ELEKTROTEHNIŠKI VESTNIK 92(4): 221-228, 2025
ORIGINAL SCIENTIFIC PAPER

A methodology to develop an information and control system to monitor the technical state of power transmission lines

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Abstract. The paper presents the methodology to develop an information and control system to monitor the technical state of power lines. The relevance of the topic is due to the need to improve the reliability and safety of power systems in the context of the growing requirements to power quality. The key stages of information and control system development are described, including requirements definition, architecture design, technology selection and testing. Special attention is paid to the use of modern technologies, big data processing to create a system capable of promptly responding to changes in the state of power lines. Data visualisation, integration of different technologies and cyber security are also addressed. The paper emphasises the importance of user training and support during the implementation phase of the system, as well as the prospects for further development of the system in the field of energy resource management.

Keywords: information and control system, monitoring, power lines, development methodology, big data processing.

Metoda za razvoj informacijskega in nadzornega sistema za spremljanje stanja elektroenergetskih vodov

Prispevek predstavlja metodologijo razvoja informacijskega in nadzornega sistema za spremljanje tehničnega stanja elektroenergetskih vodov. Področje je pomembno zaradi potrebe po večji zanesljivosti in varnosti elektroenergetskih sistemov ob naraščajočih zahtevah glede kakovosti napajanja. Opisani so glavni koraki razvoja sistema: določitev zahtev, načrtovanje arhitekture, izbira tehnologij in testiranje. Poseben poudarek je na uporabi sodobnih tehnologij ter obdelavi velikih podatkov za hitro odzivanje na spremembe stanja vodov. Obravnavani so tudi vizualizacija podatkov, integracija tehnologij in kibernetska varnost. Izpostavljen je pomen usposabljanja uporabnikov ter možnosti nadaljnjega razvoja sistema na področju upravljanja energetskih virov.

1 INTRODUCTION

Transmission lines play a critical role in ensuring the power supply stability. Their reliability directly affects the functioning of the entire power system. Failures in their operation can lead to significant economic losses, accidents, as well as threats to human lives and the environment [1; 2]. In the conditions of the global growth of the electricity consumption and the increasing load on the energy infrastructure, the problem of ensuring the reliability of the power transmission lines becomes especially urgent [3; 4].

Received: 3 May 2025
Accepted: 14 August 2025

The development of effective information and control systems for monitoring the technical state of power lines is a complex task that requires the integration of multiple technologies and disciplines. The information and control systems allow to promptly collect and analyse data on the state of the power infrastructure, which significantly improves the reliability and efficiency of the power grid management [5; 6]. However, to date, there are several key issues in the development of such systems that require more in-depth research and practical implementation.

According to the current research, information and control systems for actively monitoring power lines use various sensor technologies to collect the data on the state of the equipment [7; 8]. The temperature, vibration, pressure sensors, and unmanned aerial vehicle (drone) technologies are actively used to inspect hard-to-reach areas, which significantly speeds up the diagnostic process and minimises risks to the personnel. Leading energy scientists point out that with the development of the Internet of Things (IoT) and cloud technologies, it is possible to integrate various devices and systems into a single network, allowing real-time monitoring and analysis. These developments provide a high level of accuracy in detecting faults and predicting their occurrence [9].

Despite significant advances in the application of sensors and sensing for monitoring, a number of studies highlight the existence of challenges in integrating the data from different sources [10; 11]. There are certain challenges associated with processing data from a large number of sensors in real time. These challenges include the need to quickly receive, filter, aggregate and interpret huge amounts of information, which requires a reliable and high-speed data transmission infrastructure. Moreover, significant computing resources are needed to effectively analyze and process so-called "big data" [12; 13; 14]. This includes powerful servers, specialized software, storage systems and high-performance algorithms that can handle a large flow of the data without delays. All this makes the task of real-time data processing extremely resource-intensive and technologically complex.While most of the current systems focus on data collection using different sensors, the critical point is the synchronisation and quality of the data, which significantly affects the accuracy of fault prediction [15].

In addition, one of the current problems is the insufficient development of algorithms for predicting failures based on the accumulated data. There are several approaches based on machine learning methods that are used to predict possible equipment failures and malfunctions [16]. One of the most common methods is neural networks - algorithms inspired by the work of the human brain, capable of identifying complex patterns and dependencies in large volumes of the data [17]. They are trained on the historical data about the system's operation, including the data on previous failures, operating conditions, sensor readings, and other parameters. In addition to neural networks, regression models are also widely used, which allow you to estimate the probability of a malfunction based on numerical dependencies between different variables. Such models can be both simple (linear regression) and more complex (logistic regression or gradient boosting methods), depending on the complexity of the problem and the amount of the available data [18].

These methods not only allow you to identify potential problems before they actually occur, but also provide the ability to predictive maintenance, which significantly reduces the risk of unplanned downtime and increases the overall efficiency of equipment operation. However, as noted by researchers, such algorithms are still insufficient for accurate and timely detection of potential threats, especially in the context of dynamically changing external factors such as weather conditions that can significantly affect the power lines state [19; 20]. The existing models do not always account for the full range of variables, which reduces their accuracy and makes predictions less reliable.

One major gap is the lack of integration of the new technologies, such as blockchain, to ensure the reliability of power line state data [21; 22]. In recent years, studies on blockchain technologies in the power industry have been emerging, but their application for power line monitoring remains limited despite the obvious benefits such as an increased security and data transparency [23; 24; 25]. Also, the issue of interoperability between different system components, including sensors, algorithms and interfaces for operators, requires a further research and practical development.

Based on the above, there are several key issues that require further research:

How to improve the synchronisation and quality of the data from different sensors and devices to improve the monitoring accuracy? The existing systems often face the problems of integrating the data from different sources, which reduces their efficiency.

Which machine learning algorithms are most effective for predicting failures on power lines given unstable external factors? Improvements to existing models and development of new approaches are required to handle data under variable externalities [26].

How to integrate modern technologies (e.g., blockchain) to improve the reliability and transparency of transmission line state data? While the use of blockchain technologies is discussed in theory, their implementation in practice in monitoring systems remains limited.

How to develop better interfaces for operators to improve decision making based on the data analysis and system predictions? It is necessary to investigate the interaction between operators and information and control systems from the point of view of convenience and speed of decision making.

Thus, although the developments in the field of information and control systems for monitoring the technical state of power lines are quite extensive, many issues remain unresolved or insufficiently researched (27; 28]. The most urgent are the problems of data integration, improvement of fault prediction algorithms and implementation of new technologies to improve the reliability and transparency of the system [29; 30]. Addressing these issues is essential to improve the safety and efficiency of transmission line operation in the face of increasing load on the energy infrastructure.

2 MATERIALS AND METHODS

The development of an information and control system for monitoring the power lines technical state (Figure 1) requires an integrated approach. The methodology includes several stages, starting with the requirements analysis and ending with the system implementation and testing.

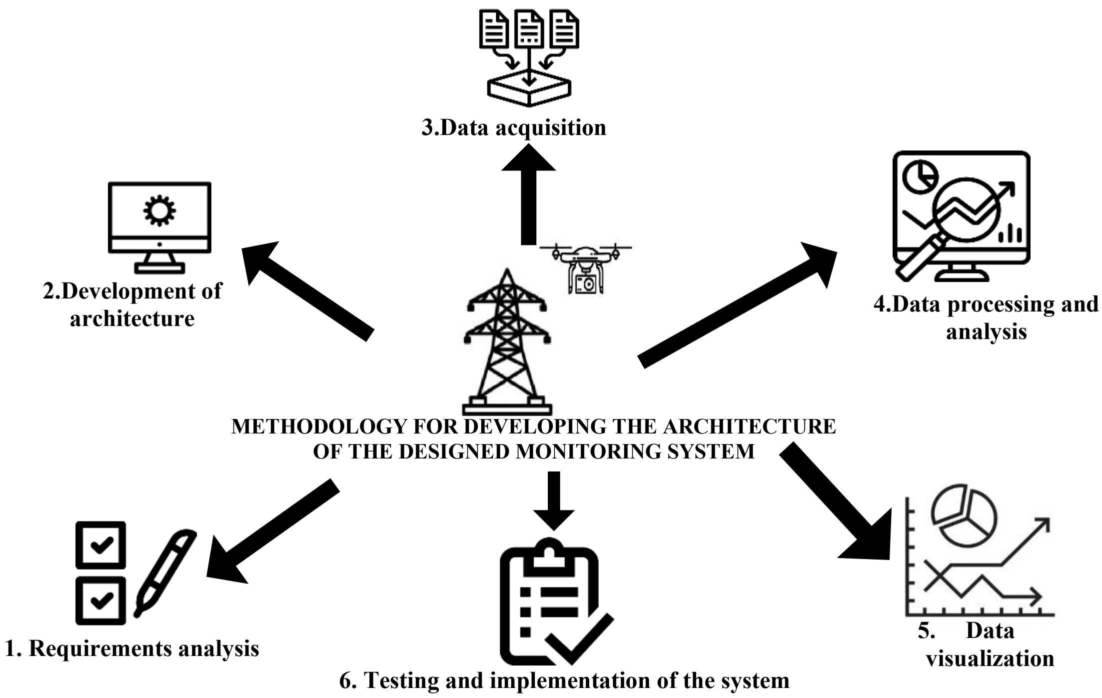

Figure 1. Methodology for developing the architecture of the designed monitoring system

1. Requirements analysis (data collection for the terms of the reference)
In the first step, it is important to collect information about the current state of the lines and identify the key parameters that need to be monitored [31; 32]. To perform this step, it is possible to use a survey of experts (engineers) who specialise in technical inspection of lines to identify the parameters that need to be monitored. It is also necessary to thoroughly review all regulatory documentation (regulations, standards, existing reports on the state of transmission lines) to have an idea of the current state of the process [33].

2. Architecture design
It is worth to decide on the type of system architecture. The most commonly used architectures for monitoring the technical state of objects are modular architecture and service-oriented architecture [34; 35]. Modular architecture allows to divide the system into independent modules, each of which is responsible for certain functions. In turn, service-oriented architecture - software product is a set of easy-to-use services with a convenient graphical interface.

Further it is necessary to define the technologies used for the system operation [36; 37]. It is worth paying special attention to the programming language, databases for storing information and visualisation tools.

3. Data acquisition
The choice of sensors and data communication system depends on the specific requirements of the project, such as the range of operations, environmental conditions and the required measurement accuracy [38]. The integrated use of these sensors and communication systems will enable effective ice detection and warning of potentially hazardous road conditions [39]. In order to select the sensors, it is necessary to calculate the pairwise correlation coefficients of the fault factors that cause problems in line operation [40]. The following factors were taken to analyse the percentage of faults occurring during transmission line operation:
Y - the percentage of faults in the operation of power lines, %;
X1 - ice thickness on wires, relative unit;
X2 - ambient temperature, relative unit of the measurement;
X3 - wind speed factor, relative unit of the measurement;
X4 - electrical load, a relative unit of the measurement;
X5 - precipitation frequency, a relative unit of the measurement.

In selecting, the factors for the model, preference is given to the factor that, although fairly closely related to the outcome, is least closely related to the other factors. In our example (table 1), we find that the informative factors are x1 and x5.

Table 1. Matrix of paired correlation coefficients

	Y	**X1**	**X2**	**X3**	**X4**	**X5**
Y	1					
X1	0,95	1				
X2	0,74	0,81	1			
X3	0,83	0,87	0,64	1		
X4	0,48	0,32	0,11	0,32	1	
X5	0,97	0,95	0,73	0,83	0,43	1

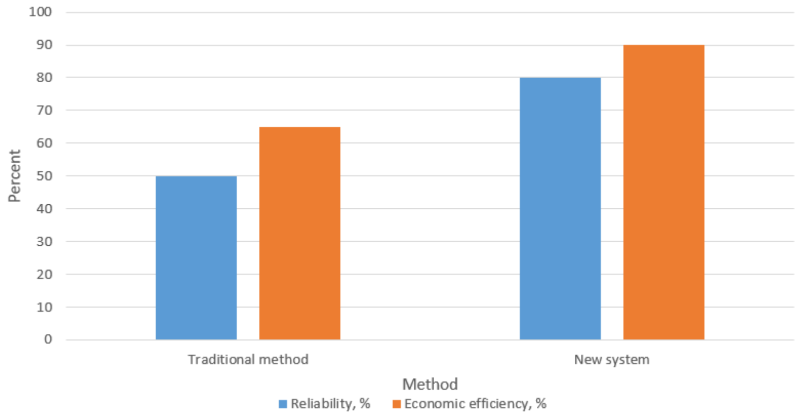

Figure 2. Comparison of reliability and economic efficiency of the traditional method and the proposed system

4. Data processing and analysis

It is required to decide on the algorithms used to process the data [41; 42]. The algorithms may consist of static analysis data (identifying anomalies and trends in the data) or the use of machine learning elements (classification and regression algorithms to predict possible faults).

5. Data visualisation

It is worth paying attention to the development of a user interface to enable quick and convenient display of the line inspection data [43]. It is possible to use a web application or a mobile application for faster access to the obtained information. To visualise the maintenance data, it is worthwhile to decide on the metrics we want to highlight and use graphs that display the information in a more revealing way (time series graphs, heat maps, etc.).

6. System testing and implementation

It is necessary to carry out functional and load testing of the designed system to be able to foresee all variants of failures and to be able to solve problems arising during the operation of the system in a short period of time [44; 45]. Also, an important stage during the implementation of the system is the training of personnel and support and maintenance of the system itself [46].

3 Results

An information and control system was developed, which includes components to improve the reliability and efficiency of power line monitoring [47]. The system demonstrates high results in the following parameters:

Comparative analysis with traditional methods showed a significant improvement in the accuracy of fault diagnosis and prediction (Figure 3). The new system uses time series and correlation coefficient analyses to account for factors such as ice thickness, wind speed and precipitation frequency. This allows for more accurate prediction of potential problems and prevention of accidents.

The system cost-effectiveness of the system (Figure 2) has been evaluated in comparison to traditional control methods. By automating data collection and analysis and integrating machine learning techniques for prediction, maintenance costs were reduced and many potential faults were avoided. The system is estimated to provide up to 80% savings in the operating costs compared to the conventional methods.

The implementation of the machine learning algorithms improves the fault detection rate from 65% in traditional systems to 90% in the proposed system (Figure 3). The increased efficiency is due to an automated analysis of incoming data and regular updating of the prediction model based on the new data.

The system provides convenient tools for real-time data visualisation, which enables quick response to changes in line status. Visual components (time series graphs, correlation diagrams) help operators better understand the current situation and make prompt decisions.

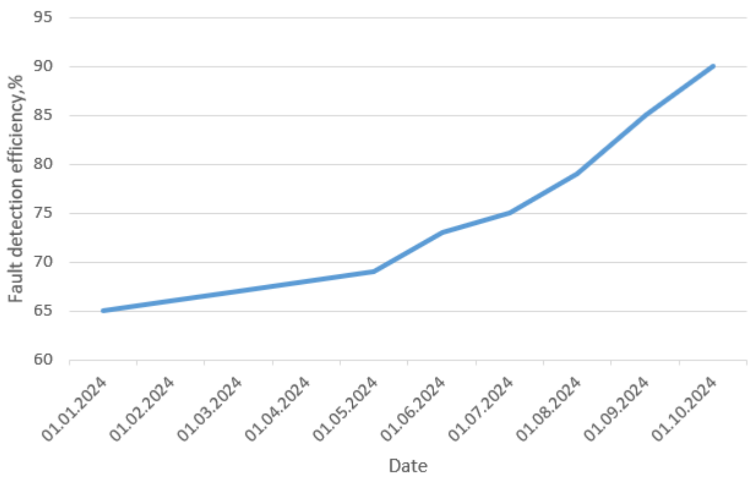

Figure 3. Dynamics of improvement in fault detection performance over time

Due to the timely warning of abnormal situations, the system allows to increase the level of personnel safety, reduce emergency risks and ensure more stable operation of the power line.

Thus, the results of the study confirm the effectiveness of the developed system for monitoring the technical state of power lines [48]. The system allows not only to improve the accuracy and efficiency of diagnostics, but also to significantly reduce the cost of operation, increase the safety and reliability of the energy infrastructure.

4 Discussion

Development of an information and control system for monitoring the technical condition of power transmission lines is a multifaceted task that requires not only technological expertise, but also a comprehensive approach to organisation and integration of new solutions into existing processes. In light of the increasing requirements for the reliability of power supply, the need to minimise the risks of emergency situations and ensure the sustainability of the energy infrastructure, the creation of such a system becomes an important and relevant step [49; 50].

However, for the successful implementation of information and control systems, as shown by the results of our study, several key aspects that can significantly affect the performance of the system need to be taken into account. These aspects range from technological solutions to organisational and social factors, each of which has its own importance for the final result.

The technological component is the basis of any information and control system for monitoring the technical state of power lines. First of all, it is worth noting the importance of selecting the right sensors and data collection devices. Technologies such as unmanned aerial vehicles (drones), Internet of Things (IoT) systems, temperature and vibration sensors play a central role in ensuring monitoring accuracy. The introduction of new generation sensors can significantly improve data reliability and provide more accurate diagnosis of problems, which in turn reduces the number of accidents and improves the efficiency of the entire power system.

However, as analyses have shown, not all problems are solved by new technologies alone. Difficulties in integrating data from different types of sensors, ensuring their synchronisation and compliance with technical standards remain one of the key challenges for the developers of such systems. In particular, in a real-time environment, it is important not only to collect data but also to process it so that the system can respond quickly to changes in the operational state of the line. In addition, machine learning algorithms used for failure prediction need constant updating and refinement to keep up with changes in external factors and improve the accuracy of predictions [51].

In addition to the technological component, successful implementation of an information and management system requires careful consideration of organisational changes. The incorporation of the new system into existing energy infrastructure management processes must be integrated without compromising the efficiency and safety of current operations. This requires not only the customisation of software and hardware, but also a revision of the internal structure for working with technical data, as well as a change in approaches to personnel management. One important aspect is the training of employees who will be working with the new system. Even the most perfect and high-tech solutions may not bring the desired effect without proper involvement and training of users.

As practice shows, successful implementation of new technologies requires the company to be ready for changes. This includes organising courses and trainings for operators, holding training seminars and regular checks of user skills. The more prepared the specialists are, the faster they can adapt to the new approach and use the system more effectively to fulfil their tasks. Training also plays a key role in increasing the level of staff responsibility for decisions, which in turn contributes to a higher level of reliability and safety [52; 53].

The social aspect of implementing information and control systems for monitoring power lines plays no less important a role than the technological and organisational ones. One of the main benefits of such systems is increased safety in the workplace. The monitoring system allows for the early detection of potential problems such as overloads, faults or threats from external factors (e.g. heavy snowfall or high temperatures), which reduces the risk of accidents and minimises the danger to workers in the field.

In addition, the use of monitoring systems contributes to the overall transparency of energy resource management processes, which becomes an important factor in the context of increasing attention to environmental and sustainability issues. Energy companies that implement such systems can demonstrate their commitment to environmental regulations and standards, which in turn enhances their reputation in the eyes of the public and regulators. In the context of increasing global requirements for sustainability and carbon footprint reduction, the use of high-tech monitoring systems can become not only a tool for improving the efficiency of energy infrastructure, but also a part of the sustainable development strategy of companies.

Thus, the development and implementation of information and control systems for monitoring the technical state of power lines requires a comprehensive approach that includes not only technological innovations, but also organisational changes, as well as attention to social and environmental aspects. This requires a holistic vision and willingness to change, from the introduction of new technologies to the education and training of personnel.

A system development methodology that covers all these aspects can significantly improve the reliability and efficiency of energy systems. It is important to remember that in today's society, where sustainable development and safety are becoming top priorities, the successful implementation of such solutions can not only improve operations, but also contribute to the global goals of reducing carbon emissions and improving people's quality of life.

The results of our study confirm that the development of information and control systems for power line monitoring is an important and relevant task [54]. However, the current analysis shows that there are several problems that require further attention. In particular, the issues of improving the integration of data from different sensors, improving the accuracy of fault prediction taking into account external factors, and the need for extended work with social and organisational aspects all require further research and practical developments.

Prospects for a further research include not only improving the data acquisition and processing technologies, but also exploring new approaches to organising and implementing such systems into the existing infrastructure. An integrated solution to these problems will be an important step in improving the reliability, safety and sustainability of energy systems.

5 Conclusion

The development of an information and control system for monitoring the technical state of power lines is a complex and multi-stage process that requires in-depth analysis of both the technical and organisational aspects. The study has identified key findings that emphasise the importance of the topic:

1. With the increasing load on the power systems and the need to improve their reliability, the creation of an effective monitoring system becomes critical. The system allows not only to monitor the current state of the lines, but also to predict potential emergency situations, which helps to reduce risks and maintenance costs.
2. System architecture design should consider a layered approach where each layer is responsible for specific functions. This ensures that the system is flexible and can be scaled up in the future.
3. The use of big data techniques and machine learning algorithms can effectively analyse the collected information, identify patterns and predict possible faults. This provides a basis for making informed repair and maintenance decisions.
4. effective visualisation of information is a key element of successful system operation. Graphical interfaces should be intuitive for users so that they can quickly interpret data and make decisions based on the information obtained.
5. It is important to ensure that the new system is compatible with existing management and monitoring systems. This will avoid duplication of functions and optimise management processes.
6. The success of the system implementation largely depends on the level of user training. It is necessary to organise training for employees so that they can effectively use the system and respond to emerging problems.

Thus, the methodology of developing an information and control system for monitoring the technical state of power lines is a complex process that requires an interdisciplinary approach. Successful implementation of such a system can significantly improve the efficiency of energy resource management and ensure the reliability of electricity supply.

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