ABSTRACT

of the dissertation on the topic

"Research on the impact of teletraffic characteristics on blockchain technology in Smart Grid networks"

submitted for the degree of Doctor of Philosophy (PhD) in the specialty 8D06201 "Radio Engineering, Electronics and Telecommunications"

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Relevance of the work: The development of Smart Grid systems is accompanied by an increase in the number of distributed generation facilities and prosumers, each of which acts as an independent node of data exchange within the power system. This circumstance changes the requirements for the information and communication infrastructure. The centralized and predictable structure of information flows characteristic of traditional electrical networks is being replaced by a distributed architecture in which data exchange among metering devices, inverters, renewable energy source controllers, storage systems and prosumer agents must be carried out continuously, with minimal delay and with the required level of protection.

Smart Grid is an intelligent electric power system that uses information exchange, digital control technologies, sensors, and actuators to coordinate its participants and improve the reliability of electricity supply.

The growth in the number of distributed nodes increases the uncertainty of network operating modes and creates the need to develop mechanisms of interaction among energy market participants oriented toward decentralized principles of data and energy exchange. The implementation of such mechanisms, including peer to peer electricity trading and platforms based on distributed ledger technologies, requires solving problems of scalability and interoperability of data transmission protocols, as well as synchronization of telemetric information in real time.

Despite the considerable body of research devoted to Smart Grid architecture and cybersecurity issues in energy systems, questions related to the construction of comprehensive models of information interaction among distributed prosumers, which simultaneously account for the scalability requirements of the communication infrastructure and its resilience to targeted attacks on individual segments, remain insufficiently studied. In particular, further development is required for methods of assessing the security of distributed communication architectures with regard to the specifics of data exchange protocols among heterogeneous Smart Grid devices, as well as for approaches to designing fault tolerant information platforms for decentralized energy trading.

Purpose of the study: To study the effectiveness of applying teletraffic theory methods and blockchain technologies in Smart Grid.

Object of the study: The communication infrastructure of Smart Grid.

Subject of the study: The Influence of Teletraffic Characteristics on the Effectiveness of Blockchain Technologies in Communication Infrastructure.

Research methods: The work employs methods of queueing theory, teletraffic theory and graph theory. Computer modeling was carried out using MATPOWER (MATLAB), Visual Studio Code and Ganache.

Research objectives:

1. To investigate the effect of incoming traffic intensity on the performance metrics of a Smart Grid system.
2. To develop and implement an algorithm for routing energy requests based on a graph model of the network, with transactions executed and verified through smart contracts within the blockchain infrastructure.
3. To experimentally evaluate the effectiveness of the proposed model using communication system quality-of-service metrics, including request-processing time, data transmission delay, and network throughput.

Main statements submitted for defense:

1. An algorithm is proposed for switching the operating modes of the Smart Grid communication system in response to power shortages and teletraffic intensity.
2. A blockchain-based smart contract algorithm is proposed for the Smart Grid network, using graph-based loss minimization.
3. A model is developed that integrates a teletraffic management algorithm with a routing algorithm and blockchain-based transaction verification. Its performance in Smart Grid networks is also evaluated.

Scientific novelty of the study:

1. To investigate the effect of incoming traffic intensity on the performance metrics of a Smart Grid system.
2. To develop and implement an algorithm for routing energy requests based on a graph model of the network, with transactions executed and verified through smart contracts within the blockchain infrastructure.
3. To experimentally evaluate the effectiveness of the proposed model using communication system quality-of-service metrics, including request-processing time, data transmission delay, and network throughput.

Personal contribution of the author: All research results presented in the dissertation were obtained through the author's direct participation in experimental studies and processing of experimental results.

Approbation of the dissertation results: The main results of the dissertation research were presented and discussed at the international ACM conference (Almaty, 2021), the international conference on communications, information, electronic and energy systems CIEES 2022 (Varna, 2022), the annual international congress on renewable energy sources (Oxford, 2024), and the international conference on technologies and applications for renewable energy integration ICREITA-24 (Rome, 2024).

Practical significance of the study: The scientific results of the dissertation have been implemented in the corporate environment of Internet Training Center in the form of a software solution developed using MatLab and MatPower tools, allowing the modeling and optimization of electricity flows. The developed software is used as an applied basis for the further development of methods for optimizing

power system operating modes and expanding the application of renewable energy sources. The fact of implementation is confirmed by a corresponding act.

Publications: The main results of the dissertation have been published in 9 scientific publications. Of these, 2 articles were published in scientific journals recommended by the Committee for Quality Assurance in Education and Science of the Ministry of Science and Higher Education of the Republic of Kazakhstan, and 3 articles were published in foreign scientific journals indexed in the Scopus database. In addition, 3 presentations were delivered and their materials published at international scientific and practical conferences. On October 4, 2024, a copyright certificate of the Republic of Kazakhstan No. 50222 was obtained for research on the topic "Integration of Blockchain Technologies into Intelligent Power Systems."

Scope and structure of the dissertation: The dissertation consists of an introduction, definitions, abbreviations, four chapters, a conclusion, a list of references and appendices. The bibliography includes 109 titles. The total volume of the work is 118 pages, containing 34 figures and 9 tables.

The dissertation is devoted to the development of a model for managing energy flows in intelligent networks based on the integrated application of teletraffic theory, graph optimization and blockchain technologies. On this basis, a management model was developed and subsequently compared with existing approaches according to criteria of effectiveness, resilience and scalability.

The first chapter is devoted to an analysis of the energy sector of Kazakhstan. The main trends in the development of renewable energy sources and Smart Grid technologies in the country are identified. Low carbon development strategies and the place occupied within them by solar and wind generation are examined separately.

At the same time, renewable energy is subject to a number of limitations. The main one is the instability of generation caused by dependence on weather conditions and time of day, which requires the use of energy storage systems to maintain the stability of network operating modes during peak load periods. Separate attention is given to issues of state regulation, investment support and the implementation of energy efficient technologies. An analysis is carried out of modern technological approaches to building intelligent energy systems, including methods of queueing theory, graph theory, Internet of Things technologies and blockchain. The advantages and limitations of existing approaches are identified, their scientific and technical problems are determined, and the need for developing a comprehensive approach to managing intelligent networks is substantiated.

The second chapter examines the theoretical and technological foundations of modeling intelligent systems based on the integration of teletraffic theory, graph theory and distributed digital technologies. The possibilities of applying queueing models to describe priority management processes during emergency situations, as well as to assess network operating characteristics including load and the probability of overload, are analyzed. The application of graph theory for the structural representation of systems in the form of weighted directed graphs is considered. It is shown that this approach allows the formalization of processes for constructing optimized routes based on the criterion of minimal losses in order to improve

efficiency in generator selection. The possibilities of using blockchain technologies to organize decentralized interaction among energy market participants are investigated. It is noted that the use of smart contracts and distributed ledgers ensures transparency, automation of settlements and increased reliability of energy resource exchange. Overall, the second chapter substantiates the appropriateness of the integrated application of the aforementioned methods for building a new generation of smart systems aimed at improving efficiency, resilience and reliability of operation.

The third chapter examines mathematical models of teletraffic theory with a two level priority system for requests, ensuring differentiated processing of various traffic types and improved quality of service for critical requests. Models of the steady state operating mode of the electric power system were also studied using the MatLab environment and the MatPower package, which provide calculation of power flows, voltage levels and network losses. Based on the modeling results, a graph representation of the power system is proposed, in which the nodes correspond to buses and the edges correspond to transmission lines with weights determined by active power losses. To optimize energy transmission routes, Dijkstra's algorithm is applied, allowing the determination of paths with minimal total power losses between generators and consumers. The blockchain verification mechanism is examined separately. It records the selected routes and verifies them using cryptographic hash functions and smart contracts, thereby eliminating the possibility of route data substitution after selection.

As a result, the chapter combines four different approaches, namely steady state calculation, teletraffic theory, graph theory and blockchain, into a single model for optimizing the power flow distribution of the intelligent system.

The fourth chapter verifies the proposed blockchain architecture in practice. The experiments were conducted in a test Ethereum environment based on Proof of Authority (Ganache/Truffle). Four indicators were evaluated, namely operation execution time, transaction processing delay, bandwidth and computational resource consumption. The results additionally underwent statistical validation, and the question of scalability, that is, how the system behaves under increasing load, was examined separately.

The conclusion summarizes the main results of the dissertation research. It is shown that the integration of graph theory, teletraffic and blockchain technology methods makes it possible to create an effective architecture for managing energy flows in intelligent power grids. The developed system provides optimized management within the intelligent network, increased transparency of energy transactions and automation of energy exchange processes. The use of smart contracts within a permissioned blockchain network ensures the reliability, immutability and auditability of operations. The results obtained confirm the prospects of applying the proposed approach for the development of decentralized systems and for improving the efficiency of smart infrastructure management.

The following conclusions were drawn from this dissertation:

1. The effect of incoming traffic intensity on the performance of the Smart Grid communication system was investigated. The results show that the system

switches to emergency mode under conditions of power shortage. When the offered load reaches $A \geq 7$ Erlangs, the system enters overload mode, where the waiting time for request servicing increases sharply. This relationship was used to develop an operating-mode switching algorithm.

2. A blockchain-based smart contract algorithm for routing energy requests was developed and implemented. The route with the lowest losses is determined using a graph model of the network, while transactions are executed and verified by smart contracts. Smart contract execution latency does not exceed 0.5 seconds.

3. The performance of the Smart Grid information-flow management model was evaluated experimentally. Relative to the baseline model, request-processing time decreased by 20.9%, transaction latency decreased by 21%, and throughput (TPS) increased by 48.9%. These results demonstrate improvements in the system's scalability and performance.

The appendices contain key data related to the research results.

1. Smart contract code
2. Copyright certificate