V International Scientific and Technical Conference Actual Issues of Power Supply Systems

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AIPCP25-CF-ICAIPSS2025-00054 | Article

Analyzing the technical and operational condition of 6–10/0.4 kv low-voltage electric power networks

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Abstract: Due to increased focus on processing industrial and agricultural products in the Republic, the number of manufacturing and processing enterprises is rising sharply. This makes the reliable supply of electrical power to these facilities an urgent concern. Because agro-industrial enterprises are mainly designed to operate at low voltage, this paper presents a technical and operational analysis of 6–10/0.4 kV electrical distribution networks.

INTRODUCTION

Currently, high network losses remain a critical challenge for the energy sector; while it is obvious that losses cannot be eliminated entirely, ensuring they do not exceed economically justified levels is crucial. Deviations from technical and technological consumption norms signal underlying network issues, necessitating identification of loss causes and targeted mitigation strategies, as explored below.

Losses in electrical networks represent the difference between the electricity generated and transmitted by the producer and that consumed by the end user. These losses arise in transmission lines, transformers due to Foucault currents, reactive loads on equipment, and poor insulation quality of conductors. For calculation and normalization purposes, losses are classified as follows:

- Technological losses;
- Operational (commercial) losses.

Technological losses stem from the inherent characteristics of power line layouts and energy distribution processes. They encompass energy consumed by technological, auxiliary, and supplementary electrical equipment. Losses occur due to constant factors, climatic variations, and fluctuations in network load.

Operational losses occur during the operation of auxiliary and supplementary equipment and in creating working conditions for staff. Errors in metering and measurement devices can also be categorized as commercial losses.

Assuming total losses equal 100%, transmission network losses constitute the largest share at 67%. Another loss type, known as corona effect, accounts for 17% of total losses. Analyses confirm that technological losses dominate the overall composition.

Scientifically grounded calculation of electricity losses identifies their root causes. Each transformer features a ferromagnetic core with windings where a significant portion of electrical energy converts to heat. Network operation in underloaded or overloaded regimes directly impacts loss magnitude.

In the former case, losses remain constant, independent of external factors. In the latter, they vary with the load current from connected consumers over specific time intervals, necessitating time-series monitoring for analysis. Losses in high-voltage overhead lines result from conductor heating and air dielectric breakdown via corona discharges. Losses across generation, transmission, metering, and consumption equipment are quantified using electricity meters.

EXPERIMENTAL RESEARCH

Based on the Resolution of the President of the Republic of Uzbekistan No. PQ-4249 dated March 27, 2019, “On the strategy for further development and reform of the electric power sector in the Republic of Uzbekistan”, the Joint-Stock Company “Hududiy Elektr Tarmoqlari” (Regional Electric Networks) was established to manage territorial electric grid enterprises responsible for the distribution and sale of electric energy to final consumers.

The 12 regional branches and 2 regional enterprises ("Bukhara RETC" JSC and "Fergana RETC" JSC) under REC JSC handle the operation of 0.4–6–10 kV power networks, as well as new construction, reconstruction, capital, and current maintenance activities within the scope of these facilities' development. Across the 12 regional branches and 2 regional enterprises ("Bukhara RETC" JSC and "Fergana RETC" JSC), 211 district and city electricity supply enterprises manage the transmission of electricity from 1,839 substations at 110–35–10 kV through 97,003 transformer substations and 293.2 thousand km of power transmission lines to household and legal entity consumers throughout the Republic of Uzbekistan.

As of January 1, 2025, the total number of electricity consumers in the Republic of Uzbekistan stands at 8,301,831, distributed as follows:

Legal entities: 464,691;

Household consumers (population): 7,837,140 households.

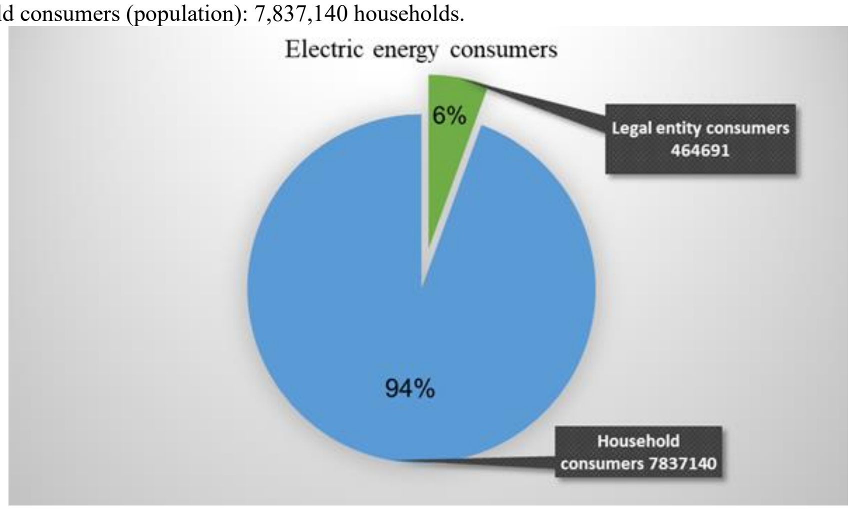

FIGURE 1. Shares of electricity consumers

As of January 1, 2025, the total length of electricity transmission networks under the management of Regional Electric Networks JSC, spanning 0.4–110 kV, reached 293,162.4 km. This includes 16,739.1 km of 110 kV lines, 15,382.5 km of 35 kV lines, 103,636.4 km of 6–10 kV lines, and 157,404.3 km of 0.4 kV networks.

For comparison, at the end of 2023 figures showed 15,396.9 km of 110 kV lines, 13,596.8 km of 35 kV lines, 102,191.3 km of 6–10 kV lines, and 142,411.8 km of 0.4 kV networks, yielding a total network length of 273,596.8 km.

Likewise, the diagram in Figure 2, based on Regional Electric Networks JSC data from 2022, illustrates the system's ongoing development, reflecting targeted investments that, in turn, enhance the quality and reliability of electricity supply to consumers.

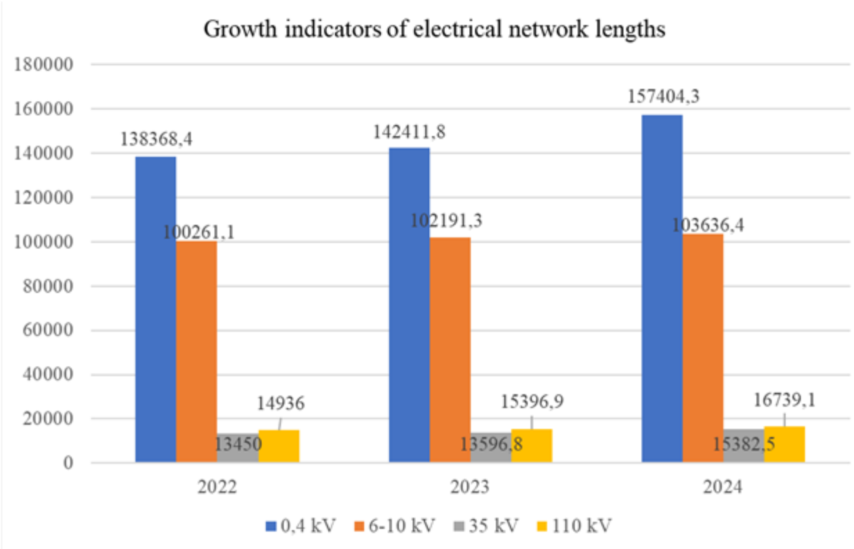

FIGURE 2. Annual growth indicators of existing electricity transmission networks

In 2022, the Republic hosted 697 substations at 110 kV, 1,048 at 35 kV, and 86,300 transformer substations at 6–10/0.4 kV. Over a short period, their total count rose from 88,045 to 98,803 units, reflecting a 12% increase in system modernization (as of November 29, 2024). A more precise breakdown reveals 724 substations at 110 kV, 1,076 at 35 kV, and 97,003 transformer substations at 6–10/0.4 kV, enhancements that improve the consumer electricity supply framework.

Key activities in 2024. In 2024, Regional Electric Networks JSC delivered 64.8 billion kWh of electricity (useful supply), achieving a growth rate of 101.4% compared to the corresponding period in 2023.

To ensure electricity supply stability throughout 2024, 29,496 km of 0.4–110 kV networks and 10,221 transformer substations underwent complete overhaul. Additionally, 100 power transformers at 35–110 kV substations received full repairs.

Upgrades encompassed 6,759 km of 0.4–6–10 kV networks and 2,629 transformer substations. Furthermore, 178 km of 35–110 kV transmission lines were constructed, alongside 21 new substations and modernization of 99 others.

Production in 2024 reached 141,945 reinforced concrete poles and over 152,220 traverse products. To date, 8,041,081 electronic meters enabling ASCUE system connectivity have been installed across consumers, with 400,190 added during 2024 alone. Currently, 7,995,762 consumers connect to the billing system.

Nevertheless, international analyses indicate that much of the existing electrical equipment exceeds 30 years of service life, guaranteeing energy losses beyond acceptable thresholds. These data enable practical assessment of low-voltage network lengths, transformer counts, energy efficiency, reliability, and power quality, while facilitating recommendations to curb losses.

International practices highlight loss reduction measures such as:

Consumer regime optimization. Analyze existing regimes by first quantifying losses in lines, equipment, and power transformers, then balancing active and reactive power at network nodes. Assess network efficiency regarding energy losses, quality, reactive power levels, and supply reliability.

High-voltage transmission. Modern high-consumption buildings should employ "deep input" schemes with 380 V cable lines to minimize usage. Upgrading networks to higher voltage classes proves highly effective, though technologically challenging due to equipment adaptation requirements.

Reactive power compensation. Maintaining active-reactive power balance substantially boosts network efficiency and reduces transmission losses.

Voltage regulation in lines. Deploy capacitor banks or automatic voltage-regulating transformers to minimize losses and ensure required voltage levels, enabling efficient control and enhanced energy efficiency.

Adoption of energy-efficient modern equipment. Replace transformers exceeding no-load loss norms, past service life, obsolete, or non-compliant with efficiency standards; modern units significantly cut network losses.

Reducing power plants' auxiliary consumption. For instance, use LED lighting, motion sensors, and other efficient devices to lower costs.

Implementing automation for remote network control, will significantly improve energy efficiency.

RESEARCH RESULTS

Energy efficiency and network reliability form core components of modern infrastructure. Electricity losses, supply unreliability, and power quality issues rank among the energy sector's paramount challenges. New methods and technologies address these, with scientific solutions and guidelines for efficiency, reliability, and quality holding critical importance.

Achieving aforementioned nominal indicators requires timely technical measures under real conditions, such as identifying loss points and causes:

1. Phase current leakage to ground via cracked or broken insulators (ShF-10, TF-20, etc.);
2. Conductor wires (AC-aluminum-steel, A-aluminum, other bare wires) contacting tree branches;
3. Number and condition of wire connections;
4. Inter-phase short circuits from sagging conductors between poles;
5. Use of obsolete transformer substations, oil switches (commutators), pump units (asynchronous motors), etc.;
6. Idle operation of transformer substations (TPs);
7. Absence or non-compliant reactive power compensators (static capacitor banks) at legal entity consumers;
8. Solar panel capacity and installation compliance;
9. Network conductors connected to equipment without lugs;
10. Uneven phase-wise consumer load distribution.

These factors precipitate energy losses in low- and high-voltage networks across the Republic. Energy audits identify and eliminate them, enabling reliable, quality supply to consumers.

Below is detailed explanation of how can aforementioned problems can be tackled.

1. Dust accumulation on network insulators over years characterizes regional climates. Rain moistens particles, boosting conductivity and enabling ground leakage under adverse weather, causing losses. Aging, mechanical damage, cracking, or shattering further degrades dielectric properties, allowing current flow from conductors via insulator holders, inducing short circuits and losses alongside energy waste.

Solution: conduction of timely cleaning of dust-contaminated insulators and replacement cracked or mechanically damaged ones with new units.

2. Nearly 80% of existing transmission networks in the Republic utilize wire conductors (AC-brand aluminum-steel wires), which contact tree branches during operation, inducing electricity losses. Research reveals that resistance varies from 1,500–2,000 Ω depending on tree moisture content. Thus, the ground leakage current through branches contacting phase wires at nominal network voltage can be precisely quantified.

$$W = I^2 R t \qquad (1)$$

Here, I denotes the leakage current through the tree to ground (A); R the tree's active resistance (Ω); and t the time (h).

As a solution, conductштп comprehensive network inspections twice annually, trimming tree branches contacting conductors can be recommended. Notably, higher voltage levels amplify ground leakage current, thereby escalating energy losses.

3. Phase conductors in electrical networks lose mechanical strength over time or due to short-circuit damage, potentially leading to breaks. Connections must strictly adhere to standards, as poor contact generates heating and excess losses.

Solutions include using clamping lugs (clamps), proper splicing techniques (aluminum wire fusion), or modern secure fastening methods during conductor joining.

4. In low-voltage (0.4 kV) overhead networks, sagging wires must maintain at least 5 m clearance from ground and roadways, with spans not exceeding 40 m. Compliant designs prevent excessive sag; wind-induced contact causes inter-phase short circuits and losses. Vehicles may also snag lines, triggering outages.

Solutions require monitoring sag per regional conditions and accounting for thermal expansion/contraction of metallic conductors in heat/cold.

5. Post-repair of transformers and inductive equipment, mismatched replacement parts—especially windings—alter parameters, exceeding nominal losses.

Solutions entail installing compliant spares (e.g., rewinding with wire matching original cross-section), followed by comparative testing to verify passport specifications.

6. Many legal entity transformer substations (TPs) operate below nominal capacity; loads under 30% of rating constitute no-load (idle) mode. No-load losses are given by the following expression:

$$\Delta W_x = \Delta P_x \sum_{i=1}^{m} T_{pi} \left(\frac{U_i}{U_{nom}}\right)^2 \quad (2)$$

where: T_{pi}: operating time of the transformer in no-load mode; ΔP_x: active power loss of the transformer during no-load operation; U_i: measured voltage of the transformer's high-voltage winding; U_{nom}: nominal voltage of the transformer.

7. Reactive Power Compensation. Installing reactive power compensation devices at industrial enterprises reduces current draw from electrical networks and minimizes energy losses. Proper sizing of compensation equipment to match the consumer's load profile lowers overall costs. Compliance of installed reactive power compensation capacities with normative standards in existing industrial facilities can be verified through the following expressions:

$$Q_{kq}=P_{\sum x} \cdot (tg\varphi_1 - tg\varphi_2) \quad (3)$$

$$tg\varphi 1 = \frac{Q_x}{P_{\Sigma x}} \quad (4)$$

where: $P_{\Sigma x}$: active accounted power (obtained from consumer balance electricity meter); Q_x: reactive accounted power (obtained from consumer balance electricity meter); $\tan \varphi_1$: tangent of phase shift angle before compensation; $\tan \varphi_2$: normative tangent value (0.328).

Resolving this issue enables 2–5% electricity savings proportional to the network power factor improvement.

8. Solar Panel Installation Issues. A primary challenge in solar panel deployment involves shading on installed panels. Shading not only halts power generation from the affected panel but also prevents grouped panels from transmitting output to the inverter, nullifying the entire array's production. Improper installation of panels—intended as energy sources—fails to deliver passport-specified capacities, manifesting as network losses.

Solution: Strict adherence to established GOST standards for solar panel installation is essential. Currently, connection to the grid is recommended only upon full compliance with requirements outlined in SNiP 2.04.15-22, approved by the Ministry of Construction of the Republic of Uzbekistan.

9. Lugless Cable Connections. Using cable lugs for connections to switching apparatus ensures large contact surfaces, preventing heating. Direct connection without lugs reduces conducting area, causing energy losses. Moreover, compression without lugs leads to conductor spreading sideways, compromising contact quality.

Solution: Identify and remedy lugless connections. New networks require strict monitoring of specified lug types.

10. Phase Imbalance in Transformer Substations. In 10/0.4 or 6/0.4 kV transformer substations, low-voltage side (0.4 kV) voltage variations and inequality due to asymmetry induce 3–5% additional energy losses.

Solution: Reassess phase-wise consumer distribution and install auxiliary transformer substations (TPs) for remote single households. Multi-stage reactive power compensation devices at all TPs also resolve this issue.

CONCLUSIONS

This study critically examines a set of recommendations aimed at formulating effective strategies for minimizing energy losses in electric power networks, enhancing the reliability of electricity supply, and maintaining power quality indicators within established regulatory limits. The analysis of the proposed strategies and technical measures leads to the formulation of three key conclusions, which address improvements in energy efficiency, the achievement of a high level of supply reliability, and the systematic control of factors influencing electric power quality.

First, prioritize strategies minimizing network energy losses through production-distribution efficiency gains, routine maintenance, voltage optimization, and reactive power compensator installation.

Second, implement reliability enhancement strategies including backup systems, smart technologies, and balanced load distribution to ensure operational continuity.

Third, improve quality indicators via harmonic filters, voltage regulators, and UPS systems to eliminate issues and protect sensitive equipment.

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