ІНФОРМАЦІЙНО-КОМУНІКАЦІЙНІ ТЕХНОЛОГІЇ ТА МАТЕМАТИЧНЕ МОДЕЛЮВАННЯ

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Improvement of Video Measuring Systems for Electric Traction Network Diagnostics

Purpose. The purpose of the article is system analysis of the state of electric traction networks, as well as methods of complex diagnostics of the contact network from a moving laboratory car to increase the resolution capability of the systems for monitoring the quality of interaction between the contact network and current collectors. **Methodology**. The problem was solved by theoretical analysis and experimental studies of the current collection parameters, a generalized model of the device for monitoring the wear of the overhead wire and its functional units in order to determine the factors affecting the control error, as well as the development of methods that reduce the specified error. The apparatus of factor analysis, the theory of optoelectronic circuits and methods of statistical information processing were used. **Findings**. Innovative approaches and qualitatively new diagnostic tools are proposed that allow expanding the functionality of the laboratory cars for testing the contact network for power supply enterprises of electrified railways, industrial and urban electric transport. Hardware and software have been developed to improve the system for measuring the parameters of the overhead wire and other components of the contact network. **Originality**. The theoretical maximum permissible, from the point of view of the contact network operation, error in monitoring the wear of the overhead wire and other components of the electric traction network has been determined. A method for increasing the resolution capability of a stereo television system and an adaptive lighting system is proposed. It consists in preliminary image transformation and expansion of the dynamic range of image measurement. The ways of introducing a high-speed real-time compression algorithm and using LED backlighting are proposed. **Practical value**. The quality of the contact network diagnostics in difficult conditions for video surveillance has been improved. A camera with a built-in image compression module without losing its performance is proposed, which allows capturing and transmitting full-frame images to a computing complex for the application of new diagnostic algorithms for contact network components. The modernized video measuring systems for the wear of the overhead wire for monitoring the grounding of the contact network supports are proposed, as well as elements of track facilities located in the visibility zone of specialized cameras, which ensure the operability of the systems at any time of the day at speeds up to 160 km/h. An air curtain subsystem was implemented to protect the cameras.

Keywords: diagnostic systems; contact network; overhead wire wear; optical measurement methods

Introduction

The basis for ensuring the traffic safety is systems for diagnosing the state of infrastructure devices, which allow predicting their possible failures and eliminating emergency situations in a timely manner. A non-redundant link of electrified lines of railways and urban electric transport is a contact network (CN), the failures of which lead to delays of trains, urban electric transport and, as a consequence, to economic damage [1–12]. An important feature of the CN is its participation in the current collection, which causes the appearance of loads requiring the improvement of interaction

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models of current collectors with the CN and the development of a theory of high-current contact to improve the diagnostic systems [3, 14]. The uniqueness of the CN places high demands both on the design of its devices and to the methods of their technical operation [4, 7].

Reliable and economical operation of the CN is impossible without automated diagnostic devices that allow detecting the locations of malfunctions or other aberrations, as well as analysing them to develop managerial decisions to ensure the uninterrupted movement of the rolling stock [9, 11–13, 16].

Railway and industrial companies in many countries strive to eliminate interruptions in the movement of trains and electric industrial and urban electric transport through high-quality diagnostics of the CN and malfunction repair. In this case, the economic aspect associated with the optimization of the service life of the CN devices and, first of all, the overhead wire (OW) plays the most important role [7, 8].

Today, the triangulation method for determining the height and zigzag of the OW, the phase measuring method based on the use of light sources, the method of monitoring the position of the video camera system and OW wear are known in application. The existing methods are based on one of two basic principles: contactless measurement or contact one, when the sensor is installed on the current collector and touches the overhead wire. Using the contactless systems, measurements can be made at any movement speed, but the measurement accuracy is reduced. Contact systems have higher accuracy, but they provide measurements at low speeds [15, 17].

The optical method of automatic control involves installation of several optical systems on the roof of the laboratory car for testing the contact network (LTCN), which films the catenary suspension with supporting structures on the move from different points and transfers the resulting images to a storage unit.

In the measurement system, specialized high-speed television cameras are used, and fan-shaped raster pulse laser illuminators are used to illuminate the overhead wires.

On the German Railways Network (DBAG), for monitoring small devices, such as bolt heads or torn wire strands of the carrier cable, the optics resolu-tion is 1–2 mm, and the flash duration when illuminating the object should not exceed 45 μs. When measuring the OW wear, comparison with previous results is not required. A comparison with the cross-section of the new wire is enough here. The measurement accuracy of this type is 0.1 mm, and a decrease in the wire thickness can be detected already at a length of 2–3 cm [15, 17].

In recent years, qualitatively new diagnostic tools have been developed based on video measuring systems. Their speed and detection reliability when diagnosing the CN elements have been increased. Computing power has been significantly increased, new more advanced photoreceiving components and image processing algorithms have been developed [9, 13–17]. Therefore, there is a scientific problem of improving video measuring diagnostics systems to ensure reliable and economical current collection on electrified lines of railways and urban electric transport.

Purpose

The main purpose of the article is a systematic analysis of the state and development prospects of electric traction networks of electrified railways and urban electric transport, the development of hardware and software for improving video measuring diagnostic tools and expanding the functionality of laboratory cars for testing the contact network.

Methodology

In our opinion, in the current situation, it is necessary to solve the problem of complete replacement of most of the devices of electric traction networks of railways and urban electric transport by investing significant funds in modernization. This is evidenced by the experience of foreign countries. On many railway sections of transport corridors, as well as in large cities, a new CN is required, and only in this case safe and economical operation of the power supply for train traction system and urban electric transport will be ensured [6, 14].

The problem of increasing the resolution capability of the quality control systems of the current collectors and CN's interaction from the moving laboratory car was solved using a complex approach. This approach includes theoretical analysis and experi-

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mental research of the parameters of the control object – overhead wire (OW), modelling of the control device of the wear of overhead wire and its functional units, determination of factors influencing the control error [3, 4, 7, 10]. At the same time, the apparatus of factorial analysis, the theory of optoelectronic circuits and methods of statistical information processing were used to determine the theoretically maximum allowable error in monitoring the wear of the OW and other components, from the point of view of the operation of CN.

Findings

Analysis of the state and development prospects of electric traction networks of railways and urban electric transport. At all stages of the development of railways, electrification was the leading link in their reconstruction, qualitatively changing the operational work (Fig. 1). For the period 1994–2011 more than 1700 km of the operational length of railways were electrified, the polygon of electrified lines was increased by 21%, while the volume of electric traffic increased to 89.7%. The highest electrification rates were achieved in 2011–2012 on the sections of the accelerated movement of passenger trains with an operational length of 176 km. The specific weight of the length of electrified lines increased to 47.3%, and the specific weight of electric cargo turnover was more than 91.2% [1].

The task of further electrification was planned in the volume of phased implementation: in total for the period 2013–2020 – about 1 841 km. However, this program failed. At the same time, in recent years, there has been a tendency for the development of urban electric transport in large cities.

The rate of ageing of power supply devices, given the existing funding shortfall, continues to outstrip the rate of reconstruction. The length of the electrified lines operated beyond the average period (40 years) increased from 5012 km (or 52.0%) in 2007 to 6393 km (or 62.3%) in 2012, and in 2020 up to 6820 km (or 67.9%). Today, 73% of the total number of traction substations of urban electric transport operate with a service life of more than 40 years, and 43% with a service life of more than 50 years. Thus, a complete reconstruction of more than 80% of the length of the contact network and traction substations of urban electric transport is required. There is no global experience in operating

a contact network with such ageing rates. Specific damage to CN, which has served for 40 years or more, is 2.7 times higher than in the sections with a service life of 10 years [1, 2].
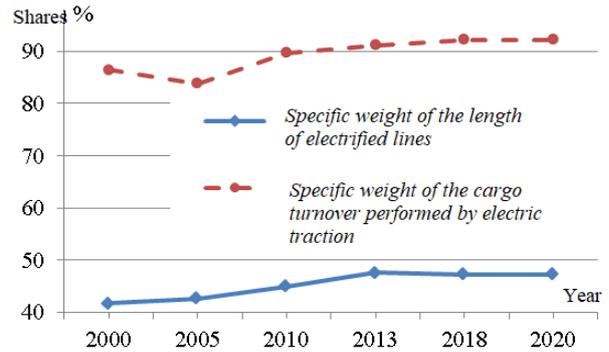

Fig. 1. Specific weight of electric traction
in the railway network length and
in the total cargo turnover

Analysis of the replacement dynamics of the main CN devices (Fig. 2) shows that the average values and root-mean-square deviations (shown in brackets) have the following values: overhead wire – 188 km (80 km); carrier cable – 134 km (79 km); high-voltage insulators – 40 thousand pcs. (17 thousand pieces); supports – 2340 pcs. (751 pcs.). Thus, the existing rate of replacement of the main devices of the CN is incommensurate to the rate of their ageing, and since 2021, it can cause a snowballing growth of failures [2].
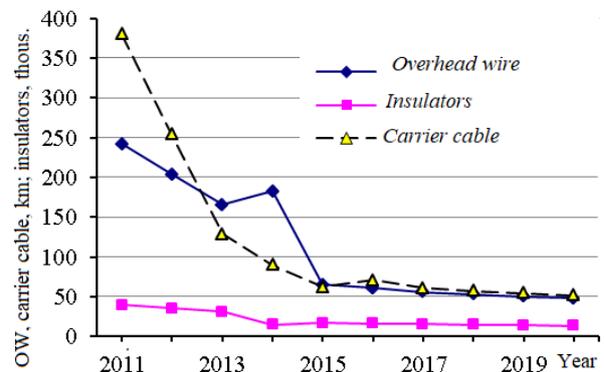

Fig. 2. Replacement dynamics of the main
elements of the CN

Analysis of the number of damages at all junctions of the CN of the railways for different periods shows that the most often fail the overhead wire and cables, insulators, droppers, clamps and parts. Fig. 3 shows the failure dynamics of these devices for railways. This is explained by the fact that structurally all other elements of the CN are designed to support the OW in the set position. Failures of any element of the CN often result in OW failure. On the other hand, the OW is the element of CN that directly interacts with the current collector. Interaction with the current collector during the current collection process causes intensive ageing of wires and a large number of sudden failures caused by malfunctions of the electric rolling stock.
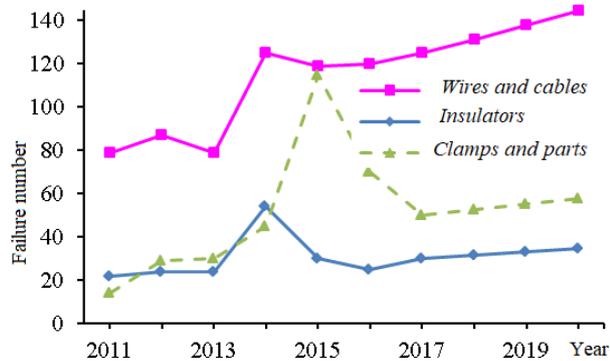

Fig. 3. Failure dynamics of the most damageable catenary devices

Over the past 10 years, there has been a tendency for an increase in the number of CN failures due to mechanical and electromechanical wear of droppers, as well as clamps and parts. The height depletion of the support structures, which occurred on a significant part of the polygon due to multiple track repairs, also became a problem. The specified problem can be solved only with the overhaul repair of the CN [2].

Calculations have shown that over the past 10 years, there have been changes in the failure risks, which reflected the growth of ageing, wear and degradation processes of the CN. The most significant is the risk of OW failures. The risk of failures of catenary suspension and current collectors in monetary terms is so great that it requires drastic solutions in the field of investments both in overhaul repair or construction of new catenary suspension and current collectors of electric rolling stock, and in new systems for diagnostics of current collection.

Analysis of damage to power supply devices for urban electric transport shows that the overwhelming amount of damage is accounted for by contact networks, especially in the sections with a service life of more than 40 years. Significantly less damage occurs at traction substations (TS). Damage distribution by the types of devices: CN – 49.7%; TS – 5.4%; cable lines and trackways – 44.6%.

The ratio of mathematical expectations and root-mean-square deviations of damage to the contact network and current collectors as a result of delays of trams and trolleybuses in percent of the total number of delays over the past 10 years are as follows: 194.5 and 15.5, which is 64.3% and 3.4%, respectively.

The need to expand tram and trolleybus lines and modernize power supply devices in a resource-saving environment requires new technologies for the design, construction and operation of infrastructure facilities. For the first time in Kharkiv, a new generation of traction substation with dry transformers, 12-pulse rectification circuits, digital protection and equipment diagnostics was put into operation, ensuring operation according to condition. It is necessary to create automated systems for laboratory cars for testing CN of trams (LTCN–T), which recognize hidden defects in CN (Fig. 4), as well as laboratories on the basis of trolley buses or trucks for trolleybus CN. This task is posed in our country for the first time [7–12].

The modern LTCN–T include an optical-mechanical unit; laser fast-acting system for OW diagnostics; video surveillance and information processing system; additional power supply system; complex control panel and functional panel; rotation angle sensors, stresses, lateral displacements, ambient temperature, car movement speed.

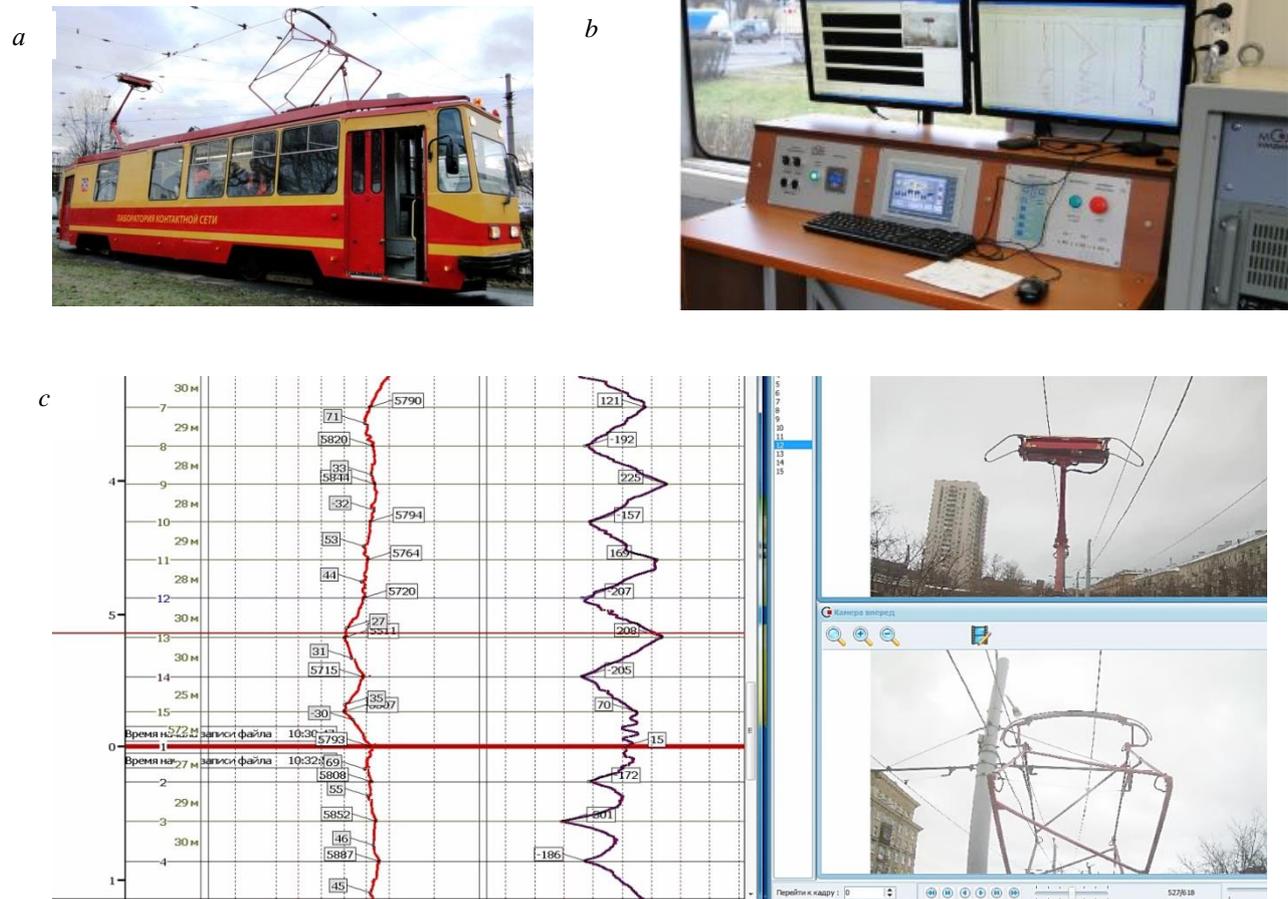ІНФОРМАЦІЙНО-КОМУНІКАЦІЙНІ ТЕХНОЛОГІЇ ТА МАТЕМАТИЧНЕ МОДЕЛЮВАННЯ

Fig. 4. LTCN–T:
a – appearence; *b* – workplace in the car;
c – operation of the video surveillance system and information processing synchronously
with the determination of the car geolocation

LTCN–T allows controlling the current height position, OW displacement; OW suspension defects; OW wear; distance travelled; movement speed; ambient air temperature; CN voltage; GLONASS/GPS coordinates; CN state with the help of video recording.

The tram laboratory for a comprehensive assessment of the infrastructure state, in addition to the LTCN–T parameters, allows performing measurements of track depression and alignment, longitudinal track gradient, acceleration on the bogie and body, track width, rail wear, CN support dimensions, as well as video monitoring of the rail track, connections of assembling joints, connection of supply cables, inter-rail connections.

For example, a specialized video system (Fig. 4, *c*) records a video image, the viewer of which is shown on the screen. The programs work synchronously. This makes it possible to stop the tape in the places where clarification is needed (for example, a large zigzag), enter the video program at this place and take a photo with the necessary comment to analyse, issue to the repair site and for serviceability.

The use of LTCN–T allows obtaining objective data on the CN state, conducting an automated assessment of the CN state by one or several passes, linking the measurement results to a place on the map and performing video surveillance of the CN infrastructure. All the above makes it possible to create databases on the state of the contact network, track, cable lines, etc., as well as the conditions for the transition of their service by state. The solution of the problem allows improving the assessment

quality of the CN state and reducing the possibility of failures, as well as ensuring energy and resource saving in the process of passenger transportations.

Video measuring systems for diagnostics of contact networks. In recent years, hardware and software have been developed to improve the system for measuring the OW parameters and other CN components. A method for increasing the resolution of a stereo television system and an adaptive lighting system is proposed. It consists in preliminary image transformation and expansion of the dynamic range of image measurement. The quality of CN diagnostics in difficult conditions for video surveillance has been improved. A camera with a built-in image compression module without loss of its fast action has been proposed, which allows capturing and transmitting full-frame images to a computer complex for the application of new CN diagnosing algorithms [8, 10, 15, 16].

The stereo television system is based on a specialized fast-acting television camera of a new generation, and the lighting system can operate both in continuous and in pulsed mode with a duration of light pulses from 20 µs. Cameras can be equipped with lenses with automatic iris control according to the P-iris standard; serial interface; serial interfaces and high-speed video compression module and frame grabber.

For the enterprises of power supply of electrified railways, industrial and urban electric transport, innovative means of complex diagnostics of the CN state have been developed. They are laboratory cars, which provide monitoring of OW wear, the state of high-voltage insulation, heating of electrical connections, grounding of supports on rail.

An automated video-measuring system for monitoring the CN supports grounding and its other equipment, as well as elements of the track facilities located in the visibility zone of specialized cameras, which ensure the system's operability at any time of the day at speeds up to 160 km/h, is proposed: discretization of image lines along the track length from 0.5 mm; the value of the electronic shutter at a speed of 160 km/h is not more than 22 µs; the number of pixels in a line is at least 1000. An air curtain subsystem is implemented to protect the cameras.

Development of new diagnostic tools for the contact network and improving the efficiency of existing ones is a priority area of activity of DAK-Energetika LLC, which carries out the entire range of works, including research, design, manufacture, installation, commissioning, warranty and service.

The manufactured measuring equipment is included in the State Register of Measuring Instruments and Register of Measuring Instruments, Test Equipment and Methods of Measurements Used in Ukrainian Railway OJSC, and is metrologically certified and protected by patents.

Improvement of WEAR laser fast-acting system for measuring the parameters of the contact wire. The Aptima MT9M413C36STC video sensor used in the WEAR system has a 100-bit output data bus that transmits a block of 10-bit brightness readings of 10 neighbouring pixels of the current line per one cycle of the operating frequency f_e. Each line of the image has a size of 1280 pixels and is transmitted in a block consisting of 128 f_e cycles. For contactless measuring of the profile of the worn out OW part, measuring the position of the OW relative to the current collector axis, detecting OW overturns and lateral slopes of the OW clips (dropper, pull-off, etc.), LTCN is equipped with WEAR fast-acting laser diagnostic OW system.

This diagnostic system belongs to the group of systems that measure OW wear by its profile, their operating principle is indicated in [8, 10, 13].

The measuring system consists of 8 laser fan-shaped emitters, in which the collimated laser beam is converted into a flat fan out light beam 0.3–0.6 mm thick using a spreading system, and 4 matrix television cameras. When the fan beam of light strikes the OW, a visible line of its intersection with the plane is formed on the wire surface, in which the correct beam lies. It is this intersection line that is distinguished by the processing system from the resulting image of the current frame of the television camera. In this case, the shape of the fixed line weakly depends on the OW inclination and is mainly determined by its wear. The program provides the ability to display a 3-D OW model with imposed measured wear for the selected camera (Fig. 5).

The use of LED illumination, which effectively illuminates the entire surface of the lower part of the overhead wire and clamps, together with the possibility of obtaining a full frame of the image at the input of the information-computing complex, can significantly increase the informativeness of the

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WEAR system. Thus, many unclear situations caused by the insufficient informativeness of the measuring system can be resolved in real time by visual or programmatic assessment of the received frames corresponding to the CN section that causes questions.
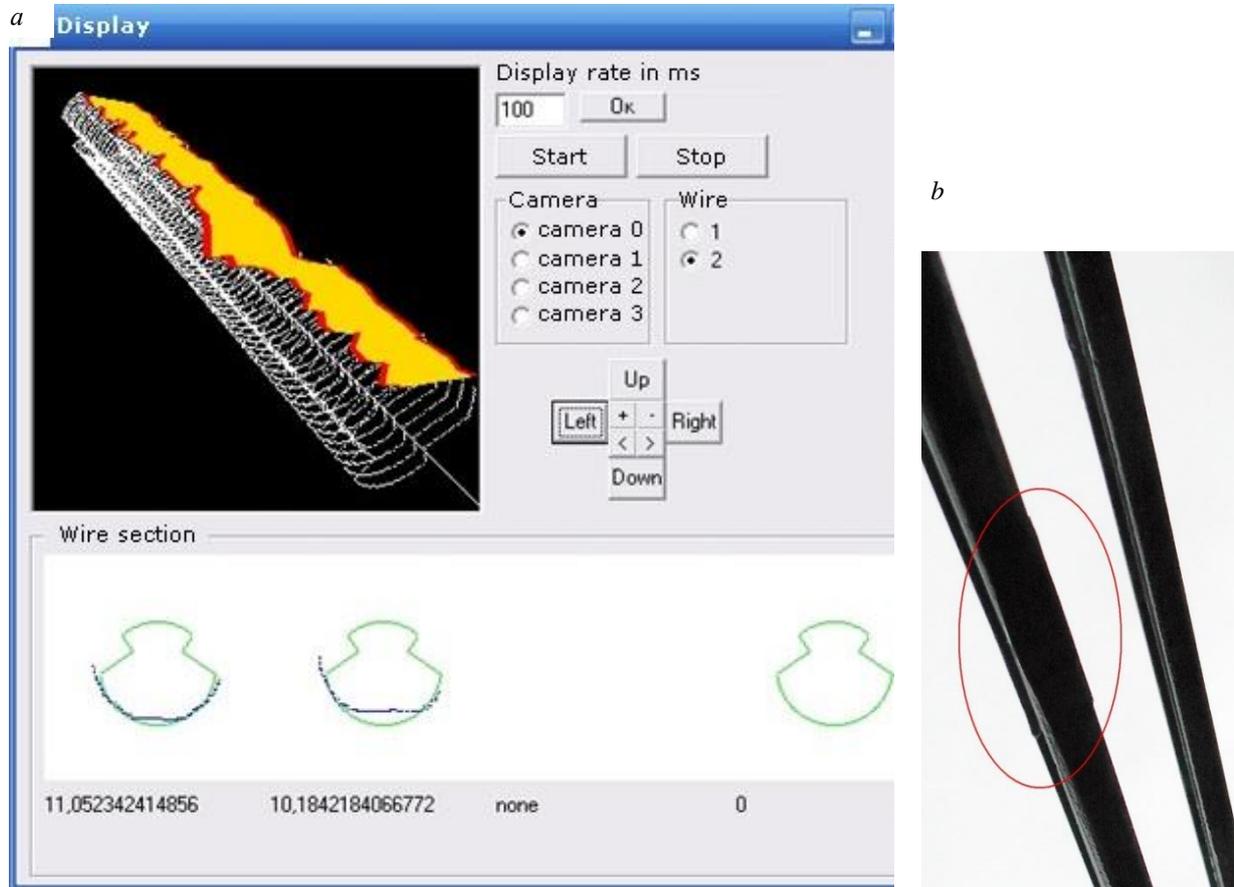

Fig. 5. Reconstructed 3-D model of the worn-out section
of the OW (*a*) and a photograph of this place (*b*)

The second important aspect of the WEAR system modernization is the need to obtain full-frame illuminated images of the CN elements at a high speed for continuous scanning of objects of interest. Based on the optical characteristics of the lenses, the frame resolution and the distance at which the cameras are located relative to the measured objects, the field of view along the OW is $l = 37$ mm. The maximum speed at which the WEAR system operates is $\upsilon = 72$ km/h. The maximum time T of receiving one frame, at which continuous scanning of the CN is provided, is determined by the expression $T = c \cdot (l / \upsilon)$, where $c = 0.0036$ is the reduction coefficient of values to the SI system.

With the given values l and υ $T = 0.00185$ s, which corresponds to the frequency of obtaining frames $f = 541$ fps.

The required bandwidth of the channel C for transmitting only an uncompressed image for a frame with a resolution r and a bitness of one pixel n is determined by the following expression: $C = r \cdot n \cdot f$. With $r = 1\,280 \cdot 128$ and $n = 10$ $C = 846$ Mb/s.

Test results of the WEAR system. The automated system for measuring the wear of the overhead wire installed on the LTCN was tested along the 1 and 2 station track in variable cloud conditions at a temperature of +28°C. A double contact wire MF-100 is suspended within the test section. Automated measurements were carried out at a measuring car speed of 37 km/h.

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Manual wear measurements were taken between the 69th and 71st supports along the first station track. For accurate synchronization of measurements, manual measurements were carried out next to the dropper and pull-off clips, since such places can be easily identified using the measurement data from the WEAR system. The measurements results are given in Table 1.

It was found that at the points being checked, the difference between the automated measurements of the WEAR system and manual measurements of the residual height does not exceed 0.26 mm.

Table 1

**Results of manual and automated measurements
of OW wear along the first station track**

Distance from support, cm	Manual measurements, mm		Wear system measurement, mm		Error, mm	
	left	right	left	right	left	right
0	10.47	8.1	10.3	8.35	0.17	–0.25
075	9.57	9.49	9.5	9.29	0.07	0.2
150	10.13	9.57	10.16	9.54	–0.03	0.03
850	9.45	8.92	9.8	8.9	–0.35	0.02
1 875	9.36	9.1	9.3	8.98	0.06	0.12
2 875	8.5	9.38	8.65	9.05	–0.15	0.23
3 745	8.17	8.75	8.25	8.9	–0.08	–0.15
4 025	9.8	8.71	9.5	8.76	0.2	–0.05
4 085	9.24	8.71	9.7	8.7	–0.26	0.01
4 875	9	8.93	9.12	8.93	–0.12	0.11
5 850	9.8	9.35	9.5	9.2	0.24	0.23
6 000	9.37	9.67	9.2	9.5	0.16	0.26
6 075	9.2	9.76	9	9.61	0.25	0.15

During the test drive on the second station track, several places were found where, due to lateral wear of the overhead wire, the wear area reached the clamp itself, as a result of which the bite wear began (Fig. 5).

The difference between manual and automatic measurements (Table 2) does not exceed 0.33 mm in the residual wire height, except for the reference point at the mark of 4 473 cm (right wire), where there is strong lateral wear of the wire and an error could be made during manual measurements.

Table 2

**Results of manual and automated measurements
of OW wear along the second station track**

Distance from support, cm	Manual measurements, mm		Wear system measurement, mm		Error, mm	
	left	right	left	right	left	right
0	11.5	11.5	11.4	11.3	0.1	0.2
25	9.25	10.4	9.11	10.43	0.14	–0.03
1 075	9.27	11.2	9.04	10.63	0.23	0.57
1 174	9.27	11.75	9.35	11.7	–0.08	0.05
1 211	9.38	11.65	9.19	11.63	0.19	0.02
1 982	9.75	10.95	9.78	10.88	–0.03	0.07
2 767	9.45	10.12	9.89	9.855	–0.24	0.265
2 839	10.1	10.15	10.03	10.01	0.07	0.14
3 557	10.45	11.55	10.37	11.7	0.08	–0.15
4 390	11	11.15	10.73	10.94	0.27	0.21
4 408	9.32	11.25	8.9	11.05	0.32	0.2
4 420	11	11.05	10.7	10.75	0.3	0.3
4 446	11.65	11.15	11.32	10.85	0.33	0.3
4 473	11.27	11.16	11.1	10.35	0.17	0.81

Originality and practical value

The theoretical maximum permissible, from the point of view of the contact network operation, wear control error of the overhead wire and other components of the electric traction network has been determined. A method for increasing the resolution capability of a stereo television system and an adaptive lighting system is proposed, which consists in preliminary image transformation and expansion of the dynamic range of image measurement.

The quality of diagnostics of the contact network in difficult conditions for video surveillance has been improved. A camera with a built-in image compression module without loss of its performance has been proposed, which allows capturing and transmitting full-frame images to a computer

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complex for the application of new diagnostic algorithms for the components of the contact network of electrified railways and urban electric transport.

Conclusions

To reduce the wear of the overhead wire and current collector plates, to ensure reliable and economical current collection in the process of transportation by electric transport, high-quality diagnostics of the electric traction network is required. The proposed video system has the following speed characteristics: obtaining a JPEG image with a compression ratio of $k> = 10$ and a resolution of 1 280 x 128 at a speed of 976 fps. In this case, the required maximum speed of compressed data transfer does not exceed 85 Mb/s. The system is equipped with fast-acting LED backlighting, which makes it possible to obtain a continuous illuminated image of the CN elements in real time. Thus, the improvement of the WEAR laser fast-acting system can significantly increase the reliability and reduce the detection time of emerging OW malfunctions and other CN components.

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Удосконалення відеовимірювальних систем діагностики електротягової мережі

Мета. Основною метою статті є системний аналіз стану електротягових мереж, а також методів комплексної діагностики контактної мережі (КМ) з рухомого вагона-лабораторії для підвищення роздільної здатності систем контролю якості взаємодії контактної мережі і струмоприймачів. **Методика**. Поставлену задачу вирішено шляхом теоретичного аналізу та експериментальних досліджень параметрів струмозняття, узагальненої моделі пристрою контролю зносу контактного проводу (КП) та його функціональних вузлів із метою визначення факторів, що впливають на похибку контролю, а також розробки методів, що знижують зазначену похибку. При цьому використано апарат факторного аналізу, теорію оптико-електронних схем і методи статистичної обробки інформації. **Результати**. Запропоновано інноваційні підходи та якісно нові діагностичні засоби, що дозволяють розширити функціональні можливості вагонів-лабораторій випробування контактної мережі для підприємств електропостачання електрифікованих залізниць, промислового й міського електротранспорту. Розроблено апаратні та програмні засоби для вдосконалення системи вимірювання параметрів контактного проводу та інших компонентів контактної мережі. **Наукова новизна**. Визначене теоретичну максимально допустиму, із точки зору експлуатації контактної мережі, похибку контролю зносу контактного проводу та інших компонентів електротягової мережі. Запропоновано метод підвищення роздільної здатності стереотелевізійної системи й адаптивної системи освітлення, що полягає в попередній трансформації зображення й розширенні динамічного діапазону вимірювання зображення. Запропоновано шляхи впровадження високошвидкісного алгоритму стиснення реального часу й застосування світлодіодного підсвічування. **Практична значимість**. Підвищено якість діагностики контактної мережі в складних для відеоспостереження умовах. Запропоновано камеру із вбудованим модулем стиснення зображення без втрати її швидкодії, що дозволяє захоплювати й передавати в обчислювальний комплекс повнокадрові зображення для застосування нових алгоритмів діагностики компонентів контактної мережі. Запропоновано модернізовані відеовимірювальні системи вимірювання зносу контактного проводу, контролю заземлення опор контактної мережі, а також елементів колійного господарства, розташованого в зоні видимості спеціалізованих камер, які забезпечують працездатність систем у будь-який час доби на швидкостях до 160 км/год. Для захисту камер реалізовано підсистему повітряної завіси.

Ключові слова: системи діагностики; контактна мережа (КМ); знос контактного проводу (КП); оптичні методи вимірювань

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