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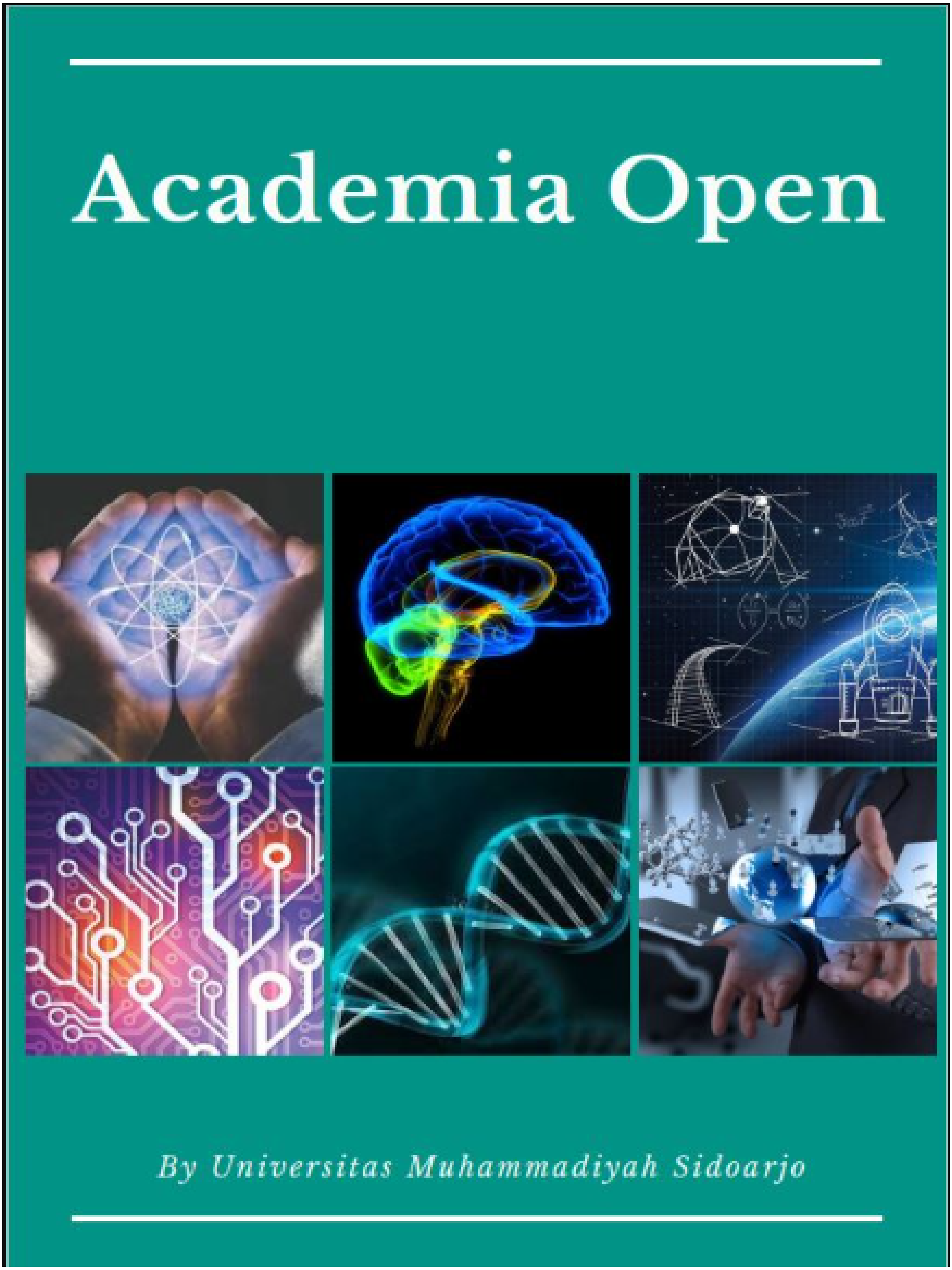


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# Table Of Contents

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Vol. 11 No. 1 (2026): June
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# Problems Of Reducing Electrical Energy Losses In Power Transmission Networks And Their Techno-Economic Solutions

**Baynazov Umid, ub629418@gmail.com (*)**
*Associate Professor, Almalyk State Technical Institute, Uzbekistan*

**Nuriddinov Sardor , mr.john.1991@list.ru**
*Associate Professor, Almalyk State Technical Institute, Uzbekistan*

**Yusupova Dilshoda, yusupovad@gmail.com**
*Almalyk State Technical Institute, Faculty of Energy and Mechanical Engineering, Group 15-24 EM, Uzbekistan*

**Madiyorov Azamat, madiyarovazamat52@gmail.com**
*Almalyk State Technical Institute, Faculty of Energy and Mechanical Engineering, Group 15-24 EM, Uzbekistan*

**Islomov Zoir, zoirislomov62@gmail.com**
*Almalyk State Technical Institute, Faculty of Energy and Mechanical Engineering, Group 15-24 EM, Uzbekistan*

**Abdujaborov Sherzod , abdujaborovsh@gmail.com**
*Almalyk State Technical Institute, Faculty of Energy and Mechanical Engineering, Group 15-24 EM, Uzbekistan*

(*) Corresponding author

## Abstract

**General Background:** Electrical energy losses in transmission and distribution networks challenge economic efficiency, energy security, and environmental sustainability. **Specific Background:** Rising demand and renewable energy integration require more efficient network operations to minimize technical and commercial losses. **Knowledge Gap:** Comprehensive studies integrating power loss analysis, reactive power compensation, transformer optimization, load balancing, and intelligent control remain limited. **Aims:** This study analyzes modern engineering solutions for reducing energy losses and evaluates their techno-economic significance. **Results:** Upgrading transmission voltage, modernizing conductors, applying reactive power compensation, optimizing transformers, and balancing loads effectively reduce technical losses. Additionally, Smart Grid technologies (AMCS, SCADA, and intelligent sensors) enable real-time power flow optimization. Combining these measures can reduce total network losses by 25–30% while enhancing reliability. **Novelty:** This study integrates conventional engineering strategies with Smart Grid technologies into a unified techno-economic framework. **Implications:** The findings provide practical guidance for developing efficient, intelligent, and sustainable power networks that support renewable integration and improve energy utilization.

**Keywords:** Electrical Energy Losses, Power Transmission Networks, Reactive Power Compensation, Smart Grid, Energy Efficiency

**Key Findings Highlights**

Higher transmission voltage levels reduce resistive losses in electrical networks.

Compensation technologies improve power factor and optimize network operation.

Intelligent monitoring systems support real-time control and loss minimization.

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## Introduction

The sustainable development of modern civilization and the rapid growth of industrial sectors are continuously increasing the demand for electrical energy. The principal task of a power system is not only to generate electrical energy but also to deliver it to consumers with minimal losses. The losses of electrical energy that arise in power transmission lines (PTL) and distribution networks not only adversely affect the economic efficiency of energy enterprises, but also lead to additional fuel consumption and, consequently, to an increase in harmful anthropogenic emissions released into the atmosphere [1].

In the present era, when alternative and renewable energy sources (solar and wind power plants) are being widely integrated into the grid, increasing the transmission capacity of both traditional and innovative electrical networks and reducing their energy losses through scientifically grounded methods is regarded as one of the most important strategic objectives of global engineering.

The total losses in electrical transmission and distribution systems are divided into technical (physical) and commercial (organizational) losses. Commercial losses arise mainly from errors in the metering system, illegal connections, and the low accuracy class of meters, whereas technical losses are directly related to the physical processes occurring in electrical apparatus and conductors [2]. The stages at which these losses originate, along with their main sources throughout the chain from generation to delivery to the consumer, are presented in a generalized form in Figure 1.

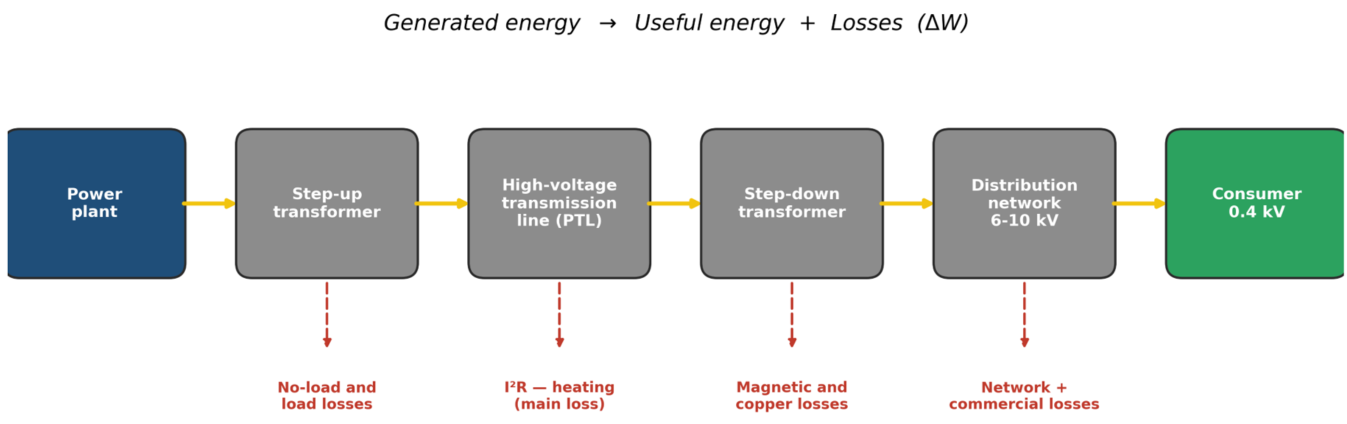


Figure 1. Figure 1. The power transmission chain and the sources of energy losses

In every link of the power transmission chain — in step-up and step-down transformers, in high-voltage lines, and in distribution networks — losses of a specific nature arise. The overall composition of these losses and their distribution across the network links can be seen in Figure 2.

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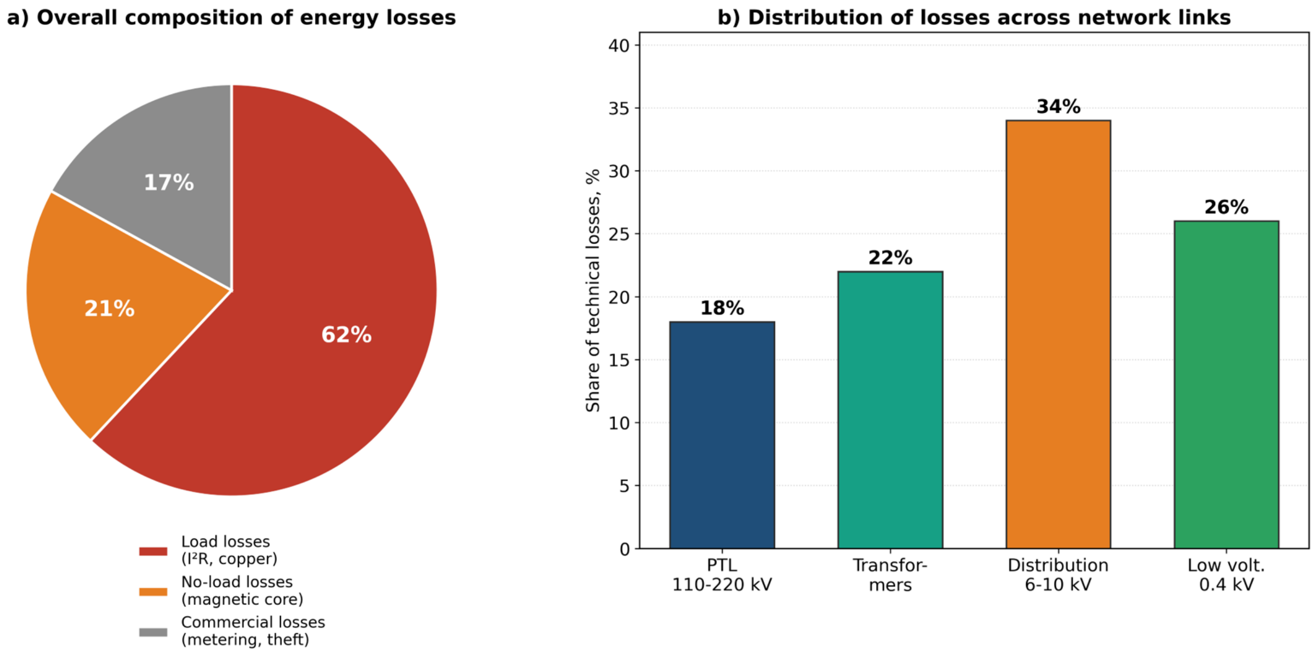


Figure 2. Figure 2. The composition and distribution of electrical energy losses

The main part of technical losses consists of Joule–Lenz heat losses, which are released due to the active resistance of the conductors. Under the effect of the current flowing through the conductor, the active power loss in the line (ΔP) is expressed by the following fundamental equation:

$$\Delta P = 3 * I^2 * R$$

where I is the current in the line (A) and R is the active resistance of the conductor (Ω). As this formula shows, the active power loss is directly proportional to the square of the current (Figure 3). Taking into account the relationship between the apparent power (S) transmitted through the network and the voltage (U), where $I = S / (\sqrt{3} * U)$, the loss expression takes the following form:

$$\Delta P = ((S^2 * R)) / U^2$$

From this relationship it follows that the principal direction for reducing losses is to increase the voltage level of the network, since the loss is inversely proportional to the square of the voltage.

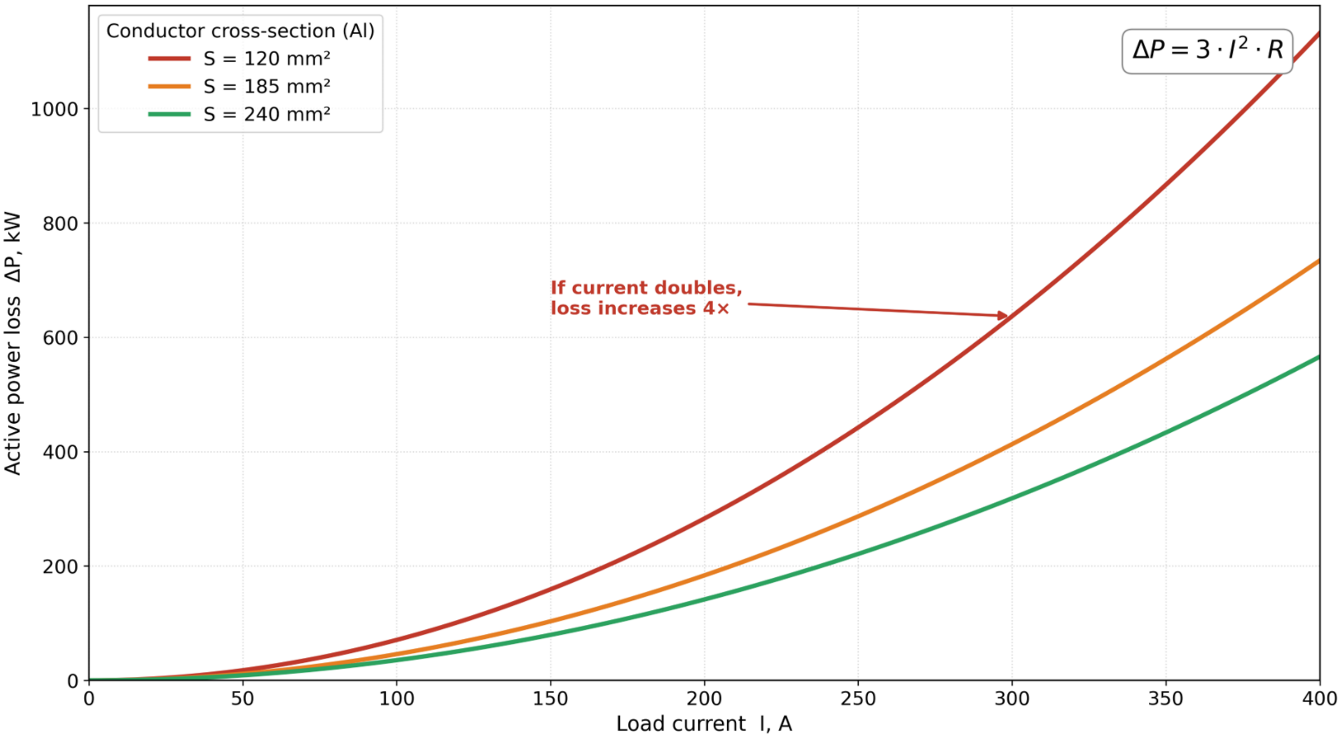


Figure 3. Figure 3. The quadratic dependence of active power loss on the load current

In addition, in high-voltage lines (110 kV and above), “corona discharge” losses arise as a result of the ionization of the air dielectric medium, while magnetic losses occur in the steel core of transformers due to magnetization and eddy currents (Foucault currents) [3]. Reducing technical losses in power transmission systems requires a comprehensive engineering approach. Today, the following effective methods are widely used in practice:

**Increasing the voltage class and modernizing the lines.** When energy is transmitted over long distances, raising the voltage to ultra-high levels (500–750 kV and above) sharply reduces the current and, consequently, decreases the $I^2R$ heat loss in the lines (Figure 4). It is also necessary to replace old wires with modern composite-material conductors of higher conductivity [11].

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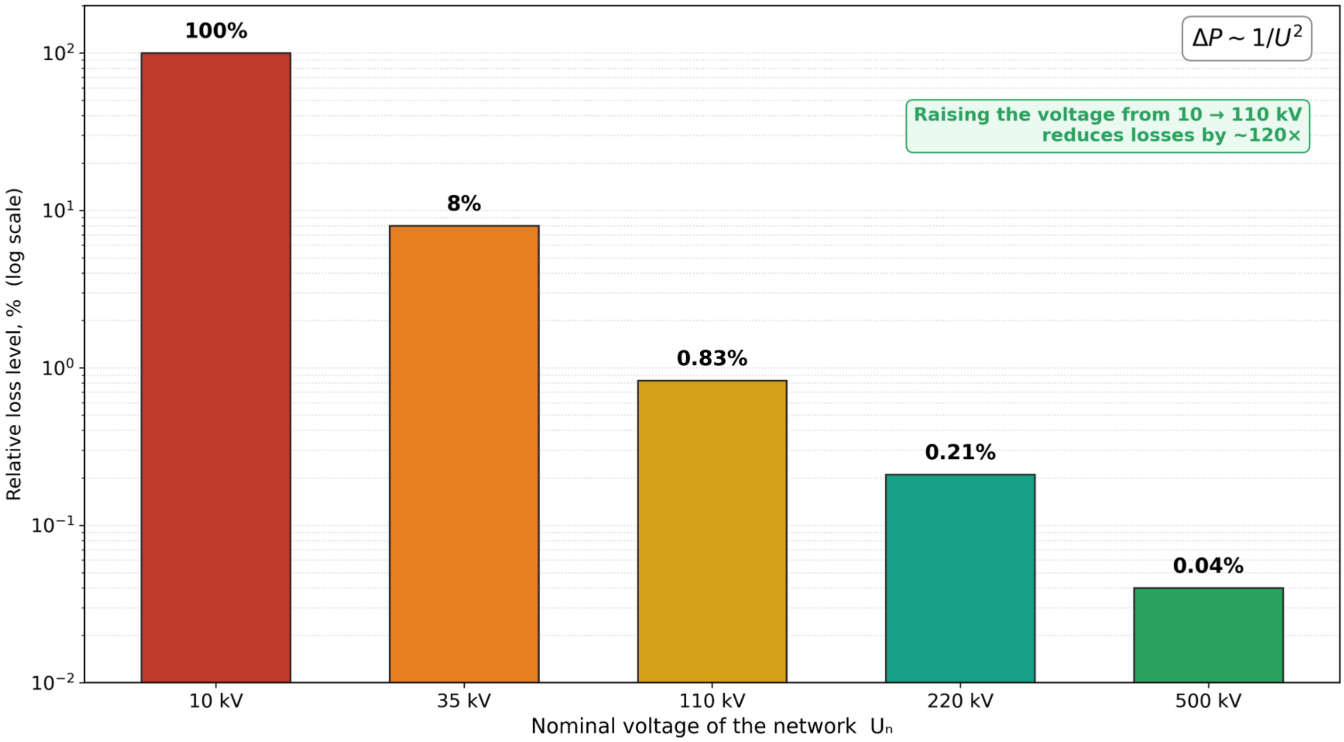


Figure 4. Figure 4. The dependence of losses on the voltage level when transmitting the same power

Reactive power compensation. Because inductive loads (motors, transformers) are high in industrial enterprises and domestic consumers, a flow of reactive power arises in the network. Reactive power performs no useful work, yet it loads the lines, causes additional losses, and leads to voltage drops. To increase the power factor (cos φ), static capacitor banks (SCB) or synchronous compensators are installed in the network (Figure 5) [4].

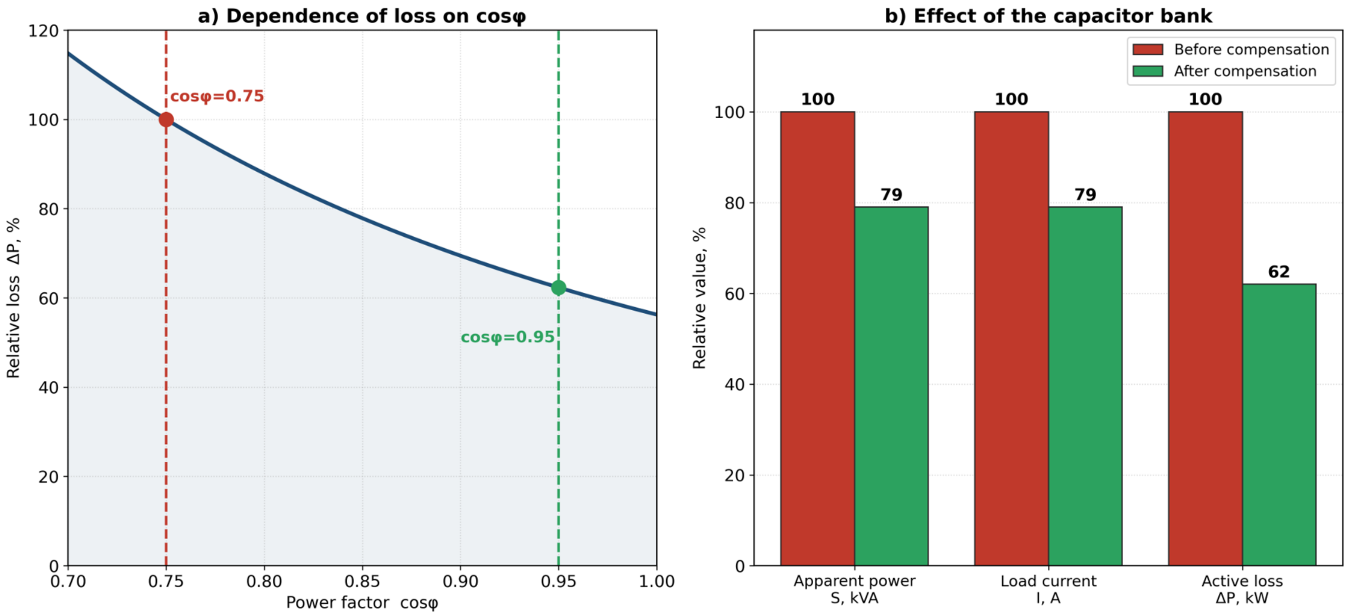


Figure 5. Figure 5. The effect of reactive power compensation on losses

| Compensation method | Advantages | Disadvantages | Efficiency level |
| --- | --- | --- | --- |
| Static capacitor banks (SCB) | Inexpensive, easy to install, | Regulated in steps, | High (reduces active losses by |

Vol. 11 No. 1 (2026): June
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| | | | |
|---|---|---|---|
| | low operating cost | susceptible to the effect of harmonics | up to 15–20%) |
| Synchronous compensators | Smoothly regulated, improves network stability | Expensive, subject to mechanical wear, high noise | Medium–high (for systemic transmission networks) |
| Modern STATCOM devices | Very fast, operate in dynamic mode, filter harmonics | Very high initial capital costs | Maximum efficiency (in Smart Grid systems) |

Table 1. Table 1. Comparative analysis of reactive power compensation methods

**Optimizing transformer transformation ratios and balancing loads.** In distribution networks, the uneven distribution of loads among phases (asymmetry) creates additional currents and losses in the neutral wire. Distributing loads equally across the phases and transmitting energy through economical, low-loss amorphous-core transformers yields high efficiency [5,12,13].

Today, the digital transformation of the energy sector is becoming a decisive factor in reducing electrical losses. Within the framework of the “Smart Grid” concept, the implementation of AMCS (the Automated Metering and Control System for electrical energy) and SCADA systems makes it possible to analyze load profiles in real time [6].

With the help of intelligent sensors and remote control systems, the network elements are brought to their most optimal configuration. Using mathematical modeling and artificial intelligence algorithms, the operating regimes in electrical networks are forecast and optimal power flows are distributed. This makes it possible to reduce to near zero not only technical losses but also the commercial losses associated with the human factor [7,14,15].

Reducing electrical losses in power transmission lines and distribution networks is a strategic direction for ensuring the energy security and efficiency of the national economy. Alongside traditional methods (raising the voltage, compensating reactive power, improving wire conductivity), integrating modern digital systems (Smart Grid, intelligent monitoring) and economical transformers makes it possible to significantly reduce the total network losses (by up to 25–30%). The techno-economic efficiency and payback periods of such measures are presented in Figure 6 [8, 9, 10].

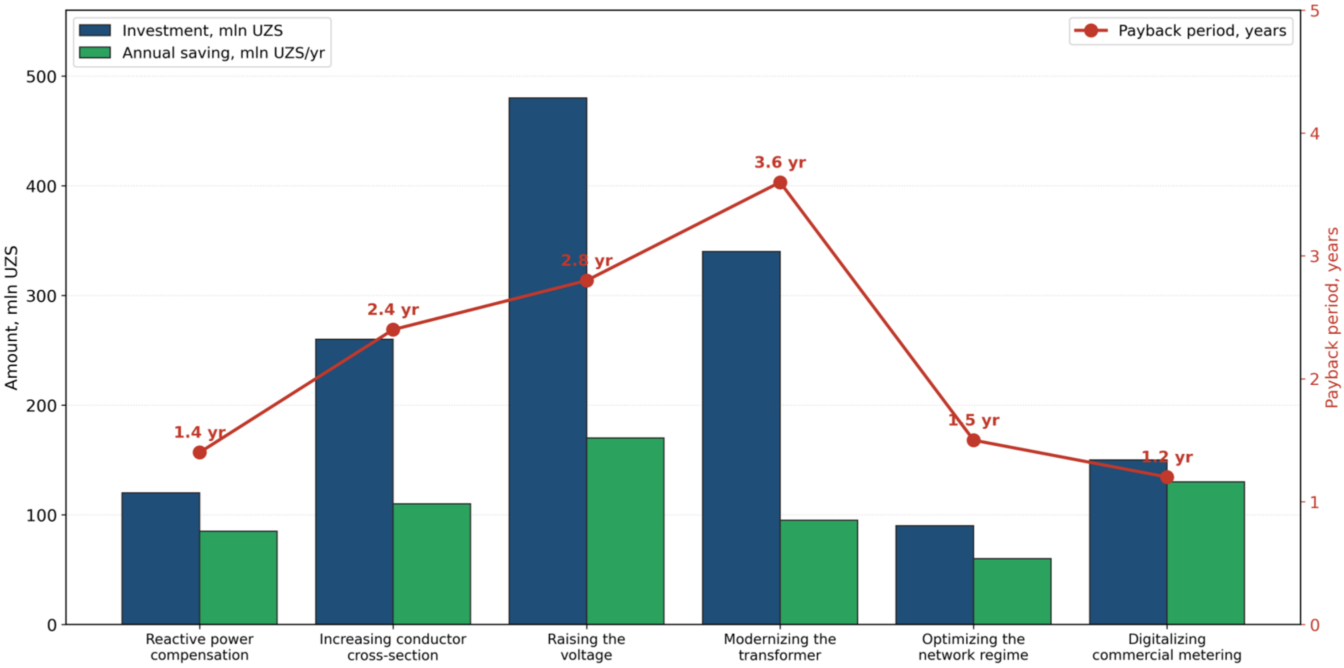


Figure 6. **Figure 6.** The techno-economic efficiency of loss-reduction measures

At a time when renewable energy sources, including wind and solar power plants, are being intensively built in the Republic of Uzbekistan, establishing the intelligent management of power transmission networks, modernizing the main (backbone) networks, and applying scientific and technical innovations to the sector serve as the principal criterion for conserving fuel resources and forming a sustainable green energy system.

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