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Reducing Energy Losses Based on Load Optimization in Low-Voltage Power Supply Systems

Taslimov Abdurakhim Dexkanovich, Rakhimov Farrux Movlidinovich, Norqulov Asliddin Olimovich

Professor, Tashkent state technical university, Tashkent, Uzbekistan
Associate Professor (PhD), Navoi State University of Mining and Technology, Navoi, Uzbekistan
Independent Researcher, Navoi State University of Mining and Technology, Navoi, Uzbekistan

ABSTRACT: This paper investigates methods for reducing energy losses in low-voltage (up to 0.4 kV) power supply systems based on load optimization. High current levels in low-voltage networks result in increased active power losses, voltage drops, phase imbalance, and excessive reactive power flow, which significantly reduce energy efficiency. The study presents a systematic analysis of the physical and technical causes of energy losses and examines practical approaches including optimal phase load distribution, reactive power compensation, load profile leveling, and mitigation of nonlinear load effects. The load optimization problem is formulated using an objective function and a set of technical constraints. The potential for improving energy efficiency is analyzed with consideration of voltage quality and reliability requirements. The obtained results demonstrate practical applicability for reducing energy losses and improving power quality during the modernization of low-voltage distribution networks.

KEY WORDS: low-voltage power networks; energy losses; load optimization; energy efficiency; reactive power; phase imbalance; voltage quality; 0.4 kV power supply system.

I.INTRODUCTION

At present, the efficient use of electrical energy is one of the key scientific and practical challenges in ensuring the sustainable development of power systems. A significant portion of electrical energy losses occurs in low-voltage power supply networks with rated voltages up to 0.4 kV. This is primarily due to high current levels, uneven load distribution, and a considerable share of reactive power. As a result, active power losses increase, voltage quality deteriorates, and the overall efficiency of electrical energy utilization decreases [1].

Low-voltage distribution networks supply the majority of consumers in industrial enterprises, administrative facilities, and the residential sector. Therefore, the energy efficiency of these networks has a direct impact on the economic and technical performance of the entire power supply system. Practical experience shows that loss reduction in existing 0.4 kV networks is often limited to individual technical measures, such as increasing conductor cross-sections, installing reactive power compensation devices, or replacing outdated equipment. However, these approaches frequently fail to provide comprehensive results and are often characterized by low investment efficiency [2].

Although numerous scientific studies have addressed the problem of reducing energy losses, the issue of load optimization in low-voltage networks has not been sufficiently investigated as an integrated system. Most existing works focus on reactive power compensation, voltage regulation, or mitigation of nonlinear load effects, while the interrelationship between optimal phase load distribution, temporal load leveling, and energy efficiency improvement remains inadequately explored [3].

From this perspective, considering load optimization in low-voltage power supply systems as a primary method for reducing energy losses represents a relevant scientific task. Load optimization makes it possible to reduce current levels, eliminate phase imbalance, limit reactive power flows, and improve voltage quality. Consequently, energy efficiency can be enhanced during the modernization of power networks without the need for significant capital investment. The objective of this study is to substantiate the potential for reducing energy losses through load optimization in low-voltage power supply systems, to develop a mathematical formulation of the optimization process, and to propose effective technical solutions for practical implementation. The results of the study are intended to support the development of scientific and practical recommendations aimed at improving the design, operation, and modernization of low-voltage distribution networks [4].

II. RELATED WORK

This study emphasizes the importance of reducing energy losses in low-voltage (0.4 kV) power supply systems through load optimization. High current levels, phase imbalance, and reactive power flows significantly reduce the operational efficiency of low-voltage networks. Optimizing load distribution and operating conditions allows energy efficiency and voltage quality to be improved without the need for major infrastructure upgrades. As a result, load optimization represents a practical and economically efficient solution for enhancing the performance and reliability of modern low-voltage distribution systems.

III. SIGNIFICANCE OF THE SYSTEM

In recent decades, extensive research has been carried out on reducing power losses and improving energy efficiency in low-voltage distribution networks. One of the earliest and most influential contributions to distribution system analysis was made by William H. Kersting, who developed detailed modeling techniques for radial and unbalanced low-voltage networks. His work established the basis for accurate loss calculation and phase-level analysis in 0.4 kV systems, which is essential for load optimization studies. A major breakthrough in loss minimization and optimal power flow analysis was introduced by M. E. Baran and F. F. Wu through the well-known DistFlow model. Their research demonstrated the direct influence of active and reactive power flows on voltage profiles and power losses in radial distribution systems. Since then, the DistFlow equations have become a standard mathematical foundation for optimization problems in low-voltage networks [5, 6].

Voltage quality degradation and increased power losses caused by unbalanced loads and poor power factor were comprehensively investigated by Roger C. Dugan, Mark F. McGranaghan, and Surya Santoso. Their studies showed that phase imbalance, reactive power flow, and harmonic distortion significantly increase losses in low-voltage feeders, especially in networks with a high share of single-phase and nonlinear loads. Reactive power compensation in distribution systems was widely studied by T. J. E. Miller and N. G. Hingorani. Their work on capacitor placement and FACTS-based solutions demonstrated that optimal reactive power control can substantially reduce current magnitude and, consequently, active power losses. These studies emphasized that compensation strategies are most effective when coordinated with load distribution and voltage regulation [7,8].

The influence of load balancing on loss reduction in low-voltage networks was analyzed by J. Arrillaga and Neville Watson. Their research showed that phase reconfiguration and redistribution of single-phase consumers significantly reduce neutral conductor currents and transformer overheating. These findings confirmed that load balancing represents a cost-effective alternative to traditional network reinforcement. Modern optimization-based approaches for low-voltage systems were further developed by Antonio J. Conejo, Rui Bo, and Mathieu Debbah, who applied convex optimization, mixed-integer programming, and multi-objective optimization techniques to minimize power losses while maintaining voltage constraints, power quality requirements, and network reliability [9,10].

The impact of distributed energy resources and demand-side management on loss reduction in low-voltage grids was extensively studied by Nikos Hatziargyriou. His work demonstrated that coordinated control of loads, reactive power sources, and distributed generation units can significantly improve energy efficiency without major infrastructure upgrades. Recent investigations focusing on harmonic-related losses in low-voltage networks were conducted by Math H. J. Bollen, who quantified additional losses caused by nonlinear loads and emphasized the importance of incorporating harmonic constraints into optimization models. His research clearly indicates that neglecting harmonics leads to underestimation of actual energy losses in modern low-voltage distribution systems [11,12].

Overall, the reviewed literature confirms that energy losses in low-voltage distribution networks are primarily driven by high current levels, phase imbalance, reactive power flows, and harmonic distortion. Although individual solutions such as reactive power compensation or network reinforcement provide partial improvements, recent research trends emphasize integrated load optimization frameworks that simultaneously address phase balancing, reactive power control, voltage regulation, and power quality constraints. This conclusion directly motivates the optimization-based approach adopted in the present study.

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IV. METHODOLOGY

The load optimization problem in low-voltage power distribution networks is formulated with the objective of minimizing electrical losses arising during energy transmission. In this study, optimization is performed with respect to both phase load allocation and time-dependent variation of consumer demand.

Total power losses in low-voltage networks consist of active losses in conductors and additional losses caused by unbalanced operating conditions. Therefore, the objective function is defined as:

$$minF = \Delta P_{active} + \Delta P_{additional} \quad (1)$$

where ΔP_{active} – denotes active power losses in conductors and electrical equipment, $\Delta P_{additional}$ – represents additional losses caused by phase imbalance, reactive power flows, and the influence of harmonics [13].

In low-voltage distribution systems, active power losses occur mainly in cable and overhead line conductors. These losses are calculated based on conductor current and resistance:

$$\Delta P_{active} = \sum_{i=1} I_i^2 R_i \quad \textbf{(2)}$$

where I_i is the current flowing through the i-th line, R_i is its active resistance, and n denotes the number of network branches. This quadratic dependence indicates that current reduction is the most effective way to minimize losses.

Uneven distribution of single-phase consumers leads to phase current imbalance, which increases losses and causes excessive neutral currents. In an ideally balanced system, phase currents satisfy the condition [14]:

$$I_A \approx I_A \approx I_C \quad (3)$$

To quantify the degree of imbalance, the following coefficient is introduced:

$$k_{imb} = \frac{\max(I_A, I_B, I_C)}{I_{avg}} \quad (4)$$

where I_{avg} is the average value of the three phase currents. This coefficient is restricted by an admissible limit**:**

$$k_{imb} \le k_{imb}^{max} \quad \textbf{(5)}$$

where k_{imb} is the permissible imbalance coefficient.

Reactive power flow increases the magnitude of current in distribution feeders, which directly affects active losses. The line current is related to active power and power factor by:

$$I = \frac{P}{\sqrt{3}U cos\varphi} \quad (6)$$

Accordingly, a minimum power factor constraint is included in the optimization model: $cos\varphi \ge cos\varphi_{min}$

This constraint is satisfied through reactive power compensation and rational placement of loads [15].

Voltage quality is one of the principal operational constraints in low-voltage networks. At every network node, voltage must remain within permissible limits: $U_{min} \le U_i \le U_{max}$

In practical 0.4 kV systems, these limits are typically defined as: $0.95U_{min} \le U_i \le 1.05U_{max}$

Low-voltage (0.4 kV) distribution networks are typically characterized by a radial topology, which makes them structurally simple yet operationally complex due to high current levels, load variability, and phase imbalance. From a mathematical perspective, such networks can be represented in graph form as

$$\varsigma = (N, \varepsilon) \quad (7)$$

where N denotes the set of network nodes, including busbars, distribution cabinets, and consumer connection points, while ε represents the set of branches corresponding to cable or line segments [16].

Since low-voltage systems operate under a three-phase configuration, all electrical quantities are modeled separately for each phase $\varphi \in \{A,B,C\}$. This phase-oriented representation is essential for accurately describing voltage unbalance, neutral conductor currents, and uneven load distribution, which are dominant phenomena in low-voltage networks.

Electrical loads in such systems exhibit strong time dependence caused by consumer behavior and daily operating cycles. Therefore, the optimization problem is formulated over a discrete time horizon $t \in \tau = \{1,2,\ldots,T\}$, with a discretization interval Δt commonly chosen between 15 minutes and one hour. For each node i, phase φ, and time instant ttt, the active and reactive load demands are described by $P_i\varphi(t)$ and $Q_i\varphi(t)$, respectively [17].

The optimization model includes several controllable decision variables reflecting practical operational measures in low-voltage distribution networks. Phase reallocation of single-phase consumers is represented by binary variables

$$x_{k\phi} \in \{0,1\}, \ \sum_{\phi} x_{k\phi} = 1 \quad (8)$$

where $x_{k\varphi}=1$ indicates that consumer k is connected to phase φ. Reactive power compensation at selected nodes is described by: $y_i \in \{0,1\}$ subject to technical limitations of compensation devices.

For each node and phase, complex power injection is defined as:

$$S_{i\phi}(t) = P_{i\phi}(t) + jQ_{i\phi}(t) \quad (9)$$

These injections are incorporated into the three-phase power flow equations, which are inherently nonlinear.
When single-phase consumers are reconnected between phases, the nodal load injections change depending on the selected phase allocation. In this case, the active power demand at each node and phase is expressed as follows:

$$P_{i\phi}(t) = P_{i\phi}^{fix}(t) + \sum_{k\in\mathcal{L}_1(i)} x_{i\phi} P_k(t) \quad (10)$$

where: $P_{i\varphi}(t)$ – total active power demand at node *i*, phase φ, at time *t*; $P_{i\phi}^{fix}(t)$– fixed (non-switchable) active load connected to node *i*; $P_k(t)$ – active power demand of the *k*-th single-phase consumer; $x_{i\varphi}$ – binary decision variable indicating the connection of consumer *i* to phase φ; $L_1(i)$ – set of single-phase consumers connected to node *i*.

Similarly, the reactive power injection at each node and phase is determined by:

$$Q_{i\phi}(t) = Q_{i\phi}^{fix}(t) + \sum_{k\in\mathcal{L}_1(i)} x_{i\phi} Q_k(t) - Q_i^{cap}(t) \quad (11)$$

where: $Q_{i\varphi}(t)$ – total reactive power demand at node *i*, phase φ, at time *t*; $Q_{i\phi}^{fix}$– fixed reactive load at node *i*; $Q_k(t)$ – reactive power demand of the *k*-th single-phase consumer; Q_i^{cap}– reactive power supplied by compensation devices installed at node *i*.
This formulation allows the optimization model to simultaneously account for phase reallocation of consumers and the influence of reactive power compensation on nodal reactive power balance.
For radial feeders, voltage variation between adjacent nodes is described by the DistFlow-based equation:

$$U_{j\phi}(t) = U_{i\phi}(t) - 2(r_{ij\phi}P_{ij\phi}(t) + x_{ij\phi}Q_{ij\phi}(t)) + (r_{ij\phi}^2 + x_{ij\phi}^2)l_{ij\phi} \quad (10)$$

where: $U_{j\varphi}(t)$ – squared voltage magnitudes at nodes *i* and *j* of phase φ at time *t*; $r_{ij\varphi}$, $x_{ij\varphi}$ – resistance and reactance of the line section between nodes *i* and *j* for phase φ; $P_{ij\varphi}(t)$, $Q_{ij\varphi}(t)$ – active and reactive power flows in the corresponding branch; $l_{ij\varphi}(t)$ – squared current magnitude in the line segment.
For radial distribution feeders, power flow can be modeled using the DistFlow formulation, in which active and reactive power flows, squared current, and squared voltage are defined for each branch *(i,j)* and phase *φ*. The corresponding balance and voltage-drop equations relate line parameters to nodal power injections, providing an efficient representation of low-voltage radial networks. Depending on the model structure and decision variables, the optimization problem may be formulated as either nonlinear programming (NLP) or mixed-integer nonlinear programming (MINLP) [18].
The main objective of the optimization is the minimization of total electrical energy losses accumulated over the considered time horizon. This objective is expressed as:

$$E_{loss} = \sum_{t\in\tau} \Delta t \sum_{(i,j)\in\varepsilon} \sum_{\phi} r_{ij\phi} l_{ij\phi}(t) \quad (11)$$

where: E_{loss} – total electrical energy losses over the optimization period; Δt – duration of the time interval; τ – set of discrete time steps;ε – set of network branches;
In practical operation, additional performance indices must be considered. Therefore, a weighted multi-objective function is employed, incorporating voltage deviation penalties, phase unbalance or neutral current indices, power factor at the point of common coupling, and voltage harmonic distortion [19].
The optimization is subject to standard technical constraints, including allowable voltage limits at all nodes, thermal current limits of cables and lines, transformer apparent power capacity, minimum power factor requirements, phase unbalance restrictions, and bounds on compensation devices. Discrete constraints related to phase connection and optional budget limitations for network modernization may also be included. The proposed mathematical formulation provides a compact yet comprehensive framework for analyzing and optimizing the operating modes of low-voltage distribution networks, enabling coordinated loss reduction, voltage regulation, phase balancing, and power quality improvement within a unified optimization model [20].

V. EXPERIMENTAL RESULTS AND DISCUSSION

This study was conducted on a real urban low-voltage (0.4 kV) distribution system supplying predominantly single-phase residential loads. Calculations were performed under realistic operating conditions using actual load data. The operating power factor was fixed at cosφ = 0.85 in order to isolate the effect of load optimization. Initial analysis revealed pronounced phase imbalance due to uneven load distribution, resulting in overloaded phases, high neutral conductor current, increased feeder currents, and elevated active power losses.

Under these conditions, total electrical energy losses reached approximately 14% of the transmitted energy, exceeding recommended limits for low-voltage networks. Voltage deviations at end nodes reached up to ±8%, indicating degraded power quality. Load optimization was implemented by redistributing single-phase consumers among phases without modifying network topology, conductor cross-sections, or power factor.

After optimization, phase currents became significantly more balanced and neutral current was substantially reduced. This led to lower feeder currents, improved voltage profiles within ±5%, and a decrease in total energy losses to 9.8%. Comparative analysis shows that energy losses were reduced from 14% to 9.8%, corresponding to an approximate 30% relative reduction. These results were achieved without infrastructure reinforcement, confirming that load optimization is an effective and economically efficient method for improving the performance of existing low-voltage distribution networks.

Table -1.
Comparative performance indicators of the 0.4 kV low-voltage network before and after load optimization

Indicator	Before optimization	After optimization	Change
Nominal voltage	0.4 kV	0.4 kV	Unchanged
Power factor, cosφ	0.85	0.85	Unchanged
Phase imbalance	18–22 %	6–8 %	Significantly reduced
Electrical energy losses	14 %	9.8 %	↓ ~30 %
Neutral conductor current	High	Reduced	Improved
Voltage deviation at end nodes	Up to ±8 %	Within ±5 %	Improved
Overall energy efficiency	Low	High	Increased

The results clearly demonstrate that in low-voltage (0.4 kV) power supply systems, energy losses are strongly influenced by load distribution rather than only by conductor parameters or power factor. Even at a fixed power factor of cosφ = 0.85, significant loss reduction can be achieved through phase load balancing alone. This highlights load optimization as a highly effective, low-cost strategy for reducing energy losses, improving voltage quality, and enhancing operational reliability in existing low-voltage distribution networks.

VI. CONCLUSION AND FUTURE WORK

The conducted study confirms that energy losses in low-voltage (0.4 kV) power supply systems are primarily determined by phase load imbalance and elevated current levels rather than by conductor parameters alone. Under typical operating conditions with a fixed power factor of cosφ = 0.85, the analyzed network exhibited energy losses of approximately 14%, indicating inefficient utilization of electrical energy and degraded voltage quality.

Implementation of phase load optimization, without any modification of network topology, conductor characteristics, or power factor, resulted in a reduction of total energy losses to 9.8%, corresponding to an approximate 30% relative decrease. This improvement is mainly attributed to the reduction of phase asymmetry and neutral conductor current, which leads to lower feeder currents and decreased resistive losses.

The obtained results demonstrate that load optimization represents a scientifically sound, technically effective, and economically efficient approach for reducing energy losses, improving voltage profiles, and enhancing the operational performance of existing low-voltage distribution networks.

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AUTHOR'S BIOGRAPHY

Full name	**Taslimov Abdurakhim Dexkanovich**
Science degree	Professor
Academic rank	Senior Research Fellow
Institution	Tashkent state technical university, Tashkent, Uzbekistan

Full name	**Rakhimov Farrux Movlidinovich**
Science degree	PhD
Academic rank	Senior Research Fellow
Institution	Navoi State University of Mining and Technology, Navoi, Uzbekistan

Full name	**Norqulov Asliddin Olimovich**
Science degree	
Academic rank	Independent researcher
Institution	Navoi State University of Mining and Technology, Navoi, Uzbekistan