ABSTRACT

of the dissertation for the degree of Doctor of Philosophy (PhD) in the specialty 8D06101 – "Information Systems"

Shermantayeva Zhazira Utegenovna

DEVELOPMENT OF AN INFORMATION SYSTEM FOR ELECTRIC POWER INDUSTRY USING IoT TECHNOLOGY

Relevance of the work. The electric power industry is the foundation of development for any state. Today, Kazakhstan faces the necessity to modernize its power system and transition to more environmentally friendly technologies. The country is gradually increasing the share of renewable energy sources (RES); however, solar and wind generation are highly dependent on weather conditions: at times there is excess energy, while at other times it is insufficient. This creates significant difficulties in maintaining stable operation of the power system.

The situation is further complicated by the high wear rate of electrical networks (approximately 56 %) and the annual growth in electricity consumption. In 2024, the installed capacity of Kazakhstan's power system was approximately 22 GW, of which 80 % was accounted for by thermal power plants and only about 7 % by RES. Under such conditions, the risk of emergency outages increases, and network management requires more rapid and accurate decisions.

To address these challenges, the state has launched projects aimed at modernizing networks, connecting new energy sources, and increasing the share of RES in the country's energy balance. All of this necessitates the introduction of modern digital technologies capable of improving monitoring and control of power facilities.

Internet of Things (IoT) technologies, Smart Grid intelligent networks, and FPGA-based hardware-software solutions enable: • real-time tracking of equipment condition, • rapid response to faults, • increased energy efficiency, • reduction of electricity losses by up to 12 %, • enhanced reliability of power supply.

Thus, the development of an intelligent monitoring and control system for electric power facilities using IoT and FPGA technologies is a highly relevant task that supports Kazakhstan's energy security and aligns with global sustainable development trends.

Object of research: Local electric power systems of the Turkestan Region of the Republic of Kazakhstan, including 35/10/0.4 kV distribution electrical networks and the 35/10 kV "Novaya" substation of "Ontustik Zharyq Transit" LLP, operating under conditions of a high share of renewable energy sources and significant physical wear of equipment.

Main objective of the dissertation: Development and practical implementation of an intelligent real-time information system based on IoT, Smart Grid, and FPGA data processing technologies for electric power systems.

The system is designed to provide: • continuous real-time monitoring, • operational forecasting and prevention of emergency modes, • automatic control of network operating regimes with a high share of renewable energy sources.

As a result, reliability of electricity supply is increased, technological electricity losses are reduced, and the operation of local electric power systems is optimized.

Idea of the work. The core idea of the dissertation is to create an intelligent management and monitoring system for local electric power systems that integrates Internet of Things (IoT), Smart Grid, and high-speed data processing on FPGA. The system ensures continuous monitoring of network condition, forecasting of emergency situations, and automatic optimization of operating regimes, thereby enabling efficient integration of renewable energy sources, minimization of technological losses, and enhancement of power supply reliability under conditions of high network infrastructure wear and variable generation patterns.

Justification of novelty and significance of the obtained results. The research conducted in the dissertation possesses scientific novelty and practical significance, as it addresses current challenges of ensuring stability and reliability of local electric power systems (LEPS) in Kazakhstan amid the growing share of RES and aging network infrastructure.

1. A model based on Markov processes and similarity theory has been developed, allowing comprehensive assessment of LEPS stability while taking into account the probabilistic nature of equipment operation and the variability of generation and load regimes. The proposed approach makes it possible to: • forecast probable emergency states and failure risks, • improve the substantiation of power system architecture selection, • optimize the structure and operating regimes of distribution networks. The novelty of the model lies in the integration of Markov process methods and similarity principles for the analysis of real networks with a high share of distributed generation, an approach that has previously been practically unused in domestic power engineering.
2. A hybrid IoT monitoring complex based on FPGA and ESP32 has been developed, providing high-speed real-time data processing and the capability for remote intelligent control of substation equipment. The use of FPGA enables: • reduction of emergency signal processing delays, • increased system fault tolerance, • scalability and integration with Smart Grid platforms. The information system supports secure IoT protocols for data transmission and has a modular architecture, making it suitable for industrial deployment in Kazakhstan’s grid companies.

Research tasks:

1. Analysis of modern digital transformation technologies in the power industry Conduct a systematic review of current approaches and digitalization technologies in electric power engineering, including Smart Grid, IoT, and FPGA solutions. Identify their impact on reliability, energy efficiency, and ecological sustainability of local and distributed power systems, and determine possibilities for adaptation to Kazakhstan’s conditions.

2. Development of a model for the operation of electrical networks with renewable energy sources Create mathematical and simulation models of local electrical networks integrated with RES, taking into account the variable nature of generation and load fluctuations. The model enables forecasting of possible emergency situations, assessment of network stability, and adoption of optimal decisions regarding its structure and operating regimes.
3. Creation of an IoT device for monitoring the operating regimes of power equipment Develop a hardware-software solution based on FPGA and ESP32 microcontrollers capable of real-time data collection from substations, analysis of equipment operating regimes, and transmission of information to the information system. This ensures rapid response to changes in network parameters and reduction of accident risks.
4. Construction of an intelligent Smart-monitoring information system Create a software-hardware platform for centralized management of local electric power systems. The system provides: • collection and processing of data from IoT devices, • visualization and analytical control of regime parameters, • forecasting of emergency and critical situations, • support for managerial decision-making to enhance network stability and efficiency.

Main provisions submitted for defense:

1. A model for assessing the stability of local electric power systems using Markov processes and similarity theory has been developed, enabling forecasting of possible emergency situations and selection of optimal network structures taking renewable energy sources into account.
2. An architecture of an intelligent Smart-monitoring system has been proposed that collects and processes data from substations, visualizes regime parameters, and assists in operational management of local power systems.
3. A hybrid IoT device based on FPGA and ESP32 has been created for equipment monitoring, providing fast real-time data collection and transmission as well as remote control of substations.
4. The effectiveness of applying IoT and FPGA technologies to increase reliability, energy efficiency, and reduce energy losses in local power systems with a high share of renewable generation has been proven.
5. Practical recommendations have been developed for implementing the proposed system at electric power facilities in Kazakhstan, taking into account the specifics of distributed networks and requirements for stability and efficiency of LEPS.

Research methods. The dissertation employed the following research methods:

1. Mathematical modeling and criterion-based evaluation methods – for quantitative analysis of local electric power systems operation, assessment of stability, and efficiency of various network structures.
2. Simulation modeling – to reproduce the dynamics of distributed electrical networks with renewable energy sources and verify the effectiveness of the proposed control algorithms.

3. System analysis and comparative methods – for comprehensive study of power systems, identification of strengths and weaknesses of existing solutions, and selection of optimal architectures and approaches.
4. Models based on Markov processes and similarity theory – for forecasting failure probabilities, analyzing network reliability, and making decisions on the optimal structure and operating regimes of LEPS.

Practical significance. The results of the work enable improvement of reliability and energy efficiency of Kazakhstan's local electric power systems. The developed model and FPGA-ESP32-based IoT device provide monitoring and operational control of substations, reduce energy losses, and accelerate response to emergency situations. The proposed solutions can be implemented by energy companies for network modernization and integration of renewable energy sources.

Compliance with science development directions and state programs of the Republic of Kazakhstan. The work fully corresponds to:
1. Priority directions of science in the Republic of Kazakhstan for 2024–2026: "Energy, advanced materials and transport" and "Advanced manufacturing, digital technologies" (digitalization of power engineering and RES).
2. State program "Digital Kazakhstan" (measure 2.4 – digitalization of electric power industry, introduction of IoT and Smart Grid).
3. Concept of development of the fuel and energy complex and electric power industry of the Republic of Kazakhstan for 2023–2029 (Government Resolutions No. 260 and No. 263 dated 28.03.2023) – tasks of loss reduction and RES integration.
4. National Development Plan of the Republic of Kazakhstan until 2029 (Presidential Decree No. 127 dated 01.02.2023) – task No. 58 "Modernization and digitalization of electric power industry".
5. UN Sustainable Development Goal No. 7.

Justification and reliability of results and conclusions. The reliability of the obtained results is ensured by the use of modern mathematical and simulation modeling methods, criterion analysis, and a systematic approach. The application of Markov processes and similarity theory allows forecasting the operation of local electric power systems taking into account probabilistic changes in load and generation.

The development and testing of the FPGA- and ESP32-based IoT device were carried out on an experimental test bench, which confirms the practical applicability of the proposed system for monitoring and controlling substations. All conclusions are based on modeling results, experimental tests, and system analysis, thereby ensuring their scientific validity and reliability.

Volume and structure of the work. The dissertation consists of an introduction, a main part comprising four chapters, and a conclusion. The total volume is 152 pages of typewritten text. The work contains 84 figures, 11 tables, a list of 149 references, and 7 appendices.

Description of the main research results:

- A model for assessing the stability of local electric power systems based on Markov processes and similarity theory has been developed. The model enables

forecasting of probable emergency situations, evaluation of the impact of renewable energy sources on network operation, and selection of optimal structures for distribution systems.

- An intelligent Smart-monitoring system has been created that provides collection, processing, and visualization of data from substations. The system allows control of regime parameters, forecasting of critical states, and support for operational management of local power systems.
- A hybrid IoT device based on FPGA and ESP32 has been developed for real-time monitoring of substation equipment operation. The device ensures fast data processing and remote control of network operating regimes.
- The effectiveness of the proposed solutions has been evaluated using simulation modeling and experimental tests on a test bench. The results demonstrated increased reliability, reduction of energy losses by up to 12 %, and improved management of distributed networks with a high share of renewable generation.
- Practical recommendations have been developed for implementing the proposed system at electric power facilities in Kazakhstan, taking into account the specifics of distributed networks, RES integration, and requirements for energy efficiency and stability of LEPS.

Area of application: Real-time monitoring and control of 35–10–0.4 kV substations and distribution networks, enhancement of reliability with high RES penetration, integration of solar and wind plants, implementation of Smart Grid and IoT technologies within the “Digital Kazakhstan” program and distribution complex modernization for 2025–2030.

The developed solutions are recommended for use by transmission organizations, regional electricity companies, and industrial enterprises with their own generation capacities.

Contribution of the PhD candidate to each publication During the approbation and publication of the dissertation results, the PhD candidate, Shermantayeva Zhazira Utegenovna, prepared the following scientific works. In **all** publications, the candidate made a **decisive contribution (60–100 %)**: development of models, calculations, simulations, experiments, writing the text, and formatting. This confirms her active and substantial scientific contribution to research on intelligent monitoring and control systems in the electric power industry.

1. ***Articles in Scopus-indexed journals (6 articles, one of which is in the 85th percentile)***

1. Wójcik W., Lezhniuk P., Shermantayeva Z. Integrated Assessment of the Quality of Functioning of Local Electric Energy Systems. Energies, 2025, Vol. 18, Issue 1, Article 137. DOI: https://doi.org/10.3390/en18010137 (22 p.). PhD candidate – 3rd author, developed the MSSB algorithm for comprehensive quality assessment of local power systems, performed all mathematical calculations and simulations, wrote 70 % of the text (85th percentile in Scopus).
2. Mamyrbayev O., Shermantayeva Zh. Cybersecurity Framework for IoT-Integrated Electric Power Information Systems. International Journal of Industrial

Engineering and Management, 2024. DOI: https://doi.org/10.24867/ijiem-376 (12 p.). PhD candidate – 2nd author, proposed the cybersecurity framework for IoT in power systems, conducted threat analysis, wrote 80 % of the article.

3. Kalimoldayev M., Wójcik W., Shermantayeva Zh. Development Of A Monitoring System For Electric Power Substations Based On IoT And Implementation Of Designs On FPGA. International Journal of Electronics and Telecommunications, 2023. DOI: https://doi.org/10.24425/ijet.2023.147708 (10 p.). PhD candidate – 3rd author, independently designed and implemented the FPGA module for substation monitoring, wrote the main technical section.

4. Wójcik W., Tymchenko L., Shermantayeva Z. Optical System Visualization of Combined Reflectance Model Based on Cubic and Quadratic Functions. Proceedings of SPIE, 2023. DOI: https://doi.org/10.1117/12.3023138 (8 p.). PhD candidate – 4th author, developed visualization algorithms for optical models in power systems, performed simulations, wrote 60 % of the text.

5. Kalimoldayev M.N., Abdildayeva A.A., Shermantayeva Zh.U. Implementation of a Database on Solar Resources for the Design of PV Solar Technologies. Book Chapter, 2024. DOI: https://doi.org/10.1007/978-3-031-49711-7_26 (15 p.). PhD candidate – 3rd author, created the solar resource database for PV system design, performed calculations, wrote the chapter.

2. ***Articles in journals recommended by the Committee for Control of Education and Science of the Republic of Kazakhstan (4 articles)***

1. Kalimoldayev M., Shermantayeva Zh. Model Development and Calculations for 35/10 kV Electrical Substations in Turkestan Region Using RastrWin3 Program. Scientific Journal of Astana IT University, 2024. DOI: https://doi.org/10.37943/16DGMZ9449 (14 p.). PhD candidate – 2nd author, developed the substation model in RastrWin3, performed regime calculations and analysis, wrote the main text.

2. Wójcik W., Shermantayeva Zh.U. Problems of Development of the Electric Power Industry Based on IoT Technology. Bulletin of Abai Kazakh National Pedagogical University, 2022, Vol. 78, No. 2. DOI: https://doi.org/10.51889/2022-2.1728-7901.16 (9 p.). PhD candidate – 3rd author, conducted a review of IoT issues in power engineering, analyzed risks, wrote 70 % of the article.

3. Shermantayeva Z., Mamyrbayev O. Development and Creation of Hybrid EWT-LSTM-RELM-IEWT Modeling in High-Voltage Electric Networks. News of the National Academy of Sciences of the Republic of Kazakhstan, Physico-Mathematical Series, 2024, Vol. 3, No. 351, pp. 223–240. DOI: https://doi.org/10.32014/2024.2518-1726.302 (18 p.). PhD candidate – 1st author, created and trained the hybrid forecasting model, conducted experiments, wrote the full article.

4. Wójcik W., Shermantayeva Zh. Parallel-Hierarchical Optical Network as a Model of Natural Neural Network. Optical Fibers and Their Applications, 2023. DOI: https://doi.org/10.1117/12.3023432 (6 p.). PhD candidate – 2nd author, developed the optical network model for neural systems in power engineering, wrote 65 % of the text.

3. ***International conference proceedings (4 papers)***

1. Shermantayeva Zh. Overview of the Internet of Things (IoT) in Electric Power Engineering and Energy Systems. 3rd Online International Conference on Renewable Energy and Sustainable Technologies, 2022. Proceedings: pp. 97–108 (12 p.). PhD candidate – sole author, prepared the full review and text.
2. Shermantayeva Zh.U., Akhmetzhanov M.A. Internet of Things for Modern Power Systems. VII International Scientific-Practical Conference “Informatics and Applied Mathematics”, Almaty, 20–21 October 2022. Proceedings: pp. 112–120 (9 p.). PhD candidate – 1st author, performed IoT analysis in power engineering, wrote 85 % of the text.
3. Shermantayeva Zh.U. Application of IoT-Based Data Analysis and Processing Methods for Electrical Substations in the Republic of Kazakhstan. International Conference “Problems of Optimization of Complex Systems”, Novosibirsk, 14–22 August 2023. Proceedings: pp. 85–92 (8 p.). PhD candidate – sole author, developed data processing methods and prepared the presentation.
4. Shermantayeva Zh.U., Alshinbayeva D.O. Monitoring and Fault Elimination in Transformer Distribution Using IoT Technology. VIII International Scientific-Practical Conference “Informatics and Applied Mathematics”, Almaty, 2023. Proceedings: 7 p. PhD candidate – 1st author, developed transformer monitoring algorithms, wrote the text.

4. ***Patents and certificates of intellectual property (3 items)***

1. Software Complex for Determination and Visualization of the Dynamics of a Two-Machine Power System. Copyright Certificate No. 34772, 18.04.2023. PhD candidate – co-author, developed the algorithm and visualization interface.
2. Energy Monitoring 360. Copyright Certificate No. 49103, 16.08.2024. Authors: Shermantayeva Zhazira Utegenovna, Mamyrbayev Orken Zhumazhanovich. PhD candidate – 1st author and principal developer of the system.
3. System for Monitoring and Forecasting Emergency Situations at Power Substations Based on the Internet of Things and Hybrid EWT-LSTM-RELM-IEWT Model. Utility Model, Reg. No. 2024/1652.2, 25.12.2024. Authors: Mamyrbayev O.Zh., Shermantayeva Zh.U. PhD candidate – co-author, originator of the idea and model description.

Keywords: IoT, Smart Grid, FPGA, renewable energy sources, local electric power systems, real-time monitoring, Markov processes, energy efficiency, power system reliability, Kazakhstan.