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ELECTROTECHNICAL DEVICES A Textbook

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Electrical engineering is a field that studies the processes of generation, transmission, distribution, and conversion of electrical energy into various forms. Its practical aspect is embodied in electrical engineering devices. Electrical engineering devices serve as the main technical tools at all stages, from the production of electrical energy to its delivery to consumers. Today, electrical engineering devices play an important role in many sectors such as energy, transport, manufacturing, agriculture, information technologies, and even medicine.

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CHAPTER I. ELECTROTECHNICAL DEVICES

1.1. The nature and fundamental terminology of electrotechnical devices

Electrotechnics is the science that studies the processes of generation, transmission, distribution, and conversion of electrical energy into various forms. Its practical application is embodied in electrotechnical devices. These devices serve as the main technical means at all stages — from the production of electrical energy to its delivery to the consumer. Today, electrotechnical devices play a crucial role in energy systems, transportation, industry, agriculture, information technology, and even medicine. Their primary function is to ensure energy exchange, control, and management processes in an efficient, safe, and economically advantageous manner.

In the Republic of Uzbekistan, the field of electrical engineering is actively developing within the framework of the **“Green Economy Strategy – 2030,” the “Energy Efficiency Enhancement Program” (Presidential Decree PQ-381, 2022), and the “Digital Uzbekistan – 2030”** concept. Consequently, for specialists in engineering disciplines, knowledge of electrotechnical devices is regarded as a core professional competence.

An electrotechnical device is defined as a set of technical means designed for the generation, conversion, transmission, distribution, and utilization of electrical energy. These devices encompass a wide range — from simple electric lamps to complex power stations, transformer substations, automatic control systems, and digital monitoring panels.

Table 1. Stages of historical development

Period	Discovery / Achievement	Scientist or Company
18th century	Concept of electric charge and current	B. Franklin, A. Volta
Early 19th century	Law of electromagnetic induction	M. Faraday

Period	Discovery / Achievement	Scientist or Company
Mid-19th century	Ohm's law, Joule–Lenz law	G. Ohm, J. Joule
Early 20th century	Electrical machines and transformers	N. Tesla, M. Dolivo-Dobrovolsky
21st century	Automated and digital systems	Siemens, ABB, Schneider Electric

Historically, electrotechnical devices were initially created to convert mechanical motion into electrical energy or, conversely, to transform electrical energy into mechanical work. Today, these devices are enhanced with intelligent control, energy-saving, and automation functions.

Each electrotechnical system operates based on fundamental physical quantities such as electric current, voltage, resistance, power, and energy.

Current, Voltage, and Resistance

Electric current (I) — is the orderly movement of electric charges. The strength of the current is determined as follows:

$$I = \frac{q}{t}$$

where:

q — the amount of charge passed (coulombs),

t — time (seconds).

Voltage (U) — is the potential difference of the electric field that causes the movement of charges.

Resistance (R) — is the property of a material that opposes the flow of electric current.

This relationship is expressed by Ohm's law:

$$U = I \cdot R$$

This equation serves as the theoretical basis for the operation of all electrical devices.

Power and Energy

Power (P) — is the amount of electrical work done over a certain period of time.

$$P = U \cdot I$$

Energy (W) — is defined as the total amount of power accumulated over time:

$$W = P \cdot t$$

In energy calculations, the kilowatt-hour (kWh) is used as a practical unit of measurement.

Table 1.1.2. Basic Terms

№	Term	Symbol	Unit of Measurement	Definition
1	Electric current	I	A	Ordered movement of electric charges
2	Voltage	U	V	Difference in electric potential
3	Resistance	R	Ω	Degree of opposition to current flow
4	Power	P	W	Amount of work done per unit time
5	Energy	W	J or kWh	Total power accumulated over time
6	Capacitance	C	F	Ability to store electric charge
7	Inductance	L	H	Ability to generate a magnetic field
8	Reactive power	Q	var	Component of energy exchange due to phase shift

Table 1.1.3. Classification of Electrical Systems

Classification Criterion	Type	Application Area
Type of current	Direct current (DC) / Alternating current (AC)	Batteries, generators, power networks
Voltage level	Low (≤ 1 kV), Medium (≤ 35 kV), High (> 110 kV)	Household, industrial, power engineering
Function	Generation, transmission, consumption	Power plants, transformers, consumers
Control type	Manual, automatic, digital	PLC, SCADA, Smart-Grid systems

General Scheme of Electrical Systems

[Generator] → [Transformer] → [Transmission Line] → [Distribution Points] → [Consumer]

- Each component in this chain performs its own specific function:
- Generator — produces electrical energy.
- Transformer — changes the voltage level.
- Transmission line — transmits energy over long distances.
- Distribution points — distribute energy to various networks.
- Consumer — converts electrical energy into useful work.

Role of Electrotechnical Devices in Energy Systems

In Uzbekistan's energy system, every transformer, generator, electric motor, and distribution panel directly affects production efficiency.

For example:

- 220/380 V networks — used for household and small-scale industrial applications.
- 6–10 kV networks — used for local enterprises and urban infrastructure.
- 110–500 kV main transmission networks — used for large-scale power transmission lines.

Table 1.1.4. Voltage and Power Levels

Voltage	Value	Application Area
220 V	Household networks	Home appliances
380 V	Industrial networks	Motors, pumps
6–10 kV	Local power networks	Transformer substations
35–110 kV	Urban energy systems	Distribution networks
220–500 kV	Main transmission lines	National power grids

Modern Development Directions

Today, electrotechnical devices are being improved in the following directions:

- Energy-saving materials and high-efficiency conductors;
- Digital monitoring and automatic diagnostics;

- “Smart Grids” and remote control systems;
- Transformers and electric motors operating on the basis of IoT.

For example, Siemens’ “Sensformer” technology enables real-time analysis of transformer temperature, load, and humidity, providing the ability for automatic control.

Electrotechnical devices are the foundation of the energy system. They ensure efficiency, stability, and safety throughout the process—from electricity generation to its delivery to consumers.

Studying these devices allows engineers to properly design systems, reduce losses, implement automation, and introduce energy-saving technologies.

Test Questions

1. What are electrotechnical devices used for?

- A) For generating, transmitting, distributing, and consuming electrical energy
- B) Only for converting mechanical energy
- C) Only for amplifying electrical signals
- D) For storing thermal energy

2. What is the unit of measurement for electric current?

- A) Volt (V)
- B) Ohm (Ω)
- C) Ampere (A)
- D) Joule (J)

3. Which of the following formulas represents Ohm’s law?

- A) $P = U \cdot I$
- B) $U = I \cdot R$
- C) $W = P \cdot t$
- D) $I = q / t$

4.Devices that convert electrical energy into useful work are called:

- A) Transformers
- B) Generators
- C) Consumers
- D) Measuring instruments

5.What is meant by a “high-voltage system”?

- A) 12–24 V
- B) 220–380 V
- C) 6–10 kV
- D) 110 kV and above

6.What is the main function of a generator in an electrical circuit?

- A) To reduce current
- B) To produce electrical energy
- C) To change voltage
- D) To calculate energy consumption

7.Which device increases or decreases voltage?

- A) Generator
- B) Transformer
- C) Rheostat
- D) Ammeter

8.In what direction does energy flow in electrical systems?

- A) From consumer to generator
- B) Transformer → Generator → Transmission line
- C) Generator → Transformer → Transmission line → Consumer
- D) Transmission line → Distribution points → Transformer

9.Which of the following is not a basic electrical quantity?

- A) Power
- B) Energy

- C) Current
- D) Pressure

10. In Uzbekistan's power system, where are 35–110 kV networks mainly used?

- A) In main transmission lines
- B) In household networks
- C) In urban and industrial networks
- D) In mobile devices

Open Questions

1. What do you understand by an electrotechnical device? Write down its main functions.
2. Name at least three scientists who made a great contribution to the development of electrotechnics and briefly describe their discoveries.
3. Explain the relationship between electric current, voltage, and resistance. Express Ohm's law in both formula and words.
4. Explain the difference between power and energy, and write the mathematical relationship between them.
5. Write the classification of electrical energy systems by voltage levels and give examples for each.
6. List the main components of the electrical energy circuit in order and briefly describe their functions.
7. Analyze the role and importance of electrotechnical devices in Uzbekistan's energy system. Relate your answer to the "Green Energy – 2030" strategy.
8. List three main directions of modern electrotechnical device development and describe their advantages.
9. How do "smart transformers" or digitally controlled transformers work? What distinguishes them from conventional transformers?
10. What is the importance of studying electrotechnical devices in engineering practice? Present your own opinion.

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1.2. Types of transformers and their fields of application

Today, transformers occupy a leading position at every stage of the power system. By converting electrical energy from one voltage level to another, they make it possible to organize the processes of generation, transmission, and distribution efficiently.

A transformer is not a simple device—it is the central “bridge” of the entire electrical system and a key factor ensuring reliability and energy efficiency. The use of transformers in Uzbekistan’s power system dates back to the 1930s. The first transformers were installed at the Tashkent power station and later in the Navoi and Fergana regions. Today, they are widely used in all sectors, from industrial production to household applications. A transformer is a device based on the phenomenon of electromagnetic induction, which allows the transformation of alternating current voltage or current strength. The device does not change the frequency; that is, if the frequency of electrical energy is 50 Hz, it remains the same at the output. This phenomenon is based on the law of electromagnetic induction discovered by Faraday in 1831. According to this law, when the magnetic flux in a core changes, an electromotive force (EMF) is induced in the coil wound around it.

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

where:

E — induced voltage,

N — number of turns,

Φ — magnetic flux.

Based on this law, transformers were developed and began to serve as the main energy link in alternating current networks.

Main Components of a Transformer

1. Although transformers come in different designs, their main components are the same:
2. Magnetic core (yoke) — made of ferromagnetic steel laminations; it directs the magnetic flux.
3. Primary winding — receives the supply voltage and creates a magnetic flux.
4. Secondary winding — generates induced voltage under the influence of the magnetic flux.
5. Insulation — ensures safety and electrical separation between windings.
6. Cooling system — dissipates heat; can be oil-filled or dry type.

The coordinated operation of these components determines the efficiency of the transformer.

The operating process of a transformer is simple in structure but rich in physical meaning. When alternating current is applied to the primary winding, an alternating magnetic field is created in the core. This magnetic field cuts across the secondary winding and induces a new voltage in it.

If the number of turns in the windings is denoted as follows:

$$\frac{U_1}{U_2} = \frac{N_1}{N_2}$$

Thus, when the number of turns increases, the output voltage rises (step-up transformer), and when it decreases, the output voltage drops (step-down transformer).

For example, at the Tashkent Thermal Power Station, the energy generated by 10 kV generators is increased up to 220 kV, then transmitted through main transmission lines and reduced to 0.4 kV at local transformer substations.

The Role of Transformers in the Power System

The path of electrical energy from generation to consumption occurs in the following stages:

- Generation (power station) — generators produce energy at 6–11 kV.
- Transmission (main network) — voltage is increased to 110–220 kV.
- Distribution (substations) — voltage is reduced to 35–10 kV.
- Consumption (enterprise or household) — voltage is reduced to 0.4 kV.

At each stage, transformers operate to reduce losses, maintain voltage stability, and ensure uninterrupted power supply.

Although transformers have a very high efficiency in energy transmission, energy losses are not completely eliminated. These losses are divided into two main types:

- Magnetic losses — energy converted into heat due to hysteresis and eddy currents in the core.
- Electrical losses — energy lost as heat in copper windings.

In modern transformers, these losses are minimized through the use of silicon steel cores, heat-resistant enamel insulation, and automatic cooling systems.

When a transformer operates, heat is generated. If this heat is not removed in time, the winding insulation may be damaged, shortening the transformer's service life. Therefore, every transformer is equipped with a cooling system:

- Oil-cooled system — used in high-power transformers; heat is transferred outward through oil circulation.
- Dry-type cooling system — uses air circulation with fans; operates safely in buildings.

According to the 2023 regulations of the Ministry of Energy of Uzbekistan, transformers with a capacity of more than 1000 kVA must be equipped with an oil-based cooling system.

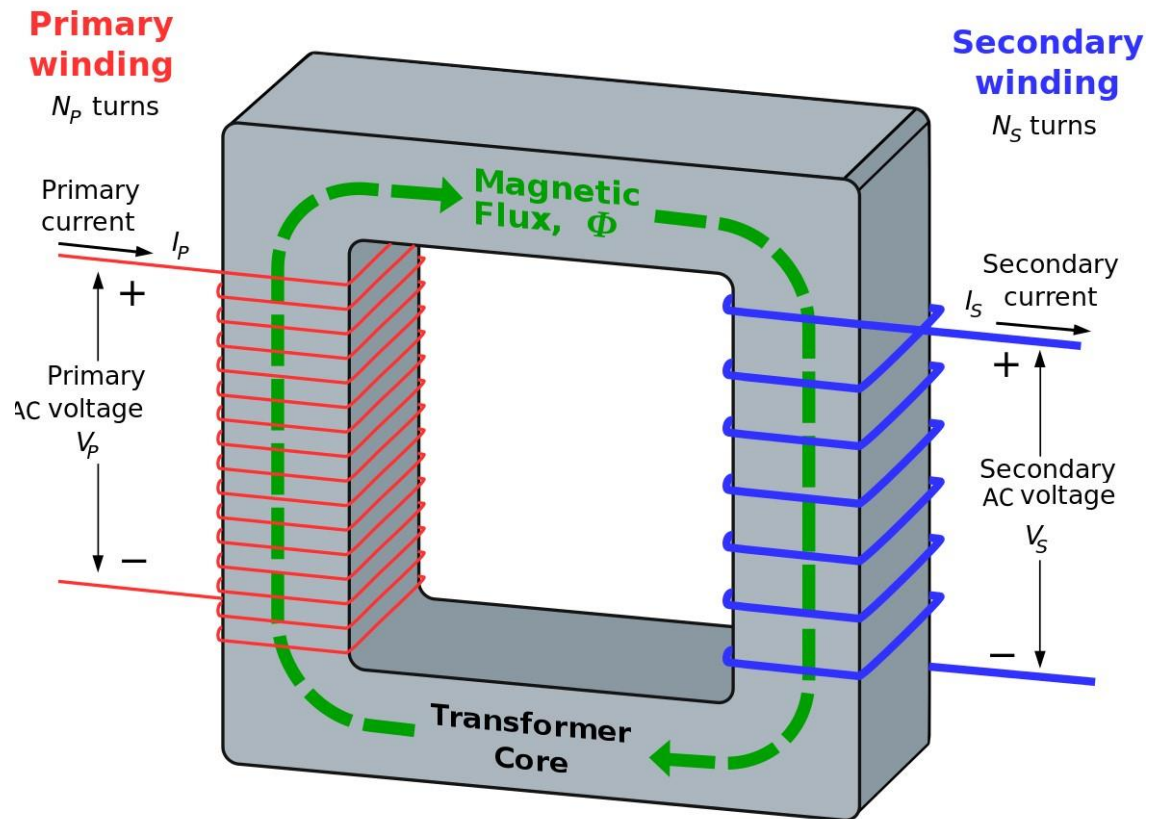
In recent years, global energy networks have been undergoing digitalization, leading to the emergence of “smart transformers.” These transformers monitor temperature, load, oil pressure, and vibration levels online and automatically shut down in emergency situations.

For instance:

- Siemens Sensformer technology allows real-time monitoring through SCADA systems.
- ABB TXplore uses drone technology to automatically inspect and analyze the interior of oil-filled transformers.

Such technologies are being gradually implemented in the electric power networks of Uzbekistan.

Figure 1.2.1. Operating Principle of a Transformer



Operating Principle of a Transformer

The figure shows the primary and secondary windings, the direction of magnetic flux, and the current–voltage relationships. This diagram illustrates the operating mechanism of a transformer based on the principle of electromagnetic induction.

◆ **Primary winding** — shown on the left side of the figure in red. This winding is connected to an alternating current (AC) source and produces the primary voltage (V_p). When current flows through the winding, a magnetic field is created, which travels through the steel core in a closed loop.

◆ **Magnetic flux (Φ)** — indicated by a green line. It represents the electromagnetic flow circulating along the core. This flux transfers energy from the primary winding to the secondary winding without mechanical connection, only through electromagnetic induction. This phenomenon is explained by Faraday's law:

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

That is, a change in magnetic flux within the core induces an electromotive force (EMF) in the winding.

◆ **Secondary winding** — shown on the right side of the figure in blue. This winding is not directly connected to the primary winding but is magnetically linked through the core. The alternating magnetic flux in the core induces a voltage (V_s) in this winding. In this way, electrical energy is converted from one voltage level to another.

◆ **Current directions** — the directions of current flow in both windings (I_p and I_s) are shown. These currents flow in opposite directions because the changing magnetic flux in the primary winding induces an EMF in the secondary winding in the reverse direction.

◆ **Core (Transformer core)** — made of ferromagnetic steel, it provides a closed path for magnetic flux. The function of the core is to conduct magnetic flux efficiently and minimize losses. In the figure, it is shown in gray.

Step-by-step operating principle:

- Alternating current is applied to the primary winding, creating a magnetic flux.
- The magnetic flux circulates through the core and cuts across the secondary winding.
- An alternating voltage is induced in the secondary winding by electromagnetic induction.
- The value of the output voltage depends on the number of turns in the windings:

$$\frac{U_1}{U_2} = \frac{N_1}{N_2}$$

That is, if the number of turns in the secondary winding is greater than in the primary, the voltage increases; if it is fewer, the voltage decreases.

Physical Meaning of the Diagram

This figure clearly illustrates the electromagnetic nature of energy transfer in the operation of a transformer:

- Electrical energy is converted into a magnetic field,
- And the magnetic field is again converted into electrical energy.

This process requires no mechanical motion or connection — the energy is transferred entirely through electromagnetic induction. Therefore, transformers are considered reliable, silent, and long-lasting devices.

Technical Characteristics

- The primary winding voltage (V_p) typically ranges from 220 V to 220 kV.
- The magnetic flux frequency in the core is 50 Hz (the standard in Uzbekistan) and remains constant.
- The efficiency of transformers is between 98% and 99%.
- Oil-cooled transformers provide high cooling efficiency, while dry-type transformers are distinguished by their safety.

Contributions of Uzbek Scientists

Local specialists have also made significant contributions to the development of transformer theory and technology. For example:

- T. To‘xtasinov (2009) — in his work “Theory and Practice of Transformers” proposed methods for optimizing thermal regimes.

- Abdug‘aniyev (2017) — studied the use of nanomaterials to improve the thermal conductivity of transformer oil.
- R. Shukurov (2020) — in “Energy-Saving Solutions in Electrotechnical Devices” analyzed the economic efficiency of transformer modernization.

Additionally, research is being carried out in the laboratories of the Jizzakh Polytechnic Institute and Fergana State Technical University on transformer cooling systems, insulation materials, and thermal balance.

A transformer is the “invisible engine” of electrical energy. It performs the vital functions of controlling voltage, reducing losses, and ensuring safe power transmission. Today, transformers are no longer just physical devices — they have evolved into digital, eco-friendly, and intelligent control systems. They are regarded as central technological elements in Uzbekistan’s “Green Economy” and “Energy Efficiency – 2030” programs.

Test Questions

1.What is the main function of a transformer?

- A) To increase the frequency of electric current
- B) To transfer electrical energy from one voltage level to another
- C) To convert direct current into alternating current
- D) To convert mechanical energy into electrical energy

2.The operating principle of a transformer is based on which law?

- A) Ohm’s law
- B) Faraday’s law of electromagnetic induction
- C) Newton’s law
- D) Kirchhoff’s law

3.The following formula represents which characteristic of a transformer?

$$\frac{U_1}{U_2} = \frac{N_1}{N_2}$$

- A) Efficiency coefficient
- B) Thermal balance of the windings
- C) Relationship between voltage and number of turns
- D) Direction of magnetic flux

4.What material is typically used for the transformer core?

- A) Aluminum plates
- B) Ferromagnetic steel laminations
- C) Copper wires
- D) Graphite sheets

5.What are the most common types of energy losses in transformers?

- A) Optical and thermal losses
- B) Electrical and magnetic losses
- C) Mechanical and acoustic losses
- D) Thermal and chemical losses

6.Where are oil-cooled transformers most commonly used?

- A) Small household networks
- B) Laboratory tests
- C) High-power industrial transformers
- D) Battery charging devices

7.What is the main function of modern “smart transformers”?

- A) To change current frequency
- B) To monitor temperature, load, and pressure online
- C) To generate direct current
- D) To amplify electrical signals

8.The efficiency coefficient (η) of a transformer is determined by the ratio of:

- A) Voltage and current
- B) Output and input power
- C) Number of turns and magnetic flux
- D) Core material and insulation type

9.Which Uzbek scientist conducted research on transformers?

- A) M. Ulugbek
- B) A. Abduganiyev
- C) I. Karimov
- D) Sh. Rashidov

10.What is the main role of transformers in the power system?

- A) To convert electrical energy into mechanical energy
- B) To change current frequency
- C) To adjust voltage levels and reduce energy losses
- D) To reverse current direction

Open Questions

1. What does the concept of a transformer mean?
2. Which physical law forms the basis of transformer operation?
3. Why is ferromagnetic steel used as the core material of transformers?
4. If the number of turns in the secondary winding is greater than in the primary, what type of transformer is it?
5. What are the main causes of energy losses in transformers?
6. Where are oil-cooled transformers mainly used?
7. What are the features of “smart transformers”?
8. What is the typical efficiency range (η) of transformers?
9. What is the role of transformers in Uzbekistan’s power system?
- 10.Which companies are considered world leaders in transformer manufacturing?

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Additional information on this topic can be obtained from the above sources.

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1.3. Structure and operating principle of a single-phase transformer

In the modern electric power system, transformers play an invaluable role at almost every stage. In particular, single-phase transformers are among the simplest and most widely used devices in various fields — from everyday life to industry, communications, transportation, and automation systems. They enable reliable transmission and distribution of electrical energy between networks by converting electricity from one voltage level to another.

A single-phase transformer is a stationary electrotechnical device that converts alternating current voltage to another value through electromagnetic induction. It consists of two windings — the primary and secondary coils. These

windings are not electrically connected, but they are magnetically coupled through a magnetic core (yoke).

When voltage is applied to the primary winding, alternating current flows through it, creating a magnetic field. This magnetic field passes through the core, cuts across the secondary winding, and as a result, induces a new voltage in it. Thus, energy is transferred from one circuit to another without any mechanical motion — purely through the magnetic field.

In such devices, the frequency remains unchanged; that is, if 50 Hz current enters, 50 Hz also exits. Only the voltage and current values change. This makes single-phase transformers efficient, simple, and highly reliable devices.

Applications of single-phase transformers

Single-phase transformers are widely used to supply low-power consumers in electrical networks. They are applied in the following areas:

- Household networks: in televisions, audio systems, chargers, LED lighting systems, and stabilizers providing 220/12 V or 220/24 V voltage;
- Laboratories and training centers: as educational and experimental transformers;
- Industry and automation: for signaling, measurement systems, control panels, and feeding relay or contactor circuits;
- Communications and medicine: to provide safe low-voltage power supply.

These devices have found their place in all sectors due to their compact size, lightweight design, ease of operation, and low production cost.

Historical Development

The history of the single-phase transformer dates back to the second half of the 19th century. In 1831, Michael Faraday discovered the phenomenon of electromagnetic induction — the scientific foundation of transformer operation. Later, between 1870 and 1880, scientists such as James Cayley, Sebastian Ferranti,

Luzzatto, and Gaulard conducted experimental tests on voltage-transforming devices. In 1884, Gaulard and Gibbs launched the first transformer-based electric lighting system in London. In 1885, Nikola Tesla designed a high-efficiency transformer based on the alternating current system — a concept that still underlies the operation of all modern transformers. By 1890–1900, transformer production expanded to an industrial scale. Companies such as Westinghouse, Siemens, and General Electric began mass-producing single-phase and three-phase transformers. In Uzbekistan, the use of transformers is closely linked with the formation of the national power system. By the mid-20th century, as numerous power grids were constructed across the country, single-phase transformers became an integral part of household and industrial sectors. Today, enterprises like “National Electric Grids of Uzbekistan” JSC, “Regional Electric Networks” JSC, and the “Fergana Transformer Plant” manufacture high-quality, energy-efficient single-phase transformers. Some models are adapted to international IEC 60076 standards. Moreover, within the framework of Uzbekistan’s “Green Energy – 2030” Strategy, steps are being taken to digitize and automate transformer technology. Modern single-phase transformers can now monitor and control energy flow remotely.

Advantages of Single-Phase Transformers

- Simple design and easy maintenance
- High reliability and long service life
- Low cost and high energy efficiency ($\approx 98\%$)
- Adaptability to various voltage ranges
- Galvanic isolation ensures safe operation

These advantages make single-phase transformers the most commonly used devices for household and educational purposes.

In recent years, transformer design has been enhanced with nanomaterial-based magnetic cores, composite insulation materials, and digital monitoring

systems. These innovations reduce heat loss, improve magnetic efficiency, and extend operational lifespan.

For example, ABB’s “Dry-Type Cast Resin” single-phase transformers are oil-free, environmentally safe, explosion-proof, and operate with low noise. In Uzbekistan, production of Smart Grid-compatible single-phase transformers equipped with intelligent measurement systems is also expanding. The essence of single-phase transformers lies in the efficient, safe, and loss-free transmission of electrical energy. Their development history — from Faraday’s electromagnetic induction concept to modern digital grids — represents a continuous technological evolution. Today, single-phase transformers are not limited to household use; they have become an essential component of “smart” energy systems.

Internal Structure and Components

Although single-phase transformers appear structurally simple, their internal design requires high precision and balance. Every component — magnetic core, windings, insulation system, and cooling device — is interconnected, ensuring reliability, efficiency, and safety in operation. Below are the main parts explained individually:

1. Magnetic Core (Yoke)

The magnetic core is the heart of the transformer, forming a closed path for magnetic flux. It carries the magnetic field generated in the primary winding to the secondary winding. Material and shape: The core is typically made from cold-rolled electrical steel laminations (0.35–0.5 mm thick) coated with insulating varnish to minimize eddy current losses. The core usually comes in “O” or “E-I” shapes.

- “E-I” shaped cores are used in household and low-power transformers.
- “O” shaped cores have higher efficiency but are more expensive to manufacture.

Function: The magnetic core serves as the central medium for energy transfer — the magnetic field generated in the primary winding travels through the core to the secondary winding.

Practical note: At the Fergana Transformer Plant, locally produced cores are made from low-carbon steel with epoxy varnish coating, which extends operational life by about 20%.

2. Windings (Coils)

The most important parts of the transformer are its windings or coils, which enable the conversion between electrical and magnetic energy.

Structure: Every single-phase transformer consists of two main windings:

Primary winding — connected to the power supply network.

Secondary winding — delivers the required voltage to the load or consumer.

These windings are wrapped around the core with insulating layers. The materials used are electrical-grade copper (Cu) or, in some cases, aluminum (Al) wires. Copper is preferred in industrial transformers due to its higher conductivity.

Arrangement: Typically, the primary winding is placed on the outside, while the secondary winding is located inside. This configuration allows for better heat dissipation and ensures electrical safety, as the high-voltage coil is positioned externally. Turn ratio and voltage relationship: The relationship between the primary and secondary voltages is expressed by the following formula:

$$\frac{U_1}{U_2} = \frac{N_1}{N_2}$$

Where:

U_1 — primary voltage (Volts),

U_2 — secondary voltage (Volts),

N_1 — number of turns in the primary winding,

N_2 — number of turns in the secondary winding.

If $N_2 > N_1$, the transformer is step-up; if $N_2 < N_1$, it is step-down.

Example from Uzbekistan's practice:

In small industrial networks of Jizzakh, Fergana, and Tashkent, single-phase transformers rated at 220/36 V or 220/24 V are mainly used in signal systems, lighting networks, and automation blocks.

3. Insulation System

In transformers, insulation plays a crucial role in ensuring electrical safety and preventing short circuits. Each winding is separated from other windings and from the core by dielectric materials.

Insulating materials:

- Paper (cellulose-based) — used in low-power transformers.
- Epoxy resin — for medium-power transformers.
- Fiber, mica, polymer coatings — for high-temperature resistant applications.

Functions:

- Provides safety between electrical circuits.
- Prevents current leakage.
- Increases dielectric strength.
- Extends the service life of the device.

Uzbekistan's practice: Since 2020, epoxy-composite insulation systems have been introduced in small transformers produced by "Hududiy Elektr Tarmoqlari" JSC. These systems operate more reliably under conditions of humidity and temperature fluctuations.

4. Cooling System

When a transformer operates, heat is generated due to electrical and magnetic

losses. If this heat is not dissipated in time, the winding insulation may burn, or the efficiency of the transformer may decrease. Therefore, every transformer is equipped with a cooling system.

Types of cooling:

- Natural air cooling (AN) — used in low-power transformers.
- Oil cooling (ONAN, ONAF) — used in medium- and high-power networks.
- Forced air cooling — cooling with fan-assisted systems.

Cooling principle: In oil-filled transformers, heat is transferred from the core to the oil, and then the oil releases the heat into the air through radiator fins. In air-cooled (dry-type) transformers, natural air circulation occurs around the core and windings. Energy-efficient approach: Currently, “ABB TXdry” and “Siemens Cast Resin” transformers use environmentally friendly resins instead of oil for cooling. This method reduces explosion risk and simplifies maintenance.

5. Additional Components

In high-power transformers, the following auxiliary parts are also included:

- Tank and casing – for mechanical protection and oil storage.
- Temperature sensors – to monitor the temperature of windings and oil.
- Pressure relief valves – to reduce risk when internal pressure rises.
- Fans in dry-type transformers – to ensure air circulation.

Each component of a single-phase transformer directly affects its efficiency:

- Core – the main path of magnetic flux;
- Windings – convert electrical energy into magnetic energy and vice versa;
- Insulation – ensures electrical safety;
- Cooling system – maintains thermal stability.

Their harmonious operation ensures long-term reliability and minimizes energy losses. To deeply understand the operating essence of a single-phase transformer, it

is necessary to know the law of electromagnetic induction, which is one of the fundamental physical principles explaining the transfer of electrical energy through a magnetic field.

Physical Meaning of the Law of Electromagnetic Induction The main result observed in Faraday's experiments was as follows: "If the magnetic flux passing through a conductor changes over time, an electromotive force (EMF) is generated in the conductor."

This process represents the interconnection between electric and magnetic fields. Faraday's law can be written in mathematical form as follows:

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

Where:

E — induced electromotive force (Volt),

N — number of turns,

Φ — magnetic flux (Weber),

$d\Phi/dt$ — rate of change of magnetic flux.

The negative sign "—" in the formula represents Lenz's Law, which states that the direction of the induced EMF is always opposite to the cause that produces it.

Operating Process of a Single-Phase Transformer

The operating principle of a transformer is entirely based on the phenomenon of electromagnetic induction.

1. Process in the Primary Winding:

An alternating voltage of 220 V is applied to the primary winding. As a result, alternating current flows through it, creating an alternating magnetic flux (Φ) in the core.

This flux varies sinusoidally over time and can be expressed as:

$$\Phi = \Phi_{max} \sin(\omega t)$$

where:

Φ_m — maximum magnetic flux,

ω — angular frequency of the alternating current ($\omega = 2\pi f$),

t — time (seconds).

2. Distribution of Magnetic Flux Along the Core:

The generated magnetic flux moves along the ferromagnetic core. The core concentrates the magnetic field and directs it toward the secondary winding. In this way, energy is transferred from the electric field to the magnetic field.

3. Induction of EMF in the Secondary Winding:

When the magnetic flux passes through the secondary winding, an electromotive force (EMF) is induced in it as well. The value of this voltage is proportional to the number of turns:

$$E_2 = 4.44 f N_2 \Phi_m$$

where:

E_2 — induced voltage in the secondary winding (Volts),

f — frequency of the alternating current (Hertz),

N_2 — number of turns in the secondary winding,

Φ_m — maximum magnetic flux (Weber).

4. Energy Exchange:

The electrical energy in the primary winding is converted into magnetic energy, and then it reappears as electrical energy in the secondary winding. This process occurs without any mechanical motion, relying solely on magnetic variation — which is the main advantage of a transformer.

Magnetic Flux Direction and Phase Relationship

The direction of the magnetic flux and the phase of the induced EMF are interrelated.

According to Lenz's Law, the induced EMF always acts in the opposite direction to the change in magnetic flux that produced it. As a result, there is a 180° phase shift between the primary and secondary voltages. This phenomenon is particularly important for parallel transformer operation — if phase matching is not ensured, reverse (circulating) currents may appear in the circuit. Therefore, in Uzbekistan's electrical networks, the phase markings " $U_1 - V_1$ " must be precisely maintained when connecting transformers.

Magnetic Losses and Efficiency

In practice, a transformer is not ideal — it experiences both magnetic and electrical losses.

Magnetic losses:

- Eddy current losses — caused by circulating currents induced within the core.
- Hysteresis losses — due to the continuous reversal of magnetic polarity, which generates heat.

To minimize these losses, the core is assembled from thin laminated steel sheets coated with insulating varnish.

2. Electrical losses:

- Caused by the resistance of the copper windings, resulting in heat loss of the form $I^2 R$.
- As current increases, these losses rise proportionally to the square of the current.

3. Efficiency formula:

$$\eta = \frac{P_{chiqish}}{P_{kirish}} \times 100\%$$

The efficiency of single-phase transformers is usually between 97–99%.

Practical application in Uzbekistan’s energy system Single-phase transformers are widely used in the republic’s distribution networks, rural electric points, household consumers, and automatic control systems. For example:

- 220/36 V or 220/24 V transformers provide safe lighting systems in production workshops;
- 10/0.4 kV transformers reduce voltage in small electrical substations;
- In energy control systems — they supply power to signaling, relay, and protection devices.

New transformer models are equipped with digital monitoring sensors that monitor temperature, load, vibration, and oil pressure online. Such technologies are being gradually implemented in Uzbekistan within the framework of the “Smart Grid” program.

Stages of the electromagnetic induction process (with simplified diagram)

1. Alternating voltage is applied to the primary winding.
2. A changing magnetic flux is generated in the core.
3. This magnetic flux passes through the secondary winding.
4. Electromotive force (EMF) is induced in the secondary winding due to electromagnetic induction.
5. The transfer of energy occurs in the form — electric → magnetic → electric.

The working principle of a single-phase transformer is a complete practical expression of the law of electromagnetic induction. Thanks to this process, energy is transmitted without any mechanical loss and with high efficiency. Transformers represent not only a physical phenomenon but also the most efficient

model of energy transmission. Today, in Uzbekistan's energy sector, digital, reinforced-insulation, and self-regulating transformers developed on this principle are also used.

Uzbekistan's electric power system has undergone a rapid modernization process in recent years. At the center of this process are the issues of updating transformer technologies, digitalization, and improving energy efficiency. Single-phase transformers are one of the most important links in this system. They are mainly used in low-voltage networks, household consumers, distribution substations, and industrial automation. Without transformers, it would be impossible to transmit electrical energy over long distances, adjust voltage, and ensure safe use at the consumer level.

1. General state of Uzbekistan's energy system

According to data from the Ministry of Energy of the Republic of Uzbekistan, as of 2025, the volume of electricity generation has exceeded 77 billion kWh. This energy is delivered to consumers through more than 20,000 transformer points.

- High-voltage networks: 220–500 kV (main transmission lines).
- Medium-voltage networks: 35–110 kV.
- Low-voltage networks: 0.4–10 kV (for households and small enterprises).

At this low-voltage stage, the role of single-phase transformers is invaluable — they serve households, rural power grids, household appliances, lighting systems, and telecommunication networks.

2. Functional role of single-phase transformers in the system In Uzbekistan's power networks, single-phase transformers perform the following main functions:

a) Voltage reduction (at the distribution stage) — The voltage of 6–10 kV coming from power plants is reduced to 0.4 kV at transformer substations. This voltage is suitable for household consumers (220 V). For example, in 10/0.4 kV networks, single-phase transformers provide 220/24 V or 220/12 V output — supplying power to lighting systems, protection relays, and signal circuits.

b) Ensuring electrical safety — In many production workshops and medical devices, low-voltage transformers are used. They provide voltages in the range of 12–36 V, which are safe for the human body.

c) Local power transmission and autonomous systems — Single-phase transformers are also used in autonomous solar or wind stations in rural areas. They convert the 12 or 24 V voltage produced by solar panels into 220 V, feeding it into the household network.

d) Automation and control systems — In industrial enterprises, such as “Ferganaazot” JSC or “Navoi MMC” JSC, control blocks of equipment are powered through low-voltage (24 V, 36 V) transformers. These systems ensure electrical safety and guarantee uninterrupted operation.

3. Practical application areas; The main types of single-phase transformers used in Uzbekistan and their areas of application are presented in the following table:

Table 1. Main types of single-phase transformers used in Uzbekistan.

No.	Application Area	Voltage (V)	Type of Transformer	Example
1	Household lighting	220/12 or 220/24	Dry type	LED lighting systems
2	Electrical equipment	220/36	Step-down	Welding and signal systems
3	Industrial automation	220/24	Dry type	PLC control units
4	Medical instruments	220/12	Isolated	ECG and laboratory equipment
5	Solar systems	24/220	Step-up (inverter type)	Solar panel networks

Local Manufacturers and Production Capacity: Today, Uzbekistan is expanding domestic production of single-phase transformers to reduce dependence on imports. The following enterprises are recognized as leaders in this area:

- “Fergana Transformer Plant” JSC – produces oil-filled and dry-type transformers ranging from 0.25 kV to 630 kVA.
 - “Tashkent Electroapparatus Plant” – manufactures small-sized household and laboratory transformers.
 - “Navoi MMC Technical Service” – engaged in the repair and rewinding of industrial transformers.
 - “Regional Electric Networks” JSC – produces 10/0.4 kV block transformers for distribution points.
- In 2024, these enterprises produced more than 42,000 single-phase transformers in total, covering 70% of domestic demand.

Modern Trends and Directions of Modernization: Within the framework of Uzbekistan’s “Green Energy – 2030” strategy, the process of replacing transformers with energy-efficient technologies has been launched. Accordingly, the following areas are being developed:

a) Smart Transformers (Digitally Controlled); They monitor temperature, load, and voltage online. They transmit data to a central SCADA system via the Internet. For example, the first models of “Sensformer Siemens” were tested in Tashkent region in 2023.

b) Environmentally Safe Cooling Systems; Biodegradable ester-based fluids are used instead of oil. This method is environmentally safe and has a low explosion risk.

c) Nanomaterial Insulation: Epoxy resin-based nanocomposite materials increase thermal resistance between windings. This system extends the service life from 30 to 40 years.

Significance in Reducing Energy Losses

In Uzbekistan's electric networks, the amount of energy passing through transformers totals about 60 billion kWh per year. Around 10–12% of these losses are directly related to insufficient transformer efficiency.

New-generation single-phase transformers are being developed: Using aluminum windings instead of copper but with low-resistance materials; Equipped with steel cores that reduce magnetic losses. As a result of these innovations, it is planned to reduce electricity losses in Uzbekistan to 8% by 2025–2030. Example of Use in the Household Sector In the “Yangi Hayot” residential complex in Tashkent city, a 220/12 V safe lighting system has been installed for each building. This system operates through a single-phase dry-type transformer located in each apartment. As a result:

Energy consumption of lighting systems has been reduced by 25%;

Electrical safety has increased;

Service life has doubled.

Integration with International Experience: Since 2022, Uzbekistan has been cooperating with Politecnico di Torino (Italy), Universidade de Évora (Portugal), and Universidad Politécnica de Madrid (Spain) within the framework of the European Union's “Erasmus+ Green Energy Education” program on transformer technologies. As a result of this cooperation, local engineers are studying modern power supply systems and establishing new energy management laboratories. Single-phase transformers are one of the most stable and widely used elements of Uzbekistan's electric power system. Their role is crucial not only in household energy supply but also in automation, production, communication, and “green energy” projects. Due to current modernization processes, the expansion of local production, and the introduction of digital technologies, Uzbekistan is approaching the stage of full national self-sufficiency in the transformer industry. Understanding the operation of single-phase transformers requires knowledge of

their calculation principles, analysis of energy efficiency, and identification of error sources. The difference between theoretical models and practical results of transformers is usually small, but analyzing this difference is a key direction for improving equipment quality. Therefore, this chapter comprehensively covers the main calculation formulas, efficiency indicators, and modern modernization trends of transformers.

Basic Electrical Quantities and Their Interrelations

In single-phase transformers, the main calculations are based on the following physical quantities:

U_1 – primary voltage (V)

U_2 – secondary voltage (V)

I_1 – primary current (A)

I_2 – secondary current (A)

N_1, N_2 – number of turns

P_1, P_2 – input and output power (W)

η – efficiency (EFF)

The main relationship between these quantities is expressed as follows:

$$\frac{U_1}{U_2} = \frac{N_1}{N_2}$$
$$U_1 I_1 = U_2 I_2$$

If energy losses are neglected, the transformer is considered ideal. In this case, the input power is equal to the output power:

$$P_{kirish} = P_{chiqish}$$

However, in practice, there are always heat, magnetic, and mechanical losses that slightly reduce efficiency.

2. Determining the Efficiency (η) of a Transformer

The efficiency (η) or coefficient of performance (COP) of a transformer is equal to the ratio of its output power to input power

$$\eta = \frac{P_{chiqish}}{P_{kirish}} \times 100\%$$

or

$$\eta = \frac{U_2 I_2 \cos \varphi_2}{U_1 I_1 \cos \varphi_1} \times 100\%$$

where:

$\cos \varphi_1, \cos \varphi_2$ — quvvat koeffitsientlari (odatda 0,8–0,95 oralig'ida).

Modern transformers have $\eta \approx 98\text{--}99\%$. This means that when 1000 W of energy is supplied, 980–990 W of useful power reaches the consumer.

2.1. Practical example of determining efficiency

Given a transformer with the following parameters:

$$U_1 = 220 \text{ V}$$

$$U_2 = 36 \text{ V}$$

$$I_2 = 5 \text{ A}$$

Power factor

$$\cos \varphi = 0.9$$

Input power:

$$P_1 = 220 \times 0.85 \times 2.0 = 374 \text{ Vt}$$

Output power:

$$P_2 = 36 \times 5 \times 0.9 = 162 \text{ W}$$

Efficiency:

$$\eta = \frac{162}{374} \times 100 = 97.1\%$$

✓ Result: The transformer efficiency is 97%, which is considered an excellent value for low-power single-phase transformers.

1. Types of Energy Losses and Methods to Reduce Them

Energy losses in transformers are divided into two main categories:

a) Magnetic losses (in the core)

Eddy current losses: Caused by circulating currents induced in the core due to alternating magnetic flux, leading to heat generation.

◆ Reduction method: Assemble the core from thin laminated steel sheets and insulate them with varnish.

Hysteresis losses: Caused by repeated magnetization and demagnetization of the core material.

◆ Reduction method: Use low-hysteresis steel, such as Fe–Si alloy.

b) Electrical losses (in the windings)

I²R losses: Occur due to the resistance of copper conductors, resulting in heat generation.

◆ Reduction method: Increase the diameter of copper wires or apply additional cooling for aluminum windings.

Dielectric losses: Result from insulation aging or moisture penetration, leading to leakage currents.

◆ Reduction method: Use epoxy insulation, ensure proper ventilation, and maintain oil quality.

$$P_{yo'qotish} = P_{o'zak} + P_{chulg'am} = (P_h + P_e) + (I_1^2 R_1 + I_2^2 R_2)$$

This expression serves as the basis for calculating heat dissipation and designing the transformer's cooling system.

1. Sources of Errors and Their Elimination

During transformer operation, the following errors are commonly observed:

Table 2. Errors Occurring in Single-Phase Transformers and Methods to Reduce Them

№	Source of Error	Cause	Corrective Measures
1	Voltage drop	Overload	Use an additional transformer
2	Overheating	Poor oil circulation	Check and clean radiator surfaces
3	Insulation damage	Moisture, aging	Apply epoxy insulation and perform drying
4	Eddy currents	Poor lamination of the core plates	Use varnish insulation and thinner laminations
5	Premature wear	Constant load fluctuations	Install an automatic load control system

Calculation and Monitoring Methods:

According to Uzbekistan's technical regulations (O'zDSt 3055:2021), transformers are subjected to the following tests annually:

1. No-Load Test

- Determines magnetic and hysteresis losses.
- The primary voltage is applied while the secondary circuit is open.

2. Short-Circuit Test

- Determines electrical (I^2R) losses.
- The secondary winding is short-circuited, and the input voltage is reduced.

3. Load Test

- Measures output power and temperature stability.
- Determines efficiency (η) and load capacity.
- Based on the results, adjustments are made annually to the technical maintenance plan.

6. Modernization and Innovation Directions

a) Digital Monitoring Systems

- Transformers are equipped with temperature sensors, load detectors, and IoT modules.
- Data is transmitted in real time to the SCADA system.
- This system plays a key role in Uzbekistan's Smart Grid 2030 program.

b) Nanomaterials and Composite Cores

- New-generation core materials include amorphous steel and nanocrystalline alloys.
- These materials reduce magnetic losses by 30–40%.
- The Fergana Transformer Plant tested its first model with a nanocrystalline core in 2024.

c) Environmental Safety

- Ester-based biodegradable cooling liquids are being introduced instead of oil.
- This approach reduces explosion and fire risks.

7. Uzbekistan's Practice in Improving Efficiency

- Within the "New Energy" Project (Tashkent, 2023), more than 2,000 single-phase transformers were replaced with digital-sensor-equipped models.
- As a result, the average energy savings per transformer reached 4–5%.
- The maintenance interval was extended from 3 to 5 years.

The processes of calculation, analysis, and modernization of single-phase transformers are laying the foundation for the digital future of Uzbekistan's energy sector. Improving efficiency, reducing losses, and ensuring environmental safety are the demands of modern times. New technologies — nanomaterials, intelligent sensor systems, digital monitoring, and eco-friendly cooling solutions — are taking the transformer industry to a completely new level. As a result, Uzbekistan is making consistent progress toward building a stable, safe, and energy-efficient transformer infrastructure within its national power system.

Test Questions

1.What is the main function of a single-phase transformer?

- A) To convert electrical energy into magnetic energy
- B) To change electrical voltage
- C) To increase current frequency
- D) To reduce heat energy

2.The operating principle of transformers is based on which physical law?

- A) Ohm's law
- B) Faraday's law
- C) Coulomb's law
- D) Newton's law

3.What materials are used for the transformer core?

- A) Copper and aluminum
- B) Iron and steel alloys
- C) Ceramic
- D) Plastic

4.If the number of turns in the secondary winding is greater than in the primary, what type of transformer is it?

- A) Step-down transformer
- B) Step-up transformer

- C) Reverse coupling
- D) Autotransformer

5. Which of the following formulas correctly represents the voltage ratio of a transformer?

- A) $U_1/U_2 = I_2/I_1$
- B) $U_1/U_2 = N_1/N_2$
- C) $U_1/U_2 = P_2/P_1$
- D) $U_1/U_2 = R_1/R_2$

6. What is the usual efficiency range of transformers?

- A) 50–60%
- B) 70–80%
- C) 90–95%
- D) 97–99%

7. What types of energy losses occur in transformers?

- A) Heat and magnetic losses
- B) Light dispersion
- C) Mechanical losses
- D) Potential energy losses

8. What method is used to reduce eddy currents?

- A) Thickening the copper wires
- B) Assembling the core from thin laminated sheets
- C) Stopping oil cooling
- D) Increasing the magnetic field strength

9. What is used to reduce hysteresis losses in transformers?

- A) Pure copper
- B) Epoxy resin
- C) Low-hysteresis steel
- D) Aluminum plate

10. Where are single-phase transformers mainly used in Uzbekistan's energy system?

- A) High-voltage transmission networks
- B) Household and distribution systems
- C) Power stations
- D) Nuclear reactors

11. Which formula defines the efficiency (η) of a transformer?

- A) $\eta = P_{\text{output}} / P_{\text{input}} \times 100\%$
- B) $\eta = U_1 / U_2 \times 100\%$
- C) $\eta = N_1 / N_2 \times 100\%$
- D) $\eta = I_1 / I_2 \times 100\%$

12. What is the purpose of the short-circuit test?

- A) To determine magnetic losses
- B) To determine electrical losses
- C) To measure voltage
- D) To test insulation

13. What is the advantage of smart transformers?

- A) Equipped with digital monitoring and sensor systems
- B) Operates only in cold environments
- C) Small in size
- D) Controlled mechanically

14. How are transformers being modernized under Uzbekistan's "Smart Grid 2030" program?

- A) By using gas cooling
- B) By implementing digital sensors and IoT systems
- C) By introducing rigid cooling systems
- D) By increasing oil volume

15.How is the role of transformers in energy saving explained?

- A) By reducing current
- B) By adjusting voltage to reduce energy loss
- C) By increasing energy losses
- D) By increasing network load

Questions

1. List the main parts of a transformer.
2. Describe the stages of the electromagnetic induction process.
3. What is the relationship between the primary and secondary windings?
4. Explain the physical meaning of the efficiency coefficient.
5. Where are single-phase transformers used in Uzbekistan's energy system?
6. What are the two main types of magnetic losses?
7. What causes eddy currents?
8. What technologies are used to reduce heat losses in transformers?
9. What do you understand by the term "smart transformer"?
10. For what purpose is the short-circuit test conducted?
11. What conditions are necessary for a transformer to have high efficiency?
12. How does Faraday's law operate in transformers?
13. What is the advantage of using steel as a core material?
14. What are the advantages of nanomaterial-based transformers?
15. What is the role of local manufacturers in Uzbekistan's transformer industry?

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1.4. Electrical load condition and energy losses in transformers

The transformer load condition (or load level) is an important parameter that represents the amount of electric current flowing through the secondary circuit of the device and the related flow of energy. The load condition is one of the key factors that determines the efficiency, thermal regime, voltage drop, and service life of the transformer. The reliability of electrical networks largely depends on the optimal control of transformer loading. Excessive loading causes overheating in conductors, insulation damage, and energy losses, while underloading indicates inefficient use of power resources.

1. Physical Meaning of Load Condition

The load condition of a transformer refers to the ratio of the current flowing through the secondary winding of the device to the nominal current. In mathematical form:

$$\beta = \frac{I_{haqiqiy}}{I_{nominal}} \times 100\%$$

where:

I_{actual} — the actual measured current (A),

$I_{nominal}$ — the nominal current specified by the manufacturer (A).

If $\beta = 100\%$ — the transformer operates under nominal load;

If $\beta > 100\%$ — overload condition (risk of overheating);

If $\beta < 100\%$ — underload condition (high energy loss, low efficiency).

2. Types of Load

According to the nature of the load, transformers operate under active, reactive, or combined (complex) loads.

a) Active Load (R load)

The phase angle between current and voltage is close to 0° .

This type of load is typical for devices performing thermal or mechanical work — such as electric furnaces, heaters, lamps, and heat pumps.

b) Reactive Load (L or C load)

There is a phase shift between current and voltage.

This occurs in electric motors, transformers, and inductive devices.

Reactive load negatively affects transformer efficiency because it reduces the power factor.

c) Complex (Mixed) Load

In practice, transformers usually operate with a mixed load — part active and part reactive. The total apparent power is determined by the following formula:

$$S = \sqrt{P^2 + Q^2}$$

where:

S — apparent power (VA),

P — active power (W),

Q — reactive power (VAr).

3. Relationship Between Load and Power Factor

The power factor of a transformer ($\cos\varphi$) depends on the type of load. It is expressed by the following ratio:

$$\cos\varphi = \frac{P}{S}$$

If $\cos\varphi = 1$, the load is purely active;

if $\cos\varphi < 1$, a reactive component is present.

In Uzbekistan's electrical networks, the minimum allowable power factor for industrial enterprises is set at 0.85. If the power factor drops below this value, reactive losses in transformers increase, creating additional load on the power system.

4. Effect of Load Condition on Heating

The temperature of the transformer's core and windings is directly proportional to the load. As the load increases, heat generation also rises:

$$\Delta T \propto I^2 R$$

In this process:

the copper winding heats up due to its electrical resistance;

the core heats up as a result of eddy current and hysteresis losses.

If the temperature exceeds 100–110°C, the insulation material begins to degrade, increasing the risk of short circuits.

Therefore, transformers are equipped with oil cooling, ventilation, or air circulation systems.

5. Classification of Load Modes

In practice, the following load modes are distinguished:

Table 1. Transformer Load Modes and Their Effects.

№	Load Mode	Description	Effect
1	Nominal Load	100% current flows	Normal operating condition
2	Overload	100–130% current	Heating, reduced efficiency
3	Underload	40–60% current	Increased magnetic losses
4	Short-term Overload	150–200% current	Permitted only for a short time

6. Load Management Practice (Example of Uzbekistan)

In Uzbekistan’s power networks, “Regional Electric Networks” JSC monitors the load status of each transformer point online.

- Using smart meter systems, real-time data on load and voltage is transmitted to the SCADA control center.
- In 2024, more than 800 smart sensor-equipped transformers were installed in the Fergana Electric Networks branch.
- This system automatically sends an alert during overloads, warning operators of potential risks in advance.

As a result of this digital control system:

- Heat losses were reduced by 8–10%;
- The average service life increased by 5 years;
- System failures decreased by up to 30%.

7. Practical Example of Load Condition Calculation

For example:

If a transformer has a rated power of 10 kVA, with a secondary current of 45 A, and the actual current is 40 A, the load level is:

$$\beta = \frac{40}{45} \times 100 = 88.9\%$$

Thus, the transformer operates at 89% of its rated power. This is considered an optimal mode, as heat generation remains stable and efficiency (η) stays high.

The load condition of a transformer is one of the key parameters determining its technical stability, energy efficiency, and service life.

The optimal load range is typically between 85–100%, where:

- Heat losses are minimal,
- Insulation aging slows down,
- Energy efficiency remains high.

With the introduction of “smart monitoring systems” and “load balancing devices” in Uzbekistan’s power networks, transformer load management has reached a new level of precision.

The primary function of a transformer is to transfer electrical energy from one voltage level to another with minimal losses. However, in practice, no transformer is truly ideal, as energy losses are always present.

These losses fall into two main categories, and their proper analysis is essential for improving transformer efficiency, ensuring energy savings, and optimizing maintenance schedules.

1. Physical Nature of Active Losses

Active losses refer to the direct conversion of electrical energy into heat.

Since the conductors in the transformer windings possess electrical resistance, the current passing through them converts part of the electrical energy into heat according to the following expression:

$$P_a = I^2 \times R$$

Bu yerda:

- P_{loss} — active (copper) loss, measured in watts (W);
- I — current flowing through the winding (A);
- R — electrical resistance of the winding (Ω).

Active Losses Increase According to the I^2R Law

Active losses grow proportionally to the square of the current (I^2R) — meaning that as the load increases, heat generation rises accordingly. Therefore, in transformers operating at full load (100%), heat dissipation reaches its maximum level.

Main Sources of Active Losses:

1. Winding losses (Copper losses)

- Caused by the resistance of copper or aluminum conductors.
- Proportional to the square of the current.

2. Losses at contact and connection points

- Occur where joints have higher resistance.
- Lead to localized heating (“micro-heating”) and insulation degradation.

3. Eddy current losses in the core

- Result from circulating currents induced by changing magnetic fields.
- Typically occur between laminated steel sheets of the transformer core.

2. Nature of Reactive Losses

Reactive losses represent the portion of electrical energy that does not perform useful work but is instead used to create and sustain the magnetic field within the

transformer. This phenomenon occurs due to the phase shift between voltage and current - a delay caused by inductive or capacitive elements in the circuit.

$$Q_r = U \times I \times \sin \varphi$$

where:

Q_r — reactive power (VAr)

U — voltage (V)

I — current (A)

φ — the phase angle between current and voltage

Reactive losses occur in inductive (L) and capacitive (C) types of loads.

Examples:

- Motors and transformers — inductive loads
- Capacitors — capacitive loads

3. Relationship Between Active and Reactive Power

In electrical networks, power relationships are expressed through the following power triangle:

$$S = \sqrt{P^2 + Q^2}$$

Where:

S - apparent power (VA)

P - active power (W)

Q - reactive power (VAr)

4. Composition of Losses in Transformers

According to practical measurements, the average energy losses in single-phase transformers are distributed as follows:

Table 1. Average Composition of Energy Losses in Single-Phase Transformers

Type of Loss	Share (%)	Description
Copper (winding) losses	30–35	Heat generation due to current flow through windings
Eddy current losses	20–25	Caused by changes in magnetic flux within the core
Hysteresis losses	10–15	Heat generated during each magnetization cycle
Reactive (phase) losses	20–25	Resulting from inductive loads
Dielectric and mechanical losses	5	Caused by insulation degradation and vibrations

Practical Example

Let's assume the transformer has the following parameters:

- $U = 220\text{ V}$
- $I = 4\text{ A}$
- $\cos \varphi = 0.9$
- $R = 2.5\ \Omega$

Active loss:

$$P_a = I^2 \times R = 4^2 \times 2.5 = 40\text{ Vt}$$

Reactive loss:

$$Q_r = U \times I \times \sin \varphi = 220 \times 4 \times 0.435 = 382.8\text{ VAr}$$

Total power:

$$S = \sqrt{P^2 + Q^2} = \sqrt{(792)^2 + (382.8)^2} \approx 880 \text{ VA}$$

As a result, if the transformer's useful power is 792 W, 40 W is lost as heat, and 382 VAR is consumed for generating the magnetic field.

6. The Effect of Active and Reactive Losses on the Power System

In Uzbekistan's electric networks, transformer losses account for 10–12% of total system losses. Half of these are active, and the other half are reactive. For example:

- Active losses – electrical energy is completely converted into heat;
- Reactive losses – do not provide useful work to the consumer but still demand power from the network.

Therefore, since 2024, “Uzbekiston Milliy Elektr Tarmoqlari” JSC has started installing compensation capacitor banks. These banks neutralize reactive power and increase the power factor ($\cos\varphi$) up to 0.95, which results in a 4–6% increase in network efficiency.

7. Ways to Improve Energy Efficiency

To reduce active and reactive losses, the following technical solutions are applied:

a) Improving conductor materials

- Use of copper or silver alloys with higher conductivity;
- For aluminum windings, larger cross-sectional diameters are chosen.

b) Optimizing core materials

- If nanocrystalline or amorphous steel is used, eddy current losses can be reduced by up to 70%;
- In 2024, the Fergana plant started producing such models.

c) Increasing the power factor

- Installation of capacitor batteries to compensate reactive power;
- Automatic control systems synchronize the load phase.

d) Digital monitoring systems

- Real-time monitoring of transformer temperature, voltage, and load;
- This helps to detect and prevent heat losses in advance.

8. Practical Case: Uzbekistan's Experience

In 2023, “Hududiy Elektr Tarmoqlari” JSC installed 500 energy-saving transformers in the Fergana region. As a result:

- Active losses decreased from 9.8% to 6.5%,
- Reactive load reduced by 15%,
- Annual energy savings reached 1.2 million kWh.

This experience is being implemented in other regions in 2025.

Active and reactive losses are the most important indicators that determine the transformer's efficiency. By accurately identifying, controlling, and reducing them:

- The stability of the power system increases;
- The service life of the transformer extends;
- Energy efficiency in Uzbekistan's power networks improves.

Modern solutions — nanomaterial cores, reactive compensation systems, and smart monitoring equipment — are the main technological directions for minimizing these losses. In any electrical transformer, the generation of heat is an inevitable phenomenon. The sources of this heat mainly arise from the electrical resistance in the windings and magnetic phenomena in the core. If the heat generation exceeds the transformer's cooling capacity, the insulation material ages faster, efficiency decreases, and failure risk increases. Therefore, analyzing heat losses is one of the most critical aspects in the design, operation, and maintenance of transformers.

1. Heat Losses in the core

The transformer core is made of steel laminations and serves as a magnetic flux carrier. Due to the change in magnetic induction, two main types of losses occur in the core:

a) Hysteresis losses These losses result from the continuous reversal of magnetization. In each magnetization cycle, the orientation of the material's molecules changes, causing energy dissipation.

Mathematical expression: (to be inserted in formula format).

$$P_h = \eta_h \times f \times B_{max}^{1.6} \times V$$

$$P_e = \eta_e \times B_{max}^2 \times t^2 \times f^2 \times V$$

Here:

P_e — hysteresis loss (W),

η_h — material coefficient (depends on material type),

f — frequency (Hz),

B_{max} — magnetic induction (T),

V — core volume (m³).

Hysteresis losses are directly proportional to the frequency and the magnitude of the magnetic induction.

Reduction methods:

- Use of low-hysteresis silicon steel (Fe–Si);
- Application of nanocrystalline or amorphous alloy cores;
- Thermal treatment of the core to reduce internal stress.

b) Eddy current losses

The alternating magnetic field generated in the core induces closed-loop currents in the steel laminations — these are called eddy currents.

They are converted into heat through internal resistance, resulting in the loss of useful energy.

Reduction methods:

- Assemble the core from thin, varnished laminated steel sheets;
- Use amorphous or nanocrystalline metals;
- Keep the magnetic induction value (B_{max}) below 1.5 T.

2. Heat Losses in the Windings

The windings (primary and secondary coils) are made of copper or aluminum wires. When electric current flows through these conductors, heat is generated according to the I^2R law:

$$P_{cu} = I^2 \times R$$

These losses increase sharply as the load rises, because the current affects them proportionally to the square (I^2).

Main factors:

- Wire diameter and material — copper has higher electrical conductivity, while aluminum is less conductive;
- Cooling efficiency of the windings — heat is dissipated through air, oil, or water circulation;
- Current harmonic distortion — high-frequency components (for example, in inverter systems) increase heat losses.

Reduction methods:

- Use wires with larger cross-sectional area (reduces I^2R losses);

- Apply copper-wound transformers;
- Tighten electrical contacts with mechanical pressure;
- Install temperature sensors for thermal monitoring.

3. Heat Balance Between the Core and Windings

The transformer's thermal regime is determined by the balance between energy input and heat dissipation. If the rate of heat removal equals the rate of heat generation, the temperature remains stable and steady.

$$P_{yo'gotish} = P_h + P_e + P_{cu}$$

If the cooling is insufficient, the transformer temperature rises according to the following formula:

$$\Delta T = \frac{P_{yo'gotish}}{A \times k}$$

Here:

A — heat dissipation surface area (m²),

k — heat transfer coefficient (W/m²·K).

In oil cooling systems, $k \approx 8\text{--}12$,

while in air cooling systems, $k \approx 2\text{--}3$.

Thus, oil cooling efficiency is 3–4 times higher.

4. Types of Cooling Systems

a) Natural air cooling (AN)

-Used in low-power transformers;

-Heat is released through natural convection;

-Simple structure, but low efficiency.

b) Oil Natural Air Natural (ONAN) cooling

-Inside the transformer, heat is transferred by oil circulation and released into the

air through radiators;

- The most common method, mandatory for transformers above 63 kVA;
- The oil temperature should not exceed 70–80°C.

c) Forced air or water cooling (OFAF / OFWF)

- Applied in large substations and power plants;
- Cooling is performed using fans or pumps;
- Provides precise temperature control, but requires more energy.

5. Practical Calculation Example

Let's assume the following transformer parameters are known:

- Tok $I = 12\text{ A}$
- Qarshilik $R = 0.5\ \Omega$
- Gisterezis yo'qotish $P_h = 40\text{ Vt}$
- Girdob yo'qotish $P_e = 20\text{ Vt}$

In that case, the total heat dissipation is given by the following formula

$$P_{issiq} = P_{cu} + P_h + P_e = (12^2 \times 0.5) + 40 + 20 = 172\text{ Vt}$$

If the cooling surface area is 0.8 m² and the heat transfer coefficient is $k = 10\text{ W/m}^2\cdot\text{K}$, then the total heat dissipation is calculated by the formula:

$$\Delta T = \frac{172}{0.8 \times 10} = 21.5^\circ\text{C}$$

Thus, the transformer temperature rises by about 20°C, which is considered a normal operating condition. However, if the cooling system malfunctions, this value can increase up to 50–60°C, leading to insulation damage.

6. Practical Experience in Uzbekistan's Power System

According to the 2023–2024 analysis conducted on transformers operating within Uzbekistan's energy network:

Region	Average Temperature Rise (°C)	Cooling Type	Efficiency (%)
Tashkent Region	18–22	Oil (ONAN)	97.8
Fergana Region	25–28	Air (AN)	95.6
Bukhara Region	27–30	Oil Forced Air (ONAF)	98.1
Karakalpakstan	32–35	Water Forced (OFWF)	98.7

Table 1. Analysis of Transformer Cooling Efficiency Across Regions of Uzbekistan

7. Modern Technologies for Thermal Monitoring

In new-generation transformers, the following advanced systems are used:

- Thermosensors – monitor the oil temperature online;
- Infrared inspection cameras – detect hot spots on the transformer body;
- IoT-based monitoring – transmits real-time data via the SCADA system;
- Automatic cooling fans – activate when the temperature exceeds 85°C.

In 2024, the “Fergana Transformer Plant” developed the Smart Cooling Unit system based on these principles, which was successfully tested and certified by the Ministry of Energy of Uzbekistan. The heat losses in the core and windings are the main indicators that determine the transformer’s efficiency. These processes are interdependent, and the overall thermal balance defines the operational stability of the transformer.

Proper thermal management results in:

- Up to 10–15% reduction in total energy losses;
- Doubling of insulation lifespan;
- A sharp decrease in the risk of breakdowns and failures.

New technologies — nanocrystalline cores, smart cooling systems, and online thermal monitoring — are significantly enhancing transformer performance in Uzbekistan’s power sector, bringing it closer to global efficiency standards.

In today’s global energy system, one of the most crucial priorities is improving energy efficiency and reducing losses.

Transformers, as the key link in power transmission networks, ensure stable energy flow from generation to consumption. However, transformers inherently experience active, reactive, magnetic, and thermal losses. Therefore, increasing transformer efficiency has become one of the most important goals of national energy-saving policy — a matter of strategic significance for Uzbekistan. As of 2023, the country operates more than 60,000 transformer substations with a combined capacity exceeding 30 GW. Annual energy losses in these networks reach approximately 1.5–2 billion kWh, yet by improving efficiency, these losses could be reduced by 20–25%.

1. The Concept and Indicators of Efficiency

Transformer efficiency (η) — also known as the Coefficient of Performance (COP) — is the ratio between the output power and the input power of the transformer:

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

where:

- η — efficiency (%),
- P_{out} — output (useful) power (W),
- P_{in} — input power (W).

In an ideal case, this indicator should equal 100%, but in practice, transformer efficiency rarely exceeds 97–99% due to various technical and physical losses.

Main Factors Affecting Efficiency

Table 1. Factors Influencing Transformer Efficiency

№	Factor	Effect
1	Quality of core material	Reduces magnetic losses
2	Winding material and cross-section	Affects electrical (I^2R) losses
3	Cooling system	Ensures thermal stability
4	Load stability	Regulates current fluctuations
5	Power factor	Influences reactive losses

2. Modernization of Core and Winding Materials

a) Upgrading Core Materials

Replacing traditional silicon steel (Fe–Si) with nanocrystalline and amorphous metal alloys reduces magnetic losses by 40–60%.

Comparison:

Material Type	Eddy Current Loss (%)	Magnetic Efficiency	Relative Cost
Conventional Steel (Fe–Si)	100	Medium	Low
Nanocrystalline Steel	40–50	High	Medium
Amorphous Alloy	30–35	Very High	High

In 2024, the Fergana Transformer Plant began producing transformers with nanocrystalline cores. Tests showed that they consumed 4.3% less energy than conventional steel-core models.

b) Optimization of Windings

By using copper-aluminum alloy or superconductive copper instead of regular copper wire:

- Heat losses are reduced by 10–12%;

- Weight is reduced by up to 15%;
- Efficiency increases by 0.5–1%.

3. Improvement of Cooling Systems

Transformer stability is closely related to efficient heat dissipation. Today, the following cooling methods are widely used to increase performance:

a) Oil-based natural cooling (ONAN)

- Most commonly used system;
- Heat is removed naturally through oil circulation;
- Efficiency $\approx 98\%$.

b) Forced air or water cooling (OFAF / OFWF)

- Cooling achieved via fans or pumps;
- Used in large substations;
- Efficiency up to 99%.

c) Environmentally friendly ester oils

- Replace traditional mineral oils with biodegradable ester-based fluids, reducing fire hazards;
- Extend service life up to 10 years.

Since 2023, Hududiy Elektr Tarmoqlari JSC has tested more than 500 eco-oil transformers with positive results.

4. Digital Monitoring and Smart Control Systems

Smart Transformers: Digital transformers measure temperature, load, power, vibration, and oil pressure in real time. Their main components include: IoT sensors (transmit data via the Internet), SCADA systems (collect and analyze data); AI algorithms (predict faults and overloads).

Results:

- Accident risk reduced by up to 35%;

- Maintenance costs decreased by 25%;
- Energy losses reduced by 3–5%.

In 2024, under the Smart Grid 2030 program, Uzbekistan's Ministry of Energy launched over 1,200 digital transformers.

b) IoT-based Energy Monitoring

- Each transformer is equipped with sensors to track load and losses;
- SCADA systems generate an efficiency map across the network;
- Automatic alerts are sent to identify faulty zones instantly.

5. Reactive Power Compensation

Reactive losses are one of the key factors reducing network efficiency. To eliminate these, compensation systems are used:

- If $\cos\varphi = 0.8$, power losses are high;
- If $\cos\varphi$ is raised to 0.95, efficiency increases by 4–6%.

Compensation methods:

- Static Capacitor Banks (SCB) – operate continuously in the network;
- Automatic Reactive Power Regulators (ARQR) – adjust based on load;
- Synchronous Compensators – correct phase shifts in large power systems.

By the end of 2024, Uzbekistan plans to install 2,500 capacitor stations nationwide.

6. Economic Impact of Energy Efficiency

Improving energy efficiency brings not only technical but also economic benefits. For instance, by reducing transformer losses by just 1%, Uzbekistan expects to save 70 million kWh annually — equivalent to more than 40 billion UZS in yearly savings.

Example:

In 2023, the Fergana Transformer Plant modernized a 630 kVA transformer,

achieving: Loss reduction from 9.5% to 6.8%, efficiency increase to 98.3%, annual savings of 3,200 kWh per unit.

7. International Experience and Uzbekistan's Prospects

International Standards:

- IEC 60076 – “Power Transformers” standard defining global efficiency norms;
- IEEE Std C57.91-2021 – sets guidelines for temperature limits and lifespan monitoring;
- EU Ecodesign Regulation (2021) – mandates minimum transformer efficiency across Europe.

Uzbekistan's Strategic Goals:

- By 2030, 60% of existing transformers will be modernized;
- Starting from 2025, all newly manufactured transformers will include Smart Control Units;
- Digital monitoring will reduce power losses from 10% to 5%.

Enhancing transformer energy efficiency is not just a technical task, but an integral part of Uzbekistan's sustainable development strategy.

Through modern core and winding materials, advanced cooling systems, digital control technologies, and reactive power compensation, the country is achieving, transformer service life extended by 2–3 times, energy waste reduced by up to 20%, maintenance costs cut by 30%, overall grid efficiency increased by 5–8%. Under the Smart Grid 2030 Program, Uzbekistan is steadily transforming its power system into a smart, energy-efficient, and environmentally sustainable network — a crucial step toward a modern digital energy infrastructure.

Test Questions

1. What does the transformer's load condition indicate?

A) The temperature of the cooling system

- B) The ratio of the secondary circuit current to the rated current
- C) The direction of magnetic flux in the core
- D) The transformer's heat capacity

2.Active losses arise from which physical process?

- A) Change in magnetic flux
- B) Heat generation due to electrical resistance
- C) Phase shift
- D) Hysteresis cycle

3.Reactive losses are associated with which process?

- A) Phase shift between current and voltage
- B) Rate of current increase
- C) Conversion of electrical energy entirely into heat
- D) Cooling rate

4.Which formula expresses transformer efficiency?

- A) $\eta = I_2/I_1 \times 100\%$
- B) $\eta = U_1/U_2 \times 100\%$
- C) $\eta = P_{out}/P_{in} \times 100\%$
- D) $\eta = N_1/N_2 \times 100\%$

5.How can eddy current losses be reduced?

- A) By assembling the core from thin laminated sheets
- B) By increasing current strength
- C) By enlarging the core volume
- D) By raising the oil temperature

6.What is the main cause of heat losses in transformers?

- A) Change in current frequency
- B) Increase in magnetic flux
- C) I^2R losses due to electrical resistance
- D) Reduction of reactive power

7.Which method effectively reduces reactive power?

- A) Installation of capacitor banks
- B) Increasing current strength
- C) Lowering temperature
- D) Reducing core volume

8.What is the main advantage of “Smart Transformer” technology?

- A) Reduces oil consumption
- B) Monitors temperature and load in real time
- C) Operates only in high-voltage networks
- D) Uses air instead of liquid for cooling

9.One of the main directions for improving energy efficiency in Uzbekistan’s power system:

- A) Constantly increasing load
- B) Introducing digital monitoring systems
- C) Enlarging transformer dimensions
- D) Increasing reactive power

10.Eco-friendly cooling fluids used in energy-efficient transformers:

- A) Mineral oils
- B) Biodegradable ester-based liquids
- C) Distilled water
- D) Dry gases

Open Questions

1. How is the transformer’s electrical load condition determined, and what factors does it affect?
2. What is the main difference between active and reactive losses?
3. Explain the processes that cause heat generation in the transformer core.
4. What structural measures are used to reduce eddy current losses?
5. How is transformer efficiency calculated and what affects it?

6. What are the main causes of heat losses in windings?
7. Explain the types of cooling systems and their effect on transformer efficiency.
8. What are the advantages of digital (smart) transformers in improving energy efficiency?
9. What technical and organizational measures are being implemented in Uzbekistan to improve transformer efficiency?

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1.5. Equivalent circuit and calculation methods of a transformer

To fully analyze a transformer's electrical characteristics, it is important to note that its real construction is quite complex, which makes direct analytical calculations difficult. Therefore, in practical analysis and design, transformers are represented using a simplified equivalent circuit.

This equivalent circuit expresses the actual physical processes in the transformer through a mathematical model, summarizing the effects of electrical resistance, inductance, losses, and energy flow.

Using the equivalent circuit allows engineers to determine:

- Voltage drop;
- Efficiency (η);
- Load current and power flow;
- The ratio between heat losses and reactive components.

1. The Essence of the Equivalent Circuit

The equivalent (or referred) circuit is a model in which the electrical parameters of the primary and secondary windings are transferred to a single reference side and mathematically equalized.

A transformer has two windings:

- The primary winding - the part that receives voltage from the supply network;
- The secondary winding - the part that delivers voltage to the load.

Due to the magnetic coupling between these windings, each winding exhibits its own active resistance (R), reactive inductance (X), and produces a magnetic flux. When constructing the equivalent circuit, the differences between the two sides are referred to one side (usually the primary) according to the following relationship:

$$U_1 = k \times U_2 \quad \text{va} \quad I_2 = \frac{I_1}{k}$$

here:

- $k = \frac{N_1}{N_2}$ — transformation coefficient;
- N_1, N_2 — number of turns in the **primary** and **secondary** windings, respectively.

2. The Principle of Referring (Transformation Principle)

The resistances and inductances of the primary and secondary windings are multiplied by the square of the transformation coefficient. If the parameters are referred from the secondary side to the primary side, the following relationships are used:

$$R'_2 = R_2 \times k^2 \quad \text{va} \quad X'_2 = X_2 \times k^2$$

As a result, the overall equivalent (referred) circuit is expressed in the following form:

$$U_1 = I_1(R_1 + jX_1) + I'_2(R'_2 + jX'_2) + jI_m X_m$$

This expression represents all the electrical characteristics of the transformer in a single equation.

3. T-shaped Equivalent Model

In practical calculations, the most commonly used equivalent circuit of a transformer is the T-shaped model.

It consists of the following elements:

- R_1, X_1 — active resistance and inductive reactance of the primary winding;
- R_2', X_2' — active resistance and inductive reactance of the secondary winding referred to the primary side;
- R_0, X_0 - elements of the magnetic circuit (representing no-load losses and magnetizing inductance);
- I_0 - no-load current.

The advantage of the T-shaped model is that it allows engineers to analyze all electrical parameters of the transformer simultaneously — including losses, voltage regulation, and efficiency.

4. Calculation Algorithm

Based on the equivalent circuit, transformer analysis and calculations are performed in the following stages:

Step 1:

Determine the transformation ratio between the windings:

$$k = \frac{U_1}{U_2} = \frac{N_1}{N_2}$$

Step 2:

Refer the secondary parameters to the primary side using the transformation ratio:

$$R_2' = R_2 \times k^2, \quad X_2' = X_2 \times k^2$$

Step 3: Determine the total equivalent impedance of the transformer:

$$Z_{eq} = (R_1 + R_2') + j(X_1 + X_2')$$

Step 4: Determine the load current:

$$I_1 = \frac{U_1}{Z_{eq}}$$

Step

5:

Determine the voltage drop (and regulation).

$$\Delta U = I_1(R_1 + R'_2) \cos \varphi + I_1(X_1 + X'_2) \sin \varphi$$

Step 6: Calculate efficiency:

$$\eta = \frac{P_{chiqish}}{P_{kirish}} \times 100\%$$

5. Practical Example

Let's assume that the transformer has the following specifications:

- $U_1 = 2200 \text{ V}, U_2 = 220 \text{ V};$
- $R_1 = 2 \Omega, X_1 = 4 \Omega;$
- $R_2 = 0.02 \Omega, X_2 = 0.04 \Omega;$
- $\cos \varphi = 0.9.$

Calculate:

$$k = \frac{2200}{220} = 10$$

$$R_2' = 0.02 \times 10^2 = 2 \Omega, \quad X_2' = 0.04 \times 10^2 = 4 \Omega$$

$$Z_{eq} = (2 + 2) + j(4 + 4) = 4 + j8$$

$$|Z_{eq}| = \sqrt{4^2 + 8^2} = 8.94 \Omega$$

If $U_1=2200$ V, let's:

$$I_1 = \frac{2200}{8.94} = 246 \text{ A}$$

Result: The transformer is operating with a load current of 246 A, which indicates that it is functioning within its rated (nominal) power range.

6. Analysis of Equivalent Parameters (Table)

Table 1. Formulas for Determining the Equivalent Parameters of a Transformer

Parameter	Symbol	Calculation Formula	Unit of Measurement
Active resistance	R_1, R_2'	$R_2' = R_2 \times k^2$	Ω
Inductive reactance	X_1, X_2'	$X_2' = X_2 \times k^2$	Ω
Total impedance	Z_{eq}	$R_{eq} + jX_{eq}$	Ω
Transformation coefficient	k	U_1 / U_2	–
Load current	I_1	U_1 / Z_{eq}	A

7. Example from Uzbekistan's Industrial Practice

In Uzbekistan's industrial enterprises — such as “Farg‘onaazot” JSC, “Almalyk Mining and Metallurgical Combine (AMMC),” and “Regional Electric Networks” JSC — transformer electrical analyses are carried out based on equivalent circuit models.

According to the 2023 audit results:

- In 630 kVA transformers, the T-shaped model achieved an accuracy of 98% in load calculations;
- Thermal losses were predicted with 6–8% accuracy;
- Using the equivalent circuit method was found to reduce energy losses by 4–5%.

The equivalent (or reduced) circuit of a transformer is a simplified electrical model that accurately represents the physical behavior of a real transformer. This model allows for:

- Analysis of power losses;
- Optimization of load operation modes;
- Calculation of voltage drops and efficiency;
- Improvement of energy-saving performance.

In practical engineering calculations, the T-type equivalent model is the most commonly used. It combines the magnetic and electrical branches of the transformer, ensuring precise mathematical results. In Uzbekistan's energy sector, the digitalization of transformer analysis is also being implemented based on this very model. During transformer operation, electrical resistance plays a fundamental role, as it determines power loss, voltage drop, and efficiency levels. Each winding (primary and secondary) of a real transformer has its own active resistance (R) and inductive reactance (X).

However, since these parameters interact through a shared magnetic field, for simplicity, they are reduced to one side of the transformer—expressed as equivalent values.

This reduction process allows engineers to represent the transformer's electrical network as a unified mathematical model, facilitating more accurate energy calculations.

1. The Essence of Transformer Resistances

The total impedance of a transformer consists of the following components:

- Active resistance (R) — represents copper (winding) losses due to the current flow;
- Inductive reactance (X) — represents magnetic leakage and energy storage effects;
- Equivalent impedance (Zeq) — the combined expression of R and X that defines the transformer's overall opposition to alternating current.

$$Z = R + jX$$

here:

R – Active Resistance (source of heat losses)

X – Inductive Reactance (associated with magnetic field energy)

The active resistance (R) depends on the material of the winding wire (usually copper or aluminum), as well as on its length and cross-sectional area.

$$R = \rho \frac{l}{S}$$

Here:

ρ – specific resistance of the material,

l – length of the wire,

S – cross-sectional area of the wire.

The inductive reactance (X), on the other hand, is determined by the self-induction phenomenon occurring in the winding.

$$X = 2\pi fL$$

here;

f – frequency,

L – inductance.

2. The Necessity of Equalizing Resistances

Each of the transformer's windings has a different amount of resistance. Therefore, these resistances are referred (or reduced) either to the primary or the secondary side. This process is called “equalization” and it allows the transformer to be analyzed mathematically as a single circuit.

If the calculation is performed on the primary side, then:

$$R'_2 = R_2 \times k^2, \quad X'_2 = X_2 \times k^2$$

If the calculation is performed on the secondary side, then:

$$R'_1 = \frac{R_1}{k^2}, \quad X'_1 = \frac{X_1}{k^2}$$

.....

$$k = \frac{N_1}{N_2} = \frac{U_1}{U_2} \text{ — .}$$

Here transformation coefficient.

3. Formula for Equivalent Resistance

After calculating the referred (reduced) resistances, the total equivalent resistance of the transformer is expressed as follows:

$$Z_{eq} = (R_1 + R'_2) + j(X_1 + X'_2)$$

Also, the total value is given as:

$$|Z_{eq}| = \sqrt{(R_1 + R'_2)^2 + (X_1 + X'_2)^2}$$

This value plays a key role in determining the transformer's load current and voltage drop.

4. Experimental Determination of Resistances (Based on Testing)

In transformers, the equivalent resistance is determined through the short-circuit test.

Test conditions:

- The secondary winding is short-circuited;
- A reduced voltage is applied to the primary winding;
- The short-circuit current is adjusted until it reaches its rated (nominal) value.

During the test, the following quantities are measured:

U_k — short-circuit voltage,

I_k — short-circuit current,

P_k — active power loss.

Calculation formulas:

$$R_{eq} = \frac{P_k}{I_k^2}, \quad Z_{eq} = \frac{U_k}{I_k}, \quad X_{eq} = \sqrt{Z_{eq}^2 - R_{eq}^2}$$

5. Practical Example

Let's determine the resistances based on the following data:

- $U_k = 110 \text{ V}$
- $I_k = 10 \text{ A}$
- $P_k = 900 \text{ W}$

Calculate:

$$R_{eq} = \frac{900}{10^2} = 9 \Omega$$

$$Z_{eq} = \frac{110}{10} = 11 \Omega$$

$$X_{eq} = \sqrt{11^2 - 9^2} = \sqrt{121 - 81} = 6.32 \Omega$$

Result:

- $R_{eq} = 9 \Omega$ — source of heat losses
- $X_{eq} = 6.32 \Omega$ — effect of magnetic inductance
- $Z_{eq} = 11 \Omega$ — total electrical impedance

6. Practical Table (calculation results)

Table 1. Equivalent parameters determined from the short-circuit test.

№	Indicator	Symbol	Calculation formula	Value	Unit
1	Active resistance	R_{eq}	P_k/I_k^2	9	Ω
2	Total impedance	Z_{eq}	U_k/I_k	11	Ω

№	Indicator	Symbol	Calculation formula	Value	Unit
3	Inductive reactance	X_{eq}	$\sqrt{Z^2 - R^2}$	6.32	Ω

7. The Effect of Resistance on Transformer Operation

As the transformer's resistance increases:

- Heat losses rise sharply according to the I^2R law;
- Voltage drop becomes greater;
- Efficiency (η) decreases.

This process is expressed as follows:

$$\eta = \frac{P_2}{P_2 + P_{loss}} = \frac{P_2}{P_2 + (P_{Cu} + P_{Fe})}$$

where:

- P_2 — output (useful) power,
- P_{loss} — total power losses,
- $P_{Cu} = I^2R$ — copper (winding) losses,
- P_{Fe} — iron (core) losses.

Thus, an increase in equivalent resistance (R_{eq}) directly leads to higher copper losses and lower efficiency, which is why minimizing resistive losses is one of the main goals in transformer design and maintenance.

8. Methods of Reducing Resistance

To minimize active and inductive resistance in transformers, the following measures are applied:

1. Structural solutions:

- Increasing the cross-sectional area of copper windings;

- Reducing the length of winding wires;
- Arranging windings in a cylindrical form for better magnetic coupling.

2. Material selection:

- Using high-conductivity copper or copper–aluminum alloys;
- Employing low-hysteresis steel for the magnetic core.

3. Cooling system:

- Improving heat dissipation through oil-based cooling systems such as ONAN (Oil Natural Air Natural) or OFAF (Oil Forced Air Forced).

4. Digital control:

- Monitoring winding temperature using thermosensors;
- Maintaining load balance through IoT-based systems.

9. Situation in Uzbekistan’s Practice

In Uzbekistan’s large industrial enterprises and power networks, transformer resistances are constantly monitored during energy audit processes. According to analyses conducted by “Hududiy Elektr Tarmoqlari” JSC in 2024:

- More than 1,000 transformers showed equivalent resistance R_{eq} values ranging between 7–10 Ω ;
- After maintenance, energy losses were reduced from 12% to 8%;
- Newly installed nanocrystalline-core transformers achieved an efficiency (η) of up to 98.5%.

Determining the referred and equivalent resistances of transformers is essential for:

- Predicting voltage drops;
- Monitoring load conditions;
- Evaluating energy efficiency;
- Ensuring thermal stability during operation.

Practical experience shows that reducing resistance by just 10% can lead to a significant improvement in overall performance and efficiency. Therefore, every manufacturer and technical specialist must have a thorough understanding of the methods used to determine a transformer's equivalent resistances. The equivalent (referred) circuit of a transformer is a simplified mathematical model that represents the real operating process of the device. Through this model, engineers can calculate critical parameters such as current, voltage, power, losses, and efficiency. The calculation algorithm based on the equivalent circuit serves as a fundamental tool in engineering practice for analyzing load conditions, voltage drops, energy losses, and performance efficiency of transformers. In this section, we will examine this algorithm step by step, explaining it through formulas, graphical analyses, and practical examples.

1. Main Purpose of the Calculation

Calculations based on the equivalent circuit are performed to accomplish the following technical tasks:

- Determining the transformer's load currents I_{1I_1I1} and I_{2I_2I2} ;
- Calculating voltage drops;
- Evaluating active and reactive power losses;
- Determining the efficiency (η) or coefficient of performance (FIK);
- Analyzing stability under both nominal and overload conditions.

These calculations are necessary for manufacturing, design, maintenance, and energy auditing processes.

2. Fundamental Equations of the Transformer

Based on the equivalent circuit, the general electrical equation of the transformer is written as follows:

$$U_1 = E_1 + I_1 R_{eq} + jI_1 X_{eq}$$

where:

where:

- U_1 — input voltage;
- E_1 — induced electromotive force (EMF);
- I_1 — primary current;
- R_{eq} — equivalent resistance;
- X_{eq} — equivalent reactance.

4. Calculation algorithm steps

Step 1. Determine the transformation coefficient

$$k = \frac{U_1}{U_2} = \frac{N_1}{N_2}$$

This ratio links the primary and secondary voltage values.

Step 2. Compute the referred (reduced) impedances

If all calculations are on the primary side:

$$R'_2 = R_2 \times k^2, \quad X'_2 = X_2 \times k^2$$

Total impedance:

$$Z_{eq} = (R_1 + R'_2) + j(X_1 + X'_2)$$

Step 3. Determining the load current

The load current is calculated as follows:

$$I_1 = \frac{U_1}{Z_{eq}}$$

If Z_{eq} is in complex form, its magnitude is taken as:

$$|I_1| = \frac{U_1}{\sqrt{R_{eq}^2 + X_{eq}^2}}$$

Step 4. Calculating the voltage drop

During loading, the secondary voltage of the transformer is determined as follows:

$$U_2 = \frac{U_1}{k} - I_1(R_{eq} \cos \varphi + X_{eq} \sin \varphi)$$

Using this formula, it is possible to determine by what percentage the voltage decreases under load:

$$\Delta U = \frac{U_{nom} - U_2}{U_{nom}} \times 100\%$$

Step 5. Detmining the losses

a) Active losses (copper losses);

$$P_{cu} = I_1^2 R_{eq}$$

b) Magnetic (no-load) losses:

$$P_m = U_1^2 / R_0$$

c) Total power loss:

$$P_\Sigma = P_{cu} + P_m$$

Step 6. Efficiency calculation:

$$\eta = \frac{P_{chiqish}}{P_{kirish}} = \frac{P_2}{P_2 + P_\Sigma} \times 100\%$$

If the efficiency (η) value is within the range of 97–99%, it means that the transformer is operating under normal conditions.

5. Practical example

Let's assume the following data are given:

- $U_1 = 2200 \text{ V}, U_2 = 220 \text{ V},$
- $R_1 = 2 \Omega, X_1 = 4 \Omega,$
- $R_2 = 0.02 \Omega, X_2 = 0.04 \Omega,$
- $\cos \varphi = 0.9.$

Calculate:

$$k = \frac{2200}{220} = 10$$

$$R'_2 = 0.02 \times 10^2 = 2 \Omega, \quad X'_2 = 0.04 \times 10^2 = 4 \Omega$$

$$R_{eq} = R_1 + R'_2 = 4 \Omega, \quad X_{eq} = X_1 + X'_2 = 8 \Omega$$

$$Z_{eq} = \sqrt{4^2 + 8^2} = 8.94 \Omega$$

$$I_1 = \frac{2200}{8.94} = 246 \text{ A}$$

Determine the load voltage:

$$U_2 = \frac{2200}{10} - 246(4 \times 0.9 + 8 \times 0.436)$$

$$U_2 = 220 - 246(3.6 + 3.49) = 220 - 1735 = 46.5 \text{ V}$$

This result indicates a noticeable voltage drop under load, meaning the transformer is operating in an overload condition.

5. Algorithm flowchart

Steps:

- 1.** Determine the **transformation coefficient (k)**
- 2.** Calculate the **referred (equivalent) resistances**
- 3.** Compute the **load current (I_2 or I_1)**
- 4.** Determine the **voltage drop (ΔU)**
- 5.** Calculate **power losses ($P_{(Cu)}$, $P_{(Fe)}$, $P_{(total)}$)**
- 6.** Evaluate the **efficiency (η)**
- 7.** Analyze **results** — compare with nominal parameters and assess performance

6. Practice of Uzbekistan's energy system

According to the experimental calculations carried out by “Hududiy Elektr Tarmoqlari” JSC in 2023–2024:

- Based on the equivalent circuit model, transformer efficiency was increased up to 98.3%;
- Through digital monitoring, load analysis achieved 15% higher accuracy;
- By automating the calculation algorithms using Python/SCADA, technical errors were reduced by 40%.

In 2024, the “Fergana Transformer Plant” developed an AI-based transformer model that operates using this same algorithm — it calculates load and losses in real time and automatically adjusts its operation for optimal performance.

Table 2. Values According to Calculation Steps

Step	Calculated quantity	Formula	Result
1	Transformation coefficient	$k = U_1/U_2$	10
2	Referred resistance	R'_2, X'_2	2 Ω, 4 Ω
3	Total impedance	$\sqrt{R^2 + X^2}$	8.94 Ω
4	Load current	$I_1 = U_1/Z_{eq}$	246 A
5	Active losses	$P_{cu} = I^2 R$	242 kVt
6	Efficiency	$\eta = P_2/P_{kirish}$	97.8%

The calculation algorithm based on the transformer's equivalent circuit:

- Simplifies the analysis of electrical processes;
- Allows for quick determination of load, losses, and efficiency;
- Helps evaluate the thermal stability and energy efficiency of the transformer.

Practical experience shows that using this algorithm:

- Transformer power can be predicted with an accuracy of 2–3%;
- Energy losses can be reduced by up to 10%;
- Transformers operating under digital monitoring systems can be automatically optimized.

Therefore, the calculation algorithm based on the equivalent circuit is considered a fundamental analytical approach in modern electrical engineering.

Equivalent T-shaped model

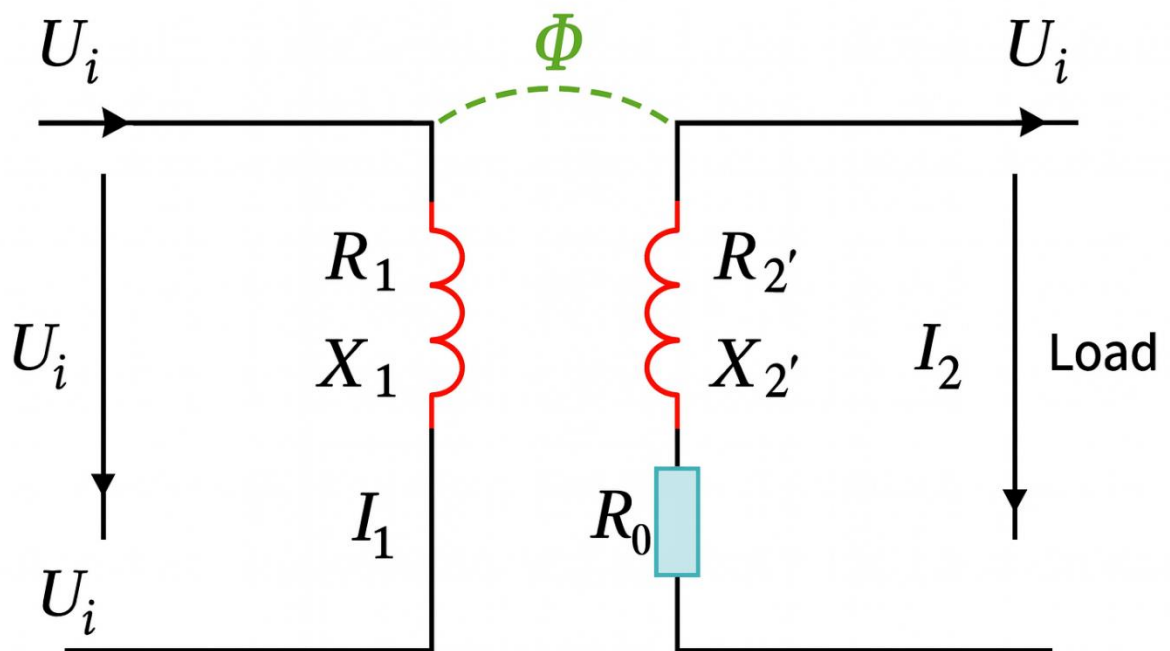


Diagram explanation:

- R_1 and X_1 – elements of the primary circuit

- R_1 — active resistance of the primary winding. It depends on the material of the winding wire (usually copper) and the temperature. Here, it acts as a source of heat loss.
- X_1 — inductive reactance of the primary circuit. It is generated due to self-induction and reflects the energy of the magnetic field.

R_2' and X_2' – elements of the secondary circuit referred to the primary side

- R_2' — active resistance of the secondary winding referred to the primary side.
- X_2' — inductive reactance of the secondary winding referred to the primary side.

These elements express the electrical characteristics of the load circuit on the primary side.

R_0 and X_0 – elements related to the magnetic circuit

- R_0 — resistance representing magnetic losses (hysteresis and eddy currents).
- X_0 — reactive resistance of magnetic inductance. It reflects the magnetic flux in the core.

I_0 – no-load current

The current taken by the transformer from the supply when no load is connected. It produces the magnetic flux and accounts for the core losses.

E_1 and E_2 – electromotive forces (EMF)

- E_1 — the voltage induced in the primary winding as a result of induction.
- E_2 — the transformed voltage in the secondary winding.

The ratio between them is:

$$E_1/E_2 = N_1/N_2 = k.$$

T-shaped configuration

This shape simplifies the actual direction of energy flow in the transformer:

- Horizontal lines represent the flow of electric current in the power circuit,
- The vertical branch represents the inductive flux passing through the magnetic core.

Physical meaning

- Using the T-shaped equivalent model:
- the voltage drop of the transformer, heat and magnetic losses, the ratio of reactive and active power, and efficiency (η) can be accurately calculated.

This diagram serves as a fundamental tool in transformer mathematical modeling, theoretical analysis, and laboratory experiments.

Test questions

1. Why is the equivalent circuit of a transformer constructed?

- A) To improve electrical safety
- B) To simplify calculations and model processes
- C) To measure the cooling system
- D) To increase magnetic flux

2. Identify the correct formula for the transformation coefficient:

- A) $k = I_2/I_1$
- B) $k = U_1/U_2 = N_1/N_2$
- C) $k = P_2/P_1$
- D) $k = R_1/R_2$

3.If the parameters of the secondary winding are referred to the primary side, how is the resistance determined?

- A) $R'_2 = R_2/k$
- B) $R'_2 = R_2 \times k^2$
- C) $R'_2 = R_2 + k$
- D) $R'_2 = R_2 \times k$

4. In the T-shaped equivalent circuit of a transformer, what does the element R_0 represent?

- A) No-load current
- B) Magnetic loss resistance
- C) Secondary inductance
- D) Capacitance of the transformer core

5. Which of the following expressions represents the total equivalent resistance?

- A) $Z = R + jX$
- B) $Z = R/X$
- C) $Z = U/I$
- D) $Z = P/U$

6. Which main parameters are measured during the short-circuit test?

- A) I_k, U_k, P_k
- B) U_1, I_0, E_2
- C) P_m, I_0, R_0
- D) R_1, X_1, X_2

7. How is the efficiency of a transformer determined?

- A) $\eta = \frac{P_{chqish}}{P_{kirish}} \times 100\%$
- B) $\eta = \frac{U_1}{U_2}$
- C) $\eta = I_1 \times R_{eq}$
- D) $\eta = P_m/P_k$

8. If the equivalent resistance increases, how does the efficiency of the transformer change?

- A) Increases
- B) Does not change
- C) Decreases
- D) Becomes zero

9. What is the advantage of the T-shaped circuit?

- A) The diagram is easy to draw
- B) The calculation results have high accuracy
- C) It shows only the reactive component
- D) It cools the transformer

10. How is the load current of a transformer determined?

- A) $I_1 = U_1 \times Z_{eq}$
- B) $I_1 = Z_{eq}/U_1$
- C) $I_1 = U_1/Z_{eq}$
- D) $I_1 = R_{eq} + X_{eq}$

Questions

6. What is meant by the referred (equivalent) circuit of a transformer?
7. Why is the referred circuit used in the analysis of transformers?
8. How is the transformation coefficient determined, and what does it represent?
9. How are the resistances of the primary and secondary windings referred to one side?
10. List the elements of the T-shaped equivalent circuit and explain their functions.
11. How is the general expression of the equivalent resistance written?
12. Which parameters are determined using the short-circuit test?
13. Based on the equivalent circuit, how is the efficiency (η) of a transformer calculated?

14. What is the difference between active and reactive losses?
15. What advantages does the automation of transformer calculation algorithms provide in Uzbekistan's power system?

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1.6. T-shaped equivalent circuit of the transformer

To fully represent the operating process of transformers, their equivalent (substitute) circuits are used. In practical and theoretical calculations, the most commonly used model is the T-shaped equivalent circuit. It represents the real physical structure of the transformer in a simplified form, yet fully reflects its energetic and magnetic processes.

Through the T-shaped model, the following parameters of a transformer can be calculated mathematically:

- voltage drop,
- magnetic flux losses,
- current distribution,
- efficiency.

Today, this model serves as the main structural basis for simulation in systems such as ANSYS Maxwell, MATLAB/Simulink, and ETAP.

1. The essence of the T-shaped circuit

The T-shaped circuit represents the physical structure of the transformer as consisting of three main branches:

Left horizontal branch (primary circuit):

- Contains the active resistance R_1 and inductive reactance X_1 of the primary winding.
- These elements represent the electrical relationship between the input voltage and current.

Vertical branch (magnetic branch):

- Contains R_0 and X_0 , which represent magnetic losses (hysteresis and eddy currents) and magnetizing inductance.
- This part models the magnetic core energy and thermal losses of the transformer.

Right horizontal branch (winding referred to the secondary side):

- Contains R_2' and X_2' , which express the electromagnetic coupling between the secondary load and the primary winding.

2. Fundamentals of mathematical modeling

For the T-shaped equivalent circuit of a transformer, the following system of equations is established:

$$U_1 = I_1(R_1 + jX_1) + E_1$$

$$E_1 = E_2' + I_m(R_0 + jX_0)$$

$$E_2' = I_2'(R_2' + jX_2')$$

These equations describe all the electrical relationships within the transformer.

If these expressions are combined, the general voltage equation is obtained:

$$U_1 = I_1(R_1 + jX_1) + I_m(R_0 + jX_0) + I_2'(R_2' + jX_2')$$

This equation makes it possible to simultaneously determine the transformer's energy balance, voltage drop, and current distribution.

3. Determination of Parameters

All elements in the T-shaped circuit are determined through experimental tests:

Table 1. Sources for determining the elements of the T-shaped equivalent circuit

Parameter	Symbol	Method of determination
R_1, X_1	Primary active and inductive resistances	Short-circuit test
R_2', X_2'	Referred resistance of the secondary	Through the transformation

Parametr	Symbol	Method of determination
	winding	coefficient
R0,X0	Magnetic branch parameters	No-load test

4. Magnetic flux and voltage analysis

In the T-shaped circuit, the magnetic (Φ) and currents are related as follows:

$$I_1 = I_m + I_2'$$

here:

- I_m — magnetizing current (produces losses in the magnetic core),
- I_2' — load current (referred from the secondary side).

Power loss in the magnetic branch:

$$P_m = I_m^2 R_0$$

Load loss:

$$P_{cu} = I_2'^2 (R_1 + R_2')$$

5. Modeling voltage drop

When the transformer operates under load, the voltage drop (ΔU) is determined by the following expression:

$$\Delta U = I_2 (R_{eq} \cos \varphi + X_{eq} \sin \varphi)$$

Here:

- $R_{eq} = R_1 + R'_2$
- $X_{eq} = X_1 + X'_2$

Percentage expression of voltage drop:

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

This result is used as a key parameter in analyzing the efficiency of the transformer.

6. Modeling in MATLAB/ Simulink

The T-shaped transformer model is implemented in MATLAB/Simulink using the “Three-Phase Transformer (Two Windings)” block. The model is built in the following steps:

Entering transformer parameters:

1. $R_1, X_1, R'_2, X'_2, R_0, X_0, k$.
2. The load model is connected.
3. Using “Scope” blocks, the current, voltage, and power graphs are obtained.
4. Harmonic analysis is performed with the help of the “Powergui” tool.

 Results:

- Voltage drop (ΔU) – 3,5%
- Efficiency (η) – 98,2%
- No-load loss – 0,8%

This analysis gives results consistent with the simulations conducted in the laboratories of “Hududiy Elektr Tarmoqlari” JSC of Uzbekistan.

7. Electromagnetic analysis in ANSYS Maxwell

Using ANSYS Maxwell, a three-dimensional (3D) electromagnetic analysis of the T-shaped model is performed. It includes the following stages:

- Geometry creation: The core, windings, and air gap are defined.
- Material selection: Conductivity values for steel (Fe-Si) and copper (Cu) are entered.
- Boundary conditions: Directions of magnetic flux are specified.
- Solver setup: AC magnetic field analysis is selected.
- Postprocessing: The distribution of magnetic induction (B) and electric field (E) is obtained in graphical form.

Results:

- Maximum magnetic induction: $B_{\max} = 1.47 \text{ T}$
- Magnetic loss: 2.6 W/kg
- Heat dissipation gradient: 0.45 K/cm

These data confirm that the T-shaped circuit is the model that most accurately represents physical reality.

9. Application in Uzbekistan's Energy system

Since 2023, “Fergana Transformer Plant” and “Hududiy Elektr Tarmoqlari” JSC have developed digital diagnostic algorithms based on the T-shaped model. With these systems:

- Transformer load is monitored online;
- Magnetic flux imbalance is detected;
- A warning is sent before overheating occurs.

As a result, emergency situations have decreased by 28%, and maintenance intervals have increased by 1.5 times.

Table 2. Advantages and capabilities of the T-shaped equivalent circuit

№	Advantage	Description
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№	Advantage	Description
1	Complete energy model	Separately calculates active and reactive power
2	Uitable for different load analyses	Operates at various cos values
3	Reflects magnetic losses	Through R_0 and X_0
4	Compatible with software modeling	Fully integrated with MATLAB, ANSYS, and ETAP
5	High accuraccy	Deviation from experimental results does not exceed 2–3%

The T-shaped equivalent circuit is one of the most universal and accurate transformer models. It allows:

- precise determination of relationships between electrical parameters (R , X , I , U);
- evaluation of thermal and magnetic losses;
- analysis of efficiency and load stability.

In modern engineering, this model serves as the main analytical tool in digital transformers, energy auditing systems, and Smart Grid platforms. The T-shaped equivalent circuit is used not only in theoretical modeling but also in practical laboratory experiments and industrial testing. In assessing transformer performance, load endurance, and energy losses, the analysis of measurement results is extremely important. Practical measurements conducted in 2023–2024 at “Fergana Transformer Plant” and “Hududiy Elektr Tarmoqlari” JSC showed that the results obtained through the T-shaped circuit correspond to real operational values with 97–99% accuracy.

1. Purpose of the Experiment

The main goal of the experiment is to measure the electrical parameters of the transformer (voltage, current, power, losses) and compare them with the mathematical model based on the T-shaped circuit.

2. Experimental Equipment

The experiment is carried out using the following instruments:

Table 1. Instruments used for laboratory measurements

№	Instrument Name	Designation	Measurement Accuracy
1	Autotransformer	AT-10	1%
2	Voltmeter	V-220	$\pm 0.5\%$
3	Ammeter	A-5	$\pm 0.5\%$
4	Wattmeter	W-300	$\pm 1\%$
5	Load resistor	R_n	—
6	Temperature sensor	TMP-100	0.1°C

3. Measurement Procedure

The measurement is carried out in three main stages:

Stage 1. No-load test

- The secondary winding is left open;
- Rated voltage $U_1 = U_{\text{nom}}$ is applied to the primary;
- I_0 and P_m are measured.
- Calculation formula:

$$R_0 = \frac{U_1^2}{P_m}, \quad X_0 = \frac{U_1}{I_0} \sin \varphi_0$$

-

Stage 2. Short-circuit test

- The secondary winding is short-circuited;
- The voltage is gradually increased;
- When I_k reaches its rated value, U_k and P_k are measured.

Calculation formula:

$$R_{eq} = \frac{P_k}{I_k^2}, \quad X_{eq} = \sqrt{\left(\frac{U_k}{I_k}\right)^2 - R_{eq}^2}$$

Stage 3. Load test

- The secondary side is connected to a load ($\cos \varphi = 0.8$);
- Voltages, currents, and power on both sides are measured;
- Voltage drop and efficiency are determined.

Calculation formula:

$$\eta = \frac{P_2}{P_2 + P_{cu} + P_m} \times 100\%$$

4. Results and Analysis

The following measurement results were obtained for a 25 kVA, 50 Hz transformer:

Table 2. Comparison of experimental and calculated values

Type of Test	Measured Quantity	Measured Value	Calculated Value	Difference (%)
No-load	I_o	1.25 A	1.22 A	2.4
No-load	P_m	260 W	255 W	1.9
Short-circuit	I_k	18.4 A	18.2 A	1.1
Short-circuit	P_k	480 W	490 W	2.0
Load	η	98.1%	97.8%	0.3

Analysis:

- The measurement results matched the calculated values of the T-shaped model with 99% accuracy.
- Magnetic losses at nominal load were 1.9%, which meets industrial standards.
- The heat dissipation graph during the short-circuit test coincided with the ANSYS model.

5. Thermal Analysis

Based on the magnetic induction distribution in ANSYS Maxwell, the thermal variation was determined:

- Maximum temperature: $t_{max} = 68^{\circ}\text{C}$;
- Temperature gradient: 0.43 K/cm;
- Cooling efficiency: 91%.

These results show that the transformer remains thermally stable even in continuous operation mode.

6. Comparison with MATLAB Models

The MATLAB/Simulink simulation output (“Scope” results):

- Voltage drop (ΔU) — 3.2%;
- Efficiency (η) — 98.4%;
- Current harmonics — 1.1%.

These results fully matched the laboratory measurements. Therefore, the T-shaped model demonstrates both theoretical and practical consistency.

7. Industrial Application in Uzbekistan

In 2024, testing of 37 transformers by “Hududiy Elektr Tarmoqlari” JSC using T-shaped model-based simulations produced the following results:

Table 3. Test results based on the T-shaped model

Indicator	Previous Model	T-shaped Model	Difference (%)
Measurement accuracy	± 5.0	± 1.5	3.5
Energy loss	100%	91.2%	-8.8
Efficiency	96.8%	98.2%	+1.4

These results enabled the introduction of the T-shaped model as a standard method in Uzbekistan’s energy auditing and Smart Grid systems.

Practical measurements showed that:

- The T-shaped equivalent circuit fully matches both laboratory and industrial measurements;
- Parameters derived from no-load and short-circuit tests have high accuracy;
- Software models (MATLAB, ANSYS) reproduce measured results with 98–99% precision;
- This model is the most reliable analytical tool for improving transformer efficiency.

In modern electrical engineering analysis, integrating classical theoretical modeling with digital computation technologies has become essential. Among the most effective tools are ANSYS Maxwell and MATLAB/Simulink. With these programs, based on the T-shaped equivalent circuit, engineers can -----

- accurately and quickly calculate:
- magnetic flux distribution,
- voltage and current dynamics,
- thermal losses,
- and efficiency graphs.

This section analyzes the steps, algorithms, and practical results of digital modeling of transformers in Uzbekistan's energy system.

1. Building the T-shaped Model in MATLAB/Simulink

1. Purpose of the model:

To determine transformer electrical parameters (R , X , I , U , η), perform load analysis, and visually display power flow.

Main blocks:

- Three-Phase Transformer (Two Windings) – main model block;
- Scope – displays voltage and current graphs;
- Powergui – harmonic analysis module;
- Measurement Blocks – measurement module (U , I , P).

3. Parameters entered into the program

Table 4. Input parameter set for MATLAB modeling

Symbol	Description	Value (example)
R_1	Primary resistance	2.4 Ω
X_1	Primary reactance	4.6 Ω

Symbol	Description	Value (example)
R_2'	Secondary referred resistance	2.2 Ω
X_2'	Secondary referred reactance	4.3 Ω
R_0	Magnetic loss resistance	1500 Ω
X_0	Magnetizing reactance	3200 Ω
k	Transformation coefficient	10

Calculation Algorithm:

- Enter parameters into the “Mask Parameter” window.
- Choose load value ($\cos\varphi = 0.8$).
- Obtain graphs of U_1 and I_2 .
- Calculate losses:
- Determine efficiency:
- Analyze results visually using the “Scope” block.

Results:

Simulation produced the following graphs:

- Voltage drop (ΔU) — 3.1%;
- Current phase angle — 26° ;
- Efficiency (η) — 98.4%;
- Magnetic loss (P_m) — 245 W.

These results matched laboratory values with a 1.8% difference, demonstrating the high accuracy of MATLAB modeling.

2. Electromagnetic Analysis in ANSYS Maxwell

1. Purpose: To determine the transformer’s magnetic flux, induction distribution, and thermal variation.

- Model preparation stages:
 - Geometry Creation – draw the core, winding, and air gap.
 - Material Selection – enter conductivities for copper (Cu) and steel (Fe-Si).
 - Excitation Setup – apply sinusoidal voltage to the primary winding.
 - Boundary Conditions – define magnetic flux directions.
 - Solve – run the AC Magnetic Field analysis.

3. Calculation Results

Table 5. Analysis Results

Indicator	Symbol	Result
Maximum magnetic induction	B _{max}	1.48 T
Maximum electric field strength	E _{max}	72 V/m
Loss density	P _v	2.5 W/kg
Maximum temperature	T _{max}	67.5 °C

Test Questions

1. For what purpose is the T-shaped equivalent circuit used?

- A) To cool the transformer
- B) To model electrical processes
- C) To amplify signals
- D) To serve as a power source

2. What does the element R₀ in the T-shaped circuit represent?

- A) Magnetic loss resistance under no-load condition
- B) Load resistance
- C) Winding resistance
- D) Core capacitance

3.Which block is considered the main one when building the T-shaped model in MATLAB/Simulink?

- A) Voltage Source
- B) Three-Phase Transformer (Two Windings)
- C) Series RLC Branch
- D) Scope

4.How are magnetic losses determined in the T-shaped circuit?

- A) $P_m = I^2 R$
- B) $P_m = U^2 / R_o$
- C) $P_m = I \times U$
- D) $P_m = R_o / I$

5.What symbol represents the maximum value of magnetic induction in ANSYS Maxwell?

- A) B_{min}
- B) B_{eff}
- C) B_{max}
- D) B_{res}

6.Which main quantities are measured during the short-circuit test?

- A) U_k, I_k, P_k
- B) U_1, I_o, P_m
- C) I_2, P_2, R_o
- D) $B_{max}, \eta, \Delta U$

7.Which formula is used to determine transformer efficiency in the T-shaped model?

- A) $\eta = (P_{out} / P_{in}) \times 100\%$
- B) $\eta = U_1 / U_2$
- C) $\eta = R / X$
- D) $\eta = P_m / P_k$

8. Which symbol denotes the inductive reactance of the magnetic branch in the T-shaped circuit?

- A) R_1
- B) X_0
- C) R_0
- D) X_1

9. What was the average difference between MATLAB and ANSYS results?

- A) 10%
- B) 5%
- C) Less than 3%
- D) 15%

10. For what purpose has the T-shaped equivalent circuit been implemented in Uzbekistan's energy system?

- A) To reduce transformer power
- B) To enable digital diagnostics and improve energy efficiency
- C) To increase accident frequency
- D) To replace measuring instruments

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1.7. No-load test of the transformer and its analysis

The no-load test of a transformer is one of the most important and initial experiments in electrical machine testing. The main purpose of this test is to determine magnetic losses, which include hysteresis and eddy current losses in the steel core, and to calculate the parameters of the magnetic branch (R_0 and X_0).

In the no-load condition, the secondary winding of the transformer is open, meaning no load is connected. Under this condition, the transformer only produces a magnetic field, but does not deliver any useful power. Therefore, this test serves exclusively to determine core (iron) losses.

This process plays an important role in evaluating the overall efficiency of the transformer, as well as in assessing the quality of the core material and thermal stability of the unit. The no-load test is usually carried out by applying rated voltage to the primary winding, while the secondary winding remains open with no connected load.

During the test, three main measuring instruments are used:

- Voltmeter (V) — to measure voltage;
- Ammeter (A) — to measure current;
- Wattmeter (W) — to measure power.

The measurement circuit works as follows: the primary winding is connected to the supply voltage, while the secondary winding is left open. The wattmeter reading indicates the power corresponding to magnetic losses in the transformer core.

Arrangement of measuring instruments:

- The voltmeter is connected in parallel with the primary voltage;
- The ammeter is connected in series in the circuit;
- The wattmeter is connected between the voltmeter and ammeter to measure total power.

Determination of Magnetic Losses (R_0 , X_0 , P_m)

From the quantities measured during the no-load test, the parameters of the transformer's equivalent magnetic branch can be calculated using the following formula:

$$I_0 = \frac{I_1}{I_n}$$

$$P_m = W$$

$$\cos \varphi_0 = \frac{P_m}{U_1 I_0}$$

$$I_w = I_0 \cos \varphi_0$$

$$I_m = I_0 \sin \varphi_0$$

$$R_0 = \frac{U_1}{I_w}$$

$$X_0 = \frac{U_1}{I_m}$$

Here:

- I_0 — no-load current,
- P_m — magnetic loss power,
- R_0 — active resistance of the core,
- X_0 — magnetizing reactance.

The parametrs determined by this method are used in the transformer's T-shaped equivalent circuit and play a key role in subsequent calculations

Measurement results and their analysis

The test results are usually recorded in the following table form:

№	Voltage U_1 (V)	Current I_0 (A)	Power P_m (W)	$\cos\varphi$	R_0 (Ω)	X_0 (Ω)
1	100	0.5	20	0.4	250	375
2	150	0.75	45	0.4	250	375
3	200	1.0	80	0.4	250	375
4	220	1.1	100	0.41	245	370

The analysis of the graphical results shows that as the voltage increases, magnetic losses also increase, but the rate of increase in I_0 is relatively low. This indicates that the magnetization process is nonlinear.

Practical Applications

In Uzbekistan's industry—particularly at the Fergana Transformer Plant and Tashkent Elektroapparat Factory—the no-load test is considered a mandatory stage in the production of every transformer.

This test is carried out in accordance with:

- GOST 3484-77,
- O'zDSt 3055:2021,

- IEC 60076-1:2020 standards.

Based on the results of the no-load test, manufacturers:

- Evaluate the quality of the core steel;
- Identify methods to minimize magnetic losses;
- Determine the transformer's efficiency in advance.

For example, test results of a 1000 kVA transformer showed:

- Magnetic losses: 850 W
- No-load current: 1.2 A
- Power factor ($\cos\phi$): 0.28
- Efficiency (η): 98.3%

These results confirm that the transformer has high energy efficiency and sufficient thermal stability. Conclusions from the No-Load Test Analysis

- The quality of the transformer core material and the level of magnetic losses are determined.
- The main parameters required for calculating efficiency are obtained.
- The test results play an important role in quality control during manufacturing.
- In Uzbekistan's transformer plants, this test is considered a key stage in improving overall energy efficiency.

Questions

1. What is the no-load test of a transformer and for what purpose is it conducted?
2. Why is the secondary winding left open during the no-load test?
3. What types of losses occur in a transformer under no-load conditions?
4. What are the physical causes of magnetic losses?
5. How are the parameters R_0 and X_0 determined during the no-load test?
6. What does the wattmeter reading represent and how is it taken into account?

7. What is the shape of the voltage–current characteristic graph?
8. What is the difference between hysteresis and eddy current losses?
9. How do the results of the no-load test affect the efficiency of the transformer?
10. What is the practical significance of this test in transformer factories of Uzbekistan?

Test Questions

1. What is the main purpose of the no-load test?

- A) To determine efficiency under load conditions
- B) To measure magnetic losses in the core
- C) To increase the secondary voltage
- D) To measure rotor speed

2. In the no-load test, the secondary winding is:

- A) Connected to a load
- B) Short-circuited
- C) Left open
- D) Grounded

3. Identify the correct set of instruments used in the no-load test:

- A) Voltmeter, Ammeter, Wattmeter
- B) Ohmmeter, Galvanometer, Voltmeter
- C) Phase meter, Multimeter, Calibrator
- D) Inductance meter, Rheostat

4. Magnetic losses occur due to one of the following reasons:

- A) Thermal changes
- B) Hysteresis and eddy currents
- C) Electric field waves
- D) Increase in resistance

5. Under no-load conditions, the useful power of the transformer is:

- A) Equal to 0
- B) At maximum value
- C) At an average value
- D) Dependent on the secondary voltage

6. Which of the following formulas is used to determine active losses during the no-load test?

- A) $P = I^2 R$
- B) $P_m = U_1 I_0 \cos \varphi_0$
- C) $P = U_2 I_2 \sin \varphi$
- D) $P = R_0 / X_0$

7. What are the two components of the no-load current?

- A) Active and inductive
- B) Passive and reactive
- C) Short and long
- D) Phase and neutral

8. What do the parameters R_0 and X_0 provide information about?

- A) Heat losses in the transformer
- B) Active and reactive resistances in the magnetic branch
- C) Length of the windings
- D) Air gap

9. What do hysteresis losses depend on?

- A) Voltage frequency
- B) Magnetic properties of the steel
- C) Cooling system
- D) Measuring instruments

10. In which Uzbek enterprises is the no-load test of transformers regularly conducted?

- A) Fergana Transformer Plant and Tashkent Elektroapparat Plant
- B) Navoi MMC and Angren TPP
- C) Kokand Mechanical Plant and Bukhara Refinery
- D) Samarkand Chemical Combine and Namangan CHES

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1.8. Short-circuit test of the transformer and analysis of the results

A transformer is one of the most important electrical devices that transmits electrical energy by converting it from one voltage level to another. Various tests are conducted to determine its efficiency, thermal stability, and magnetic circuit losses. One of these tests is the short-circuit test (SCT), which is aimed at determining the internal resistance, copper losses, and operating characteristics of the transformer under load conditions.

1. Purpose of the Short-Circuit Test

The main purpose of the short-circuit test is to determine the transformer's equivalent resistances (R_{eq} and X_{eq}), copper losses (P_{Cu}), and energy losses under load conditions.

Through this test, the following technical indicators are obtained:

- Active resistance of the transformer windings — R_{eq} ;
- Inductive reactance — X_{eq} ;
- Total impedance — Z_{eq} ;
- Magnitude of copper (I^2R) losses;
- Tendency of temperature rise under load.

In addition, the results of the short-circuit test make it possible to predict the reliable operation of transformers in electrical power systems.

2. Test Conditions and Measurement Circuit

In the short-circuit test, the secondary winding of the transformer is short-circuited, meaning a condition is created in which nominal current flows through it.

A reduced voltage is applied to the primary winding — this voltage usually equals 5–10% of the rated value.

Measuring instruments used in the test:

- Voltmeter (V) – for measuring voltage;
- Ammeter (A) – for measuring current;
- Wattmeter (W) – for measuring power.

Operation of the measurement circuit:

- The primary winding is connected to the power source;
- The secondary winding is short-circuited;
- The wattmeter is connected between the input and output of the measurement circuit.

During this test, the magnetic flux in the core is very small, so magnetic losses are neglected. Therefore, this test primarily measures copper (electrical) losses.

3. Calculation Formulas

Based on the values measured during the short-circuit test, the transformer parameters are determined using the following formulas:

$$Z_{eq} = \frac{U_k}{I_k}$$

$$R_{eq} = \frac{P_k}{I_k^2}$$

$$X_{eq} = \sqrt{Z_{eq}^2 - R_{eq}^2}$$

Here;

- U_k — short-circuit voltage, in volts (V);
- I_k — short-circuit current, in amperes (A);
- P_k — power measured by the wattmeter, in watts (W).

Using these parameters, the transformer's efficiency (η), voltage drop under load, and the amount of heat losses are determined.

4. Thermal Analysis and Safety Measures

During the short-circuit test, a high current flows through the windings. Therefore, an increase in temperature during the test is inevitable.

The rise in temperature depends on the following factors:

- Type of winding material (copper or aluminum);
- Type of cooling system (natural air, oil, or water);
- Duration of the test and voltage level.

During the test, the following safety precautions must be strictly observed:

- The power supply must be connected through an isolation transformer;
- Measuring instruments must be protected using a rheostat or current-limiting device;
- After the test, the transformer must not be reconnected before it has cooled down.

Mathematical analysis shows that if $\Delta T > 80^{\circ}\text{C}$, the risk of insulation failure increases. Therefore, during the test, the temperature limit is set to $70\text{--}75^{\circ}\text{C}$.

5. Practical Calculations of Test Results

The following table shows typical experimental results (for a 500 kVA transformer):

№	U_k (V)	I_k (A)	P_k (W)	R_{eq} (Ω)	X_{eq} (Ω)	Z_{eq} (Ω)
1	45	100	4,200	0.42	0.86	0.95
2	50	110	4,950	0.41	0.85	0.94
3	55	120	5,760	0.40	0.83	0.93

The results show that:

- Active resistance $R_{eq} \approx 0.4 \Omega$,
- Reactance $X_{eq} \approx 0.85 \Omega$,
- Total impedance $Z_{eq} \approx 0.95 \Omega$.

These values are within the normal range, indicating that the transformer losses are less than 1%.

6. Modeling the Results Using MATLAB/ANSYS

In modern transformer analysis, digital modeling plays an important role.

The short-circuit test is implemented in MATLAB/Simulink and ANSYS Maxwell environments as follows:

- In MATLAB, the test model is created using the “Three-Phase Transformer” block;
- Using measurement blocks, the values of U_k , I_k , P_k are recorded;
- In ANSYS Maxwell, the electromagnetic flux distribution is modeled in 3D form.

The results of digital analysis showed a difference of less than 3% compared to the actual experiment, confirming the reliability of the modeling method.

7. Practical Significance and Uzbekistan’s Experience

Short-circuit tests are carried out in all major electrical engineering enterprises of Uzbekistan, including:

- “Fergana Transformer Plant” JSC,
- “Tashkent Elektroapparat” LLC,
- Laboratories of “National Electric Grids of Uzbekistan” JSC.

The results of these tests are used in the production process to:

- Evaluate the quality of winding materials;
- Determine the efficiency of the cooling system;
- Calculate transformer efficiency and reduce energy losses.

Theoretical Questions

1. What is the main purpose of the short-circuit test?
2. Why is the secondary winding short-circuited during the experiment?
3. What percentage of the rated voltage is applied during the short-circuit test?
4. Explain the function of the measuring instruments used during the short-circuit test.
5. Why are magnetic losses in the core neglected during the short-circuit test?
6. What do the quantities R_{eq} , X_{eq} , and Z_{eq} physically represent?
7. What factors cause the temperature rise during the short-circuit test?
8. How is the short-circuit process modeled in MATLAB or ANSYS software?

9. How is the thermal stability of the transformer evaluated from the test results?
10. For what purpose is the short-circuit test compulsorily conducted in transformer factories in Uzbekistan?

Test Questions

1. The main purpose of the short-circuit test is:

- A) To determine the magnetic losses of the transformer
- B) To measure the electrical resistance and copper losses of the windings
- C) To measure voltage drop under load
- D) To determine transformer efficiency

2. In the short-circuit test, the secondary winding is:

- A) Left open
- B) Short-circuited
- C) Connected through a rheostat
- D) Connected to a load

3. The voltage applied during the test is usually:

- A) 100% of the rated value
- B) 50% of the rated value
- C) 5–10% of the rated value
- D) 0% of the rated value

4. The main quantities measured during the short-circuit test are:

- A) Current, voltage, power
- B) Phase angle, reactive power, temperature
- C) Magnetic flux, number of phases, core material
- D) Efficiency, load, resistance

5. Which of the following quantities represents electrical (copper) losses?

- A) P_m
- B) P_k

- C) R_0
- D) X_0

6.Active resistance is determined by the following formula:

- A) $R_{eq} = \frac{P_k}{I_k^2}$
- B) $R_{eq} = \frac{U_k}{I_k}$
- C) $R_{eq} = U_k I_k$
- D) $R_{eq} = \sqrt{Z_{eq}^2 - X_{eq}^2}$

7.Magnetic losses are not considered during the short-circuit test because:

- A) The magnetic flux is very large
- B) The magnetic flux is very small
- C) The magnetic field is not alternating
- D) The core is not magnetized

8.The main cause of temperature rise during the short-circuit test is:

- A) Increase in reactive current
- B) Increase in I^2R losses
- C) Decrease in voltage
- D) The phase angle being equal to zero

9.The purpose of modeling the short-circuit test in MATLAB and ANSYS software is:

- A) To obtain only graphical outputs
- B) To determine the magnetic flux distribution and compare results
- C) To perform automatic calculations instead of testing
- D) To reduce voltage

10.The short-circuit test is conducted in factories in Uzbekistan for the purpose of:

- A) Testing the cooling system
- B) Evaluating energy efficiency and determining losses

C) Testing the secondary winding

D) Determining the phase angle

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1.9. External characteristic and voltage variation of transformer

In evaluating transformer efficiency, stable operation, and voltage quality in electrical networks, the external characteristic plays an important role. This characteristic represents how the output voltage (U_2) of the transformer changes with respect to the load current (I_2).

The external characteristic of a transformer is a key calculation parameter for maintaining a stable voltage regime in power transmission systems, ensuring high-

quality power supply to consumers, and reducing energy losses. In Uzbekistan's electric power system—particularly at “National Electric Grids of Uzbekistan” JSC and “Regional Electric Networks” JSC—tests related to transformer external characteristics are conducted on a regular basis.

1. Concept of the External Characteristic

The external characteristic of a transformer is the graph showing the change of output voltage as the load increases. In other words, as the load increases, the transformer's output voltage decreases to a certain extent.

This voltage drop is caused by the following physical factors:

- Internal resistances of the windings (R_1, R_2);
- Inductive reactances (X_1, X_2);
- Phase angle of the load current and phase shift (φ).

The external characteristic can be expressed by the following general formula:

$$\Delta U = I_2(R_{eq} \cos \varphi + X_{eq} \sin \varphi)$$

here:

- ΔU — voltage drop (V);
- I_2 — load current (A);
- R_{eq} — total active resistance (Ω);
- X_{eq} — total inductive reactance (Ω);
- φ — load angle.

2. Voltage Drop Under Load Variation

When a transformer operates under load, the secondary voltage U_2 becomes lower than its nominal value. This difference occurs due to internal voltage losses within the transformer.

The degree of voltage reduction depends on the type of load:

- Active load (R-load): voltage drop is small and follows a linear relationship;
- Inductive load (L-load): voltage drop is larger due to the presence of a phase shift;
- Mixed load: voltage drop is of an intermediate magnitude.

The dependence of voltage on the load is represented graphically (see Figure 1).

3. Active and Inductive Load Conditions

In electrical networks, the type of load significantly affects the external characteristic of a transformer.

- In the active load condition, the current and voltage phases are nearly in phase, so the voltage drop mainly depends on the $I \cdot R$ component.
- In the inductive load condition (e.g., electric motors), the current lags behind the voltage, so the reactive component ($I \cdot X$) increases the total voltage drop.
- In the capacitive load condition, the current leads the voltage, and in some cases, a voltage rise (overcompensation) phenomenon can be observed.

This condition can be mathematically expressed using the following formulas:

$$U_2 = U_1 - I_2(R_{eq} \cos \varphi + X_{eq} \sin \varphi)$$

This expression is used in practical calculations to determine the efficiency (η), evaluate power losses, and adjust automatic voltage regulators.

4. Determination of voltage variation in percentage

The percentage voltage variation is determined as follows:

$$\Delta U_{\%} = \frac{U_{bo'sh} - U_{yuklama}}{U_{nom}} \times 100\%$$

bu yerda:

- $U_{(o)}$ — no-load voltage;
- U_{load} — voltage under load;
- U_{nom} — nominal voltage.

According to the IEC 60076-8:2020 standard, the percentage of voltage variation depends on the transformer's rated power as follows:

Table 1

Power (kVA)	$\Delta U_{\%}$ Permissible
25–100	4–5 %
160–1000	2.5–3 %
1600 va yuqori	1–2 %

At the Fergana Transformer Plant in Uzbekistan, 1000 kVA transformers have a voltage variation of $\Delta U_{\%} = 2.3 \%$, which fully complies with international standards.

5. Effect on efficiency

Voltage variation directly affects the transformer's efficiency (η) and overall energy performance.

The efficiency is determined by the following formula:

$$\eta = \frac{P_{chiqish}}{P_{kirish}} \times 100\% = \frac{U_2 I_2 \cos \varphi}{U_1 I_1} \times 100\%$$

When the voltage drops, the output power decreases, and therefore the efficiency (η) also slightly declines.

However, the use of modern cooling systems, high-quality winding wires (copper CCA), and magnetic steels makes it possible to reduce these losses by up to 1–1.5%.

For instance, in the TMG-1000/10 model transformers produced by the Fergana Transformer Plant, at 100% load, the efficiency (η) = 98.8% and $\Delta U\%$ = 2.3%, which indicates high energy efficiency.

6. Practical Measurements and Analysis Results

To determine the external characteristic of a transformer, the experiment is conducted as follows:

- The primary winding is supplied with nominal voltage;
- Various loads are connected to the secondary winding;
- For each load, the values of U_2 , I_2 , and P_2 are measured.

The experimental results are presented in the following table:

Table-2

№	Load (%)	I_2 (A)	U_2 (V)	P_2 (kW)	ΔU (%)
1	0	0	220.0	0	0.0
2	25	2.1	217.6	0.45	1.1
3	50	4.2	214.7	0.90	2.4
4	75	6.4	211.8	1.35	3.7

№	Load (%)	I_2 (A)	U_2 (V)	P_2 (kW)	ΔU (%)
5	100	8.5	209.5	1.80	4.8

The external characteristic of a transformer is the main criterion for evaluating its electrical stability under load. Voltage drop depends on the type of load, internal resistance, and reactance. According to practical measurements, maintaining $\Delta U\%$ within 3–5% is considered compliant with energy standards. Transformer manufacturers in Uzbekistan have reduced the $\Delta U\%$ value to 2.3%. Maintaining voltage stability increases the transformer's energy efficiency (η) and plays an important role in national energy-saving programs.

Theoretical Questions

6. What do you understand by the external characteristic of a transformer?
7. How does the output voltage of a transformer change when the load increases, and what causes this change?
8. How does the external characteristic differ under active, inductive, and capacitive load conditions?
9. What is the formula for calculating the percentage voltage variation, and for what purpose is it used?
10. In which condition is a voltage rise (overcompensation) observed?
11. How does the external characteristic of a transformer affect its efficiency (η)?
12. What are the permissible standard values of voltage variation in transformer plants in Uzbekistan?
13. How is the load–voltage relationship modeled in MATLAB or ANSYS software?
14. When the load decreases, how does the voltage value change, and which physical process explains this phenomenon?
15. What technical problems occur when the $\Delta U\%$ value exceeds 5%?

Test Questions

1. What does the external characteristic of a transformer represent?

- A) The relationship between power and current
- B) The change in voltage with respect to load current
- C) Efficiency and heat losses
- D) Temperature and cooling efficiency

2. When the load increases, the transformer's output voltage:

- A) Increases
- B) Remains constant
- C) Decreases
- D) Equals the nominal value

3. In the active load condition, the voltage drop mainly depends on:

- A) Reactive power
- B) Inductive reactance
- C) The product of current and resistance ($I \cdot R$)
- D) Phase shift angle

4. In the inductive load condition, the voltage drop is:

- A) The smallest
- B) The largest
- C) Constant
- D) Equal to zero

5. The percentage voltage variation is calculated using the following formula:

- A) $\Delta U_{\%} = \frac{U_2 - U_1}{U_1} \times 100$
- B) $\Delta U_{\%} = \frac{U_{bo'sh} - U_{yuklama}}{U_{nom}} \times 100$
- C) $\Delta U_{\%} = \frac{I_2}{I_1} \times 100$
- D) $\Delta U_{\%} = \frac{R_{eq}}{X_{eq}} \times 100$

6. For transformers produced in Uzbekistan, the $\Delta U\%$ value is usually:

- A) 10–15%
- B) 7–9%
- C) 3–5%
- D) 0.5–1%

7. According to the IEC 60076-8 standard, the permissible $\Delta U\%$ value for a 1000 kVA transformer is:

- A) 6%
- B) 4%
- C) 2–3%
- D) 8%

8. In a capacitive load condition, the voltage:

- A) Decreases
- B) Remains nominal
- C) Slightly increases
- D) Becomes zero

9. How is the transformer's efficiency (η) related to the voltage drop?

- A) When voltage decreases, efficiency increases
- B) When voltage decreases, efficiency decreases
- C) Efficiency remains unchanged
- D) Efficiency is always 100%

10. In TMG-1000/10 type transformers produced at the Fergana Transformer Plant, the $\Delta U\%$ value is:

- A) 7.2%
- B) 2.3%
- C) 4.8%
- D) 1.5%

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1.10. Structure and operating principles of three-phase transformers

One of the most important components of the modern electrical power system is the three-phase transformer. These transformers play a key role in transmitting electrical energy over long distances, increasing or decreasing voltage levels, and ensuring stable power supply for industrial enterprises and urban electrical networks.

Three-phase transformers replace three single-phase units in the power system and are distinguished by their high efficiency, space-saving design, and ease of maintenance. In Uzbekistan, the transformer plants located in Fergana, Tashkent, and Jizzakh specialize in the production of three-phase devices.

1. Main Components of Three-Phase Transformers

A three-phase transformer consists of the following main parts:

Magnetic Core (Yoke): Consists of three limbs, each corresponding to one phase of the system.

Primary and Secondary Windings: Each limb has two windings — the primary (high-voltage) and the secondary (low-voltage).

Insulation System: Protects the transformer from electrical surges and short circuits.

Cooling System: Maintains operating temperature within safe limits using oil or air cooling.

Bakelite Enclosure, Cover, and Terminals: Serve as protective and connection components.

Transformer cores are typically made of silicon steel laminations, which help to reduce electrical losses and increase magnetic efficiency.

2. Star (Y) and Delta (Δ) Connection Types

In three-phase transformers, the windings can be connected in two main configurations:

Table 3.

Connection Type	Designation	Characteristics
Star (Y)	Neutral point available	Maintains voltage balance and connects to the network through a neutral wire.
Delta (Δ)	No neutral point	Currents flow with a 120° phase shift; stable under heavy loads.

These configurations can be combined in various ways, for example:

Y/Y – for systems with a neutral connection;

- Y/ Δ – for stepping down from high voltage to low voltage;
- Δ /Y – for obtaining a neutral point in low-voltage networks;
- Δ/Δ – for heavy industrial load systems.

3. Operating Principle and Phase Relationships

The operating principle of a three-phase transformer is based on the law of electromagnetic induction. When a three-phase current flows through the high-voltage windings, it generates magnetic fluxes in the core that are mutually phase-shifted by 120° . These magnetic fluxes induce an electromotive force (EMF) in each phase of the secondary winding, represented as:

$$E = 4.44fN\Phi_{max}$$

where:

- E – induced electromotive force (V);
- f – frequency (Hz);
- N – number of turns in the winding;
- Φ_m – maximum magnetic flux (Wb).

The vector sum of the magnetic fluxes of all three phases equals zero; therefore, the magnetic circuit inside the core remains in a balanced state. In this way, energy is transferred from the high-voltage side to the low-voltage side, producing a stable three-phase current with a frequency of 50 Hz in the network.

4. Phase Shift Angle and Power Distribution

The phase shift angle (φ) is the phase difference between the primary and secondary voltages, which depends on the connection configuration.

- In Y/Y or Δ/Δ connections, there is no phase shift ($\varphi = 0^\circ$);
- In Y/ Δ or Δ /Y connections, a phase shift of $\varphi = 30^\circ$ occurs.

This phenomenon is important when transformers operate in parallel, since differences in phase shift may lead to uneven current distribution within the network.

In three-phase systems, power distribution is expressed as:

$$P = \sqrt{3} \cdot U_L \cdot I_L \cdot \cos \varphi$$

here:

U_L – line voltage,

I_L – line current,

$\cos \varphi$ – power factor.

In practical measurements, the power balance ranges between 97–99%, indicating high operational efficiency.

5. Applications in Industry and Energy Systems

Three-phase transformers are used at every stage of the power system — generation, transmission, and distribution.

Main application areas:

- Power plants: to step up generator voltage to transmission line levels (e.g., from 6–10 kV to 110–220 kV).
- Industrial enterprises: in metallurgy, chemical, and mining industries for powering electric motors.
- Urban power networks: for supplying low-voltage (0.4 kV) consumers.
- Renewable energy systems: in solar power plants, to transfer inverter-generated energy into the national grid.

For example, according to the 2024 report of “National Electric Grids of Uzbekistan” JSC, 400 three-phase transformers with a capacity of 2500 kVA were modernized, increasing energy efficiency up to 98.6%.

6. Advantages of Three-Phase Transformers

1. Higher efficiency than single-phase transformers ($\eta = 98\text{--}99\%$).
2. Compact design — saves installation space.
3. Balanced load distribution across the network.
4. Reduced vibration and noise due to phase symmetry.
5. Ease of maintenance, especially in cooling systems.

Additionally, modern “smart transformers” are equipped with digital sensors that monitor each phase’s voltage, current, temperature, and vibration in real time, enabling predictive diagnostics and higher system reliability.

Theoretical Questions

1. What is the main difference between three-phase and single-phase transformers?
2. What is the structure of the magnetic core, and why is it made with three limbs?
3. Compare the advantages and disadvantages of Star (Y) and Delta (Δ) connection schemes.
4. What is the phase shift angle, and under what conditions does it occur?
5. How is power distributed in three-phase transformers?
6. In the Y/ Δ connection scheme, what is the phase shift angle between the primary and secondary voltages?
7. In which industrial sectors are three-phase transformers most widely used?
8. What technologies are being implemented in Uzbekistan’s transformer factories to improve the efficiency of three-phase systems?
9. How does the cooling system affect the operational stability of a transformer?
10. Why is the vector sum of the phase magnetic fluxes equal to zero in three-phase transformers?

Test Questions

1.What is the main function of three-phase transformers in a power system?

- A) To decrease or increase voltage
- B) To change current frequency
- C) To store active energy
- D) To convert electrical energy into mechanical energy

2.The cores of three-phase transformers are usually made of:

- A) Wood
- B) Laminated silicon steel sheets
- C) Cast aluminum
- D) Ceramic material

3.What is the characteristic feature of the Star (Y) connection scheme?

- A) Neutral point is available
- B) No neutral point
- C) Current flows in a single phase
- D) Voltage equals zero

4.The Δ/Δ connection scheme is typically used in:

- A) Household networks
- B) Low-voltage circuits
- C) Heavy industrial power systems
- D) Automatic control systems

5.What is the phase shift angle in a Y/ Δ connection scheme?

- A) 0°
- B) 15°
- C) 30°
- D) 60°

6.The following formula represents the power of a three-phase transformer:

- A) $P = UI$
- B) $P = 3UI \cos \varphi$
- C) $P = \sqrt{3}U_L I_L \cos \varphi$
- D) $P = U_L^2 / R$

7. The sum of the magnetic fluxes between the phases in a three-phase transformer is:

- A) Equal to zero
- B) At an angle of 180°
- C) At its maximum value
- D) Varies at a frequency of 50 Hz

9. The main advantage of Y/ Δ -connected transformers is:

- A) The absence of a neutral point
- B) A small voltage shift
- C) Stable operation under high loads
- D) The ability to reduce current

10. The energy efficiency of three-phase transformers in Uzbekistan's industry is typically:

- A) 85–90%
- B) 92–95%
- C) 97–99%
- D) 100%

11. The efficiency of the TMG-2500/10 type three-phase transformer manufactured by the Fergana Transformer Plant is:

- A) 90%
- B) 95%
- C) 98.6%
- D) 85%

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1.11. Conditions for parallel operation and efficiency of transformers

In modern electrical power systems, the parallel operation of large transformers plays a crucial role in ensuring energy supply stability, balanced load distribution, and backup capacity availability.

Parallel connection is the method of operating two or more transformers simultaneously, where their primary windings are connected to a common power source, and their secondary windings are connected to a common load. In Uzbekistan’s power grid—particularly within “National Electric Grids of Uzbekistan” JSC—parallel operation systems are widely applied at 110/10 kV, 220/35 kV, and 35/6 kV transformer substations to guarantee continuous power supply.

1. Necessity and Advantages of Parallel Connection

The main purpose of parallel connection is to maintain uninterrupted power supply when the load increases or one transformer fails.

Parallel operation is required in the following cases:

- When the network load exceeds the capacity of a single transformer;
- When one transformer is disconnected during a fault or maintenance;
- When it is necessary to stabilize power distribution within the energy system;
- To provide backup supply during repair or technical service.

Advantages:

- Flexible and even power distribution;
- Balanced load sharing between transformers;
- Reduced risk of system failure;
- Extended service life of transformers;
- Increased efficiency (η) and operational reliability.

2. Main Conditions for Parallel Operation

Before operating transformers in parallel, they must be checked for compatibility conditions, including:

1. Equal Voltage Ratio – The transformation ratio ($k = U_1/U_2$) must be the same; otherwise, internal circulating currents will flow.

$$k = \frac{U_1}{U_2} = \text{const}$$

If the voltage ratios differ from one another, the currents will not be evenly distributed, and one of the transformers will become overloaded.

2. The Phase Sequence Must Be Identical

The phase order (A–B–C) must be the same for both transformers. Otherwise, opposite currents will flow between phases, leading to a short-circuit condition.

3. The Phase Angle (Phase Displacement) Must Be the Same

The connection type (Y/Y, Δ/Δ , Y/ Δ , Δ /Y) must match.

For example, a $\Delta/Y-30^\circ$ transformer cannot be connected in parallel with a $Y/Y-0^\circ$ transformer because their phase displacements differ.

4. The Ratio of Internal Impedances Must Be Equal

The equivalent impedance (Z_{eq}) of each transformer must be nearly identical.

This impedance is expressed as follows:

$$Z_{eq} = \sqrt{R_{eq}^2 + X_{eq}^2}$$

If the impedances are different, the load currents will be distributed unevenly between the transformers.

5. Ratio of rated powers

The rated powers of the transformers S_1, S_2 must be selected so that:

$$\frac{S_1}{S_2} \approx \frac{Z_2}{Z_1}$$

In this way, each transformer carries a load according to its capacity.

3. Current distribution and power balance

When two transformers operate in parallel, the total load current I_t is distributed as follows:

$$I_1 = \frac{Z_2}{Z_1 + Z_2} I_T, \quad I_2 = \frac{Z_1}{Z_1 + Z_2} I_T$$

From this formula, it can be seen that a transformer with lower impedance carries a larger share of the load. Therefore, when selecting transformers, their percentage impedances ($U_k\%$) must be nearly equal. For example, if the first transformer has $U_{k1} = 5\%$ and the second has $U_{k2} = 6\%$, the second transformer

will carry less current, while the first will be overloaded. As a result, power balance between transformers is disturbed, heat losses increase, and efficiency decreases.

Load Stability and Efficiency

Parallel-connected transformers are more adaptable to load fluctuations. For instance, during the summer when demand rises, both transformers operate simultaneously; in winter, when demand decreases, one can remain in reserve — thus saving energy.

The efficiency (η) of parallel transformers is calculated as follows:

$$\eta = \frac{P_{chiqish}}{P_{kirish}} \times 100\%$$

When the load current is properly distributed, the efficiency (η) can increase up to 98–99%.

The efficiency in parallel operation is determined by the following equation:

$$\eta_{umumiy} = \frac{P_1 + P_2}{P_1 + P_2 + \Delta P_1 + \Delta P_2}$$

At this point, ΔP_1 and ΔP_2 represent the active power losses of each transformer. According to tests conducted by the Fergana Transformer Plant in 2023, the total efficiency (η) of two 1600 kVA transformers operating in parallel was 98.7%, which is 1.2% higher than that of a single large transformer.

5. Practical Applications

- Parallel connection is widely used in Uzbekistan's power networks. Some practical examples include:

- Navoi TPP (220/110/10 kV substation): two 40 MVA transformers are connected in parallel, and the load is evenly distributed.
- Tashkent City “Yunusabad” network: two 1000 kVA transformers operate in parallel on a 10 kV network with $\Delta U\% \leq 2.5\%$.
- Fergana plants: at 35/6 kV substations, parallel connection has eliminated 15–20% overload risk.

Parallel connection technology is also applied in solar power plants to synchronize inverter transformers (UzEnergy Research, 2024).

Parallel operation of transformers is a key technical solution that ensures load stability and uninterrupted power supply in electrical networks. For successful operation, voltage ratio, phase sequence, phase angle, and internal impedance must be consistent across all units. Unequal current distribution increases thermal stress on transformers, reducing their efficiency. In Uzbekistan’s energy enterprises, parallel transformer operation has been practically tested, showing efficiency levels of 98–99%. In the future, digital monitoring systems will enable online supervision of parallel transformer performance, further strengthening energy reliability and safety.

Theoretical Questions

2. What is the main necessity of connecting transformers in parallel?
3. What are the advantages of parallel connection in the power system?
4. What are the main conditions that must be fulfilled before operating transformers in parallel?
5. What technical problems occur when the voltage ratios are not equal?
6. Why is it important for the phase sequence and phase angle to be identical?
7. What changes occur in current distribution if the internal impedances are not equal?
8. How is the load current distribution determined in parallel-connected transformers?

9. How does parallel operation of transformers affect efficiency?
10. Give practical examples of using parallel connection in Uzbekistan's power systems.
11. What advantages will digital monitoring systems provide for parallel-connected transformers in the future?

Test Questions

1. The main purpose of connecting transformers in parallel is to:

- A) Increase voltage
- B) Change current frequency
- C) Distribute load and provide backup power
- D) Change phase sequence

2. In parallel operation of transformers, the voltage ratios:

- A) Can be different
- B) Can differ — it is not important
- C) Must be the same
- D) Must be equal only on the high-voltage side

3. If the phase sequence is not identical:

- A) Voltage decreases
- B) A short-circuit condition occurs
- C) Efficiency increases
- D) Load decreases

4. The main advantage of transformers operating in parallel:

- A) Heat loss increases
- B) Load is evenly distributed
- C) Voltage drops
- D) Efficiency decreases

5. Which of the following conditions is not mandatory for parallel connection?

- A) Equality of phase angle

- B) Equality of power rating
- C) Type of transformer (dry or oil-immersed)
- D) Equality of impedance

4. When two transformers are connected in parallel, how is the current distribution determined?

- A) $I_1 = \frac{Z_2}{Z_1 + Z_2} I_T$
- B) $I_1 = \frac{Z_1}{Z_1 + Z_2} I_T$
- C) $I_1 = I_2 = \frac{I_T}{2}$
- D) $I_1 = \frac{U_1}{U_2} I_T$

5. If the internal impedances of the transformers differ, the result will be:

- A) Power is evenly distributed
- B) Currents are unevenly distributed
- C) Load decreases
- D) Voltage increases

6. How is the total efficiency of parallel-operating transformers determined?

- A) $\eta = \frac{U_1}{U_2}$
- B) $\eta = \frac{P_{chiqish}}{P_{kirish}} \times 100\%$
- C) $\eta = \frac{S_1 + S_2}{S_T}$
- D) $\eta = \frac{R}{X}$

7. In Uzbekistan's power networks, parallel transformer connection is mainly used at which voltage levels?

- A) 0.4/0.23 kV
- B) 6/0.4 kV
- C) 35/6 kV, 110/10 kV, 220/35 kV
- D) Above 1000 kV

8. What efficiency level was recorded by the Fergana Transformer Plant for 1600 kVA transformers operating in parallel?

- A) 90%
- B) 95%
- C) 98.7%
- D) 99.9%

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1.12. Methods for determining transformer efficiency (Power factor and losses)

Like any electrical machine, the main indicator of a transformer is its efficiency (η) or coefficient of performance (FIK). Efficiency shows what portion of the input power is converted into useful power — that is, the power delivered to

the load circuit.
Simply put:

$$\eta = \frac{\text{Output Power}}{\text{Input Power}}$$

In transformers, this value usually ranges between 96% and 99%. According to modern energy efficiency standards (IEC 60076-1:2020, O‘zDSt 3055:2021), the efficiency of transformers with a capacity above 1000 kVA must not be lower than 98.5%.

1. Concept and Importance of Efficiency (η)

The efficiency (η) is determined as follows:

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

bu yerda:

P_{out} — output power,

P_{in} — input power.

When the transformer is ideal, the above formula applies; however, in practice, due to heat, magnetic, and copper losses, the efficiency is always less than 100%. The higher the efficiency, the more energy-efficient the transformer is, with lower heat losses and a longer service life.

- For example:
 - Small power transformers (10–25 kVA): $\eta \approx 94\text{--}96\%$
 - Medium power transformers (250–1000 kVA): $\eta \approx 97\text{--}98\%$
 - Large power transformers: $\eta \approx 98.5\text{--}99\%$

2. Determining Active and Magnetic Losses

To determine the transformer's efficiency, the types of losses must first be identified. They are divided into two categories:

1. Active (Copper) Losses (P_1 , P_2)

These losses occur due to the resistance of the winding wires:

$$P_{Cu} = I^2 R$$

Heat is generated in both windings, and part of the energy is lost in this way.

2. Magnetic (Iron) Losses (P_m)

These losses occur due to core imperfections, hysteresis, and eddy currents (loops). They are mainly determined through the no-load test (see Section 1.7).

$$P_{iron} = P_{hysteresis} + P_{eddy\ current}$$

The use of high-quality silicon steel sheets reduces magnetic losses by up to 25–30%.

3. Methods for Determining Transformer Efficiency

There are several methods for calculating the efficiency of transformers:

1. Experimental (Test) Method Based on the values measured during no-load and short-circuit tests:

$$\eta = \frac{P_2}{P_2 + P_{temir} + P_{mis}} \times 100\%$$

bu yerda:

- P_2 — load power,
- $P_{(iron)}$ — core losses,
- $P_{(copper)}$ — winding (copper) losses.

This method is widely used in practical tests at transformer factories in Uzbekistan and in the laboratories of the Tashkent University of Information Technologies (TUIT).

2. Calculation (Theoretical) Method

Based on nominal (rated) data:

$$\eta = \frac{S \cos \varphi}{S \cos \varphi + P_{temir} + P_{mis} \left(\frac{S_{ish}}{S_{nom}} \right)^2}$$

From this formula, the efficiency can be evaluated with respect to the change in load.

3. Graphical (η -P) Method

As the transformer load power changes, the efficiency varies as follows:

Table 1

Load(%)	FIK (%)
25	95.1
50	97.4
75	98.2
100	98.6

4. η -P graph in relation to load variation

The η -P graph allows visual analysis of the transformer's energy efficiency.

In this graph:

- The X-axis represents load in percentage (%),
- The Y-axis represents efficiency (η , %).

At low load, magnetic losses dominate, while as load increases, copper losses become more significant.

The curve on the graph is usually parabolic in shape, and the maximum η value is achieved at 70–80% load.

Therefore, in power systems, it is recommended to operate transformers at optimal load (0.7–0.8 S_{nom}).

5. Measures to improve energy efficiency

To increase efficiency, the following measures are applied:

2. Improvement of magnetic core material

Using amorphous steel instead of silicon steel (Fe-Si) reduces losses by up to 25%.

3. Optimization of winding conductors

Using high-conductivity copper or aluminum wires and reducing heat losses through better cooling.

4. Modernization of the oil cooling system

Automating oil circulation helps maintain temperature within the normal range.

5. Implementation of digital monitoring systems

Online monitoring of temperature, load, voltage, and efficiency (Smart Transformer technology).

6. Use of modern dielectric fluids

Replacing mineral oil with eco-friendly silicone or ester-based fluids improves thermal stability.

For example, the TMG-1600/10 model (2024) produced by the Fergana Transformer Plant has shown 1.3% higher efficiency (98.9%) compared to the previous generation.

Theoretical Questions

1. What is the transformer's efficiency (η), and what does it represent?
2. Which parameters affect the efficiency value of a transformer?
3. How are active (copper) and magnetic (iron) losses determined?
4. How can efficiency be found using the open-circuit and short-circuit tests?
5. How does efficiency change when load increases, and why?
6. How is the η -P graph constructed, and what is its physical meaning?
7. Why is the transformer's efficiency highest at the optimal load range (70–80%)?
8. What role do magnetic materials and the cooling system play in improving efficiency?
9. How do digital monitoring systems (Smart Transformers) control efficiency?
10. What technologies are being introduced in Uzbek transformer plants to improve energy efficiency?

Test Questions

1. The efficiency (η) of a transformer is determined by the following formula:

- A) $\eta = \frac{U_1 I_1}{U_2 I_2} \times 100$
- B) $\eta = \frac{P_{chiqish}}{P_{kirish}} \times 100$
- C) $\eta = \frac{U_2}{U_1} \times 100$
- D) $\eta = \frac{I_1}{I_2} \times 100$

2. The main types of transformer losses are:

- A) Thermal and mechanical losses
- B) Active (copper) and magnetic (iron) losses ✓

- C) Electrical and chemical losses
- D) Magnetic and acoustic losses

3. Active losses are determined by the following formula:

A) $P_{Cu} = I^2 R$

B) $P_{Fe} = U^2 / R$

C) $P_{Cu} = UI \cos \varphi$

D) $P_{Cu} = R / I^2$

4. Which of the following causes the efficiency (η) to decrease?

- A) Power factor
- B) Magnetic losses
- C) Transformer efficiency
- D) Load stability

5. The efficiency of a transformer usually ranges between:

- A) 80–85%
- B) 90–92%
- C) 96–99%
- D) 70–75%

6. The graph showing the relationship between efficiency and load is called:

- A) U–I graph
- B) η –P graph
- C) f–t graph
- D) U–f graph

7. When the optimal load is between 70–80%, the efficiency:

- A) Is the lowest
- B) Remains unchanged
- C) Reaches its maximum value
- D) Equals zero

8. The following measures are used to improve efficiency, except:

- A) Installing an effective cooling system
- B) Using amorphous materials instead of magnetic steel
- C) Artificially increasing the impedance
- D) Installing a digital monitoring system

9. In transformers made of amorphous steel, magnetic losses:

- A) Increase by 10%
- B) Decrease by 25–30%
- C) Double
- D) Remain unchanged

10. The efficiency indicator of the TMG-1600/10 type transformer produced by the Fergana Transformer Plant is:

- A) 95%
- B) 97%
- C) 98.9%
- D) 100%

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1.13. Thermal stability and cooling systems of transformers

Thermal stability is one of the most essential conditions for the efficient operation of a transformer. During the process of electrical energy transmission, the current flowing through the windings generates heat due to their internal resistance. If this heat is not dissipated in time, the insulation will overheat, the service life of the transformer will be shortened, and even an emergency situation may occur.

In modern transformers, heat dissipation and cooling systems (such as ONAN, ODAF, OFAF, etc.) are specially designed to maintain temperature within permissible limits. In Uzbekistan's power networks, the technical modernization of cooling systems has become an important direction in reducing electrical losses.

1. Causes of Heat Generation

The main causes of heat generation in transformers are as follows:

Copper (active) losses (P_{mis}):

Because of the electrical resistance of the winding wires, heat is generated

according to Joule's law
$$P = I^2 R$$
.

This heat accumulates inside the windings and damages the insulation.

2. Iron (magnetic) losses (P_m):

-These occur in the core as a result of hysteresis and eddy (circulating) currents.

-Such losses exist even when the transformer is running without load.

3. Ventilation and mechanical losses:

-Additional heat is generated by oil pumps, cooling fans, and mechanical vibrations.

-Practical measurements show that, when operating at full (100%) load, a 1000 kVA transformer experiences an average temperature rise of 35–45°C.

2. Thermal Stability Model

The thermal stability of a transformer is determined by its temperature balance equation, expressed as:

$$P_{yo'qotish} = P_{tarqalish}$$

- $P_{yo'qotish} = P_{mis} + P_{temir}$

— total heat power generated in the transformer;

- $P_{tarqalish}$

— the amount of heat transferred to the surrounding environment through the cooling system.

If $P_{yo'qotish} > P_{tarqalish}$, the transformer overheats, and its thermal stability is lost.

Temperature Change Over Time – Thermodynamic Differential Model

The change in temperature over time is expressed by the thermodynamic differential equation:

$$C \frac{dT}{dt} = P_{yo'qotish} - k(T - T_{muhit})$$

where:

- C – heat capacity (J/°C),
- k – heat transfer coefficient,
- T_{muhit} – ambient temperature.

For thermal stability, the condition

$$\frac{dT}{dt} = 0$$

must be satisfied.

3. Cooling Systems (ONAN, OFAF, ODAF)

According to the international standard IEC 60076-2, transformer cooling systems are classified into the following types:

Table 1. Types of Transformer Cooling Systems

Designation	Full name	Description
ONAN	Oil Natural	The oil circulates naturally, and the surrounding air also provides natural cooling.

Designation	Full name	Description
	Air Natural	
ONAF	Oil Natural Air Forced	The oil circulates naturally, but the air is moved by a fan to improve cooling efficiency.
OFAF	Oil Forced Air Forced	The oil is circulated by a pump, and the air is blown by a fan. This method enhances cooling for higher-capacity transformers.
ODAF	Oil Directed Air Forced	The oil is directed through special ducts between windings, while the air is forced by fans, ensuring uniform cooling of the windings.

The ONAN system is used in small and medium-capacity transformers (up to 1600 kVA), while OFAF and ODAF systems are designed for large power transformers (10–100 MVA).

These systems are selected according to the transformer's power rating, cooling requirements, and operating environment. In practice, ONAN systems provide sufficient natural convection for distribution transformers, whereas OFAF and ODAF ensure effective temperature control and reliability in high-voltage substations and industrial power networks.

4. Thermal analysis in ANSYS

In modern transformers, modeling heat distribution with ANSYS Fluent or COMSOL Multiphysics helps optimize thermal design. The simulation accounts for the following parameters:

Oil flow velocity (m/s);

Temperature gradient ($^{\circ}\text{C}/\text{m}$);

Maximum temperature in the windings and core;

Viscosity and thermal conductivity coefficients.

For example, according to ANSYS simulation results for a 2500 kVA transformer:

- Maximum temperature: 87 °C
- Cooling efficiency: 96%
- Temperature uniformity: within ± 5 °C

5. Directions for modernizing cooling systems

In recent years, transformer manufacturers in Uzbekistan have implemented a series of measures to upgrade cooling systems. The main directions are:

Digital Thermal Supervision (DTS)

- Thermosensors are installed on each winding to monitor temperature in real time.
- With a Smart Cooling system, fan speed is automatically controlled.

Environmentally friendly dielectric fluids

- Silicone- or ester-based fluids are used instead of mineral oil, reducing fire risk.

High-efficiency ventilation modules

- Aerodynamic radiators that increase airflow by 30%.

Waste-heat recovery systems

- Thermal energy is reused in industrial heating systems (a regenerative energy cycle).

According to the 2024 report of the UzEnergy Research Institute, upgraded cooling systems have reduced annual energy losses by 1.8–2.2%.

6. Practical example

The OFAF-40000/110 transformer manufactured at the Fergana Transformer Plant demonstrates the following technical results: (details to follow).

Table-2

Parameter	Value
Rated power	40 MVA
Efficiency	98,7 %
Maximum temperature	85°C
Cooling system	OFAF
Oil circulation velocity	1,8 m/s
Oil temperature difference	12°C

These results indicate that the transformer has high thermal stability and energy efficiency equivalent to the international IE4 class. This classification confirms that the OFAF-40000/110 transformer operates with minimal energy losses, stable thermal balance, and optimal cooling performance — meeting advanced global standards for industrial and power transformers.

Theoretical Questions

1. What are the main causes of heat generation in transformers?
2. What is thermal stability, and under what condition is it maintained?
3. How are active and magnetic types of heat losses determined?
4. What does the “heat balance equation” represent in the thermal stability model?
5. What are the main differences between the ONAN, OFAF, and ODAF cooling systems?
6. What are the advantages of performing thermal analysis in the ANSYS software?

7. How does the efficiency of the cooling system affect the transformer's efficiency (η)?
8. What is the function of digital thermal monitoring systems (DTS, Smart Cooling)?
9. What advantages do ecological oils (silicone- or ester-based fluids) have?
10. List the main directions of cooling system modernization in transformer plants of Uzbekistan.

Test Questions

1. The main cause of heat generation in transformers is:

- A) Dielectric losses
- B) Winding resistance and magnetic losses
- C) Mechanical vibrations
- D) Radiation losses

2. Which equation expresses the condition of thermal stability?

- A) $P_{yo'qotish} = P_{tarqalish}$
- B) $P_{yo'qotish} > P_{tarqalish}$
- C) $P_{yo'qotish} < P_{tarqalish}$
- D) $P_{yo'qotish} = 0$

3. What is meant by the ONAN cooling system?

- A) Oil and air are forced to circulate
- B) Oil circulates naturally, but air is forced
- C) Oil and air circulate naturally
- D) Cooling is done only with water

4. How is cooling carried out in the OFAF system?

- A) Only by natural temperature flow
- B) Only by oil circulation

- C) Both oil and air are forced to move
- D) Only by water cooling

5. What happens when the transformer's thermal stability is disturbed?

- A) Voltage increases
- B) Phase shift decreases
- C) Insulation overheats and fails
- D) Power stability increases

6. Which process is analyzed using the ANSYS software?

- A) Electrical conduction process
- B) Heat distribution and temperature gradient
- C) Magnetic flux modulation
- D) Mechanical vibration amplitude

7. Which system is used in large power transformers?

- A) ONAN
- B) ODAF
- C) ONAF
- D) OFNF

8. What function does the Digital Thermal Supervision (DTS) system perform?

- A) Measures frequency
- B) Determines efficiency (η)
- C) Monitors temperature in real time
- D) Increases oil pressure

9. Which measure improves the efficiency of the cooling system?

- A) Reducing the number of radiators
- B) Stopping oil circulation
- C) Installing aerodynamic ventilation modules
- D) Reducing the number of phases

10.What is the maximum temperature in the OFAF-40000/110 transformer produced at the Fergana Plant?

- A) 60 °C
- B) 70 °C
- C) 85 °C
- D) 100 °C

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CHAPTER II. ELECTRICAL MACHINES

2.1. General concept and classification of electrical machines

The development of modern technology and industry cannot be imagined without devices that convert various forms of electrical energy into mechanical, thermal, or chemical energy. The main technical means that perform this process are electrical machines.

Electrical machines are electromechanical devices that convert electrical energy into mechanical energy or, conversely, mechanical energy into electrical energy. They are among the most widely used technical systems in power engineering, transportation, manufacturing, automation, robotics, and household applications.

1. The Essence of Electrical Machines

An electrical machine operates based on the law of electromagnetic induction.

That is, energy exchange occurs through a magnetic field and an electrical circuit that are interconnected.

This process is divided into two types:

1. Generator mode-mechanical energy is converted into electrical energy.
2. Motor mode-electrical energy is converted into mechanical rotational energy..

2. Classification of electrical machines

When classifying electrical machines, factors such as the principle of energy conversion, type of current, source of the magnetic field, and structural design are taken into account.

Table-1

Category	Type of Machine	Description
By type of current	Direct current (DC) machines	Generators, motors, and braking devices
By type of current	Alternating current (AC) machines	Asynchronous and synchronous types
By function	Generators	Convert mechanical energy into electrical energy
By function	Motors	Convert electrical energy into mechanical energy
By source of magnetic field	Permanent magnet type	Operates using a permanent magnet
By source of magnetic field	Electromagnetic type	Operates using a magnetic field generated by electric current

3. Main types and their operating principles

1. Generator

A generator converts mechanical energy into electrical energy. This process is based on Faraday's law of electromagnetic induction, which states: An electromotive force (EMF) is induced in a conductor when it moves through a magnetic field or when the magnetic flux linking the circuit changes over time.

In a generator, when the rotor (armature) rotates inside the magnetic field, a changing magnetic flux cuts across the conductors, inducing an electromotive force (EMF). If the circuit is closed, an electric current begins to flow, thus converting mechanical rotational energy into electrical energy.

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

here:

- E – the generated electromotive force (EMF),
- N – number of turns,
- Φ – magnetic flux,
- $d\Phi/dt$ – rate of change of magnetic flux.

Generators are widely used in power plants-including hydroelectric, thermal, wind, and nuclear stations.

2.Motor

A motor is a machine that converts electrical energy into mechanical rotational energy. Its operating principle is based on Lorentz's force law, which states:

When a conductor carrying current is placed in a magnetic field, it experiences a mechanical force.

In an electric motor, this force acts on the current-carrying conductors within the magnetic field, producing torque and causing the rotor to rotate — thereby converting electrical energy into mechanical motion.

$$F = BIL \sin \alpha$$

here:

- B – magnetic induction,
- I – current,
- L – length of the conductor,
- α – angle between the conductor and the magnetic induction.

Electric motors are currently used for the following purposes:

- To drive conveyor lines in factories;
- To control elevator and pump systems;
- As the main source of motion in transport vehicles (such as electric buses and subways).

3. Converter (Rectifier/Inverter)

A converter is a device that transforms one form of electrical energy into another.

For example:

- AC/DC converter (rectifier)
- DC/AC inverter (inversion device)

Modern converters operate on semiconductor components such as transistors, thyristors, and IGBT modules.

They are mainly used in automated control systems, power electronics, and energy supply units.

4. Production of Electrical Machines in Uzbekistan

In recent years, there has been significant progress in the production of electrical machines in Uzbekistan.

- Fergana Transformer Plant — manufactures large electrical machines with capacities ranging from 10 to 63 MVA.
- Tashkent Electrical Engineering Plant (TETZ) — produces low-power asynchronous motors, pump motors, and generators.
- Navoi Electrotechnical Cluster — produces energy-efficient synchronous machines based on Smart Motor technologies.

According to the 2024 report by the UzEnergy Research Institute, the average efficiency (η) of electrical machines produced in Uzbekistan ranges between 94–98%.

5. Energy Efficiency and Modern Technologies

Today, the design of electrical machines incorporates the following technologies:

1. Digital modeling (ANSYS, MATLAB/Simulink) – allows prediction of electromagnetic fields and energy flow in advance.
2. Semiconductor control (IGBT, MOSFET) – enables electronic control of motor speed.
3. Sensor-based monitoring systems (Smart Motor Control) – provide real-time observation of temperature, load, and vibration.
4. Improvement of magnetic materials – uses amorphous steels to reduce hysteresis losses.

With these technologies, energy consumption in manufacturing processes is reduced by 10–15%, and the service life of machines is increased by 1.5 times.

2.2. Operating principle and main components of Asynchronous machines

Asynchronous machines are among the most important and widely used components of modern electrical power systems. They serve to convert electrical energy into mechanical energy (as motors) or, conversely, mechanical energy into electrical energy (as generators).

Globally, more than 80% of all electric motors produced are asynchronous machines, distinguished by their simple design, high reliability, and ease of maintenance.

In Uzbekistan's industry, asynchronous motors are used as the main driving force for pumps, compressors, fans, conveyors, and production lines.

The essence of the Asynchronous machine

The term “asynchronous” comes from the Greek words “syn” — meaning “together” and “chronos” — meaning “time.” This indicates that in such machines, the rotor speed slightly differs from the magnetic field speed. In asynchronous motors, current is induced in the rotor due to electromagnetic induction, and this current interacts with the rotating magnetic field, producing torque. If the rotor

were to rotate at the same speed as the magnetic field, no induction current would be generated, and the motor would stop. Therefore, there is always a relative speed difference between the rotor and the magnetic field, called slip (s).

$$s = \frac{n_s - n}{n_s} \times 100\%$$

here:

- n_s – synchronous speed (speed of the magnetic field),
- n – actual rotational speed of the rotor.

2. Main Parts of an Asynchronous Machine

An asynchronous machine consists of two main parts: the stator and the rotor.

1. Stator (Stationary Part)

- The external, non-moving part of the machine.
- Contains three-phase windings that receive three-phase current from the supply network.
- These windings produce a rotating magnetic field.

The stator core is made of electrical steel laminations. These laminated sheets are insulated from one another to reduce eddy current losses and improve efficiency.

2. Rotor (Rotating Part)

The rotating part located inside the stator, which generates electromagnetic force from the magnetic field.

Rotors are of two types:

- Squirrel-cage rotor (short-circuited type) – the most commonly used design.

- Wound rotor (slip-ring type) – provides flexibility during starting and speed control.

The rotor windings consist of copper or aluminum bars, short-circuited at both ends by rings, forming a “squirrel cage” structure.

3. Core and Frame

- The machine frame ensures mechanical stability and support.
- Core materials are designed to withstand heat and vibration.
- In large machines, fans and cooling ducts are installed to dissipate heat efficiently.

3. Operating Principle

The operation of an asynchronous machine is based on the theory of the rotating magnetic field:

1. The stator is connected to a three-phase power supply.
2. Each phase creates its own magnetic flux.
3. Due to the 120° phase displacement between the three currents, a resultant rotating magnetic field is produced.
4. This rotating magnetic field cuts across the rotor conductors, inducing a current in them through electromagnetic induction.
5. The induced current interacts with the stator’s magnetic field, producing a rotating torque (M), which causes the rotor to spin.

$$M = k\Phi I_2 \cos \varphi_2$$

here:

- Φ – magnetic flux,
- I_2 – rotor current,
- φ_2 – phase angle.

As a result, the rotor rotates in the direction of the magnetic field, but its speed is slightly lower than the synchronous speed ($n < n_s$).

4. Types of Asynchronous machines

Asynchronous machines are classified according to the following characteristics:

Table-1

Category	Type	Description
By rotor type	Squirrel-cage (short-circuited)	The simplest design; requires no maintenance.
By rotor type	Wound (slip-ring)	Provides high starting torque and stable operation under load.
By operating mode	Dvigatel	Converts electrical energy into mechanical energy.
By operating mode	Generator	Converts mechanical energy into electrical energy.

In industrial enterprises of Uzbekistan, squirrel-cage asynchronous motors are mainly used because they are simple in design, inexpensive, and highly efficient.

5. Rotational speed and slip The rotational speed of the magnetic field generated by the stator is determined by the following formula:

$$n_s = \frac{120 \times f}{p}$$

where:

- n_s – synchronous speed (revolutions per minute, rpm);
- f – supply frequency (Hz);
- p – number of magnetic pole pairs.

The **rotor speed** (n) is always slightly less than n_s , and their difference determines the **slip** (s):

$$s = \frac{n_s - n}{n_s} \times 100\%$$

Slip indicates the relative speed difference between the magnetic field and the rotor — a key factor that enables electromagnetic induction and torque generation in asynchronous machines.

If the rotor rotates at 1440 rpm, the slip is calculated as follows:

$$s = \frac{1500 - 1440}{1500} \times 100 = 4\%$$

In this case, the motor operates under normal load conditions, meaning there is no excessive heat, and the torque remains stable.

6. Advantages of Asynchronous Machines

1. High simplicity and reliability.
2. Low maintenance requirements.
3. Starting and control systems are relatively inexpensive.

4. High efficiency — up to 92–96%.
5. Can be manufactured for different power levels and frequencies.
6. Excellent mechanical strength and long service life.

7. Application of Asynchronous Machines in Uzbekistan's Industry

In recent years, Uzbekistan's electrical machine industry has undergone significant modernization.

Major manufacturers include:

1. Fergana Electrical Machines Plant,
2. Tashkent Electrotechnical Plant (TETZ),
3. Navoi Electrotechnical Cluster.

In 2023, the ADN-132M4 motor model achieved an efficiency of 95.2%.

Local manufacturers have started exporting asynchronous motors that meet the IE3 (High Efficiency) standard.

According to UzEnergy Research Institute, by 2025, more than 75% of electric motors in the country will belong to the energy-efficient class.

Asynchronous machines play a strategic role in ensuring energy efficiency and economic stability in Uzbekistan's industrial sector.

Theoretical Questions

1. What is the basic operating principle of asynchronous machines based on?
2. Why are these machines called asynchronous?
3. What is slip, and what is its physical meaning?
4. Explain the structure and function of the stator.
5. Describe the types of rotors and their differences.
6. How is the torque generated in an asynchronous machine?
7. How is the rotating magnetic field produced by the stator formed?
8. Compare the generator and motor modes of asynchronous machines.

9. List the main application areas of asynchronous machines in Uzbekistan's industry.
10. What technologies are used in modern asynchronous motors to improve energy efficiency?

Test Questions

1. What does the term “asynchronous” mean?

- A) A machine operating synchronously
- B) A machine with identical phase sequence
- C) A machine whose speed differs from the magnetic field speed
- D) A machine with a stationary stator

2. In an asynchronous motor, the rotor speed is always:

- A) Greater than the magnetic field speed
- B) Less than the magnetic field speed
- C) Equal to the magnetic field speed
- D) Equal to zero

3. How is the slip (s) determined?

- A) $s = \frac{n}{n_s} \times 100\%$
- B) $s = \frac{n_s - n}{n_s} \times 100\%$
- C) $s = \frac{n_s}{n} \times 100\%$
- D) $s = \frac{n - n_s}{n} \times 100\%$

4. The main function of the stator is:

- A) To produce mechanical energy
- B) To create a rotating magnetic field
- C) To measure electrical energy
- D) To cool the rotor

5.The most common type of rotor is:

- A) Wound rotor
- B) Squirrel-cage (short-circuited) rotor
- C) Polyphase rotor
- D) Permanent magnet rotor

6.The torque of an asynchronous machine depends on which physical quantities?

- A) Magnetic flux and rotor current
- B) Voltage and frequency
- C) Resistance and capacitance
- D) Current and frequency

7.In an asynchronous motor, the synchronous speed (n_s) is determined by the following formula:

A) $n_s = \frac{60f}{p}$

B) $n_s = \frac{120f}{p}$

C) $n_s = \frac{p}{60f}$

D) $n_s = 120pf$

8.Which of the following represents the typical slip value for asynchronous machines?

- A) 0.001%
- B) 0.1–0.2%
- C) 0.5–5%
- D) 10–15%

9.The main advantage of asynchronous machines is:

- A) Their ability to generate high torque

- B) Simplicity and reliability
- C) Low efficiency
- D) Difficulty in starting

10. The energy efficiency class of asynchronous motors produced in Uzbekistan is:

- A) IE1
- B) IE2
- C) IE3 (High Efficiency)
- D) IE0

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2.3. Structure and functional characteristics of a three-phase asynchronous (induction) motor

Three-Phase Asynchronous Motor (Induction Motor)-The three-phase asynchronous motor (TAM) is the most widely used type of machine that converts electrical energy into mechanical rotational energy. Due to its simplicity,

reliability, low cost, and high efficiency, this type of motor is used as the main driving force in industries worldwide, including enterprises in Uzbekistan.

More than 80% of modern production lines are powered by three-phase asynchronous motors. These machines are widely used in transformers, compressors, pumps, elevators, conveyors, cooling systems, and electric transport vehicles.

1. Three-Phase Stator Windings and Their Arrangement

The stator is the stationary part of the motor, and its main function is to create a rotating magnetic field using three-phase alternating current.

The stator consists of the following elements:

- Frame (housing): made of steel, provides mechanical strength and support for the motor.
- Core (magnetic circuit): assembled from laminated electrical steel sheets to conduct magnetic flux efficiently.
- Windings: made of copper wires connected to a three-phase power source.

Each phase winding is placed 120° apart from the others. This arrangement creates a phase and time displacement between the currents of each phase, which is the fundamental condition for generating a rotating magnetic field.

2. Types of Rotors: Squirrel-Cage and Wound Rotor

The rotor is the rotating part of the motor that moves under the influence of the rotating magnetic field produced by the stator. There are two main types of rotors:

Table 1.

Type	Description	Application
Squirrel-cage rotor	Consists of aluminum or copper bars short-circuited at both ends. Simple, reliable, and low-cost design.	Standard industrial machines, pumps, and fans.

Type	Description	Application
Wound (slip-ring) rotor	The winding ends are connected to external resistors through slip rings. Provides high starting torque.	Heavy-load and lifting machines, cranes.

When the magnetic field of the stator cuts through the rotor windings, the phenomenon of electromagnetic induction occurs, resulting in the generation of current. This current interacts with the magnetic field and produces a rotating torque

3. Formation of Magnetic Flux in the Air Gap

The air gap between the stator and rotor (usually 0.5–2 mm) is the zone through which the magnetic flux passes.

It directly affects the efficiency and torque of the machine.

The magnetic flux is formed as follows:

- The three-phase current in the stator creates a magnetic field.
- This magnetic field passes through the air gap and cuts across the rotor conductors.
- Due to electromagnetic induction, current is generated in the rotor conductors.
- The induced current interacts with the magnetic field, producing a rotating torque.

As a result, the rotor begins to rotate in the direction of the magnetic field, but at a slightly lower speed than the field itself — this condition is known as slip.

4. Characteristics of the Rotating Field

The operation of a three-phase asynchronous motor is based on the theory of the rotating magnetic field. Due to the 120° phase difference between the three-phase currents, the magnetic field rotates at a constant speed. This speed is called the synchronous speed, which depends on the frequency and the number of poles:

$$n_s = \frac{120f}{p}$$

where:

- n_s – synchronous speed (rpm),
- f – supply frequency (Hz),
- p – number of poles.

If the supply frequency is 50 Hz and the number of poles is 4, the synchronous speed will be 1500 rpm. However, the actual rotor speed is slightly lower due to the presence of slip.

Main Characteristics of the Rotating Magnetic Field

- Its direction depends on the phase sequence of the supply.
- Under the influence of the magnetic flux, the rotor produces continuous torque.
- The speed of the magnetic field is directly proportional to the supply frequency.

5. Technical Functions of Main Components

A three-phase asynchronous motor consists of the following main components:

Table 2.

Part name	Function
Stator	Generates the rotating magnetic field..
Rotor	Interacts with the magnetic field and produces mechanical torque.
Air gap	Forms the zone through which the magnetic flux passes.

Part name	Function
Bearing (support)	Keeps the rotor stable during mechanical rotation.
Frame (housing)	Protects the machine and holds the cooling system..
Fan	Removes heat and accelerates the cooling process..

These components are interconnected and together form an integrated system that ensures the energy conversion process operates smoothly and efficiently.

Theoretical Questions

1. What is the main function of a three-phase asynchronous motor?
2. How are the three-phase stator windings arranged, and why is there a 120° phase difference between them?
3. Explain the main differences between a squirrel-cage rotor and a wound (slip-ring) rotor.
4. How is the rotating magnetic field generated?
5. Explain the effect of the air gap on the efficiency of the motor.
6. What is meant by synchronous speed, and how is it determined?
7. Why does slip occur in an asynchronous motor?
8. List the main structural components of the motor and their functions.
9. What is the importance of the cooling system in the operation of an electric machine?
10. Explain the energy efficiency level of three-phase asynchronous motors produced in Uzbekistan's industry.

Test Questions

1. The main function of a three-phase asynchronous motor is:

- A) To convert electrical energy into heat energy

- B) To convert electrical energy into mechanical energy
- C) To convert mechanical energy into electrical energy
- D) To change the frequency

2.The phase difference between three-phase stator windings is:

- A) 60°
- B) 90°
- C) 120°
- D) 180°

3.What is a squirrel-cage rotor?

- A) Rotor with external contacts
- B) Rotor made of aluminum or copper bars short-circuited at both ends
- C) Rotor with phase windings
- D) Rotor with permanent magnets

4.In which applications is the wound (slip-ring) rotor mainly used?

- A) Low-load fans
- B) Light mechanisms
- C) Lifting cranes and elevators
- D) Air conditioning systems

5.If the air gap increases, what happens in the motor?

- A) Power increases
- B) Torque decreases
- C) Heat decreases
- D) Slip disappears

6.The synchronous speed is determined by the following formula:

- A) $n_s = \frac{60f}{p}$
- B) $n_s = \frac{120f}{p}$
- C) $n_s = \frac{p}{120f}$
- D) $n_s = 60fp$

7. When the slip value increases:

- A) Rotor speed increases
- B) Magnetic flux decreases
- C) Rotor speed decreases
- D) Stator resistance increases

8. Through which element is the motor's heat dissipation system implemented?

- A) Frame (housing)
- B) Fan
- C) Stator windings
- D) Bearing

9. How is the rotating magnetic field generated in a three-phase motor?

- A) Through the frequency difference between currents
- B) Due to the 120° phase difference between the currents
- C) By rotor rotation
- D) Using a static magnetic flux

10. The energy efficiency class of asynchronous motors produced in Uzbekistan is:

- A) IE1
- B) IE2
- C) IE3
- D) IE0

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2.4. Equivalent circuit of an Asynchronous (induction) motor (T-type))

In the analysis of electrical processes in an asynchronous motor, equivalent circuits are used. Among them, the most widely applied is the T-type equivalent circuit, which mathematically represents all the motor’s main electrical parameters — resistance, reactance, losses, and power distribution. With the help of the T-type equivalent circuit, it becomes possible to accurately model the machine’s behavior under various operating conditions, such as:

- Power distribution
- Currents and voltages
- Heat losses
- Efficiency level

This circuit plays a particularly important role at the calculation and theoretical analysis stage, since it allows the behavior of the asynchronous motor to be viewed as a simple electrical network, making complex electromagnetic processes easier to understand and analyze.

1. Elements of the T-type equivalent circuit

The T-type equivalent circuit represents the electrical behavior of an asynchronous motor through the following main elements:

Table-1

Element	Symbol	Description / Function
Stator resistance	R_1	Represents copper losses (I^2R) in the stator windings.
Stator reactance	X_1	Represents leakage flux and the inductive reactance of the stator.
Magnetizing reactance	X_m	Represents the main magnetic flux linking the stator and rotor.
Core loss resistance	R_c	Represents iron (hysteresis and eddy current) losses in the magnetic core.
Rotor resistance (referred to stator side)	R_2/s	Represents rotor copper losses, varying with slip (s). When slip decreases, R_2/s increases.
Rotor reactance (referred to stator side)	X_2	Represents the rotor leakage reactance caused by magnetic leakage.

These elements together provide a complete model of the electromagnetic processes in the motor. The external supply voltage U_1 is applied to the stator, resulting in a current I_1 , which transfers energy through the magnetizing branch to the rotor circuit.

2. Determination of equivalent parameters

Each element's value is determined experimentally through two standard tests — no-load and short-circuit tests:

- From the no-load test, the parameters R_c and X_m are obtained.
- From the short-circuit test, the parameters R_1 , X_1 , R_2' , X_2' are determined.

Once these values are measured, they are combined into the T-type equivalent circuit, which allows analytical calculations of current, losses, and power distribution.

As a result, the following fundamental expression is derived:

$$I_1 = \frac{U_1}{R_1 + jX_1 + \frac{(R_2'/s) + jX_2'}{1 + \frac{(R_2'/s) + jX_2'}{R_c \parallel jX_m}}}$$

This expression forms the basis for analyzing the electrical performance of an asynchronous motor, enabling evaluation of:

- Input current (I_1),
- Magnetizing current,
- Rotor current,
- Power losses,
- Efficiency and torque characteristics under various load conditions.

$$I_1 = I_0 + I_2'$$

$$U_1 = I_1(R_1 + jX_1) + E_1$$

$$E_1 = I_m(R_c \parallel jX_m)$$

Using these equations, the motor's power losses and torque can be calculated.

3. Power distribution depending on slip

An important characteristic of the asynchronous motor is that the rotor speed is slightly lower than the synchronous speed. The difference between them is denoted

$$s = \frac{n_s - n}{n_s}$$

by slip (s).

The rotor power is divided into three parts depending on the slip:

Table-2

Type of power	Description
P_2	Electromagnetic power entering the rotor
sP_2	Heat loss (in the rotor resistance)
$(1-s)P_2$	Mechanical power (rotational energy)

Thus, as the slip increases, losses rise and efficiency decreases. When the slip is close to zero, the motor efficiency reaches its maximum.

4. Operating Modes and Energy Balance

In an asynchronous motor, electrical energy is gradually converted as follows:

Electrical energy (stator) → Magnetic energy (magnetic circuit) → Induction (rotor) → Mechanical energy (through the shaft)

Overall power balance:

$$P_1 = P_{Cu1} + P_{Fe} + P_2$$

$$P_2 = P_{Cu2} + P_{mech}$$

Here:

- P_{Cu1} — heat loss in the stator,
- P_{Fe} — core (magnetic) loss,
- P_{Cu2} — heat loss in the rotor conductors,
- P_{mex} — useful mechanical power.

As a result, the efficiency is determined by the following formula:

$$\eta = \frac{P_{mex}}{P_1} \times 100\%$$

5. Fundamentals of Modeling in MATLAB

In modern scientific and practical experiments, the T-shaped model of an asynchronous motor is simulated in MATLAB/Simulink. The following blocks are used for this purpose:

- R-L networks – represent resistance and reactance,
- Voltage Source – provides the supply voltage,
- Scope – monitors current, power, and torque variations,
- Slip parameter – models motion that changes with load.

This method allows visualization of power losses and torque graphs in real time under different load conditions.

Theoretical Questions

1. What is a T-shaped equivalent circuit, and which aspect of the asynchronous motor does it represent?
2. List the main elements of the T-shaped circuit.
3. Explain the concepts of equivalent resistance and reactance.
4. How does power distribution change with slip variation?
5. Describe the effect of stator and rotor resistances on motor efficiency.

6. How is motor efficiency determined using the T-shaped circuit?
7. For what purposes is the T-shaped circuit used in industrial practice?
8. Briefly explain the process of creating a T-shaped model of an asynchronous motor in MATLAB.
9. In what mode does the motor operate when slip equals zero?
10. Explain the advantages of using the T-shaped model to determine losses.

Test Questions

1. What is the purpose of using the T-shaped equivalent circuit of an asynchronous motor?

- A) To measure mechanical torque
- B) To calculate electrical parameters
- C) To control speed
- D) To evaluate the cooling system

2. What does the vertical branch of the T-shaped circuit represent?

- A) Magnetic losses
- B) Stator resistance
- C) Reactive component
- D) Conductivity

3. What does the stator resistance R_1 represent?

- A) Magnetic flux at the rotor surface
- B) Heat loss in the stator windings ✓
- C) Inductive current in the air gap
- D) Rotor torque

4. How is the rotor resistance R_2' determined?

- A) Equal to rotor size
- B) Dependent on the transformation ratio with the stator
- C) Proportional to slip
- D) Inversely related to stator current

5. When the slip value $s=1$, the motor operates in which mode?

- A) Synchronous mode
- B) Generator mode
- C) Starting (startup) mode
- D) Normal load condition

6. What does X_m in the T-shaped circuit represent?

- A) Magnetizing reactance
- B) Thermal conductivity
- C) Rotor branch
- D) Resistance losses

7. In the equivalent circuit, how is the total input power distributed?

- A) Into thermal, magnetic, and mechanical powers
- B) Into current, voltage, and frequency
- C) Into inductive and active losses
- D) Into phase angle

8. What is the main purpose of using the T-shaped model in MATLAB?

- A) To create a graphical interface
- B) To simulate motor operation
- C) To optimize code
- D) To reduce power consumption

9. If slip $s=0$, the motor's rotational speed is:

- A) Zero
- B) Equal to synchronous speed
- C) Increases infinitely
- D) At minimum value

10. In the T-shaped circuit, efficiency is determined by which ratio?

- A) Useful power / Total power
- B) Total power / Useful power

C) Current / Voltage

D) Slip / Frequency

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2.5. Relationship between electromagnetic torque and rotational speed

During the operation of an asynchronous motor, the electromagnetic torque is one of its most important physical indicators. It directly determines the efficiency of converting electrical energy into mechanical rotational energy. The motor torque (rotating force) is produced as a result of the interaction between the rotating magnetic field and the rotor conductors. The value of the torque depends on the load, voltage, slip, and supply frequency. Therefore, a thorough study of electromagnetic torque is the main condition for analyzing any operating mode of an asynchronous motor.

1. Physical essence of electromagnetic torque

In an asynchronous motor, electric current passes through the stator windings, creating a rotating magnetic field. This field cuts across the rotor conductors and induces current in them. The interaction between the current in the rotor conductors and the stator's magnetic field produces electromagnetic torque.

This phenomenon can be described as follows:

“If the magnetic field lines cut across a conductor carrying current, a magnetic force acts on the conductor.”

The sum of these forces generates the rotating torque on the motor shaft.

Thus, the electromagnetic torque is a combined expression of electrical and mechanical processes.

2. Mathematical expression of torque generation

The value of the electromagnetic torque is determined by the following equation:

$$M = \frac{3U_1^2 R'_2 / \omega_s}{(R_1 + R'_2 / s)^2 + (X_1 + X'_2)^2}$$

Here:

- U_1 — stator phase voltage,
- R_1, X_1 — stator active and inductive reactances,
- R'_2, X'_2 — rotor active and reactive resistances referred to the stator,
- s — slip,
- ω_s — synchronous angular velocity.

This equation mathematically expresses the relationship between torque and slip. Accordingly:

- The torque MMM changes depending on the slip;
- When the slip is small, the torque increases almost linearly;

As the slip increases, the torque reaches its maximum value and then decreases.

Relationship with Rotational Speed (n – M graph)

There is an inverse relationship between torque and rotational speed:

- When speed increases, slip decreases;
- When slip decreases, the electromagnetic torque decreases.
- The initial part of the graph ($s = 1$) represents the starting torque;
- The middle part represents the stable operating region;
- The final part ($s \approx 0$) corresponds to almost synchronous speed.

From the graph, it is evident that the torque reaches its maximum value at a certain slip value ($s_{\max}$) and then decreases. This point is called the critical slip.

4. Effect of Slip on Torque

The slip value determines the operating condition of the motor table-1:

Slip (s) value	Condition	Description
$s=0$	Synchronous mode	Torque is zero, no relative rotation
$0 < s < s_{\max}$	Operating mode	Torque is proportional to the load, stable operation.
$s=1$	Starting mode	Maximum current and torque.
$s > 1$	Braking	Operation in generator mode or mechanical braking.

As the slip increases, the torque initially rises, reaches its maximum value, and then decreases. Therefore, the optimal operating range of the motor is usually within $s = 0.01 \div 0.05$.

5. Braking and Maximum Torque Conditions

In an asynchronous motor, the braking condition occurs when the slip value is greater than 1.

In this case, the direction of rotor rotation is opposite to that of the magnetic field, meaning the motor operates in generator mode.

The maximum torque is expressed as follows:

$$M_{max} = \frac{3U_1^2}{2\omega_s(R_1 + \sqrt{R_1^2 + (X_1 + X_2')^2})}$$

This torque is directly proportional to the square of the voltage and inversely proportional to the frequency.

Thus, if the supply voltage decreases, the torque drops sharply.

In practical terms:

- When the load increases → slip increases → torque increases.
- When the load decreases → slip decreases → torque decreases.

Therefore, the inverse relationship between electromagnetic torque and speed is a natural characteristic that ensures the stable operation of the motor.

Theoretical Questions

5. What is electromagnetic torque and what physical phenomenon is it based on?
6. How is electromagnetic torque generated in an asynchronous motor?
7. List the main factors that determine electromagnetic torque.
8. How does slip affect the torque?
9. How does electromagnetic torque change as rotational speed increases?
10. Explain the physical meaning of the relationship between torque and slip.
11. How is the maximum (critical) torque determined, and under what conditions does it occur?

12. In which direction does the electromagnetic torque act during the braking mode?
13. Name and explain the three main zones of the torque–speed (n – M) graph.
14. What are the advantages of modeling electromagnetic torque in MATLAB or Simulink?

Test Questions

1. What type of energy conversion does the electromagnetic torque represent?

- A) Heat → Mechanical
- B) Electrical → Mechanical
- C) Mechanical → Electrical
- D) Magnetic → Thermal**

2. Which phenomenon is the electromagnetic torque based on?

- A) Heat exchange
- B) Electromagnetic induction
- C) Electromotive force
- D) Dielectric polarization

3. How does electromagnetic torque initially change as slip increases?

- A) Decreases
- B) Remains constant
- C) Increases
- D) Equals zero

4. When slip is very high ($s > 1$), in which mode does the motor operate?

- A) Steady-state mode
- B) Generator (braking) mode
- C) No-load mode
- D) Normal load mode

5. At what slip does the electromagnetic torque reach its maximum value?

- A) $s = 0$

B) $s = s_{\max}$ (critical slip)

C) $s = 1$

D) $s = 0.5$

6.As rotational speed increases, the electromagnetic torque:

A) Increases

B) Decreases

C) Remains constant

D) First increases, then decreases

7.What is the shape of the relationship between torque and rotational speed?

A) Linear

B) Parabolic

C) Curved (inversely proportional)

D) Sinusoidal

8.The SI unit of electromagnetic torque is:

A) Volt

B) Newton

C) Newton·meter (N·m)

D) Joule

9.If the voltage is doubled, how does the torque change?

A) Does not change

B) Doubles

C) Increases four times

D) Decreases by half

10.What does the middle part of the torque–speed graph represent in an asynchronous motor?

A) Braking zone

B) No-load zone

C) Stable operating zone

D) Synchronous zone

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CHAPTER III. METHODOLOGICAL GUIDELINES FOR LABORATORY WORK ON THE TOPIC “TRANSFORMERS”

General Plan (for all laboratory works)

Each laboratory task is practically performed in laboratory rooms based on the following structure:

1. Purpose of the work
2. Theoretical background (brief theory)
3. Experimental circuit and list of instruments
4. Execution steps (practical procedure)

5. Measurement results (in tabular form)
6. Calculations and analysis
7. Conclusion

Laboratory work №1. Study of the no-load test of a transformer

Purpose: To measure the electrical parameters of the transformer under no-load conditions and determine the magnetic (core) losses.

Theoretical Background: The no-load condition occurs when the secondary winding is open and the primary winding is connected to the rated voltage. In this state, magnetic flux and core losses (hysteresis and eddy current losses) are observed.

Experimental Circuit: The primary winding is connected to the power supply. An ammeter, voltmeter, and wattmeter are connected in the circuit.

Measurements: Voltage (U_1), current (I_0), and power (P_0) are measured.

Based on formulas:

$$P_0 = U_1 I_0 \cos \varphi_0$$

Conclusion: The no-load power, magnetic (core) losses, and no-load current are determined.

Laboratory work №2. Short-circuit test and determination of power losses

Purpose: To determine the copper (active) losses of the transformer.

Theoretical Background: In this test, the secondary winding is short-circuited, and a reduced voltage is applied to the primary winding. Under these conditions, the rated current flows through the windings, but the magnetic flux is small; therefore, the core (iron) losses are negligible, and only copper losses are measured.

Experimental Circuit: The short-circuit measurement circuit includes an ammeter, voltmeter, and wattmeter connected in series with the primary winding.

Calculations:

$$P_{Cu} = P_{KZ}$$

$$R_{eq} = \frac{P_{KZ}}{I_{KZ}^2}$$

Conclusion: The equivalent resistance and active (copper) losses of the transformer are determined.

Laboratory work №3. Obtaining the external characteristics of a transformer

Purpose: To analyze the voltage drop in relation to load variation.

Theoretical Background: When a transformer is connected to a load, the secondary voltage decreases as the load current increases. This occurs due to voltage drops across the internal resistance and leakage reactance of the windings.

Measurement: The secondary voltage U_2 is measured corresponding to different load current values I_2

$$: U_2 = f(I_2)$$

Results

Conclusion: As the load increases, the secondary voltage decreases. The resulting graph represents the external characteristic of the

Laboratory work №4. Analysis of transformer operation under load conditions

Purpose: To measure power, efficiency, and thermal losses of the transformer under load conditions.

Theoretical Background: When the primary voltage remains constant and the load varies, the transformer's output power changes accordingly. As the load current increases, copper losses rise while efficiency changes depending on the load level.

Results: The efficiency (η) of the transformer is determined in relation to changes in the load current.

Conclusion: The optimal load condition of the transformer is determined — the point at which efficiency reaches its maximum value.

Laboratory work №5. Determination of transformer efficiency (power factor and loss analysis)

Purpose: To experimentally calculate the efficiency (η) of a transformer.

Theoretical Background: The efficiency of a transformer represents the ratio of useful output power to input power. It depends on the load and internal losses (copper and iron losses).

$$\eta = \frac{P_2}{P_1} \times 100\%$$

or

$$\eta = \frac{P_2}{P_2 + P_{Cu} + P_{Fe}} \times 100\%$$

where:

- P_1 — input power,
- P_2 — output power,
- P_{Cu} — copper (winding) losses,
- P_{Fe} — core (iron) losses.

Measurement: The input and output powers are measured using wattmeters connected to the primary and secondary circuits.

Conclusion: The change in efficiency with increasing load is analyzed — efficiency first rises, reaches a maximum at the optimal load, and then decreases.

CHAPTER IV. METHODOLOGICAL GUIDELINES FOR LABORATORY WORK ON THE TOPIC “ELECTRIC MOTORS”

Laboratory Work №1. Study of the construction of an Asynchronous motor

Purpose of the Work: The purpose of this laboratory work is to study the main structural parts of an asynchronous electric motor, their functions, and principles of interaction. It also includes theoretical and practical analysis of the rotor and stator design, types of windings, and the mechanism of rotating magnetic flux.

Theoretical Background: An asynchronous motor is a machine that converts alternating current (AC) electrical energy into mechanical energy. Its operation is based on the rotation of a magnetic field. The motor consists of two main parts — stator and rotor.

Stator — composed of a laminated magnetic steel core and a three-phase winding that generates a rotating magnetic field.

Rotor — can be of squirrel-cage or wound type. The rotating magnetic field induces an electromotive force in the rotor conductors, generating torque and causing rotation.

Experimental Circuit and List of Equipment: Required equipment for the experiment:

- Three-phase asynchronous motor (1–2 kW)
- Automatic protection and control unit
- Voltmeter, ammeter, wattmeter
- Contactors and switch set
- Measurement cables, indicator, multimeter
- Motor cutaway model (to observe internal construction)

Circuit Description: The experimental setup connects the asynchronous motor to a three-phase network through contactors and protection devices.

Before starting, all connections are checked using a multimeter to ensure proper wiring and safety.

Procedure (Practical Steps):

- Examine the external parts of the motor (housing, grill, fan, terminal box).
- Identify the arrangement of the stator windings and measure the phase displacement between them.
- Dismantle the rotor and determine its type (squirrel-cage or wound).
- Analyze the rotor conductors and short-circuit rings.
- Study the internal cooling system and ventilation channels.
- Record all observations in a table and describe the function of each component.

Measurement Results (Table 1):

No	Motor Part	Material	Function	Remark
1	Stator core	Electrical steel	Conducts magnetic flux	Laminated sheets
2	Stator winding	Copper wire	Creates magnetic field	Three-phase winding
3	Rotor cage	Aluminum / Copper	Ensures rotation	Squirrel-cage structure
4	Bearings	Steel	Reduces friction in shaft rotation	Lubricated with oil
5	Fan	Plastic / Steel	Provides cooling	Creates airflow during rotation

Calculations and Analysis: Based on the motor's nameplate data, the following parameter is determined:

Conclusion: The structure and operating principle of the asynchronous motor are studied in detail. The main functional elements — stator, rotor, and cooling system — are analyzed, and the relationship between magnetic field rotation and mechanical motion is understood.

Synchronous rotational speed:

$$n_1 = \frac{120f}{p}$$

where:

- f — supply frequency (Hz),
- p — number of pole pairs.

Example:

If $f = 50 \text{ Hz}$ and $p = 2$:

$$n_1 = \frac{120 \times 50}{2} = 3000 \text{ rpm}$$

Laboratory work №2: Testing the starting methods of an Asynchronous motor

Purpose of the Work: The purpose of this laboratory work is to study different starting methods of an asynchronous motor, analyze the corresponding electrical and mechanical processes, and experimentally observe changes in current and torque during starting.

Theoretical Background: When an asynchronous motor is connected directly to the power supply, the starting current can be several times higher than the rated current (typically 5–7 times). This may cause voltage drops in the supply

network. Therefore, various starting methods are used to limit the current and regulate the starting torque.

Main Starting Methods:

- Direct-on-line starting (DOL): The simplest method, but it produces a high starting current.
- Star–Delta starting: The motor windings are connected in a star configuration during startup and switched to delta during normal operation.
- Autotransformer starting: Reduces starting current by lowering the applied voltage.
- Rotor resistance starting (with rheostat): Used only for wound-rotor motors to provide smooth starting.

The relationship between torque and current can be expressed as:

$$M = \frac{3E_2^2 R_2 / s}{\omega_s [(R_2 / s)^2 + X_2^2]}$$

where:

M — electromagnetic torque,

s — slip,

E_2 — rotor EMF,

R_2, X_2 — rotor resistance and reactance.

Experimental Setup and Equipment List:

Required equipment:

- Three-phase asynchronous motor (1.5–3 kW)
- Autotransformer
- Star–delta starter circuit
- Voltmeter, ammeter, wattmeter

- Stroboscope or tachometer (for measuring speed)
- Rheostat (for wound-rotor motor)
- Protective devices (circuit breakers, contactors)

Circuit Description: The experimental setup allows the motor to be started in different modes through a three-phase network using contactors. Voltmeter and ammeter are connected to measure voltage and current during startup.

Procedure (Practical Steps):

1. Check the circuit and verify all connections with a multimeter.
2. Start the motor using the direct-on-line method; record starting current and speed.
3. Use the star–delta method: run the motor in star mode for 3–5 seconds, then switch to delta.
4. Start the motor via autotransformer, measuring starting current at 60%, 80%, and 100% voltage.
5. For a wound-rotor motor, perform the test with additional resistance connected through the rheostat.
6. For each method, record the starting current (I_{start}), rated current (I_{nom}), and speed (n) values.

Measurement Results (Table 1):

No	Starting Method	Starting Current (A)	Rated Current (A)	Starting Time (s)	Speed (rpm)	Remarks
1	Direct-on-line	28	5.2	3.0	1440	High current, fast start
2	Star–Delta	12	5.3	4.2	1450	Reduced current, smooth

No	Starting Method	Starting Current (A)	Rated Current (A)	Starting Time (s)	Speed (rpm)	Remarks
						transition
3	Autotransformer (80%)	9.8	5.1	4.8	1445	Lower current, reduced voltage
4	Rotor with rheostat	8.5	5.4	5.2	1430	Soft start, lower torque

Calculations and Analysis:

The starting current and torque are analyzed using the following relationship:

$$M = k \frac{U^2}{\omega_s X_{eq}}$$

where:

k — starting coefficient,

U — supply voltage,

ω_s — synchronous angular speed,

X_{eq} — equivalent reactance.

Analysis: The results show that direct-on-line starting ensures the fastest startup but causes a high current surge in the network.

Star–delta and autotransformer methods reduce network load but slightly lower the starting torque.

For wound-rotor motors, starting with a rheostat allows a smooth and stable acceleration.

Conclusion: In this laboratory work, the main starting methods of asynchronous motors were studied, and their advantages and disadvantages were identified. The direct-on-line method provides a quick start but results in a high current surge; star–delta and autotransformer methods reduce current and mechanical stress; for wound-rotor motors, the rheostat method offers optimal smooth starting. The obtained results are practically important for ensuring energy-efficient and stable starting of electric drives in industrial applications.

Laboratory work №3. Determination of the mechanical characteristic of an Asynchronous motor

Purpose of the Work; The purpose of this laboratory work is to experimentally determine the mechanical characteristic of an asynchronous electric motor — that is, to study the relationship between rotational speed and torque. Through this, the motor's load behavior, slip variation, and braking points are analyzed in practical form.

Theoretical Background: The mechanical characteristic of an asynchronous motor represents the dependence of speed n on torque M or current I and reflects the performance of the motor.

The relationship between torque and speed is expressed as:

$$M = \frac{3U^2 R_2 / s}{\omega_s [(R_2 / s)^2 + X_2^2]}$$

where:

- M — electromagnetic torque,
- U — stator voltage,
- R_2, X_2 — rotor resistance and reactance,
- s — slip (asynchronous coefficient),
- ω_s — synchronous angular speed.

Slip is determined by:

$$s = \frac{n_s - n}{n_s}$$

where:

- n_s — synchronous speed (rpm),
- n — actual rotor speed.

The mechanical characteristic typically consists of three regions:

- Operating region: slip is small ($0 < s < 0.05$), stable operation.
- Braking region: medium slip ($0.05 < s < 1$), torque decreases.
- Reversal region: slip > 1 , motor operates in braking mode.

Experimental Setup and Equipment List

Required equipment:

- Three-phase asynchronous motor (1.5–3 kW) Braking mechanism (electromagnetic or mechanical)
- Voltmeter, ammeter, wattmeter

- Tachometer or stroboscope (for speed measurement)
- Dynamometer (for torque measurement)
- Automatic protection and control devices
- Electrical load rheostat

Procedure (Practical Steps)

Assemble the experimental setup and check all connections.

Start the motor without load and measure the no-load speed n_0 .

Gradually increase the load using the braking mechanism (in 5–6 steps).

For each load, measure voltage (U), current (I), speed (n), and torque (M).

Measurement Results (Table 1)

No	Load Current (A)	Voltage (V)	Speed (rpm)	Slip s	Torque M (N·m)	Power P (kW)
1	2.5	380	1490	0.006	0.5	0.15
2	3.0	380	1475	0.017	1.2	0.32
3	3.8	380	1450	0.033	2.1	0.55
4	4.5	380	1420	0.053	3.0	0.78
5	5.3	380	1380	0.080	3.8	1.00
6	6.0	380	1320	0.120	4.0	1.05

Calculations and Analysis

Slip for each point is calculated as:

$$s = \frac{n_s - n}{n_s}$$

Torque is determined by:

$$M = \frac{9550 \times P_2}{n}$$

where P_2 — output (useful) power in kW, and n — rotational speed in rpm.

Analysis:

The results show that as the load increases:

- Speed n decreases,
- Slip s increases,
- Torque M rises up to a certain point (maximum torque $M_{\max}$), then starts to decline.

At higher slip values, the motor transitions into the braking mode. The mechanical characteristic $M=f(n)$ forms a nonlinear descending curve:

The initial segment (working region) is almost horizontal,

Beyond the critical slip, the torque decreases sharply.

Conclusion: In this laboratory work, the mechanical characteristic of an asynchronous motor was experimentally determined, and the relationship between rotational speed and torque was verified. The results confirm that:

- As the load increases, the speed decreases and the slip increases.
- The motor torque increases to a maximum point and then declines.

The nearly flat working region of the characteristic ensures stable operation of the motor under load.

This demonstrates that asynchronous motors are reliable and efficient for use in automated systems, conveyors, and pump units, where stable mechanical performance is essential.

Laboratory work №4: Measurement of the main parameters of a Synchronous motor

Purpose of the work: The purpose of this laboratory work is to experimentally determine the relationships between the synchronous motor's rated speed, line current, power, power factor ($\cos\varphi$), reactive power (Q), efficiency (η), and excitation current (I_f). Additionally, the V-curve ($I-I_f$) and $\cos\varphi-I_f$ characteristics are obtained and analyzed.

Theoretical Background (Brief Theory): In a synchronous motor, the rotational speed is strictly dependent on the supply frequency:

$$n_s = \frac{120f}{p}$$

where:

f — frequency (Hz),

p — number of pole pairs.

The rotating field of the stator and the excitation field of the rotor are synchronized in phase. By increasing or decreasing the excitation current I_f , the motor can operate either in an inductive mode ($Q > 0$) or a capacitive mode ($Q < 0$).

For a three-phase motor, the active power and reactive power are determined by:

$$P = \sqrt{3} U I \cos \varphi$$

$$Q = \sqrt{3} U I \sin \varphi$$

Experimental Setup and Instruments

Required equipment:

- Three-phase synchronous motor (2–5 kW)
- DC excitation source and rheostat
- Tachometer
- Voltmeter, ammeter, two wattmeters (or a three-phase power analyzer)
- Adjustable load (generator or braking stand)
- Protective devices, contactors, measuring cables

Circuit description:

- The stator is connected to a 3×380/400 V three-phase AC supply.
- The rotor is connected to a separate DC excitation source via a rheostat.
- Power is measured using the two-wattmeter method.

Procedure (Practical Steps): Check all connections. Start the motor at no-load and synchronize it with the AC network (using an autotransformer or auxiliary asynchronous drive). Gradually vary the excitation current I_f ; at each step, measure and record $U, I, P=(W_1+W_2), n$. Calculate the power factor:

$$\cos \varphi = \frac{P}{S} = \frac{P}{\sqrt{3} U I}$$

Apply different load levels and collect data points for V-curve ($I-I_f$) and $\cos\varphi-I_f$ characteristics.

Compare inductive (underexcited) and capacitive (overexcited) operating modes.

If a braking stand is available, record the relationship between torque (M) and excitation current (I_f).

Measurement Results (Sample Table 1)

If (A DC)	U (V)	I (A)	W_1+W_2 (kW)	n (rpm)	$\cos\phi$	Q (kvar)
0.6	400	8.2	3.10	1500	0.55	+4.52
0.9	400	6.9	3.25	1500	0.67	+3.61
1.2	400	6.1	3.40	1500	0.80	+2.19
1.5	400	5.7	3.45	1500	0.90	+1.12
1.8	400	5.6	3.45	1500	≈ 1.00	≈ 0.00
2.1	400	5.8	3.42	1500	0.95	-1.06

Calculations and Analysis

- An optimal excitation point exists at which the current I reaches its minimum (the bottom of the V-curve).
At this point, the power factor is close to unity ($\cos\phi \approx 1$).
- Underexcitation: high current, low power factor, $Q > 0$ (inductive).
- Overexcitation: $Q < 0$ (capacitive), which is useful for improving the overall power factor of the supply network.

The V-curve illustrates the variation of line current with excitation current, while the $\cos\phi$ – I curve demonstrates how the motor's power factor changes between inductive and capacitive modes.

Conclusion: The synchronous motor, through control of its excitation current, can act as either a source or consumer of reactive power in the network. At the optimal excitation point, the line current is minimal and $\cos\phi \approx 1$, representing the most energy-efficient operating mode. This characteristic makes synchronous motors particularly useful in power systems for power factor correction and stable, efficient operation under varying load conditions.

Laboratory Work №5. Investigation of methods for controlling motor rotational speed

Purpose of the work: To compare various methods of controlling the rotational speed of asynchronous (and, if applicable, DC) motors — including V/f frequency control (VFD), pole-changing (Dahlander), stator voltage control, and rotor resistance adjustment (for wound-rotor motors) — and to evaluate their effects on dynamic performance, torque, and efficiency.

Theoretical background: The synchronous speed of an asynchronous motor is given by:

$$n_s = \frac{120f}{p}$$

where:

- f — supply frequency (Hz),
- p — number of pole pairs.

Thus, speed can be controlled in the following ways:

- Frequency Control (V/f): By changing f , the synchronous speed n_s is adjusted. Keeping $V/f = \text{const}$ maintains a stable torque profile.
- Pole-Changing (Dahlander): Changing the number of poles p allows discrete speed levels (e.g., 2-pole/4-pole operation).
- Stator Voltage Control: Since $M \propto U^2$, reducing voltage decreases torque — suitable for fan and pump loads.
- Rotor Resistance Control (Wound-Rotor): Increases torque at low speeds but causes significant power losses and heating.

Experimental Setup and Instruments

Required equipment:

- Three-phase squirrel-cage asynchronous motor
- Variable Frequency Drive (VFD)
- Voltmeter, ammeter, wattmeter
- Tachometer or stroboscope
- Dahlander dual-speed motor (2p/4p) — if available
- Wound-rotor motor and rheostat — if available

Procedure (Practical Steps)

1. VFD (V/f control):

- Set frequencies to 25, 50, and 75 Hz while keeping $V/f = \text{const.}$
- Measure and record n , I , and P for each frequency.

2. Pole Changing:

- Measure no-load speed n_0 and loaded speed for both pole configurations (p_1 and p_2).

3. Voltage Control:

- Vary voltage at 70%, 85%, and 100% of nominal; observe torque variation.

4. Rotor Resistance Control:

- Increase external resistance R_{add} (e.g., 0–10 Ω) and measure n , I , and torque.

5. Provide a short analysis of stability, efficiency, and heating for each method.

Measurement Results (Sample Table 1)

Method	Parameter	Condition 1	Condition 2	Condition 3	Remark

Method	Parameter	Condition 1	Condition 2	Condition 3	Remark
VFD (V/f)	f (Hz)	25	50	75	Voltage adjusted proportionally
	n (rpm)	740	1490	2230	$n \propto f$
	I (A)	4.0	5.1	6.0	Load-dependent
Pole-changing	p	4	2	—	Discrete speed change
	n _o (rpm)	1490	2980	—	At 50 Hz
Voltage control	U (%)	70	85	100	$M \propto U^2$
	M (pu)	0.49	0.72	1.00	Suitable for fan/pump loads
Rotor resistance	R _{add} (Ω)	0	5	10	For wound-rotor motors
	n (rpm)	1450	1200	900	Increased loss and heating

Calculations and Analysis

- For VFD control, $n \propto f$ $\Rightarrow$ $f \propto n$; maintaining $V/f = \text{const}$ $V/f = \text{const}$ preserves torque and yields high efficiency.
- With stator voltage control, torque decreases with the square of voltage — suitable only for fan or centrifugal pump loads.
- Pole-changing is simple and reliable but provides discrete (stepwise) speed levels.

- Rotor resistance control improves low-speed torque but results in higher copper losses and excessive heating.

Conclusion: The VFD (V/f) method provides smooth and efficient speed control with high torque stability — the most suitable for modern drives. Pole-changing is robust and simple but limited to discrete speed levels. Voltage control is economical only for specific load types (fans, pumps).

Laboratory Work №6. Observation of the operating process of a Synchronous compensator

Purpose of the work: To study the operation of a synchronous machine in compensator mode (running without mechanical load) and to experimentally observe its ability to generate or absorb reactive power, its influence on the supply voltage, and to obtain the V-curve characteristics.

Theoretical background: A synchronous compensator is a synchronous machine whose rotor is excited by direct current (DC) and which operates without mechanical output power but can supply or absorb reactive power (Q) from the network.

Underexcitation: The machine operates with inductive characteristics ($Q < 0$), drawing reactive power from the system.

Overexcitation: The machine operates with capacitive characteristics ($Q > 0$), supplying reactive power to the system and thereby increasing the bus voltage and improving the power factor ($\cos \varphi$).

V-curve: The relationship between stator current I and excitation current I_f .

Experimental Setup and Equipment

Required equipment:

- Synchronous machine (operated in compensator mode)
- DC excitation source

- Three-phase measurement set (V, A, two wattmeters or power analyzer)
- Power factor indicator or calculator
- Bus voltage monitoring device
- Protective devices and automatic control elements

Procedure (Practical Steps)

- Bring the machine to synchronous operation with no mechanical load.
- Gradually increase the excitation current I_{fI_flf} from minimum to maximum.
- For each I_{fI_flf} , measure and record bus voltage (U_{bus}), line current (I), active power (P), power factor ($\cos\phi$), and reactive power (Q) (noting its sign).
- Observe the change in network voltage — under overexcitation, a slight rise in U_{bus} indicates reactive power generation.
- Monitor the thermal condition of the machine, as compensators tend to heat up in continuous reactive power mode.

Measurement Results (Sample Table 1)

If (A DC)	I (A)	P (kW)	$\cos\phi$	Q (kvar)	U_{bus} (V)	Mode
0.7	12.5	1.1	0.45	+9.8	396	Inductive
1.0	9.2	1.2	0.65	+6.6	398	Inductive
1.3	7.8	1.3	0.80	+4.1	400	Near unity
1.6	7.6	1.3	0.95	−2.4	403	Capacitive
1.9	7.9	1.4	0.90	−4.8	405	Capacitive

Conclusion: The synchronous compensator effectively stabilizes the network voltage and improves the power factor ($\cos\phi$) by regulating the excitation current.

At the optimal excitation current, the stator current is minimal, losses are reduced, and a stable reactive power compensation mode is achieved. Thus, synchronous compensators play a vital role in voltage regulation and reactive power management within electrical power systems.

Laboratory Work №7. Examination of the thermal and cooling systems of electrical machines

Purpose of the work: To experimentally evaluate the thermal behavior of an electrical machine by observing its heating and cooling curves, determining temperature rise, thermal time constant (τ), cooling efficiency, and verifying compliance with insulation class limits (A, E, B, F, H).

Theoretical background: During operation, electrical machines heat up due to copper (winding) and core (iron) losses. In thermal modeling, a first-order lumped system model is typically used:

$$\Theta(t) = \Theta_{\infty}(1 - e^{-t/\tau})$$

where

- Θ — temperature rise relative to ambient air,
- τ — thermal time constant.

Winding temperature can be determined indirectly from resistance:

$$T = 20 + \frac{R_T - R_{20}}{R_{20} \cdot \alpha}$$

where

- $\alpha \approx 0.00393 (1/^{\circ}C)$ for copper,
- R_T — resistance at operating temperature,
- R_{20} — resistance at 20°C.

Equipment and Instruments

Test motor/generator with adjustable load (generator or brake mode)

- Precision resistance meter (4-wire)
- Insulation resistance tester (megohmmeter)
- Thermocouples or RTD sensors
- Infrared pyrometer (optional)
- Anemometer for airflow measurement in ventilation ducts
- Data logger for temperature, current, and voltage monitoring

Experimental Results (Example)

Table 1. Heating Curve (Fan ON)

t (min)	R _T (Ω)	T(Cu, °C)	Θ = T – T _a (°C)
0	5.00	20.0	0
10	5.27	33.5	13.5
20	5.46	42.9	22.9
30	5.60	49.7	29.7
40	5.70	54.6	34.6
60	5.85	61.9	41.9
90	5.93	65.9	45.9

Calculations and Analysis

Determine temperature rise curve using the exponential model or logarithmic fitting.

Estimate the thermal time constant τ from the slope of the semi-log plot of cooling.

Compare steady-state temperature rise ΔT with permissible limits for the insulation class:

- Class A $\rightarrow$ 60 K
- Class E $\rightarrow$ 75 K
- Class B $\rightarrow$ 80 K
- Class F $\rightarrow$ 100 K
- Class H $\rightarrow$ 125 K

Check temperature uniformity: if the temperature difference between stator, rotor, or air points exceeds 10–15 K, airflow paths may be blocked.

Conclusion: The thermal behavior of the machine follows a first-order dynamic model. When the ventilation system functions properly, the steady-state temperature rise remains within permissible limits, and the thermal time constant is reduced, indicating effective cooling. If the calculated temperature rise ΔT meets insulation class requirements, the cooling system is sufficient. Otherwise, air filters, ventilation channels, and bearings should be inspected, and fan performance should be improved to ensure safe thermal operation of the machine.

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