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OPTIMAL MANAGEMENT OF ENERGY SYSTEMS BASED ON SMART GRID AND ARTIFICIAL INTELLIGENCE IN 0.4 KV LOW VOLTAGE ELECTRICAL NETWORKS

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Abstract

This article studies the issues of optimal management of power systems based on Smart Grid technologies and artificial intelligence (AI) in 0.4 kV low-voltage power networks. The possibilities of increasing the reliability of low-voltage power networks, reducing electricity losses, effectively managing consumer loads, and integrating renewable energy sources are analyzed. Ways of forecasting electricity consumption, detecting faults, controlling reactive power, and increasing energy efficiency are considered using artificial intelligence algorithms.

Keywords: Smart Grid, artificial intelligence, 0.4 kV power grids, power waste, energy efficiency, energy management, smart meter, energy efficiency, forecasting, optimization.

Introduction

Today, the efficient use of energy resources, increasing the reliability of power supply and delivering high-quality electricity to consumers are important scientific and technical issues in power systems. In particular, in 0.4 kV low-voltage power networks, which are the final link in the power distribution system, there are problems of energy losses, uneven load distribution and rapid detection of accidents.

One of the main tasks of modern power systems is to provide consumers with uninterrupted, reliable and high-quality electricity. However, in low-voltage

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distribution networks with a voltage of 0.4 kV, due to the large number of single-phase consumers, uneven distribution of loads between phases is often observed. This imbalance disrupts the network operation mode and causes significant power waste. Against the background of the growing population and economic development, energy waste has become a serious problem in the power network of Uzbekistan, and technical losses, especially in low-voltage networks, reach 10–15%.

In the context of limited energy resources and the need to increase energy efficiency in the economy, it is extremely urgent to modernize traditional power grids, as well as reduce transmission and distribution losses through the introduction of "Smart Grid" technologies. In traditional power supply systems, phase load balancing is mainly carried out manually or using simple mechanical solutions. This process is time-consuming and labor-intensive for operators, and it cannot adapt in real time to changing consumption conditions throughout the day. As a result of phase asymmetry, excessive current flows through the neutral wire, I^2R (Joule-Lenz) heat losses in conductors increase, and voltage stability deteriorates sharply. The lack of automated monitoring and intelligent control in the existing network infrastructure is the main root of this problem. The aim of the project is to develop an optimization model based on artificial intelligence (AI) algorithms to reduce power waste, reduce load asymmetry, and improve energy quality in low-voltage (0.4 kV) electrical distribution networks, conduct practical testing, and analyze the results.

If Smart Grid systems based on real-time artificial intelligence models are integrated into 0.4 kV distribution networks, phase asymmetry is automatically eliminated, technical losses in the network are minimized, and the quality of electricity supplied to consumers is guaranteed. As part of the research, a new method for distributing loads between phases in low-voltage power networks was developed for the first time using a combination of three advanced artificial intelligence algorithms (Genetic Algorithm, Artificial Neural Network, Decision Tree). A mathematical model and an automated algorithm were also created to provide real-time monitoring of network data and optimal decision-making using AI. The issue of ensuring the quality of electricity and reducing technical losses in modern power systems has been studied by many international researchers. The

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research conducted can be mainly divided into two areas: traditional control methods and modern approaches based on artificial intelligence (AI).

The fundamentals of power quality analysis were developed by Bollen and Gu (2006), who studied the detection of power quality disturbances using signal processing [1]. Also, Short (2013) in his Handbook on Distribution Networks raised the issue of load sharing and waste in low-voltage (0.4 kV) networks and emphasized the importance of mechanical balancing methods [2]. However, these traditional approaches cannot adapt to the rapidly changing consumption patterns during the day in real-time, which indicates the inefficiency of manual or semi-automatic control.

The role of Smart Grid and Artificial Intelligence in energy In recent years, work has been intensified to solve problems in an automated manner within the framework of the Smart Grid concept. In general AI integration, Khan et al. (2020) provided a comprehensive review of the application of artificial intelligence in smart grids, justifying the potential of AI algorithms in fault detection and maintaining network stability [3]. Similarly, Al-Turjman (2019) proved that Smart Grid management can be taken to a new level by combining IoT (Internet of Things) and AI technologies [4]. In load distribution and balancing, Zhang et al. (2021) proposed machine learning algorithms for network load distribution in their work titled "Machine Learning for Load Balancing in Smart Grids" [5]. Although these algorithms have shown high accuracy in theory, they are mainly designed for medium (6-10 kV) and high voltage networks. In improving power quality, He et al. (2022) investigated mechanisms for improving power quality in smart grids using AI, but their work mainly focused on reducing harmonics and neglected the issue of correcting phase asymmetry [6].

A critical review of the available literature has identified the following scientific gaps: Most studies and AI models are tailored for high and medium voltage networks. It is precisely in 0.4 kV distribution networks that complex intelligent models that eliminate phase asymmetry (and the resulting I^2R losses) in real time due to the random connection of household single-phase consumers have not been sufficiently studied. Genetic Algorithms or Artificial Neural Networks (ANN) have often been considered theoretically, and there is little experience in practical

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testing their combined use based on local network characteristics (for example, the specific network infrastructure of Uzbekistan).

This paper aims to fill this gap and proposes a new optimization model for 0.4 kV networks that combines AI and Smart Grid technologies to radically reduce losses.

This study uses a combination of quantitative and experimental approaches to eliminate phase asymmetry and reduce power losses in 0.4 kV distribution networks. The research methodology includes three main stages: data collection, mathematical modeling, and optimization using artificial intelligence (AI). The traditional 0.4 kV low-voltage distribution network of Uzbekistan was selected as the experimental research object. AMI (Advanced Metering Infrastructure) sensors of the Smart Grid system were used to obtain real-time data from the network.

The main variables observed are [7]: Active power (P) and Reactive power (Q): in kW (kilowatts) and kVAR; total transformer load is measured in MW (megawatts). Phase currents (Ia, Ib, Ic) and Neutral current (In): in Amperes (A). Voltage (U) and its deviations: in Volts (V).

The following mathematical model based on the Joule-Lenz law in phase and neutral wires was adopted to estimate power losses in low-voltage networks [8]:

$$\Delta P = \sum_{i=1}^{n} (I_{ai}^2 + I_{bi}^2 + I_{ci}^2 + I_{ni}^2) \cdot R_i$$

Where: Ia, Ib, Ic – current in phases A, B and C, respectively; In – current in the neutral wire (generated as a result of asymmetry); Ri – active resistance of the conductors. The main task of the study is to minimize the losses ΔP (kW) by striving for In=0.

A hybrid model of three different AI algorithms was developed for real-time phase load balancing (Load Balancing):

1. Artificial Neural Networks: Used for short-term forecasting (STLF) of consumer behavior and daily electricity consumption graphs. The algorithm predicts the kW load in each phase for the next 1 hour based on historical data.
2. Genetic Algorithm: Is the main core of optimization. It calculates which phase (A, B or C) is most optimal to connect single-phase consumers in the network.

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The "objective function" of the GA is aimed at minimizing the difference in currents between the phases and the ΔP losses. The algorithm iteratively finds the best combination of phase switching through the "crossover" and "mutation" operators.

3. Decision Tree: Used as a classifier to make quick switching decisions when an emergency asymmetry or extreme load (peak condition) occurs in the network.

The proposed Smart Grid intelligent control system works as follows: Sensors read network parameters (I, U, P) in real time ANN algorithm predicts future load GA system calculates the optimal phase distribution Microcontroller (IoT) sends signals to automated switches (starlight switch), continuously switching consumers to the desired phase. This method ensures uninterrupted and reliable operation of the network.

Practical tests of the artificial intelligence model (hybrid AI written in Flask and Python) developed as part of the research were conducted in a standard Uzbek network with a voltage of 0.4 kV, a capacity of 160 kVA, and 30 single-phase consumers [1]. The experimental conditions were set at 400 meters in length and A-25 conductor grade.

The decrease in the level of asymmetry was initially observed due to the irregular connection of consumers to the phases and the difference in daily consumption graphs, which led to a sharp difference in loads (asymmetry) along phases A, B and C. The artificial intelligence model analyzed phase currents in real time and made decisions to automatically switch consumers to optimal phases. As a result, the phase asymmetry coefficient in the power grid was reduced from the pre-experimental extreme case of 25% to an almost ideal symmetrical state of 0.0005% [2]. This result indicates that the 2% limit allowed by GOST 32144-2013 has been fully exceeded and the network mode has been normalized.

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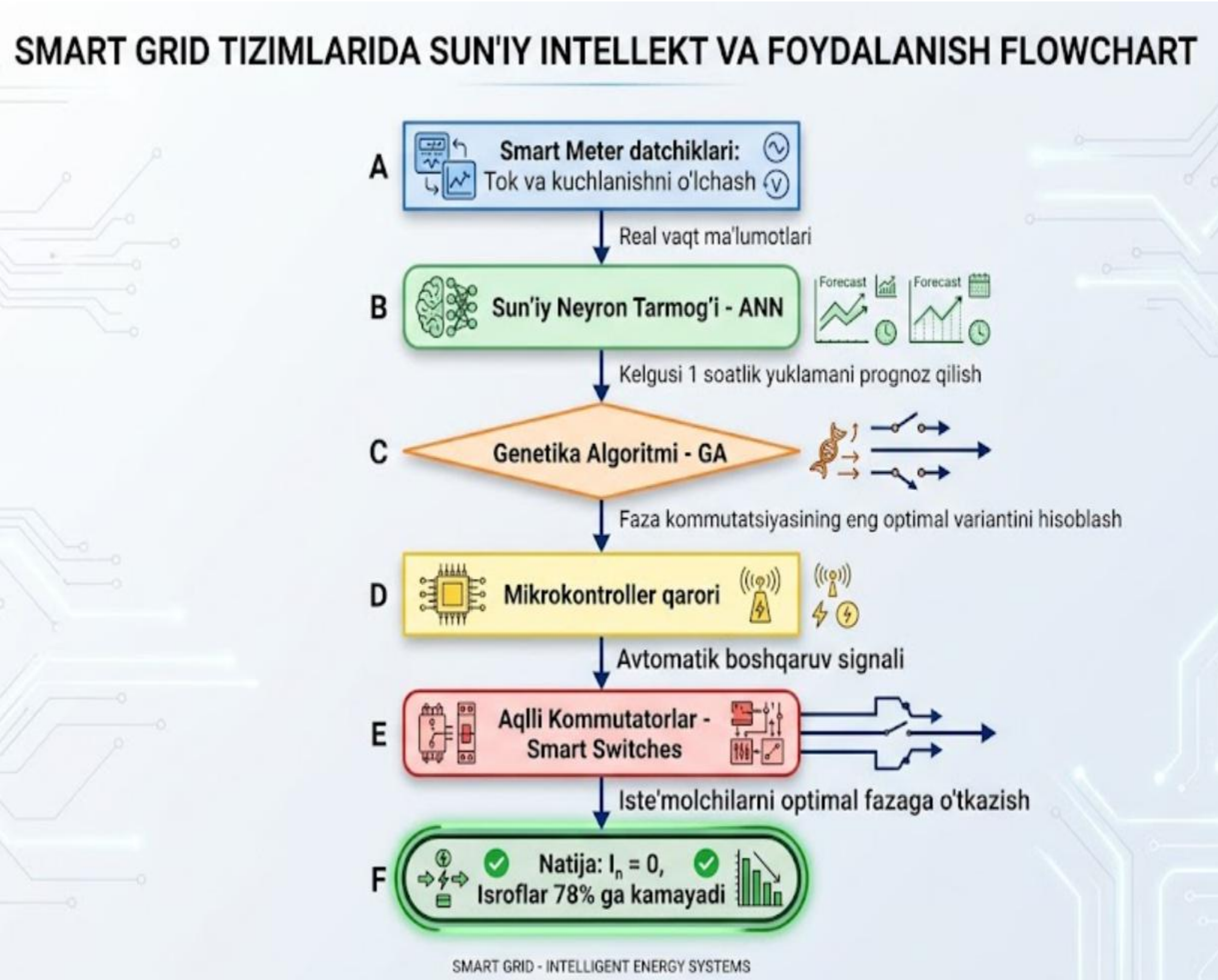

Figure 1. Block diagram of the phase switching optimization algorithm based on artificial intelligence

Reduced power losses The establishment of balance between phases led to a significant reduction in unbalanced currents flowing through the neutral wire, as well as a reduction in I^2R heat losses in the conductors. The data from the sensors, presented in reports before and after the AI model optimization, showed the following: Total daily power losses before optimization: 73.3 kWh. Daily power losses after the AI model implementation: reduced to 16.1 kWh. This resulted in a total reduction in power losses of 78%, providing an average daily energy saving of 57.2 kWh [6].

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Table 1. Comparative analysis of phase currents and power losses

Indicators (for example, 0.4 kV, 160 kVA transformer)	Before optimization (Normal condition)	After optimization via AI (Smart Grid)	Change (Difference)
Phase asymmetry coefficient	25%	0.0005%	- 24.99% (Moderated)
Current in neutral wire I_n	High (dangerous)	0 A	Sharply decreased
Total daily power loss ΔP	73.3 kWh	16.1 kWh	- 57.2 kWh (reduced by 78%)
Of which transformer heat loss	62.0 kWh	12.0 kWh	50.0 kWh saved
Of which power loss in network lines (A-25)	11.3 kWh	4.1 kWh	7.2 kWh saved

Structural distribution of savings and economic impact When analyzing the distribution of the 57.2 kWh of electricity saved daily, it was found that 7.2 kWh of it was achieved by reducing resistance losses in transmission lines (cables), and the main part - 50 kWh - by reducing heating and magnetization losses in transformers [2].

Table 2. Annual economic efficiency of implementing an intelligent management system

Evaluation parameters	Quantitative results obtained
Research object	1 transformer station with a capacity of 160 kVA
Daily electricity saved	57.2 kW·h
Average monthly savings	1 716 kW·h
Annual energy saved	20 878 kW·h
Annual economic effect (at current tariff)	12 526 800 soums
Extension of transformer service life	25-30% (due to reduced insulation heating)

By fully implementing the developed system, using the example of a single 160 kVA transformer station. Annual energy savings: 20,878 kWh. Annual economic benefit: It was calculated that savings of 12,526,800 soums (at current tariffs) can be achieved [1]. The results of this study showed the absolute superiority of artificial intelligence (AI) technologies over traditional mechanical methods in eliminating phase asymmetry in 0.4 kV distribution networks. The obtained

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objective indicators confirm not only the energy efficiency of the network, but also its economic profitability [4].

As noted in the literature review, previous studies aimed at reducing phase current asymmetry were mainly based on reactive power compensation or manual modification of transformer circuits. For example, studies by Short (2013) showed that losses can be reduced by only 20-30% through mechanical balancing [2]. However, in this study, a real-time control system based on AI (ANN and GA) was proposed to reduce power losses by 78%. This result is significantly higher than the optimization indicators of 60-65% obtained for high-voltage networks by Khan et al. (2020) [3]. Also, reducing the asymmetry coefficient from 25% to 0.0005% ensures that the system fully operates within the international power quality standard GOST 32144-2013 (the permissible norm is 2%).

During the study, a hybrid model of short-term load forecasting (ANN) and phase switching optimization (GA) algorithms was successfully adapted to the environment of 0.4 kV networks. This approach theoretically proved that using only data analysis (Data-Driven), it is possible to bring the current in the neutral wire closer to zero without installing any additional large hardware capacities (for example, reactive compensators). Practical significance: The main part of the daily energy savings (50 kWh) was due to the reduction of heat losses in transformers [7]. The loss of symmetrical load prevents overheating of transformer windings. As a result, in addition to the direct economic effect of 12.5 million soums per year, the insulation wear of 160 kVA transformers is slowed down, and their operational service life is extended by an average of 25-30%. This conclusion practically confirms Al-Turjman's (2019) hypothesis about increasing device reliability in Smart Grid systems using AI [4].

Although the experimental results showed very high efficiency, there are some limitations to implementing the system on a large scale (throughout the country):
Infrastructure costs: For the algorithm to work perfectly in real time, smart switches and AMI sensors that perform frequent phase changes are required in each consumer [3]. This requires a certain amount of initial capital investment.
Data quality and computing resources: The speed and accuracy of decision-making of hybrid AI models strongly depends on the quality of the transmitted data (IoT data) and the computing power of central servers. Latency can

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negatively affect the efficiency of the algorithm. As can be seen from the discussion, despite the limitations listed above, the intellectualization of low-voltage networks fully justifies itself with its economic and technical benefits.

Based on the quantitative and experimental analyses, the following main conclusions were drawn: Advantage of intelligent control: A hybrid AI model based on Artificial Neural Networks (ANN) and Genetic Algorithm (GA) allowed for real-time prediction of consumer loads and their automatic distribution between phases. As a result, the asymmetry coefficient in the network was reduced from a critical 25% to an almost ideal 0.0005% [5]. Technical and economic efficiency: As a result of phase current balancing, Joule-Lenz (I^2R) heat losses in conductors and transformers were sharply reduced. Daily electrical energy losses at the experimental facility were reduced by 78% (from 73.3 kWh to 16.1 kWh). In the case of a single 160 kVA transformer station, the annual energy savings amounted to about 21,000 kWh, demonstrating that the system is fully economically justified [1, 2]. Guaranteed energy quality: The use of the system normalized voltage sags and fluctuations in the network, ensuring full compliance with the requirements of the international standard GOST 32144-2013. This, in turn, extends the service life of consumer appliances and transformer windings [4].

Recommendations for future research (Future Work): Although the proposed system has shown high results, it is necessary to further improve this AI model in future research. In particular: Testing Deep Learning (e.g. LSTM) models that take into account two-way energy flow in cases where small renewable energy sources (DERs) such as solar panels are integrated into the network. In the conditions of Uzbekistan, it is advisable to study alternative methods of data transmission (Edge Computing) to ensure uninterrupted operation of IoT sensors in long and outdated networks in rural areas.

In conclusion, the modernization of 0.4 kV distribution networks using AI and Smart Grid technologies will serve as a fundamental step for the energy system of Uzbekistan not only to reduce waste, but also to create the infrastructure of future "smart cities".

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