installing capacitor banks and synchronous compensators. These are referred to as **compensation devices (CD)**.

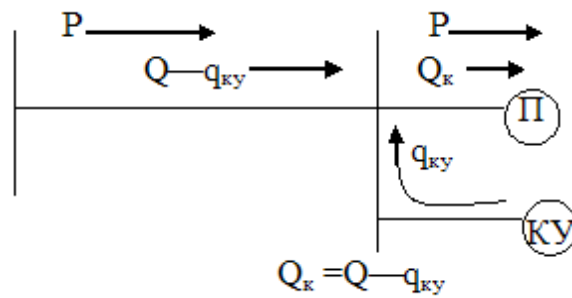


**Figure 48. Scheme of connecting compensation devices to the network.**

Here  $Q_k = Q - q_{ky}$

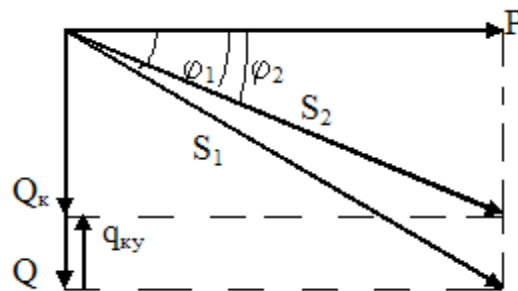


**Figure 49. Vector diagram for increasing the power factor  $\cos \varphi$ .**

$P$  – Installed compensating device (CD) for transmitting active ( $R$ ) and reactive ( $Q$ ) power to the consumer.

$q_{qu}$  – the amount of reactive power that can be supplied to the network.

As a result, the amount of reactive power transmitted to the consumer by the line decreases from the initial value  $Q$  to  $Q_k$ , and the angle  $\varphi_1$  is reduced to  $\varphi_2$ , which increases  $\cos \varphi$ . The total power  $S_1$  decreases to  $S_2$ . The active power loss in the line also decreases because:

$$\Delta P = \frac{\sqrt{P^2 + (Q - q_{ky})^2}}{U^2} R_l, \text{ kVt}$$

**The placement of compensation devices in the electrical supply scheme can be as follows:**

- **Centrally located** – in this case, compensation devices are installed at main step-down substations (BPP);
- **Installed close to consumers** – installed at the substations of factory workshops. Several devices can be installed in groups (group installation). In this case, the compensation devices (CDs) are connected to the distribution cabinets (DCs). In separate installations, the CDs are connected directly to large-capacity electrical consumers.

Several factors contribute to reducing losses during the transmission of electrical energy, primarily through the reduction of reactive power.

**Control Questions:**

1. What are the causes of losses during the transmission of electrical energy?
2. What are the components of energy that is lost?

3. What measures can be taken to reduce losses during the transmission of electrical energy?

### **3.6. Types and functions of transformers used in power networks**

#### **Types of transformers and their significance in electrical systems**

Transformers used in energy systems can generally be divided into three main groups:

1. Power transformers
2. Autotransformers
3. Special-purpose transformers

In some literature, measuring (instrument) transformers are also added as a fourth separate group.

#### **Power Transformers:**

Power transformers are considered one of the key devices in energy systems. Their main function is to convert voltage levels from one form to another along consumer lines. One of the primary reasons for using transformers in power systems is to reduce energy losses and to provide the appropriate voltage level required by the consumer.

In large-capacity power stations within the energy system, the generated electrical energy is delivered to the lowest-voltage consumers through a series of at least five transformer stages. Since the voltage of the energy generated at the station is relatively low, it is first stepped up—within the station itself—to up to 500 kV (in the case of Uzbekistan's power system) to integrate with the main transmission lines. At this stage, at least two transformers are used in series.

As electrical energy moves closer to the consumer, the 500 kV voltage is reduced step-by-step:

- from 500 kV to 220 kV,
- from 220 kV to 110 kV,
- from 110 kV to 35 kV,
- from 35 kV to 10 kV,
- and finally, once close to the consumer, from 10 kV to 0.4 kV.

At each of these voltage transformation stages, power transformers are used. Therefore, in energy systems, power transformers serve the essential function of adjusting the voltage in loaded (active) networks.

These transformations ensure efficient transmission, minimal loss, and safe delivery of electricity from the point of generation to end consumers.

Each voltage level in the transformation cascade serves a specific purpose within the energy distribution architecture. The **500 kV** and **220 kV** levels are primarily used for long-distance, high-capacity bulk transmission. These levels ensure that large quantities of electricity can be moved across the national grid with minimal loss. The **110 kV** and **35 kV** levels typically serve as subtransmission voltages, linking high-voltage substations to regional or industrial distribution centers. Meanwhile, **10 kV** and **0.4 kV** levels are used in local distribution networks to supply electricity to small industries, residential buildings, and commercial facilities. They are equipped with On-Load Tap Changers (OLTCs) for dynamic voltage regulation, and often integrated with digital monitoring systems that track parameters such as winding temperature, oil level, gas formation, and insulation degradation.



**Figure 50. General view of power transformers.**

**power transformers are divided into single-phase and three-phase types.**

Three-phase transformers are the most commonly used because they have 12–15% lower power losses and 20–23% lower consumption of active materials compared to using three single-phase transformers of equivalent total power.

(In other words, a single three-phase transformer, compared to three single-phase transformers with the same combined power capacity, results in 12–15% less power loss.)

Single-phase transformers are used in cases where manufacturing three-phase transformers is not feasible—such as when handling very high power or when transportation becomes significantly difficult.

Single-phase transformers typically have the following ratings:

- 1600 MVA at 500 kV
- 1250 MVA at 750 kV

Three-phase transformers are produced with the following specifications:

- Rated for voltages of 220 kV and 500 kV
- Power ratings up to 1000 MVA
- Examples include 500/110 kV transformers with a capacity of 250 MVA

Transformers can also be categorized based on the number of windings:

- Two-winding transformers
- Three-winding transformers

(Figure 51 illustrates this.)

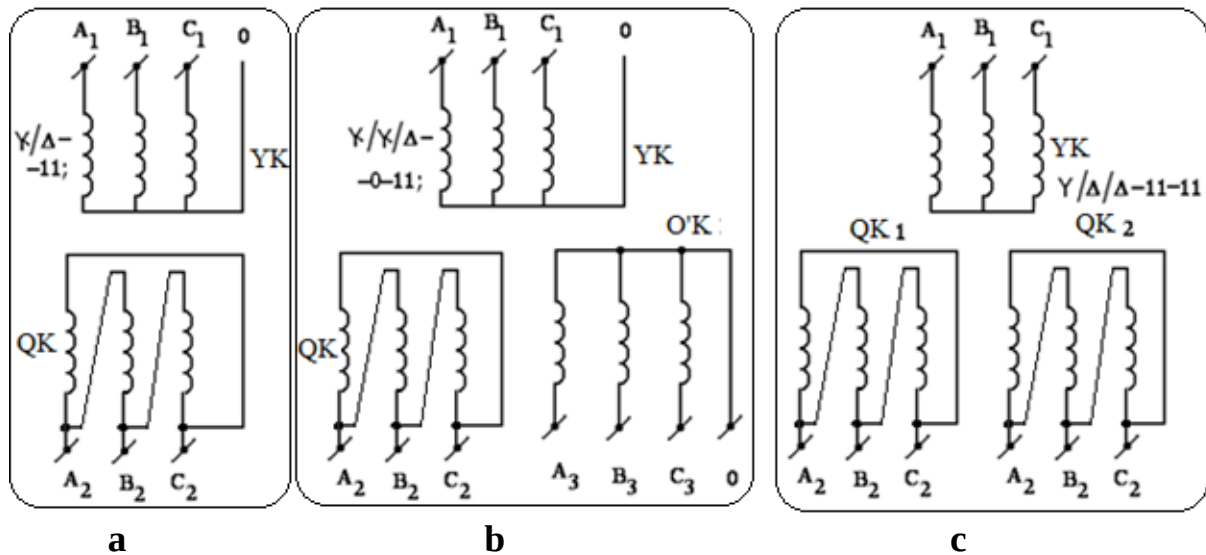


**Figure 52. General view of power transformer windings.**

a – Diagram of a transformer with a secondary winding; b – Diagram of a three-winding transformer; c – Diagram of a transformer with a secondary winding and isolated (separated) low-voltage side.

### Autotransformers

Autotransformers can be used for the same functions as power transformers, as well as for many other purposes. In energy systems, large-capacity transformers—such as those operating at 500 kV—are often autotransformers. The main difference between autotransformers and conventional power transformers is that, in addition to magnetic coupling between the windings, autotransformers also have **electrical connections** between them. They are also distinguished by their **broader range of applications**.



**Figure 53. General view of single-phase autotransformers.**

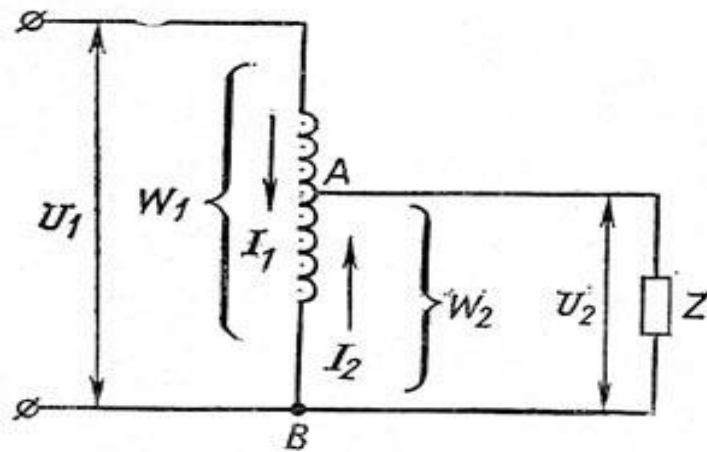


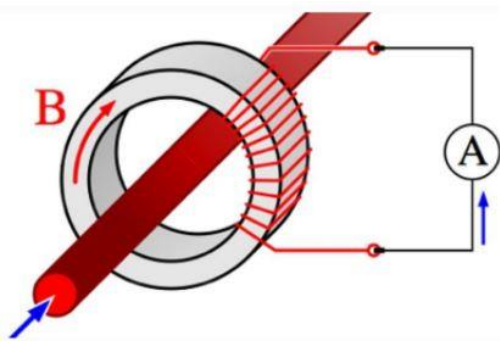
Figure 54. General view of the autotransformer windings.



Figure 55. General view of a laboratory autotransformer.

### Special Transformers

Special transformers include those designed for specific purposes. For example, a **voltage measuring transformer** is used to measure voltage, while a **current transformer** is used to measure electric current. These transformers are utilized in situations where direct measurement of voltage or current is not feasible. They work by converting high voltage or current levels into values that are more convenient and safer to measure.



Current transformer scheme



Current transformer view

**Figure 56. Schematic and external view of a current transformer.**



**Figure 57. External view of a voltage transformer.**

Transformers used in welding equipment also belong to the group of special transformers, which are manufactured specifically for the purpose of performing special tasks.



**Figure 58. External view of a welding transformer.**

## **2. Efficient Use of Power Transformers**

In electric power systems, power transformers are among the key components. They play a critical role in transmitting, distributing, and delivering electrical energy over long distances with minimal losses. Efficient use of transformers primarily contributes to the economical use of electrical energy, overall system reliability and stability, and reduced maintenance costs.

Efficient use refers to maintaining a high efficiency (useful power coefficient) of the transformer, minimizing heat losses, ensuring operation under optimal load conditions, strictly following maintenance schedules, and improving the performance of the cooling system. Power transformers constantly regulate voltage levels by stepping voltage up or down, thereby balancing the system. However, if transformers are used improperly or maintenance is neglected, it can lead to increased energy losses, damage to insulation, and premature failure of the equipment.

Losses in transformers are mainly categorized into two types: core losses and winding losses. Core losses arise due to magnetization and eddy currents in the magnetic core; these are constant and independent of the load. Winding losses, on the other hand, occur due to electrical resistance in the windings when current flows through them and increase proportionally with the square of the current. Therefore, both overloading and underloading a transformer reduce its energy efficiency. Transformers operate most efficiently—achieving 95–98% efficiency—when running at around 80–90% of their rated capacity.

Since transformers are heat-generating devices, the condition of the cooling system is extremely important. Dry-type transformers use air cooling, while oil-filled transformers use natural or forced oil circulation systems (such as ONAN, ONAF, OFAF, etc.). Malfunction of the cooling system or degradation of the oil quality can damage the insulation. Moisture or gases in the transformer oil increase the risk of electrical breakdown. Thus, regular monitoring of oil condition, gas analysis, and, when necessary, oil filtration are essential maintenance activities.

Efficient operation also requires symmetrical load distribution. The loads connected to three-phase transformers should be as balanced as possible. Otherwise, uneven currents or heat in certain phases can cause unbalanced operation, noise, vibration, and increased losses. In addition, installing automatic monitoring and diagnostic systems can significantly improve efficiency. For example, modern microprocessor-based monitoring systems can continuously track the condition of the transformer, optimize the load, control the temperature, and predict fault conditions in advance.

The energy efficiency of transformers is also economically important. High-efficiency transformers (e.g., those with class A or A+ ratings) can save significant amounts of electricity annually. This leads to substantial cost savings at both the industrial and grid levels. To enhance energy efficiency, it is necessary to use advanced magnetic materials, low-loss winding wires, and optimized designs.

All the technical and organizational measures mentioned above serve to increase the operational efficiency of transformers, save energy resources, extend service life, and reduce operational costs. This ensures that systems using transformers remain reliable, stable, and economically viable. Ongoing research, the application of innovative technologies, and the integration of digital control tools are expected to further boost transformer efficiency in the near future

### 3. Transformer Selection in Power Systems

Transformers are one of the **core technological components** in electrical power systems. Therefore, properly selecting a transformer ensures not only system efficiency and reliability but also long-term technical and technological stability. When selecting transformers, **technical, economic, and operational factors** must be considered together.

First and foremost, the **voltage levels** within the system and the **amount of transmitted power** are taken into account. Each power network operates at specific voltage levels, and a transformer with appropriate voltage is needed to ensure the flow of electricity between these levels. For example, energy generated at power plants is typically at **10–20 kV**, but to feed into the transmission network, it is stepped up to **110, 220, or 500 kV**. In such cases, **high-voltage power transformers** are selected. Conversely, when delivering energy to consumers, the voltage is stepped down to lower levels, such as **0.4 kV**, which requires **low-voltage transformers**.

The **power rating** of the transformer is also a critical selection criterion. Power is calculated under **nominal load, peak network load, and potential overload** conditions. Transformers are usually selected with a **30–40% reserve margin** to prevent overheating and early failure. The **thermal class** of the transformer—its ability to withstand maximum temperature—also plays an important role. Transformer selection is often based on **load curves**, taking into account variations in energy

consumption. **Daily and yearly load changes**, as well as stability during peak load times, influence the decision.

Another important factor is the **efficiency and energy losses** of the transformer. During operation, transformers lose a certain amount of energy, mostly in the form of heat. Therefore, core and winding losses—**magnetic saturation, eddy current losses, and copper losses**—are evaluated during selection. **High-efficiency, energy-saving transformers** (e.g., those with **A or A+ efficiency class**) are preferred because they offer significant long-term savings in both **energy and cost**.

The **structural design** of the transformer also affects the choice. For example, **oil-immersed transformers** are used for high power applications and in areas requiring significant heat dissipation. **Dry-type transformers** are preferred in **safety-critical locations, indoor installations, or areas with limited ventilation**. The **cooling system** also plays a crucial role: natural cooling (**ONAN**), forced cooling (**ONAF**), or **special cooling methods** are selected based on the operating environment.

The **geographical and climatic conditions** of the power system also influence transformer selection. For example, in **high-altitude regions**, low atmospheric pressure, extreme temperature fluctuations, or high humidity place stricter demands on insulation materials and cooling systems. In residential areas, **low-noise transformers** are required to minimize acoustic disturbance.

Apart from technical factors, **economic considerations** are also essential in transformer selection. These include **purchase price, operating costs, maintenance needs, availability of spare parts, and service life**—all of which impact the **overall economic efficiency**. Typically, the **Life Cycle Cost (LCC)** method is used. This method assesses total costs and benefits over the transformer's operational lifetime. Modern energy systems also favor **digitally compatible transformers**. These can be integrated into **advanced monitoring and control systems**, are **remotely monitored**, and are compatible with **smart grids**. Such transformers offer benefits like **automated energy distribution, early fault detection, and load balancing**.

In summary, **transformer selection** is a key decision based on a **comprehensive techno-economic analysis**, directly impacting system **reliability, energy security, and efficiency**. A properly chosen transformer guarantees **uninterrupted and stable power supply**.

When choosing the **number and power of transformers**, the **load type and consumer category** are considered.

- For **Category 1 consumers**, a **load factor of up to 70%** is used, and **dual transformers** are selected.
- For **Category 2 consumers**, the **load factor is 80–85%**, also with **dual transformers**.
- For **Category 3 consumers**, the **load factor goes up to 95%**, and either a **single or dual transformer** may be used.

## Review Questions

1. What are the different types of transformers, and what functions do they perform in the electrical system?
2. Explain the main differences between autotransformers and power transformers.
3. Give examples of special-purpose transformers and describe their application areas.

4. How does the construction of a magnetic circuit in transformers affect their operational efficiency?
5. List the main factors that influence the efficiency of power transformers.
6. What measures can be taken to reduce active and reactive losses in transformers?
7. What is a transformer load curve and load factor, and how are they determined?
8. How do cooling systems (ONAN, ONAF, etc.) affect the operational efficiency of transformers?
9. What parameters are considered when selecting a transformer, and why?
10. What are the differences in transformer selection for Category 1, 2, and 3 consumers?

### **3.7 Distribution devices and switching equipment**

An electrical device intended for receiving and distributing electrical energy among various electrical installations is called a distribution device.

A distribution device is an installation comprising equipment used to receive and distribute electrical energy, including electrical apparatus, busbars, and auxiliary equipment.

If the distribution device is installed indoors, it is called an Indoor Distribution Device (IDD); if located outdoors, it is referred to as an Outdoor Distribution Device (ODD). IDD's are generally designed for voltages ranging from 3 to 20 kV. Outdoor distribution devices are typically used for higher voltages. However, in cases where space is limited or the environment contains highly corrosive substances—such as chemical emissions—IDD's may be used even for voltages between 35 and 220 kV. Distribution devices must ensure the reliable operation of electrical equipment. This requirement is met by selecting and positioning the equipment correctly, and choosing the type and layout of the distribution device in accordance with regulatory standards. Distribution devices are classified into three types based on their structural design:

1. Indoor Distribution Devices – all electrical equipment is placed in special buildings.
2. Outdoor Distribution Devices – main equipment is installed outdoors in fenced areas.
3. Complete Distribution Devices – all apparatus, instruments, and auxiliary equipment are installed in fully or partially enclosed metal cabinets. These cabinets are manufactured and preassembled in specialized factories and are often referred to as panels or compartments, suitable for both indoor and outdoor use.

Each type of distribution device has its own advantages and disadvantages:

- Indoor Distribution Devices (IDD) offer reliable protection of all equipment from weather conditions, dust, ash, soot, etc. However, they are costly, and maintenance and repairs are more difficult due to limited access.
- Outdoor Distribution Devices (ODD) are cheaper, faster to construct, and more convenient for inspection, installation, and repairs. However, operation during harsh weather conditions becomes challenging, and the equipment is exposed to temperature fluctuations, precipitation, and dust, requiring proper protection.

**Electrical Supply System of Distribution Devices**

Depending on the location, the distribution device may be powered by:

- Generators at power stations,
- Power transformers at substations,
- Overhead or cable transmission lines,
- Indoor electrical wiring systems serving as supply or distribution lines.

From the distribution device, electrical energy is transmitted to other distribution devices, substations, power transformers, and various electric consumers via cable or overhead lines.

Distribution devices are equipped with:

- Protective and disconnecting devices for the connected lines,
- Measurement instruments for monitoring both the entire system and its individual sections.

To receive and distribute energy and interconnect components, open metal busbars are generally used. These busbars form a busbar system consisting of:

- Main (or common) busbars – serve as the primary distribution path from the energy source to the outgoing lines,
- Branching and connection busbars – used to connect different parts of the system.

In complete distribution devices, all current-carrying parts are enclosed in solid metal partitions. Racking trolleys that connect to the busbars use plug-in contacts, which are automatically shielded by safety shutters when the trolley is moved.

When work must be done on equipment within a complete distribution device (CDD), the racking trolley is completely withdrawn, shutters are closed, and a "Do not switch on – people working" sign is hung on the cell.

If the work is being carried out inside the same cell, an additional "Stop – High Voltage" warning sign is placed. The cable that may be energized is tested for voltage, grounded, and marked with a "Work in progress" sign.

Circuit breakers and equipment on racking trolleys are typically maintained away from live parts and outside the cells.

If work is to be performed inside the cabinet—on relays, measuring instruments, assemblies, wires, or switching devices—without needing to rack out the trolley, a "Work in progress" sign is placed at the work site, and a "Do not switch on – people working" sign is hung on the trolley's locking mechanism or the door handle.

Racking in or out the trolley constitutes a switching operation and must be performed only by personnel with Group IV qualification, either alone or under the supervision of an authorized operator.



**Figure 59. Closed distribution devices used at lower voltages.**



**Figure 60. Open distribution devices used at high voltages.**

**Switching equipment** is one of the most critical elements in electrical energy transmission and distribution systems. It plays a key role in controlling energy flow, ensuring uninterrupted network operation, eliminating short circuits, and detecting technical malfunctions in the system. Switching devices ensure the **safe, efficient, and reliable operation** of electrical networks.

#### **Main functions of switching equipment**

Switching equipment enables **control over the flow of electrical energy** in the network. Through these devices, energy is distributed among various networks and consumers, ensuring energy is delivered to where it is needed. Switching apparatuses help maintain the required **voltage and current conditions**.

They also play an important role in **protecting the system from short circuits and overloads**. If a short circuit or overload occurs in the network, the switching equipment automatically cuts off the energy flow and protects the system.

Switching equipment manages the **distribution of electrical energy**. For instance, disconnection devices are used to switch between energy sources or isolate parts of the network during short circuits. This enables identification and elimination of faults and issues within the network.

Switching equipment also helps **restore energy supply** after faults or short circuits have been cleared. To maintain continuous network operation, malfunctions in the system must be resolved quickly.

Additionally, switching equipment allows for **monitoring and control of the network status**. It helps track the system's performance indicators, energy flow, and other parameters, allowing for **optimization and efficient operation** of the energy system.

### Types of switching equipment

Switching equipment is divided into several types depending on their functions:

- **Circuit breakers** are used to disconnect the network during short circuits, overloads, or other emergency situations. They stop the energy flow and protect the network.
- **Disconnectors** are devices that direct the flow of energy and isolate parts of the network. They help manage energy flow, identify malfunctions, and optimize the transmission process.
- **Relays and automatic circuit breakers** detect short circuits and overloads. They help identify faults and automatically change the flow of energy when necessary.

These types of switching devices are used to control **current and voltage** in the network. To ensure efficient energy distribution, they regulate energy flow as needed.

**Switching transformers** are used to change voltage levels and maintain system balance. They aid in controlling energy flow and ensuring stable operation of the network.

Switching equipment is a crucial part of **energy systems**, playing a central role in ensuring their **reliability, safety, and efficiency**. Their functions include managing energy flow, eliminating short circuits, restoring the network, and optimizing energy distribution. With the help of **advanced technologies and modern systems**, the effectiveness of switching equipment continues to improve, making them increasingly important for the **future of energy systems**.



**Figure 61. Circuit breaker used in 0.4 kV networks.**



**Figure 62. Gas-insulated circuit breaker used in high-voltage networks.**



**Figure 63. Disconnector used in high-voltage networks.**



**Figure 64. Fuse used in high-voltage networks (3-10 kV).**



**Figure 65. Short circuit.**



**Figure 66. Arrester used in high-voltage networks.**

### **3. Selection of Switching Devices**

Switching devices are one of the essential elements in energy systems, playing a crucial role in ensuring the continuous and safe distribution of electrical energy. A proper approach to selecting switching devices guarantees the efficient operation of the system, reduces energy losses, and allows for the quick elimination of short circuits and malfunctions. Several technical and practical factors must be considered when choosing switching devices.

First and foremost, the selection of switching devices should take into account the operating conditions of the system, the voltage and current levels that the electricity will pass through, the network capacity, and possible faults. The main goal of the selection is to ensure optimal and reliable operation of the system.

When choosing switching devices, the operating voltage levels of the energy system and the current passing through the networks must be considered. If the voltage level is high, devices resistant to high voltage must be selected. Accordingly, switching and transmission equipment must be compatible with that voltage. Variations in current must also be well managed by switching devices.

Switching devices must protect the system during possible short circuits, overloads, or other emergencies. For the network to be managed at a high safety level, each switching device must be robust and fast-acting. These devices should automatically interrupt or restore the power flow.

Switching devices must function for long periods. Therefore, they must be made of durable materials and be of high quality. To ensure the reliable operation of the network, the devices should be as efficient as possible, and their technical specifications should match the different needs of the energy system.

The technical characteristics and operating environment of the switching devices must also be taken into consideration. For each device, the ability to operate in specific environmental conditions—such as temperature, humidity, and chemical exposure—plays a crucial role. If the system operates under high temperatures, high humidity, or in an aggressive chemical environment, specially adapted devices are required.

### **Factors to consider when selecting switching devices**

Switching devices are selected based on their functions. If power flow needs to be interrupted, circuit breakers are used. If power flow needs to be controlled and directed, switches and commutation transformers are selected. Protective relays and automatic disconnection devices are used to protect the network.

Safety is a crucial factor in selecting switching devices. The devices must be capable of quickly detecting short circuits and interrupting the power flow. They must meet all safety requirements to ensure the secure operation of the power network. Switching devices should be able to detect faults in the system and manage power distribution quickly. Automating the switching processes ensures the system operates efficiently. Automatic systems can detect short circuits and automatically disconnect or restore the necessary sections of the system.

During the lifespan of switching devices, frequent use may be required. Therefore, ease of maintenance and repair is an important consideration. If the devices need to be frequently replaced or serviced, the process should be quick and convenient to ensure uninterrupted system operation.

Choosing the right switching devices is a crucial factor in ensuring the efficient and safe operation of the energy system. Properly selected devices enhance the continuity, safety, and efficiency of power networks. The selection process must consider factors such as system operation, technical characteristics, compliance with safety standards, and ease of maintenance. With appropriate switching devices, system malfunctions can be quickly resolved, power flow managed, and optimal performance achieved.

### **Control Questions**

1. What is your understanding of the importance of distribution equipment in the energy system?

2. What are the main functions of distribution equipment?
3. What are switching devices and what role do they play in the energy system?
4. What can you tell about the different types of switching devices?
5. What is the role of switching devices in protecting the energy system?
6. What are the main factors to consider when selecting switching devices?
7. How does the operating environment affect switching devices, and how are selections made in this regard?
8. Which switching devices are used to detect and eliminate short circuits in the network?
9. What technical and safety requirements must be followed to ensure the effective operation of distribution equipment?
10. What are the advantages of automating switching devices?

### 3.8 Energy saving issues in power networks

#### The importance and necessity of energy saving in power networks

Power networks are one of the most important parts of the energy system, ensuring the continuous delivery of electricity throughout a region. Nowadays, the issue of energy saving is more crucial than ever—not only due to economic factors, but also because of environmental and technical considerations. The importance of energy saving in power networks is widely recognized, and this process plays a vital role not only in energy production but also in its transmission and distribution.

Energy losses occur throughout the systems of electricity generation, transmission, and distribution. Saving energy in power networks can lead to significant economic benefits because reducing energy losses improves the efficiency of electricity use. Lower losses in the network also mean a reduced need for energy production, which decreases the system's overall energy consumption and conserves energy resources. Reduced losses in the grid can lower the costs of electricity production and potentially reduce energy prices.

Energy saving also has a significant **environmental impact**. The production of electricity often relies on fossil fuels such as oil, gas, or coal, which contribute to air pollution, climate change, and other environmental problems. By saving energy within power networks, the overall demand for energy generation can be reduced, helping to mitigate environmental impacts. The use of new technologies and efficient systems in the energy-saving process helps not only conserve resources but also reduce emissions and waste.

**Technical aspects** of energy saving in power networks are equally important. Energy losses in power systems are generally divided into two types: **active losses** and **reactive energy losses**. Physical (active) losses are mainly due to changes in the transmission system, resistance in cables and wires, and the poor quality of insulation and other materials. Reactive energy losses are primarily caused by inductive loads such as electric motors. Energy saving in power networks can be achieved through the use of high-efficiency transformers, improved insulation systems, energy storage systems, and other technological improvements.

There are many technologies and methods available to implement energy-saving measures in power networks. New-generation transformers, automated control systems, high-efficiency insulation materials, and energy storage systems all play important roles in energy conservation. For example, protection systems help manage energy flows and quickly restore the system when malfunctions occur. Energy storage systems allow excess electricity to be stored and supplied to the grid when needed. All these elements contribute to the effective implementation of energy-saving measures.

#### 2. Losses in electricity transmission and the structure of lost energy

During the transmission of electricity from power stations to consumers, a portion of the energy is lost due to conductor heating, the generation of electromagnetic fields, and other effects.

Energy losses in any element of the electrical network depend on the nature of the load and how it varies over time during operation. In systems operating under a constant load with active power loss, the amount of energy lost over a time period  $t$  can be calculated as follows:

$$\Delta W = \Delta P t$$

If the load varies throughout the year, then electrical energy losses can be calculated using various methods. Depending on the mathematical model used, all available methods can be grouped into two main categories: **deterministic** and **probabilistic-statistical** methods.

One of the simplest methods to determine losses is by analyzing the **maximum loss period**. Among all possible scenarios, the condition with the highest power loss is identified. The power loss for this scenario is calculated and multiplied by the maximum loss time to estimate the annual energy loss:

$$\Delta W = \Delta P_{\text{жам}} \tau$$

The **maximum loss period** is defined as the duration in which, if the system operates at peak load, the amount of energy lost will be equal to the total energy loss over a year according to the load curve; that is:

$$\Delta W = \Delta P_1 \Delta t_1 + \Delta P_2 \Delta t_2 + \dots + \Delta P_N \Delta t_N = \Delta P_{\text{жам}} \tau$$

A relationship can be established between the energy loss and the energy received by the consumer as follows:

#### **Energy received by the consumer:**

The **maximum load period** is the time during which the energy received by a consumer operating at peak load equals the total energy the consumer would receive from the network over the course of a year according to the actual load curve; in other words:

$$T_{\text{жам}} = \frac{\sum_{i=1}^N P_i \Delta t_i}{P_{\text{жам}}}$$

### **3. Factors that reduce energy loss during transmission**

In the current conditions, reducing energy losses in electric networks is considered one of the key sources for saving fuel. When analyzing electrical energy losses, the total losses should be categorized into the following types:

- **Calculated amount of electricity loss in the energy system** – the difference between the total electricity supplied to the grid from all power stations and the total electricity recorded and paid for by consumers;
- **Technical and calculated losses** – these are determined based on certain condition parameters and the rated parameters of the network elements. These losses occur due to the heating of conductors and the formation of electromagnetic fields;
- **Commercial losses** – defined as the difference between calculated and technical losses. These are caused by factors such as underdeveloped metering systems, irregular and inaccurate meter reading, inaccuracies in the measuring instruments used, unregistered consumers, theft, etc.

Currently, the measures to reduce existing electricity losses are divided into three groups: organizational, technical, and measures to improve the technical and metering systems of electricity.

Organizational measures generally do not require additional financial investment. Technical measures, however, demand extra capital investments.

Improving the technical and metering systems of electricity allows for more accurate calculations when selecting measures to reduce losses.

In 35 kV voltage networks, 35% of the energy losses occur, while the remaining 65% are attributed to 0.22–10 kV electric networks. Despite the fact that most electricity losses occur in 0.22–10 kV networks, building these networks requires four times more non-ferrous metals compared to 35 kV and higher voltage networks. This shows that to reduce electricity losses, it is necessary to shorten the length of lines operating at up to 1000 V. For this, more substations need to be built closer to consumers. Energy losses in networks can also be significantly reduced by increasing the power factor in electrical installations. Because,

$$\Delta P = 3J^2 R_n = \frac{P^2 R_n}{U^2 \cdot \cos^2 \varphi}, \text{ kW}$$

power factor from this

$$\cos \varphi = \frac{P}{S} = \frac{P}{\sqrt{P^2 + Q^2}}$$

and the formula for time  $t$

$$\cos \varphi_{\text{св}} = \frac{W_a}{\sqrt{W_a^2 + W_p^2}}$$

Here,  $W_a$  and  $W_p$  refer to the active and reactive energy consumed over a time interval  $t$  (typically 30 minutes).

#### **Natural methods to increase $\cos \varphi$ (Power Factor):**

- Proper selection of power ratings for asynchronous motors.
- Consider that the power factor of asynchronous motors during idle operation is around  **$\cos \varphi = 0.2\text{--}0.3$** , while under nominal load it is approximately  **$\cos \varphi = 0.83\text{--}0.86$** .
- Underloaded asynchronous motors exhibit a sharp drop in  **$\cos \varphi$** . This phenomenon is also observed in arc furnaces and heating devices.

Therefore, it is advisable to **replace asynchronous motors loaded at less than 40%** with motors of lower power ratings.

Additional measures:

- Where the technological process allows, **replace asynchronous motors with synchronous motors**.
- Ensure **high-quality maintenance** of electrical equipment, and so on.

#### **Artificial methods to increase $\cos \varphi$ :**

The main method is the **installation of capacitor banks and synchronous compensators**. These are collectively referred to as **compensating devices (CDs)** – known in Russian as **KU**.

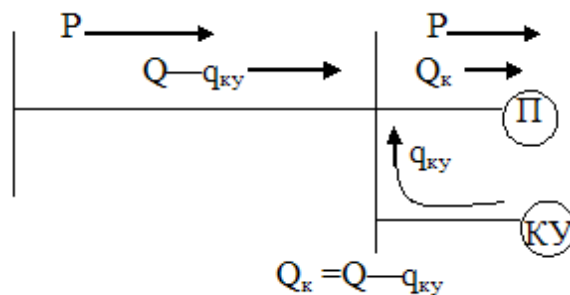


**Figure 67. Scheme of connecting compensation devices to the network.**

Here  $Q_k = Q - q_{ky}$

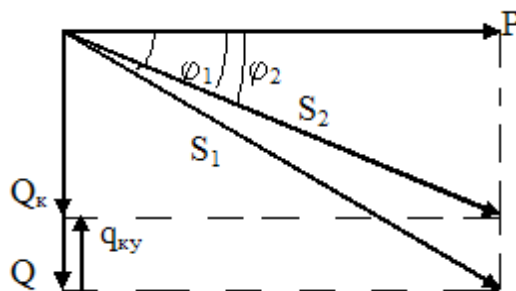


**Figure 68. Vector diagram for improving the power factor  $\cos\varphi$**

**P** – A compensating device (CD) installed for transmitting active power (**R**) and reactive power (**Q**) to the consumer.

$q_{qu}$  – The amount of reactive power that can be supplied back to the grid. As a result, the reactive power transmitted through the line to the consumer is reduced from its initial value **Q** to **Q<sub>k</sub>**, the phase angle  $\varphi_1$  decreases to  $\varphi_2$ , the power factor **cosφ** increases, and the total power **S<sub>1</sub>** decreases to **S<sub>2</sub>**. The active power losses in the line are also reduced, because:

$$\Delta P = \frac{\sqrt{P^2 + (Q - q_{k,y})^2}}{U^2} R_{\text{л}}, \text{ kVt}$$

In the electrical power supply scheme, the placement of compensation devices can be as follows:

- **Centralized installation** – In this case, compensation devices are installed at main step-down substations (MSS).
- **Installation near consumers** – Installed at substations of industrial plant workshops. Several compensation units can be installed as a group (group installation). In this case, the compensation devices are connected to distribution panels (DP). In individual installations, the compensation devices are directly connected to large-capacity electrical consumers.

There are several factors that help reduce losses during electricity transmission, one of which is the reduction of **reactive power**.

#### **Control Questions:**

1. What are the causes of losses during electricity transmission?
2. What are the components of energy that is lost?
3. What measures can be taken to reduce energy losses in power transmission?

## GLOSSARY

**Electric energy** – Useful work done by electric current, usually measured in kilowatt-hours (kWh).

**Alternative energy** – Energy obtained from non-traditional, renewable sources.

**Photovoltaic panel** – A device that directly converts sunlight into electricity.

**Wind turbine** – A device that converts wind energy into electricity through rotation.

**Hydroelectric power station (HPP)** – A station that generates electricity using water pressure.

**Biogas** – Combustible gas produced by the decomposition of organic materials.

**Geothermal energy** – Energy obtained from natural underground heat sources.

**Biomass** – Energy source based on organic materials of plant or animal origin.

**Energy storage system** – Technologies that store electricity for later use (batteries, pumped hydro, etc.).

**Inverter** – A device that converts direct current (DC) to alternating current (AC).

**Transmission line** – A system of wires delivering electricity from the source to consumers.

**Distribution network** – A network that distributes electricity to consumers.

**Transformer** – An electromagnetic device that increases or decreases voltage.

**Power electronics** – The field of semiconductor devices that efficiently manage electrical energy.

**Battery** – A device that stores electricity in chemical form.

**Smart Grid** – A digitally controlled, efficient, and reliable electrical grid system.

**Dispatch center** – A center that monitors and controls power networks.

**Energy efficiency** – The ratio of useful output to input energy.

**Reactive power** – Power that does not do useful work in circuits but is necessary.

**Synchronization** – The process of matching frequency, phase, and voltage when connecting to the grid.

**Harmonic distortion** – Quality degradation due to excessive frequencies in an electrical signal.

**Steady state** – A balanced operational condition of the electrical system.

**Frequency** – Number of current oscillations per second, usually 50 Hz.

**Voltage** – Electric pressure, measured in Volts (V).

**Power (P)** – The rate of electrical work, usually measured in watts (W) or kilowatts (kW).

**Efficiency** – A measure of how effectively a system uses input energy.

**Conduction losses** – Heat losses in wires during transmission.

**Voltage drop** – The reduction of voltage over a distance.

**Open-loop system** – An independent energy system not directly connected to an external grid.

**Closed-loop system** – A system that operates while connected to other energy sources.

**Pico HPP** – Very small-scale hydropower systems (0.1–5 kW).

**Stability maintenance** – Keeping voltage and frequency stable in the power system.

**Protection relays** – Devices that automatically act when current or voltage exceeds limits.

**Load** – The total power of all consumers connected to the grid.

**Linear load** – Load that operates in sync with sinusoidal current waveforms.

**Non-linear load** – Loads with variable characteristics, e.g., motors.

**Cogeneration** – Simultaneous production of electricity and heat.

**Heat pump** – A system that uses environmental heat for heating or cooling.

**MPPT (Maximum Power Point Tracking)** – Algorithm to maximize power from solar panels.

**Green energy** – Environmentally friendly energy that does not harm nature.

**Consumption profile** – Variation of energy use over time.

**Backup power source** – Emergency power supply (generator, battery).

**Uninterruptible Power Supply (UPS)** – System that switches to backup power automatically during outages.

**Energy regeneration** – Reusing used energy (e.g., braking energy).

**Local power system** – Independent grid serving a specific object or area.

**Load factor** – Ratio between planned and actual consumption.

**Electric load graph** – Graphical representation of energy use over time.

**Renewable integration** – Connecting alternative sources to existing networks.

**Power balance** – Matching produced and consumed power.

**Overload** – When system components operate above designed load.

**Effective current** – Average value of electric current (RMS value).

**Load stability** – System adaptability to load variations.

**Load types** – Lighting, heating, motor, and mixed loads.

**Automated control system (SCADA)** – Remote control system for electric networks.

**Grid voltage levels** – Low (0.4 kV), medium (10–35 kV), high (110–500 kV) voltages.

**Energy balancing** – Covering discrepancies using backup sources.

**High-voltage lines (HVL)** – Lines for long-distance electricity transmission.

**Dense transformer network** – Network with closely located transformer substations.

**Cogeneration station** – Industrial facility producing both heat and electricity.

**Distribution panels** – Devices distributing electricity to consumers.

**Circuit breaker** – Device that automatically interrupts circuits when current is too high.

**Lighting system** – Electric lighting network for buildings and streets.

**High-conductivity wires** – Low-loss wires made of strong metals.

**Cable lines** – Electric cables laid underground or through walls.

**Short circuit** – Direct current flow causing major damage.

**Transmission system operator (TSO)** – Organization managing electricity through the grid.

**Safety distance** – Safe distance from electrical wires for people and machinery.

**Electricity consumption** – Total electricity used over a certain period.

**Time-of-use billing** – Paying based on time-dependent tariffs.

**Tariff policy** – Methods for setting and comparing electricity prices.

**Annual production** – Total electricity produced by a source in a year.

**Weather influence** – Effect of sun, wind, clouds, and precipitation on energy production.

**Energy independence** – Reduced reliance on foreign energy sources.

**Stable energy supply** – Continuous and reliable electricity delivery.

**Stability analysis** – Assessing system resistance to failures.

**Automation** – Operating energy systems without human intervention.

**New technology integration** – Adding modern devices and software to existing systems.

**Installed capacity** – Maximum electricity a power station can produce.

**Energy monitoring** – Tracking and analyzing usage patterns.

**Fuel consumption** – Amount of fuel used to generate electricity.

**Energy export** – Sending surplus electricity to other countries.

**Autonomous system** – Standalone system not connected to the grid.

**Reverse feed** – Supplying electricity from alternative sources to the grid.

**Required energy reserve** – Ensuring enough power in emergencies.

**Production-consumption balance** – Consistency between generated and used electricity.

**Electrical safety** – Protecting people's health when working with electrical equipment.

**Insulation** – Protecting electrical wires with non-conductive material.

**Regulator** – Device stabilizing system parameters (voltage, frequency).

**Modern automation tools** – Devices using smart sensors and software.

**Construction capacity** – System's ability to handle peak loads.

**Fuel switching** – Transition from traditional to alternative fuels.

**Digital grid technology** – Internet-based grid monitoring and control.

**Remote monitoring** – Surveillance using sensors and data transmitters.

**Efficient control system** – Systems that optimally allocate resources.

**System reliability** – Likelihood of uninterrupted operation.

**Grid connection point** – Where a power source connects to the grid.

**Carbon footprint of electricity** – Emissions produced during electricity generation.

**Reusable components** – Device parts used again instead of discarded.

**System optimization** – Making changes to improve performance.

**Local energy sources** – Energy systems based on regional natural resources.

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