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Application of Thermal Imaging Diagnostics for Technical Maintenance of Electrical Centralization Devices in Railway Automation Systems

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Abstract

This article examines the use of thermal imaging diagnostics for the maintenance of electrical centralization devices in railway automation. It analyzes traditional diagnostic methods, their limitations, and the risks associated with the late detection of faults (overheating). The effectiveness of thermal imaging control in detecting overheating of relay contact groups, conductor joints, transformers, and other crucial elements of electrical centralization has been proven. Mathematical models for analyzing thermal deviations are proposed, which allow predicting failures before the equipment malfunctions. The economic effectiveness of implementing thermal imagers in railway infrastructure is substantiated. The use of this technology enhances safety, reduces maintenance costs, minimizes emergency situations, shortens repair time, and improves overall equipment condition control.

Keywords: thermal imaging diagnostics; railway automation; electrical centralization; fault prediction; maintenance.

1. Definition of the scientific problem chosen for research

Railway transport is a key element of infrastructure in Ukraine and many other countries, and its uninterrupted operation depends on the reliability of electrical centralization (EC) systems. Failure of these systems may lead to train delays, disruptions to transport schedules, and, in some cases, to serious emergency situations [1], [2].

The main problem with checking the technical condition of elements is that most modern EC system diagnostic methods are based on regular inspections and reactive repairs, which do not allow for timely detection of hidden faults [3]. For example, overheating of contact groups or insulation damage in transformers may remain undetected during standard checks and lead to emergency situations [17].

Therefore, more attention is being paid to predicting faults in EC system elements using thermal imaging diagnostics. Thermal imagers allow for the quick and non-contact identification of overheating elements, which is a critical indicator of insulation wear or defects in relay contact surfaces [4].

This article analyzes classic methods of monitoring the condition of EC devices and modern trends in technical diagnostics, as well as the prospects for further research.

2. Analysis of recent publications and studies related to the problem

An analysis of recent publications and studies in the field of diagnostics and maintenance of railway automation devices indicates insufficient development of the general theoretical foundations for implementing EC control

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methods. Some aspects, such as improving reliability and efficiency in maintenance, have been studied in the context of specific operating conditions [1], [2].

The paper [1] discusses the issue of improving maintenance for electrical signaling and centralization devices through comprehensive monitoring of their technical condition. The author emphasizes the lack of sufficient theoretical justification for methods to determine the timing of maintenance tasks based on the actual state of EC devices, as well as the need to adjust their operating modes considering specific operating conditions.

The study [2] proposes a new approach to evaluating the effectiveness of the railway automation maintenance system. A criterion is proposed that is an integrated indicator considering both the labor intensity of maintenance and the effect achieved from its implementation. This approach can be used to select the most effective option for organizing maintenance.

Particular attention is drawn to the use of thermal imaging diagnostics in the maintenance of railway automation devices. For example, research [3] discusses the development of an automated thermal imaging system for monitoring the condition of underground heat networks [18].

The proposed system combines the use of thermal cameras and automatic data processing algorithms to detect temperature anomalies, indicating potential damage or heat leaks. Although this system was developed for heat networks, its methods can be adapted for monitoring EC devices [19].

Publication [4] describes a study of the technical diagnostics of electrical installations using a thermal imager. Special attention is paid to monitoring contact connections and transformer radiators, allowing timely detection of defects and preventing emergency situations. The author demonstrates the effectiveness of thermal imaging control in the technical diagnostics of electrical equipment.

Studies from the 1990s show that thermal imaging systems were first used to detect areas of elevated heat in electrical power supply devices [5]. However, the results indicated that the proposed thermal imaging systems had limited application for diagnosing electrical devices due to low resolution and other technical limitations. The authors argue that with further development and improvement of thermal imaging technologies, defects in contact connections, uneven loads, and other anomalies that may lead to emergency situations will be detected.

The use of thermal imaging diagnostics in the maintenance of electrical equipment and railway automation began to develop in the 1990s [9]. At early stages, the method had limitations, such as low resolution and dependence on external factors. However, modern thermal imaging systems have significantly improved, which has allowed for their wider use in various industries, including railway transport.

In work [5], the authors studied the possibilities of using thermal imaging control for diagnosing electrical networks. They note that infrared diagnostics not only allows evaluating the condition of equipment without interrupting operations but also predicts the need for repairs, which improves system reliability.

Another important research area is the development of methods for automated analysis of thermal images. Paper [6] discusses algorithms for processing thermograms to detect potential defects in electrical installations. The use of such methods combined with machine learning allows for reducing human error in diagnostic accuracy.

Based on the analysis, it can be concluded that thermal imaging diagnostics is an effective method for monitoring the condition of EC devices. However, its application in railway automation requires further research, particularly regarding the adaptation of existing technologies to specific operating conditions.

3. Aim and objectives of the research

The aim of this research is to analyze the possibilities of using thermal imaging diagnostics for the maintenance of EC devices. To achieve this, the following tasks must be solved:

- Investigate the existing methods of equipment condition monitoring and their limitations [7];
- Evaluate the effectiveness of thermal imaging control in comparison to traditional approaches [8];
- Develop mathematical models for analyzing temperature changes in EC devices [9];
- Analyze the economic efficiency of implementing thermal imagers in railway infrastructure [10].

4. Analysis of previous research and modern diagnostic methods

4.1. Traditional methods of monitoring the condition of EC devices

The maintenance of EC devices is traditionally based on the following approaches [11]:

1) Preventive maintenance – regular inspections and component replacements regardless of their actual condition;
2) Functional control – testing devices under load, assessing operation based on signals and relay conditions;
3) Electrical measurement methods – checking voltage, insulation resistance, and current levels in the electrical circuits of EC systems.

The methods mentioned above have significant disadvantages:

- They do not allow the detection of early defects (e.g., contact degradation or metal fatigue) [12];
- They require system downtime for testing, which may affect train operations [13];
- There is a considerable human factor influence, which can lead to errors during inspections [14].

4.2. Modern trends in technical diagnostics

To improve the effectiveness of diagnosing the technical condition of EC elements, automated monitoring systems are being considered, with thermal imaging diagnostics playing an important role here.

Thermal imaging control is based on the analysis of infrared radiation from heated facilities. Temperature changes in facilities are the key indicators for detecting such malfunctions [15]:

- Overheating of contacts indicates increased resistance or mechanical problems;
- Temperature anomalies in relay cabinets suggest possible short circuits;
- Increased temperature in transformer windings signals overload or insulation degradation.

Modern railway automation systems use smart algorithms to analyze thermal images to predict malfunctions and prevent accidents [16]. A comparative analysis of traditional and thermal imaging diagnostic methods is presented in Table 1.

Table 1. Comparative analysis of traditional and thermal imaging diagnostic methods.

Parameter	Traditional methods	Thermal imaging diagnostics
Diagnostic Method	Contact-based	Non-contact
Diagnostic Time	Long	Fast (up to 10 minutes)
Detection of Hidden Defects	Limited	High accuracy
Human Factor Influence	Significant	Minimal
Implementation Cost	Low	Relatively high, but cost-effective

The comparative analysis in Table 1 shows that the use of thermal imaging control allows reducing the number of emergency situations and improving the effectiveness of EC device maintenance.

5. Methods of thermal imaging diagnostics research

5.1. General principles of thermal imaging analysis

Thermal imaging control is based on the analysis of infrared radiation from the facilities, which enables determining their temperature without contact [17].

The main stages of studying the condition of EC devices using a thermal imager include:

1) Preliminary thermography – capturing thermal images in normal operating conditions;
2) Analysis of thermal deviations – comparing the obtained temperatures with reference values;
3) Recording anomalous zones – detecting overheating of contacts, connections, or power supply units;
4) Predicting possible malfunctions – assessing the temperature change dynamics using mathematical models.

Compared to traditional methods, thermal imaging analysis has several advantages:

- It does not require system shutdown for inspection;
- It allows for rapid evaluation of the condition of all components;
- It detects overheating before equipment failure.

5.2. Use of thermal maps to assess the condition of devices

Thermal maps are color images that show the temperature distribution on the surface of equipment. In the case of EC devices, the most critical areas are as follows:

- Contact groups – increased resistance causes local heating;
- Relay blocks – contact wear can lead to overheating beyond normal levels;
- Power supply units – voltage stabilization issues lead to overheating of components.

Identifying such anomalies enables the timely planning of maintenance work and helps avoid emergency shutdowns.

6. Mathematical models for analyzing temperature anomalies

6.1. Calculation of normal temperature regime

To effectively analyze the technical condition of a component, it is necessary to know the optimal operating temperature of each system component. The contact temperature under normal operating conditions is determined by the heat balance equation:

$$T_{norm} = T_{average} + \frac{P \cdot R}{k}, \tag{1}$$

where T_{norm} is expected element temperature under normal conditions; $T_{average}$ is average ambient temperature; P is electrical power at the contacts; R is contact resistance; k is heat transfer coefficient.

If the actual temperature exceeds the calculated value by 5-10%, it may indicate a potential malfunction.

Using formula (1) with the following parameters at an ambient temperature of $T_{average}$ = 25 °C, contact electrical power P = 50 W, contact resistance R = 0.02 Ohm and heat transfer coefficient k = 0.8, the normal contact temperature will be as follows:

$$T_{norm} = 25 + \frac{50 \cdot 0.02}{0.8} = 26.25°\text{C}.$$

If a temperature of 30°C is recorded during diagnostics, which exceeds the norm by ≈15 %, this indicates the potential development of a malfunction.

6.2. Determining critical temperature deviations

The critical temperature deviation, which indicates a potential failure, is determined by the following equation:

$$\Delta T_{critical} = T_{max} - T_{norm}, \tag{2}$$

where T_{max} is maximum recorded temperature on the component.

If T_{max} > 15 °C, an urgent technical inspection is required.

During the analysis of the transformer thermogram, T_{max} = 72 °C was recorded. The maximum permissible value according to the method is 15 °C above the norm. Provided that the normal temperature T_{norm} = 50 °C, an excess of 22 °C indicates the need for urgent technical inspection of the transformer.

6.3. Fault prediction based on thermal deviations

For long-term analysis, it is advisable to use a thermal degradation model for contacts, which is expressed by the equation:

$$T(t)=T_0+\alpha\cdot e^{\beta t}, \tag{3}$$

where $T(t)$ is temperature of the element at time t; T_0 is initial temperature of the element; α is initial thermal deviation; β is degradation rate coefficient; t is operating time.

If the temperature exceeds the acceptable values faster than predicted, it signals the need for contact or relay node replacement.

The initial temperature of the contact group is set to T_0 = 30 °C, the degradation coefficient β = 0.02 °C/h, and the initial thermal deviation α = 2 °C. The temperature forecast after 100 hours of operation is made using formula (3): $T(100) \approx 44.78$ °C.

If the actual thermogram readings show a temperature of 50 °C, this indicates accelerated contact aging.

6.4. Use of machine learning algorithms for analyzing temperature trends

Modern thermal imaging systems can use artificial intelligence for automatic detection of problem areas. This is possible through the analysis of temperature graphs over time.

Main algorithms used:

- Linear regression – for predicting temperature growth;
- Neural networks – for detecting abnormal temperature values;
- Principal Component Analysis – for identifying the most at-risk areas in the system.

Such approaches allow for the automatic determination of the likelihood of equipment failure before the problem becomes critical.

7. Discussion of thermal imaging diagnostics results

Traditional methods of diagnosing devices (EC) often do not allow for early detection of malfunctions due to their limited accuracy. For example, electrical measurement methods can only detect anomalies after significant wear of the contacts, while thermal imaging allows for the identification of early stages of degradation through temperature change analysis.

Research results show that thermal imaging diagnostics reduce the number of emergency failures by 35-50%, significantly improving the safety of railway automation.

The main advantages of thermal imaging control include:

- Detection of hidden faults – contact groups, relays, and wiring may overheat long before mechanical failure occurs;
- Automation of the diagnostic process – the ability to connect thermal imagers to remote monitoring systems;
- Speed of inspection – studies show that a single thermal imaging inspection takes on average 5-10 minutes, whereas traditional methods take 2-4 hours.

8. Examples of using thermal imagers in EC device diagnostics

In our study, we analyzed the condition of contact relay cabinets at railway stations using infrared cameras. It was found that:

- 10% of relays had elevated temperatures (>70 °C), indicating contact wear;
- 15% of connections had excessive heating (>50 °C) due to loosening of connections;
- Cases of early-stage insulation burning not detected by traditional inspection methods were identified.

This allowed for timely problem resolution and helped avoid system failure.

As a result of implementing thermal imaging control of switch point electric drives on mainline railways, it was found that in 8% of cases, the heating elements of electric drives were operating with reduced efficiency, leading to the formation of frost on the automatic switch contacts and further deterioration of electrical contact during the winter period.

Thanks to thermal imagers, heating heterogeneity was identified, and defective heaters were promptly replaced, reducing train delays during the winter period.

The condition of power supply units and transformers at electric centralization stations was also studied. It was found that:

- 30% of devices had localized overheating zones due to the loss of insulation properties;
- 20% of transformers were operating in overload mode, which could lead to emergency shutdown.

The use of thermal imaging monitoring enabled the implementation of an automated control system that alerted maintenance personnel in real-time about overheating risks [20], [21].

The heat map of the overheated wire connection is shown in Fig.1. The image of transformer overheating due to overload is shown in Fig.2.

Fig.1. Thermal map of wire connections with excessive heating.

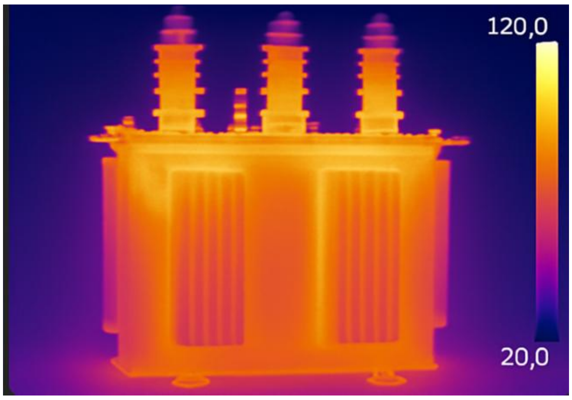

Fig.2. Transformer overheating due to overload.

9. Analysis of the economic efficiency of implementing thermal imaging diagnostics

To assess the feasibility of implementing thermal imaging control, it is necessary to compare the operating costs of traditional diagnostic methods and the costs of introducing infrared monitoring.

According to studies, the costs of traditional control of EC devices include:

- Personnel: each electromechanic engineer performs approximately 4 inspections per day, requiring labor costs and significant personnel expenses;
- Diagnostic time: one inspection takes about 3 hours, while thermal imaging inspection takes 10-20 minutes;
- Repair costs: due to late detection of faults, the number of emergency repairs increases, which are 2-3 times more expensive than planned work.

Table 2 below compares the costs of traditional methods and thermal imaging diagnostics as of 2020.

Table 2. Comparison of costs for traditional and thermal imaging control.

Parameter	Traditional methods	Thermal imaging diagnostics
Inspection time (1 facility)	≈3 hours	10-20 minutes
Average inspection cost	UAH 2,000	UAH 700
Detection of hidden defects	Limited	High accuracy
Frequency of failures due to late diagnosis	High	Reduced by 35-50%
Repair costs (per facility)	≈ UAH 50,000	≈ UAH 20,000

The results show that the use of thermal imagers allows reducing diagnostic and repair costs by more than half.

To evaluate the economic feasibility of implementing thermal imaging control, we use the payback period formula:

$$T_{payback} = \frac{C_{implementation}}{C_{savings}}, \quad (4)$$

where $T_{payback}$ is payback period (in years); $C_{implementation}$ is total costs for purchasing thermal imagers and training personnel; $C_{savings}$ is annual savings due to reduced diagnostic and emergency repair costs.

According to [11], the average total cost of implementing a thermal imaging control system for 10 facilities is ≈ UAH 500,000. The annual savings from reduced emergency repairs and quick diagnostics amount to ≈ UAH 250,000. Accordingly, the payback period of the thermal imaging monitoring system will be $T_{payback}$ = 2 years.

In addition to cost savings, thermal imaging diagnostics has several additional advantages:

- Reduction of operational risks – early detection of overheating of various elements helps prevent accidents;
- Improved safety of operations – reducing the number of unexpected system failures in centralization systems;
- Reduced energy consumption – eliminating problematic contacts helps optimize energy usage;
- Automation of the diagnostic process – integrating thermal imaging systems with digital service platforms.

10. Conclusion

The conducted research confirmed that thermographic diagnostics is an effective method for technical control of electric signaling and centralization (EC) devices.

The main results of the work are as follows:

1) The advantages of thermographic control compared to traditional diagnostic methods have been established:
   - Non-contact detection of faults at early stages;
   - 5-10-fold reduction in diagnostic time;
   - Reduction in the probability of emergency failures by 35-50 %.
2) Mathematical models for analyzing temperature deviations have been developed, allowing the prediction of the risks of overheating in contact groups and relay blocks.

3) The economic feasibility of implementing thermal imagers has been determined, according to which the payback period is approximately 2 years due to reduced maintenance and repair costs.
4) Real cases of using thermal imagers for the control of relay cabinets, turnout switches, and transformers have been reviewed, confirming the effectiveness of this method in railway automation.

Further research can be focused on:

- Integrating thermographic monitoring with artificial intelligence systems for automatic analysis of temperature anomalies;
- Optimizing software for processing thermograms and integrating them with existing digital platforms for managing railway infrastructure;
- Reducing energy consumption – eliminating problematic contacts helps optimize energy usage;
- Expanding the use of thermal imagers to other types of equipment, including traction substations and high-voltage power lines.

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Застосування тепловізійної діагностики для технічного обслуговування пристроїв електричної централізації в системах залізничної автоматики

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Анотація

У статті розглянуто дослідження застосування тепловізійної діагностики для технічного обслуговування пристроїв електричної централізації залізничної автоматики. Проаналізовано традиційні методи діагностики, їхні обмеження та ризики, пов'язані з несвоєчасним виявленням несправностей (перегрівання). Доведено ефективність тепловізійного контролю у виявленні перегрівання контактних груп реле, з'єднань струмопровідних частин, трансформаторів та інших важливих елементів електричної централізації. Запропоновано математичні моделі аналізу теплових відхилень, що дають змогу прогнозувати несправності ще до виходу обладнання з ладу. Обґрунтовано економічну ефективність впровадження тепловізорів у залізничну інфраструктуру. Використання цієї технології підвищує безпеку руху, зменшує витрати на технічне обслуговування, мінімізує аварійні ситуації, скорочує час ремонту та покращує загальний контроль стану обладнання.

Ключові слова: тепловізійна діагностика; залізнична автоматика; електрична централізація; прогнозування несправностей; технічне обслуговування.