AN INTEGRATED APPROACH TO ENSURING THE RELIABILITY OF POWER TRANSMISSION LINES IN THE CONTEXT OF DIGITAL ENERGY

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Abstract

In the context of the rapid development of digital technologies and their large-scale implementation in various sectors of the economy, the energy industry is also entering a phase of deep digital transformation. One of the key areas of this transformation is increasing the reliability and manageability of the energy infrastructure, in particular, power transmission lines (PTL), which are the main element of the electricity transmission and distribution system. Modern challenges, such as the increasing load on the power grid, changing climate conditions and the need to integrate distributed energy sources, require new approaches to reliability management. This paper discusses the key elements of digital transformation, including the use of intelligent monitoring systems, the Internet of Things (IoT), big data analysis and artificial intelligence for diagnostics and forecasting the technical condition of power transmission lines. The need for a comprehensive strategy combining technical, organizational and information measures is substantiated. Recommendations are presented for the implementation of digital solutions in the practice of operating power lines in order to increase their fault tolerance, prompt response to incidents and the overall efficiency of the power system.

Keywords: power transmission lines, digital technologies, Internet of Things, efficiency, reliability

I. Introduction

The modern electric power industry is undergoing a deep digital transformation, which covers not only the processes of energy generation and distribution, but also the operation of infrastructure facilities. One of the most important components of this infrastructure are power transmission lines (PTL), which ensure stable and continuous delivery of electricity from generation sources to end consumers. The reliability of PTL directly affects the stability of the energy system, the security of power supply, the economic efficiency of the industry and the quality of life of the population, so the effective management of these facilities is critically important for modern society.

Over the past decades, the energy industry has faced many new challenges that require a revision of approaches to the operation of PTL. Firstly, the load on electrical networks is growing due to factors such as urbanization, an increase in the number of energy-intensive facilities (for example, data centers or electric vehicles) and the development of electrified transport. In response to these changes, energy transmission systems must be more flexible and able to adapt to new conditions. Secondly, climate change, manifested in the form of increasingly frequent extreme weather events (storms, thunderstorms, hurricanes, sudden temperature changes), creates additional risks to the physical integrity and functional stability of transmission lines. For example, strong winds can break lines, while frozen wires or damage due to heavy precipitation can lead to long outages. Thirdly, against the backdrop of the global energy transition and decarbonization, there is an increasing connection of distributed energy sources, such as solar and wind power plants. These sources require a more flexible and intelligent approach to network infrastructure management in order to ensure a balance between energy supply and demand, especially in the context of variable production.

Traditional approaches to ensuring the reliability of transmission lines, such as regular scheduled maintenance and eliminating the consequences of accidents that have already occurred, are becoming insufficient to address new challenges. Previously, the main focus was on eliminating the consequences of incidents, but modern conditions require predictive and preventive management, which is based on accurate and timely data on the condition of both the elements of the power transmission line and the external environment in which they operate [1-4].

Digitalization of energy systems opens up new opportunities for increasing the reliability of power transmission lines. The use of Internet of Things (IoT) technologies, automated monitoring systems, Big Data analysis, as well as machine learning and artificial intelligence (AI) algorithms allows you to quickly collect, process and analyze information on the state of lines, predict possible failures, automate diagnostics and make management decisions in real time. All this forms the basis of intelligent power transmission line reliability management systems, allowing you to minimize the human factor and quickly respond to changing conditions. An example of such an approach is the use of sensors installed on various elements of the power transmission line, which collect information about voltage, temperature, mechanical stress and other important parameters. This data is transmitted to control systems, where the risk of a malfunction or overload can be identified in advance using AI algorithms and big data analysis.

However, the implementation of these solutions requires a comprehensive approach, including both technical and organizational measures. It is important not only to provide reliable sensors, controllers and communication channels, but also to create an appropriate information and analytical infrastructure, including software platforms, databases and forecasting algorithms. This will allow for the efficient collection and analysis of data, as well as for quick and accurate decision-making in conditions of uncertainty. The implementation of such solutions requires updating regulations, developing new standards and training specialists, which is also an integral part of digital transformation.

A key aspect of successful digitalization is ensuring cybersecurity. As the number of connected devices and transmitted data increases, the risk of unauthorized access or interference increases. This highlights the importance of using modern technologies to protect data and networks, such as encryption systems, multi-layered protection against external threats, and the use of new security technologies such as blockchain to ensure the integrity and authenticity of data.

Digitalization not only improves the quality of maintenance, but also optimizes organizational processes, speeding up decision-making and improving coordination between different services. For example, in the event of an emergency, the system can automatically redirect mobile teams and resources to fix the fault, as well as notify the responsible services about the current status of the power line [5-7].

Thus, digitalization of power lines not only increases their reliability, but also contributes to more efficient management of energy systems in the face of growing risks and new challenges. The combination of advanced technologies such as IoT, Big Data and AI with organizational and technical measures creates the basis for building an intelligent, flexible and sustainable power supply system. However, for the successful implementation of such projects, it is important to maintain a balance between technological innovation and security, as well as to provide the necessary resources for training specialists and creating an appropriate regulatory framework. In the future, given the growing use of renewable energy sources and the increasing flexibility of energy systems, the digitalization of power transmission lines will become a critical element in ensuring the sustainability of energy infrastructure, capable of effectively coping with the challenges of global change.

II. Formulation of the problem

Modern power transmission lines (PTL) operate in a significantly more complex external environment. This process is characterized by increasing operational risks associated with various climate threats, increased network loads, and requirements for energy infrastructure flexibility. The growing dynamism of external factors, such as changes in generation configuration and the use of distributed and renewable energy sources, leads to an increase in the load on energy networks. In turn, this creates new challenges for ensuring the reliability and sustainability of PTL operation, often leading to abnormal operating modes and emergency situations [8-10].

Current challenges to energy systems, such as climate instability and changing climate conditions, as well as complex network interactions, require an integrated approach to network management and increasing their sustainability. One of the main factors determining the sustainability of energy systems in such conditions is the ability of PTLs to adapt to changing loads and external threats. Effective management of power transmission line operation is impossible without the use of advanced digital technologies that can provide both monitoring and forecasting of the state of infrastructure facilities in real time. Figure 1 is a graph that shows how the efficiency of traditional maintenance is declining over time, while the efficiency of predictive maintenance and digitalization is increasing. It also highlights the increasing level of climate-related threats, highlighting the need for digital transformation in transmission line operations.

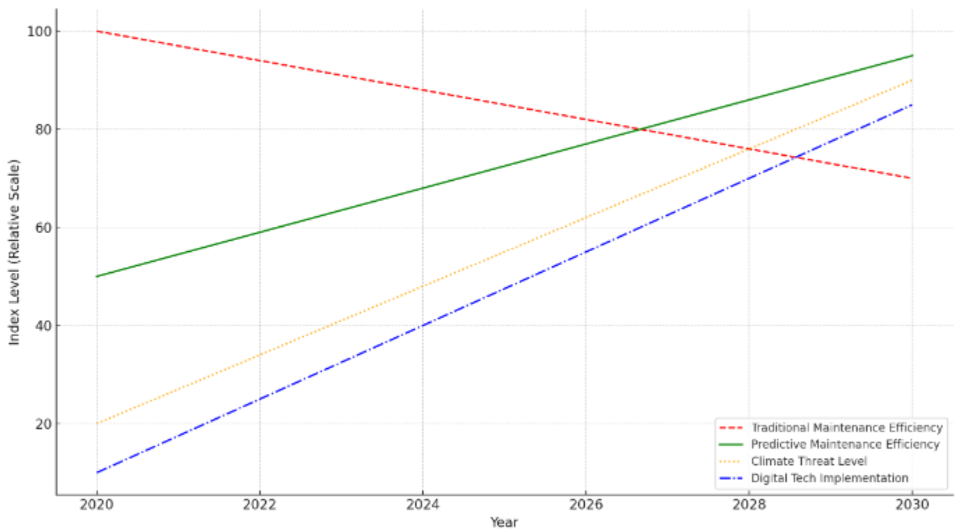

Figure 1: *Trends in power transmissions line operations: 2020-2030*

In the context of energy transformation, when the integration of various energy sources, including renewable ones, comes to the fore, traditional methods of planned and routine maintenance of power transmission lines no longer meet modern requirements. The transition from the usual approach to more flexible and intelligent systems is becoming inevitable. The use of Internet of Things (IoT), Big Data analysis and artificial intelligence (AI) technologies in the process of power transmission line operation allows creating effective systems for monitoring, diagnostics and forecasting of technical condition. However, despite the high rate of development of these technologies, their implementation in the energy industry, especially in the context of power transmission line operation, remains fragmented and lacks a clear systemic approach.

The difficulties of integrating digital solutions into the process of power transmission line operation are due to the lack of a single architecture that could combine various technological and operational components within a single system. This limits the capabilities of predictive analytics and does not allow the most efficient use of the potential of innovative solutions to improve the reliability and sustainability of energy infrastructure. This is especially relevant in the context of growing threats associated with possible shutdowns that can affect the economy and life support of critical consumers [11-14].

Purpose of the study. The purpose of this study is to develop and justify a comprehensive approach to the digital transformation of power transmission line operation aimed at increasing their reliability, sustainability and manageability in the face of modern challenges. The study focuses on the systematization of existing digital solutions, the integration of advanced technologies to create an intelligent power transmission line control architecture and the definition of the organizational and technical conditions necessary for their effective implementation.

This approach includes several important aspects. Firstly, it is necessary to create a flexible control architecture that can take into account various types of energy sources and promptly respond to changes in the network operating mode. Secondly, it is necessary to integrate monitoring and forecasting systems that can identify potential faults in advance and prevent emergency situations. Thirdly, it is important to take into account the impact of climatic factors and take them into account in the process of forecasting the state of networks. All this requires a transition to more advanced operating methods focused on long-term sustainability and risk minimization.

Scientific Novelty. The scientific novelty of the study lies in several key aspects, including:

1) Formalization of a digital model for managing the technical condition of power transmission lines. This is achieved through the integration of Internet of Things (IoT), Big Data and artificial intelligence (AI) technologies. In particular, an integrated model is being created that allows monitoring and analyzing power transmission line condition parameters in real time, predicting possible failures and optimizing resource maintenance.

2) Development of a conceptual architecture for an intelligent system for diagnosing and predicting failures in power transmission lines. An important point is to take into account climatic and load factors when developing such a system. The system should be able not only to diagnose, but also to predict failure situations with high accuracy, which will significantly reduce the number of accidents and their consequences.

3) Transition to a predictive operation paradigm. This paradigm is focused on the use of forecasting technologies and big data analysis to minimize emergency situations and optimize the maintenance process. The transition from traditional repair maintenance to predictive maintenance will significantly increase the fault tolerance of power transmission lines.

4) Creation of digital twins of power transmission lines. This will allow not only to carry out operational management, but also to carry out long-term strategic planning. Digital twins will take into account all changes in real time, including weather conditions, loads and the technical condition of the line, and provide the necessary data for analysis and decision-making.

Practical significance. The practical significance of this study is to create the basis for the transition to a more efficient and flexible model of power transmission line operation, which will be based on modern digital solutions and advanced technologies. The implementation of the proposed concept will allow:

- To increase the fault tolerance of power transmission lines. Early detection of potential faults will significantly reduce the likelihood of emergency situations and increase the overall reliability of power transmission lines.

- To reduce the response time to incidents. The use of intelligent monitoring and diagnostic systems will help to localize faults more quickly and take appropriate measures.

- Optimize maintenance costs. The transition to maintenance based on the actual condition will reduce unnecessary costs associated with unnecessary repairs and inspections, as well as reduce the cost of maintaining the infrastructure.

- Ensure continuity of power supply to consumers. Increasing the reliability of power transmission lines and reducing the time for troubleshooting will ensure a stable power supply, which is especially important for critical facilities and infrastructure.

- Adapt the operation of power transmission lines to the conditions of energy transition and climate instability. Flexibility in the management and use of renewable energy sources, as well as taking into account the impact of climatic factors, will allow power transmission lines to adapt to rapidly changing conditions of the energy market and climate change.

III. Problem solution

The implementation of the proposed integrated approach requires a systemic and multifaceted approach that covers both organizational and technical changes in the existing processes of operation and maintenance of power transmission lines (PTL). In order to successfully integrate digital technologies into the operation of PTLs, it is necessary to pay attention to several key aspects, each of which is critical to achieving long-term efficiency and sustainability of the power system [15-19].

Development and implementation of a unified digital system architecture. The first and most important step in implementing the proposed solution is the creation of an integrated digital platform for collecting, storing and processing data that will cover all key aspects of the operation of PTLs. This platform should combine various types of data, including equipment status parameters, weather data, load indicators, information on possible threats and risks, as well as forecast data obtained using artificial intelligence technologies and big data analysis.

Such data integration will allow for prompt and accurate data-based decision-making, real-time monitoring and planning of further actions. Integrating various technologies, such as the Internet of Things (IoT), Big Data and AI, into a single architecture ensures that all information is collected, processed and analyzed taking into account all factors affecting the operation of power transmission lines. It is important that the system is flexible and adaptable to changes, which will allow integrating new technologies and analysis methods as they appear. The implementation of such an architecture will create a reliable basis for ensuring the smooth operation of power transmission lines, minimizing malfunctions and optimizing operating costs.

Personnel training and development of competencies in the field of digital technologies. Successful implementation of digital transformation is impossible without appropriate training of personnel who will work with new digital systems and tools. Training and development of competencies in the field of digital technologies should become an integral part of the strategy for the implementation of innovative solutions in the operation of power transmission lines. Personnel involved in the operation and maintenance of power transmission lines must undergo comprehensive training in the use of new monitoring, diagnostics and forecasting systems, as well as master methods of working with big data, artificial intelligence and the Internet of Things. In addition, it is necessary to provide training to managers and decision-makers so that they can effectively interpret the data received from digital platforms and use it to optimize the network and increase its reliability. The training of specialists in the field of digital technologies should include not only theoretical knowledge, but also practical skills in working with new systems, which will significantly improve their efficiency and reduce the likelihood of errors in the operation and maintenance of power transmission lines [20-25].

Conducting tests and pilot projects. Before large-scale implementation of new digital technologies and solutions, it is necessary to conduct tests and launch pilot projects in limited areas of the network or in individual infrastructure segments. This will allow us to evaluate the effectiveness of the proposed solutions in real operating conditions, identify possible problems and shortcomings, and adjust approaches and algorithms for working with data depending on specific conditions. Pilot projects will provide an opportunity to test new systems for monitoring, diagnostics and failure prediction in practice, while minimizing potential risks to the functioning of the entire power system. It is important that the piloting covers all key aspects of power transmission line operation, including weather forecasting, load analysis, equipment condition diagnostics and emergency management. Based on the test results, it will be possible to optimize digital solutions and adapt them to specific operating conditions. Figure 2 is a graph illustrating the expected results of digital transformation of transmission line operations over time. It shows improvements in reliability, continuity and resilience, as well as reductions in response times and maintenance costs.

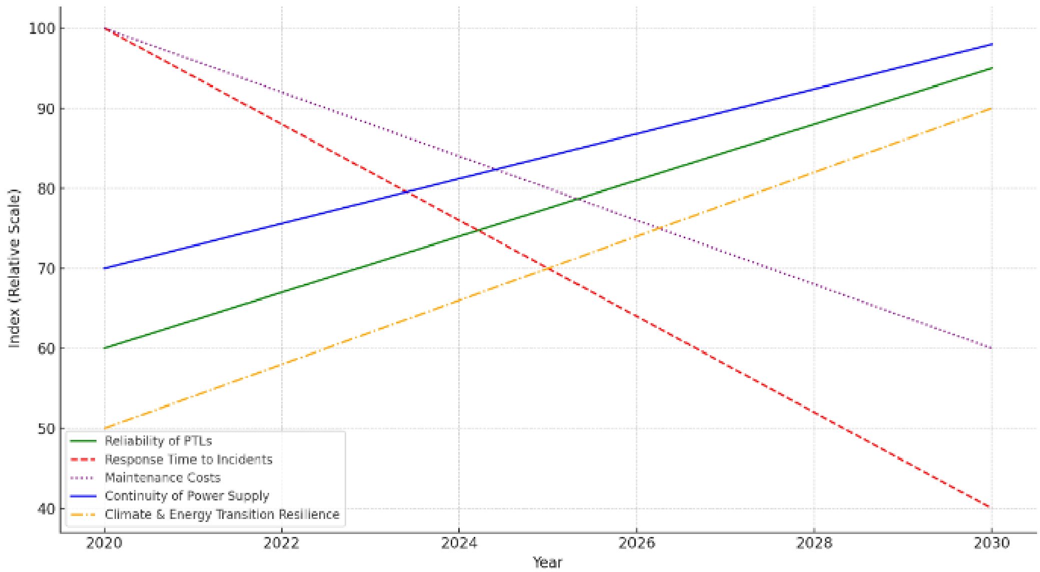

Figure 2: *Expected outcomes of digital transformation in power transmission lines (2020-2030)*

Expected results and benefits of implementing the proposed approach. Implementation of the proposed integrated approach to digital transformation of power transmission line operation will lead to a number of significant improvements and benefits that will have a positive impact on the reliability and efficiency of the electric grid infrastructure.

1. Increasing the reliability and fault tolerance of power transmission lines. One of the main results of implementing digital solutions is a significant increase in the reliability of power transmission lines. The use of intelligent monitoring and forecasting systems based on data collected in real time will significantly reduce the number of emergencies and other malfunctions. Integration of forecasting technologies will allow early detection of potential malfunctions and carry out work to eliminate them before they lead to an accident. This will help to avoid long

downtimes and increase the overall fault tolerance of the system.

2. Reducing the response time to incidents. Diagnostic systems using artificial intelligence technologies will significantly speed up the process of localizing malfunctions and taking measures to eliminate them. This will significantly reduce the response time to incidents, which is especially important to ensure uninterrupted operation of the network and critical consumers, such as hospitals, industry and other facilities that require a stable power supply. A quick response to potential problems will also reduce the impact of emergency situations on consumers and minimize economic losses associated with long outages.

3. Optimization of maintenance costs. The transition from traditional scheduled maintenance to maintenance based on the actual condition of equipment will significantly reduce maintenance costs. The use of data on the current state of power lines and forecasts based on big data analysis and artificial intelligence will minimize unnecessary repairs and inspections that were previously carried out according to a pre-set schedule, regardless of the condition of the equipment. This, in turn, will lead to significant savings in the long term, since resources will be directed only to those infrastructure elements that really need maintenance.

4. Ensuring continuity of power supply. Digital transformation of power line operation will help increase the resilience of the entire power system, which will ensure a stable and continuous power supply to consumers, including critical infrastructure facilities. Thanks to higher fault tolerance and faster response to faults, the power supply will remain stable even under extreme loads or adverse weather conditions.

5. Adaptation to energy transition conditions and climate instability. An important aspect of digital transformation is the ability to adapt power transmission lines to energy transition conditions, including the integration of renewable energy sources, and to the impact of climate factors such as strong winds, snowfalls, high temperatures and other extreme weather events. The implementation of digital solutions will allow for a flexible response to changes in energy demand and supply, as well as taking into account climate and environmental changes, which will ensure the long-term sustainability of the energy infrastructure [26-30].

IV. Conclusions

The proposed digital transformation approach includes several key aspects: the creation of an integrated architecture of the control system, the use of digital twins of power transmission lines, the introduction of forecasting technologies and the consideration of climate factors, as well as the need to train specialists who are ready to work effectively with new digital tools. This will not only improve the accuracy of diagnostics, but also significantly improve resource management and the speed of response to emerging problems. However, for the successful implementation of these solutions, it is important to take into account a number of organizational and technical factors. It is necessary to develop a single digital platform that would integrate all types of data, including information on the condition of equipment, external factors and forecasts. Personnel training is also critically important, since without the appropriate qualifications of specialists it is impossible to effectively use new systems and technologies. Testing and pilot projects aimed at testing digital solutions in real conditions will identify weaknesses and optimize the implemented technologies. Early implementation and scaling of such projects will lead to increased reliability of power transmission lines, reduced response time to emergencies, optimization of maintenance costs and, as a result, improved sustainability of the entire energy infrastructure.

The practical application of the proposed digital solutions will ensure the long-term sustainability of energy systems. Increasing the reliability and reducing the downtime of power grids, prompt localization of faults and adaptation to the conditions of global changes and energy transition will have a positive impact on the stability of energy supply, including for critical infrastructure facilities. Ultimately, the digitalization of power lines will contribute to the creation of a flexible, intelligent and secure energy network capable of effectively responding to the challenges of the future.

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