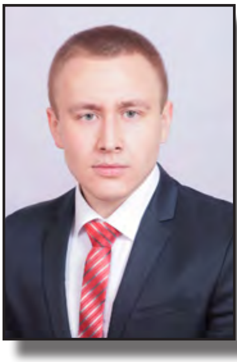
DOI: https://doi.org/10.30932/1992-3252-2020-18-62-89

Monitoring the Technical Condition of AC Electric Locomotives using Traction Energy Consumption Rates





Alexander P. SEMENOV **Victor V. SEMCHENKO** **Igor Yu. KHROMOV**

Semenov, Alexander P., *JSC Research Institute of Railway Technology, Control and Diagnostics, Omsk, Russia.*
Semchenko, Victor V., *JSC Railroad Centre of Technology Implementation of Krasnoyarsk Railway, Krasnoyarsk, Russia.*
Khromov, Igor Yu., *LLC2050-Integrator, Moscow, Russia*.*

ABSTRACT

Currently, the methods of monitoring the technical condition of locomotives using data of on-board microprocessor-based control systems are widely used. This monitoring of Russia has become an operating technology of the locomotive maintenance and repair system.

The main problem of monitoring is the limited set of sensors in locomotive circuits. Increased number of sensors leads to a decrease in reliability and to an increase in the cost of a locomotive and of its life cycle, while allowing to achieve better quality of diagnostic information.

Besides, it is advisable to have integrated indicators of the technical condition of a locomotive. The article presents a computer software product for analysing the technical condition of a locomotive based on dynamic data on consumption of traction active power and generation of reactive power. The software was developed by using algorithmic language Visual BASIC for Applications, embedded in MS Excel, using probabilistic and statistical methods of analysis.

The method for diagnosing the technical condition of a locomotive within the monitoring system is based on a comparison of dynamics of consumption of active and generation of reactive power by two sections of the same locomotive according to the principle of functional benchmarking. For monitoring the technical condition of locomotives, the term «pre-failure» is suggested, which is defined as the operable condition of a locomotive while there are internal hidden defects or damage. Pre-failure manifests itself in power consumption. To analyse the technical condition of AC electric locomotives in terms of electricity consumption, the initial data must have a high degree of unimodality, which is determined by uniformity of operating conditions.

The resulting data obtained following the analysis of the technical condition of a locomotive based on the dynamic data on consumption of tractive active energy and generation of reactive power can be used to determine a defect that causes a change in consumption of electricity at the moment when the locomotive enters technical maintenance and repair depot.

Keywords: *railway, locomotive, technical condition monitoring, train traction, electric locomotive, microprocessor control systems.*

*Information about the authors:
Semenov, Alexander P. – Ph.D. (Eng), General Director of JSC Research Institute of Technology, Control and Diagnostics of Railway Transport, Omsk, Russia, corp@niitkd.ru.
Semchenko, Victor V. – Ph.D. (Eng), General Director of JSC Railroad Centre of Technology Implementation of Krasnoyarsk Railway, Krasnoyarsk, Russia, office@dcv.ru.
Khromov, Igor Yu. – Business Analyst of LLC2050-Integrator, Moscow, Russia, KhromovIYu@yandex.ru.

Article received 13.05.2020, accepted 23.10.2020.

For the original Russian text of the article please see p. 62.

1. Experience in monitoring technical condition based on MPCS data

At present, *methods* for diagnosing the technical condition of locomotives based on the data of on-board microprocessor-based control systems (MPCS) are being widely developed [1]. The greatest experience has been accumulated by General Electric Company, whose situational centre of the diesel locomotive manufacturing facility in Erie (USA) monitors online the technical condition of more than 15 thousand sections of diesel locomotives based on data transmitted automatically from on-board locomotive MPCS using the Bright Star system [1; 2]. Siemens, Alstom, Bombardier companies have similar experience [1].

Interesting expertise has been accumulated by the Russian domestic railways sector [1; 3; 4]. For example, LokoTech group of companies has created diagnostics groups in locomotive maintenance depots (LMD), which, when a locomotive enters the depot, read information from on-board MPCSs using portable flash drives and decode it on stationary computers using special software at automated workplaces AWP MPCS. The information is used both for monitoring the operating modes of locomotives [5] and for planning the volume of maintenance and repairs works when a locomotive enters LMD [6]. Similarly, NEVZ electric locomotive plant (Novocherkassk), KZ (Kolomensky Zavod) and BMZ (Bryansk engineering plant) diesel locomotive plants of TransMashHolding Group [7] monitor locomotives under the warranty. A similar experience has been accumulated by Ural Locomotives Company [8] together with NPO [Research and Production Society] SAUT and Transinfo-Project [9].

Extensive experience in technical maintenance and repair (TMR) of electronic and microprocessor equipment using data from on-board MPCS has been accumulated in the Railroad Centre of Technology Implementation of Krasnoyarsk Railway, where a unique TMR model was developed [10], which was awarded by JSC Russian Railways in 2019 as the best system in the field of locomotive reliability management.

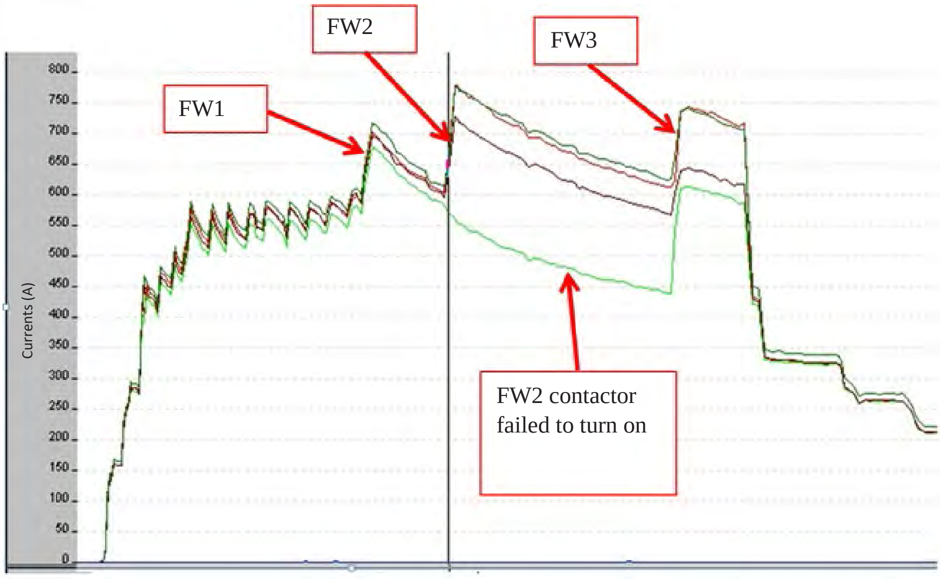
All existing monitoring systems identify failures that have occurred, localize the possible place of their occurrence [11; 12]. But pre-failure technical conditions are also of greater interest for conducting TMR of locomotives. According to GOST [State Standard] 27.002-2015 [12], they are defined as «The state of an object characterized by an increased risk of failure». In fact, this is one of the types of forecasting the residual resource according to GOST 20911-89 [11] (or the resource of the limiting state according to GOST 57445-2017). For convenience of event registration, the authors additionally suggest the term «pre-failure» as the operable state of the examined object while there is a defect or damage (defined according to GOST 20911-89).

For example, when the insulation resistance decreases, a defect occurs that increases the risk of failure, but the locomotive remains operational. Pic. 1 shows the graphs of changes in the currents of traction electric motors (TEM) of an electric locomotive of VL80S series according to the data of automatic driving system (uniform system of train automatic driving, USTAD/USAVP) [3]. When the second phase of field-weakening (FW2) was turned on, the contactor of a TEM did not work, as a result, current of a TEM did not increase that resulted in a failure. In addition, at the second (FW2) and third (FW3) phases of field-weakening, an unacceptably large spread of TEM currents was observed, so it was a pre-failure. The locomotive is operational (no observations), but repair of FW2 field-weakening contactor and adjustment of field-weakening resistors to equalize TEM currents in parallel circuits are required.

When examining, analytical and logical (parametric) methods are often used which can indicate that parameters go beyond tolerances or the corresponding trend, that there is a violation of the logic of operation. At the same time, intelligent mathematical methods of diagnostics are developing, mainly based on statistics (data mining) [2; 16]. For example, a method is used to identify pre-failure conditions in the single-type locomotive equipment (TEM, cylinder covers, etc.) according to the correlation coefficient [13]. Monitoring data are used in the technological process of TMR of locomotives [14].

Thus, monitoring the technical condition of locomotives according to data of on-board MPCS is currently an operating technology of the locomotive TMR system.

The main problem of monitoring based on MPCS data is the limited set of sensors in locomotive circuits. Their growth in their



Pic. 1. An example of detection of a failure and a pre-failure according to MPCS data [3].

Table 1

Energy consumption data from USTAD report

Series	No.	Section	Date and time of dispatch	No. of a meter	Active energy of traction current, kW • h	Active energy of recuperation current, kW • h	Reactive energy of traction current, kVAr • h	Reactive energy of recuperation current, kVAr • h
VL80R	1769	A	31.08.2019 11:40:02	0	4132097	4751613	3951915	4856641
VL80R	1769	A	31.08.2019 11:45:02	0	4132100	4751613	3951925	4856641
VL80R	1769	A	31.08.2019 11:50:02	0	4132103	4751613	3951936	4856641
VL80R	1769	A	31.08.2019 11:55:02	0	4132105	4751613	3951945	4856641
VL80R	1769	A	31.08.2019 12:00:02	0	4132108	4751613	3951956	4856641
VL80R	1769	A	31.08.2019 12:05:02	0	4132110	4751613	3951969	4856641
VL80R	1769	A	31.08.2019 12:10:02	0	4132217	4751613	3952062	4856641

number increases the diagnostic information content but decreases reliability and increases the cost of the locomotive and its life cycle. It is desirable to have integrated indicators of the technical condition of the locomotive.

Along with monitoring the technical condition of locomotives and their operating modes, remote methods of monitoring traction fuel and electricity consumption are actively being developed, which creates additional prerequisites for monitoring the technical condition of locomotives. For example, the fuel accounting system «Bort» for diesel locomotives developed by Research Institute of Railway Technology, Control and Diagnostics [15] makes it possible to monitor the technical condition of the locomotive using both logical analysis of the controlled technical parameters (the number of revolutions of the diesel engine shaft, power at each position of the driver's

Table 2

Calculation of energy consumption according to meter readings

Date and hour of the event	Calculated energy consumption, kVAr • h					
	VL80R No. 1793A			VL80R No. 1854B		
	Wa_1	Wr_1	Km_1	Wa_3	Wr_3	Km_3
19.07.2020 11:00	1694,0	1466,0	0,756	1288,0	1048,0	0,775
19.07.2020 15:00	2660,0	2041,0	0,793	2666,0	2067,0	0,790
19.07.2020 19:00	2939,0	2275,0	0,790	2943,0	2315,0	0,786
19.07.2020 23:00	588,0	488,0	0,769	634,0	523,0	0,771
20.07.2020 00:00	922,0	1201,0	0,608	939,0	1238,0	0,604
20.07.2020 04:00	1014,0	1237,0	0,634	1015,0	1230,0	0,636
20.07.2020 08:00	2928,0	2308,0	0,785	2961,0	2346,0	0,784

controller, pressure, temperature, etc.), and fuel consumption rates: if, at a diesel fuel consumption standard rate of 205 g/kW • h, a consumption of 250 g/kW • h is observed, then there is a high probability of a pre-failure of a locomotive's diesel generator set [16].

At present, electric locomotives are using modern electronic electricity meters of SEPPT type with ASIM radio online transmission to a stationary system produced by AVP Technology company [17]. In this case, the accuracy class of SEPPT in the traction mode for active energy is of 0,2 and for reactive power is of 0,5. The meter readings are transmitted to the information systems of JSC Russian Railways (approximately every four minutes). The data is reliable and available, for example, in the form of USTAD reports (Table 1).

The costs of creating an automated electricity metering system, according to the plans of JSC Russian Railways, should be recompensed through further energy savings. At the same time, an additional opportunity appears for a comprehensive assessment of the technical condition of locomotives. The Railroad Centre of Technology Implementation of Krasnoyarsk Railway of Krasnoyarsk railway has made the analysis of possibilities of monitoring the technical condition of electric locomotives by dynamics of traction electricity consumption.

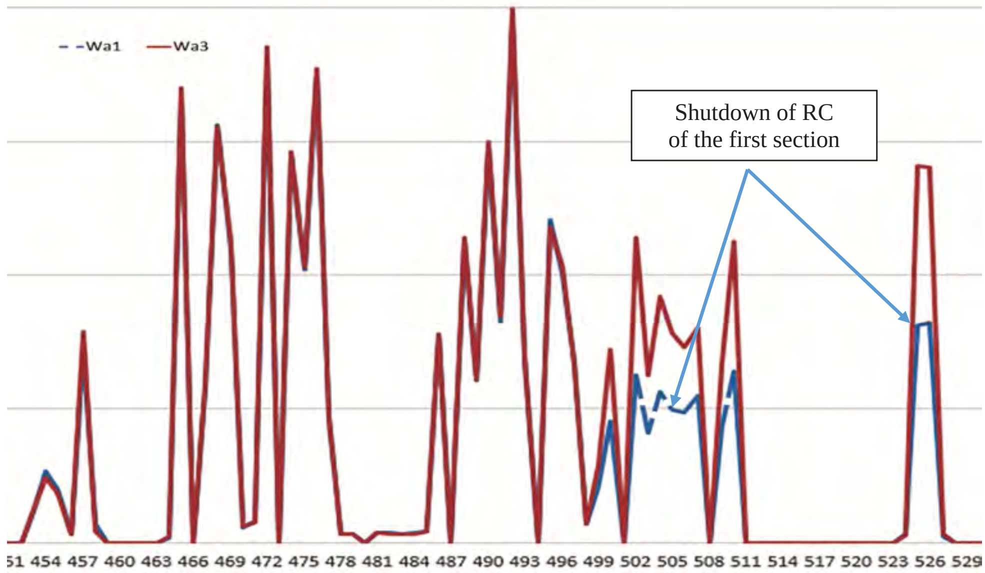
Thus, automated energy metering systems provide additional opportunities for monitoring the technical condition of locomotives.

The *objective* of the study is to increase efficiency of monitoring the technical condition of AC electric locomotives with reversible converters by diagnosing their total serviceability based on the data from electronic electricity meters transmitting data online.

2. Research methodology

Most of domestic AC electric locomotives manufactured by the Novocherkassk Electric Locomotive Plant (TransMashHolding Group) have a DC drive controlled through reversible (rectifying and inverting) converters (RC) [18; 19], which allow smooth control of traction and recuperation modes. Electric locomotives with RC (VL80R, VL85, EP1, ES5K) are more reliable than most other locomotives, while possessing effective traction characteristics [20], therefore they are operated in harsh conditions of the Eastern range of JSC Russian Railways [21–23]. The low power factor associated with a large volume of reactive energy [24; 25] should be noted as a significant drawback of their power circuit.

The Railroad Centre of Technology Implementation of Krasnoyarsk Railway of Krasnoyarsk railway has developed a methodology and corresponding software for monitoring electric locomotives with RC [26]: based on dynamic data on consumption of traction active and reactive energy (Table 1), the technical condition of the locomotive is analysed. The software was developed with the algorithmic language Visual BASIC for Applications (VBA), embedded in MS Excel [27], using probabilistic and statistical methods of analysis [28]. To avoid the influence of operating conditions of the locomotive on the results of the analysis of effectiveness of modernization, it is proposed to upgrade one section of the electric locomotive, comparing the parameters of its operation with the second non-modernized section operating in exactly the same conditions (mileage, train weight, profile, climatic and weather conditions, etc.). In addition to efficiency of modernization, the technical



Pic. 2. Dynamics of change in consumption of active energy by two sections of electric locomotives (compiled by the authors).

condition of the sections can also be monitored by comparing them with each other.

At the start of the program, the readings of the electronic meters of each section (Table 1) are converted into data on energy consumption (Table 2) according to the specified range and the summation interval.

The consumption of active and reactive energy is calculated based on the difference between the meter readings of each section of the electric locomotive for adjacent periods (Table 1). Apparent electricity W_i and power factor K_{M_i} for period i are calculated based on active W_{a_i} and reactive W_{r_i} energy:

$$W_i = \sqrt{W_{a_i}^2 + W_{r_i}^2}; \quad (1)$$

$$K_{M_i} = \frac{W_{a_i}}{\sqrt{W_{a_i}^2 + W_{r_i}^2}} = \frac{W_{a_i}}{W_i}. \quad (2)$$

To eliminate errors due to asynchronous data flow from each section and to increase the measurement accuracy, the data W_i coming from the locomotive meters are grouped by summing them:

$$W = \sum_{i=1}^{n} W_i, \quad (3)$$

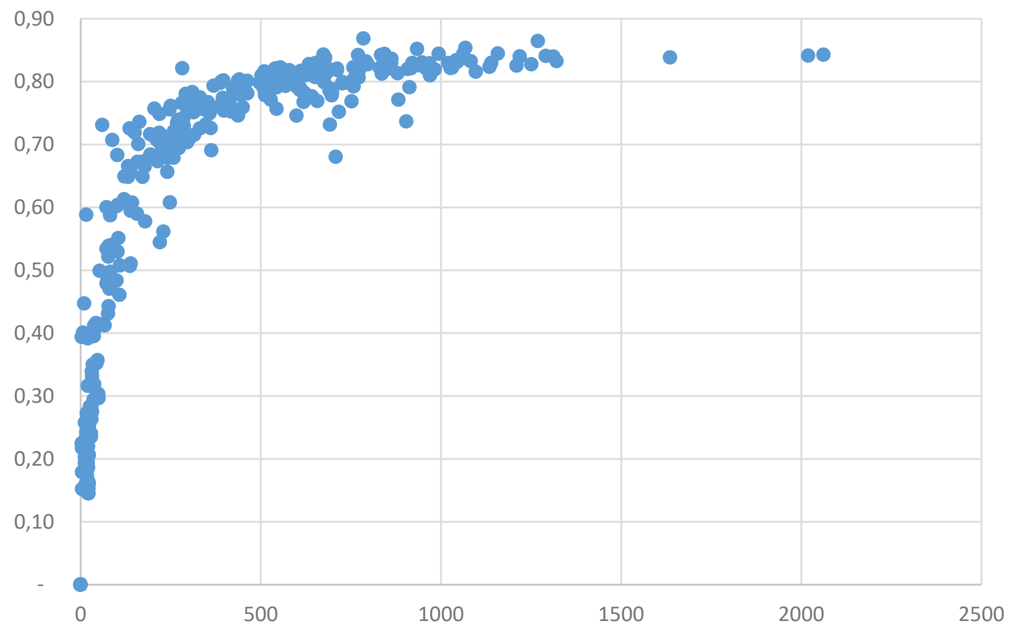
where n – number of received data for the selected time period, a divisible of an hour.

As a result, dynamic graphs of energy consumption are built. Pic. 2 shows the data for VL80R-1793A/1854B electric locomotive, according to which the shutdown of a RC of the second section was recorded with subsequent restoration of its operability: according to dynamic diagrams, it is possible to evaluate the technical condition of the locomotive online.

Pic. 3 shows the dependence of the power factor K_m on the current power W (Table 2) as the power consumption per hour. When power consumption is less than 200 kW • h (in fact, the power calculated from the power consumption), the power factor value has the character of white noise (due to the commensurate influence of auxiliary machines on the power consumption). Therefore, for analysis, data on low power (Pic. 2) is proposed not to be taken into consideration: the program converts the original table (Table 2) into a similar one, but with filtered data.

The program sequentially for both sections calculates and visualizes the mathematical expectation (MA) of parameters, their standard deviation σA, the coefficient of variation kVA, the minimum and maximum values of the parameter found in the sample [28].

An important property of a statistical sample, which confirms reliability of the initial data and correctness of the study, is unimodality. According to the law of large numbers [28], any distribution tends to normal, if there are no dominant influences. If two independent processes are involved in the sample, then distribution will be bimodal and even multimodal, for example, if locomotives of different series, different polygons, in different seasons, etc. are used in the same



Pic. 3. Point diagram of the dependence of power factor on consumed energy (compiled by the authors).

sample. As a result, conclusions may be drawn based on incorrect data. It is proposed to check unimodality of data through probability of correspondence of the data distribution *P* to one of the distribution laws of a random variable using the Kolmogorov—Smirnov test [28] with filtering the initial data according to three-sigma rule: initial data outside the range $M_A \pm 3 \cdot \sigma_A$ is rejected.

The program, according to the constant set in it, divides the total range from the minimum to the maximum value into 12 subranges, as optimal according to the results of preliminary studies. Then the number of data got in each range i is calculated. The difference λ between the intensities of getting into the range is calculated: theoretical R_{T_i} and actual R_{f_i} ones.

The maximum detected difference is taken:

$$R_{Ti} = V_{T_i} / V_T; \quad (4)$$

$$R_{f_i} = V_i / V; \quad (5)$$

$$\lambda = Max(|R_{T_i} - R_{f_i}|), \quad (6)$$

where *V* is volume of statistical sample;

V_T is volume of theoretical sample;

V_{T_i} — volume of calculated cases of getting in the range *i*:

$$V_{T_i} = V_T \cdot (1/(\sigma \cdot \sqrt{2 \cdot \pi})) \cdot \int_{d1}^{d2} e^{-\frac{(x_i - M_a)^2}{2 \cdot \sigma^2}}. \quad (7)$$

Note: integration action is implemented as summation of the areas of rectangles with ranges ($x_2 - k_1$).

Kolmogorov—Smirnov criterion *D* for normal distribution of a random variable is calculated as:

$$D = \lambda \cdot (\sqrt{V} - 0{,}001 + 0{,}85 / \sqrt{V}). \quad (8)$$

The probability of compliance with the distribution law *P* and the probability of reliable differences in the characteristics of two sections are determined from the table by the value *D*.

The calculation of λ is made according to the intensity of the first R_{1_i} and second R_{2_i} sections getting in the range *i*:

$$\lambda = Max(|R_{1_i} - R_{2_i}|). \quad (9)$$

When comparing two sections the calculation of *D* is made according to the formula:

$$D = \lambda \cdot \sqrt{V} + 1/(6 \cdot \sqrt{V_i}). \quad (10)$$

Testing the program and calculating test cases made it possible to automate the calculations as much as possible, while minimizing the probability of errors in calculations. Thus, a method for studying the energy efficiency and technical condition of domestic AC electric locomotives with RC has been developed, which has the following advantages:

• linking to the existing automated information sources of JSC Russian Railways on traction electricity consumption.

• automatic calculation of statistical indicators for a large amount of initial data (up to 2800 days).

• visualization of calculation results.

Table 3

General results of the analysis

Parameters 1793A/1854B	Pairs of sections of a locomotive under study				
	1793A/1854B	1769A/1776A	1764A/1764B	1764A/1784B	1791A/1791B
Difference W_a, %	-0,4 %	-7,1 %	6,9 %	8,6 %	0,2 %
Difference W_r, %	-0,2 %	-16,3 %	-4,4 %	-10,0 %	-6,9 %
Difference W_Σ, %	-0,3 %	-11,4	1,0 %	-0,9 %	-3,5 %
Difference K_m, %	-0,1 %	4,9 %	5,8 %	9,6 %	3,8 %
Unimodality maximum, %	59 %	88 %	51 %	61 %	45 %
Validity of differences by W_a, %	0,001 %	5 %	2 %	6 %	0,001 %
Validity of differences by W_r, %	0,55 %	81 %	93 %	84 %	52 %
Validity of differences by W_Σ, %	0,001 %	41 %	0,001 %	0,3 %	0,7 %
Validity of differences by K_m, %	20,8 %	99,7 %	99 %	97 %	95,8 %
Factor of parameters' correlation					
W_{a1}/W_{a2}	0,984	0,998	0,967	0,987	0,992
W_{r1}/W_{r2}	0,986	0,959	0,951	0,982	0,987
K_{m1}/K_{m2}	0,985	0,924	0,981	0,985	0,989
W_{a1}/W_{r1}	0,937	0,941	0,915	0,934	0,949
W_{a2}/W_{r2}	0,947	0,986	0,934	0,954	0,962

Note: the sign in the «difference» lines regarding W_a, W_r, W_Σ, K_m shows the direction of differences of the second section in relation to the first one.

• simple and visual adaptation of the program in VBA environment [26] for the peculiarities of the tasks being solved.

Thus, the developed methodology and software make it possible to perform a scientific and technical analysis of the possibility of monitoring the technical condition of AC electric locomotives with RC based on data on consumption of traction active and reactive energy.

3. Results of monitoring of the technical condition of sections

The Railroad Centre of Technology Implementation of Krasnoyarsk Railway of Krasnoyarsk railway according to USTAD reports [17] using the developed methodology and software [26], conducted the analysis of energy consumption by electric locomotives of VL80R series [21] (including three-section version): 1793A/1854B, 1769A/1776A, 1764A/1764B, 1764A/1784B, 1791A/1791B. Table 3 shows the main research results based on data for four months of 2019 (on average 36 thousand rows (see Table 1) of the initial data).

The main results of the analysis are as follows:

1. The initial data has a high degree of unimodality, which is determined by uniformity of operating conditions (profile, train weight, weather conditions, etc.) at the Eastern range of JSC Russian Railways.

2. Only one of five locomotives (VL80R-1793A/1854B) can be considered technically sound (without signs of pre-failures) since the spread of electricity consumption does not exceed 0,4 %. The rest of the locomotives obviously have problems with their technical condition; there are pre-failures.

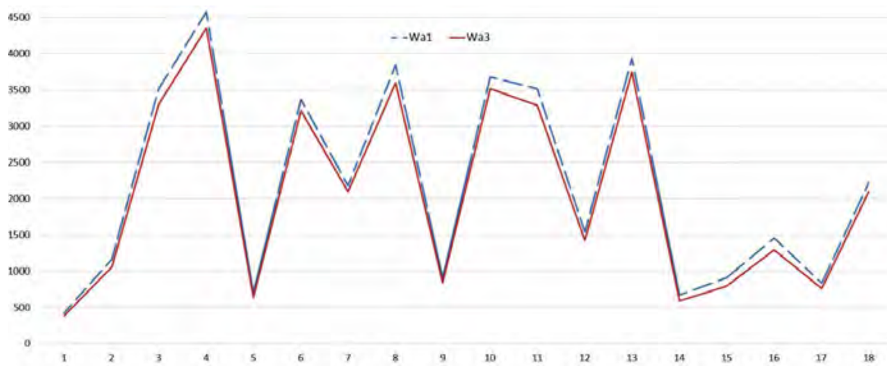
3. «Reliability of differences in power factor K_m», determined by Kolmogorov–Smirnov criterion turned out to be the most sensitive parameter. Even for VL80R-1793A/1854B, with a minimum scattering of parameter values, «Significance of differences in power factor K_m» was 20,8 %. For the rest of the locomotives, it was above 95 %.

4. The parameter «Differences in total energy W_Σ» turned out to be the least sensitive parameter which is caused by multi-directional character of differences in active and reactive energy.

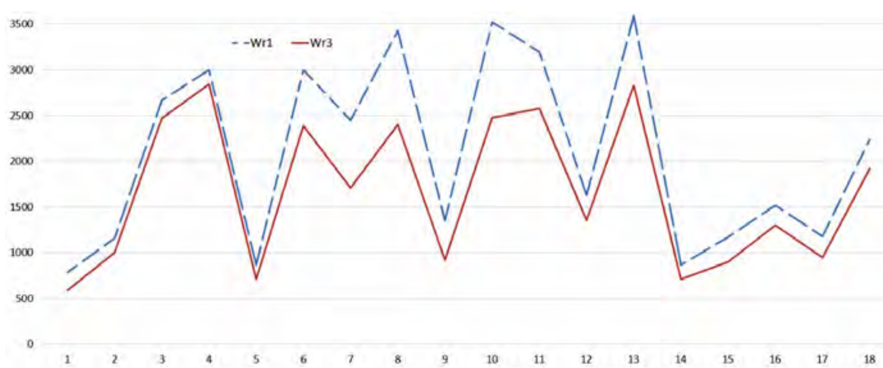
5. The correlation factor reflects the visually obvious difference in the dynamic graphs of the parameters of two sections.

Thus, monitoring the technical condition of AC electric locomotives is possible based on data on consumption of active energy and generation of reactive energy.

a – power factor



b – active energy



c – reactive energy

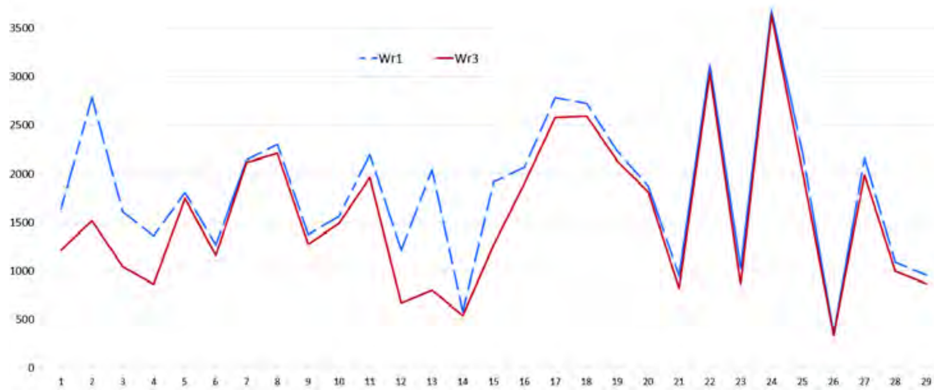
Pic. 4. Dynamics of changes in parameters of sections VL80R-1769A (1) and VL80R-1776A (3) (compiled by the authors).

Pic. 2 of the previous section shows a dynamic diagram of a serviceable electric locomotive VL80R-1793/1854B (Table 3): there is an almost complete coincidence of the graphs of electricity consumption of the first and second sections (except for the period of shutdown of one RC in section VL80R1793A). In this case, it is possible to diagnose a short-term disconnection of one RC. The deviation of the characteristics of the sections from each other regarding other locomotives indicates the presence of equipment pre-failures: for VL80R-1769/1776A locomotive (Pic. 4), there is a scatter in the power factor and reactive power, which is confirmed by the low correlation factor between the parameters (0,959 and 0,924). The spread in active power rates is low, which is confirmed by a high correlation factor (0,998). Similar patterns are observed for VL80R-1791 electric locomotive (Pic. 5).

Thus, the presence of pre-failures can be diagnosed by the correlation factor of the same-type parameters of two sections $r < 0,99$.

a – power factor

b – active energy



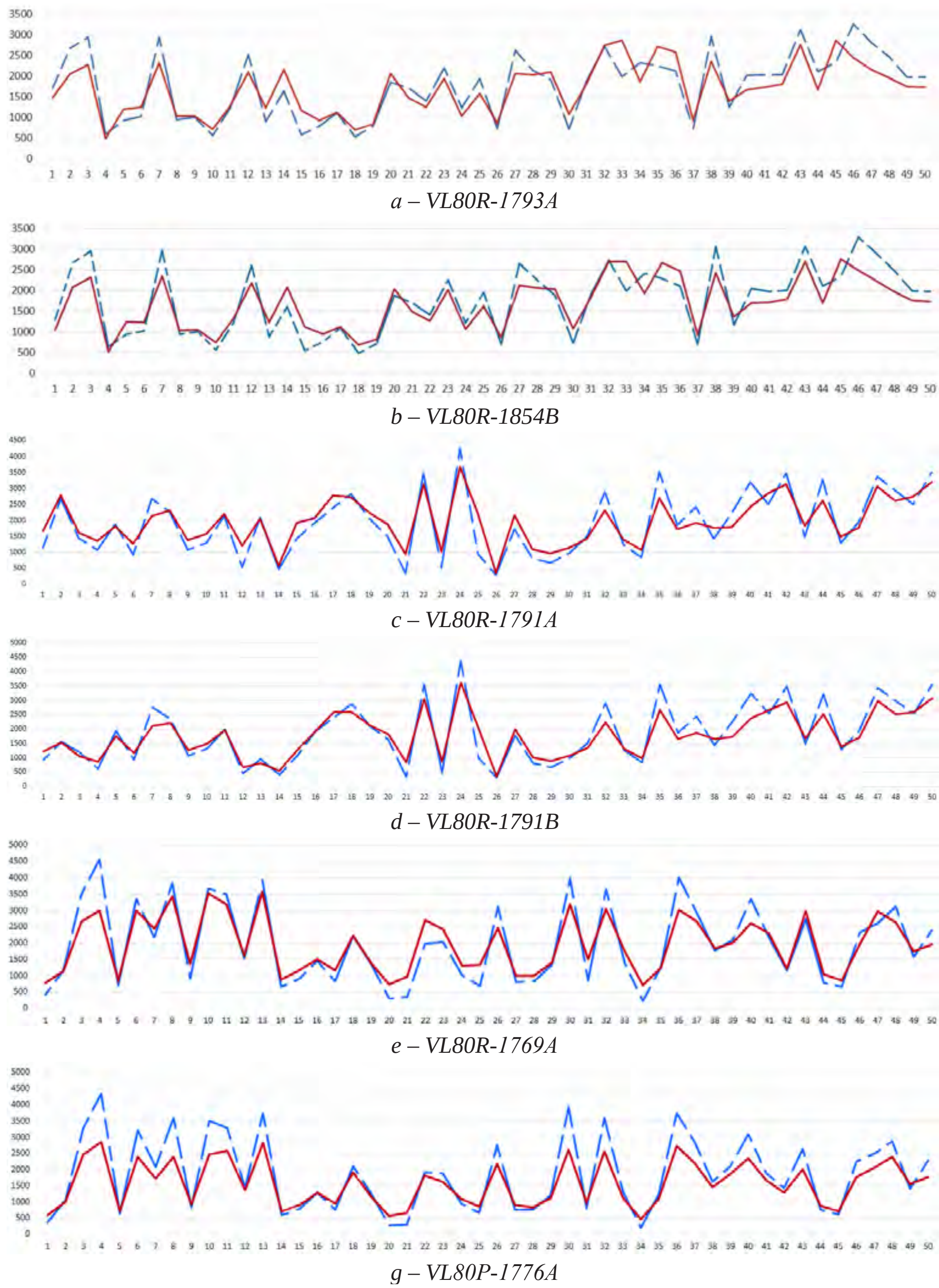
c – reactive energy

Pic. 5. Dynamics of changes in parameters of sections VL80R-1791A (1) and VL80R-1791B (3) (compiled by the authors).

Pic. 6 shows a comparison of consumption of active W_a and reactive W_r power by two serviceable sections of one locomotive (Pics. 6a and 6b) and by the sections with pre-failures (6c, 6d, 6e, 6f). For a serviceable locomotive, the change in active W_a and reactive W_r power in both sections occurs synchronously. Others lack synchronicity. All sections have a change in the power ratio: $W_a > W_r$, $W_a < W_r$, but for sections with pre-failure this does not always happen synchronously.

4. Diagnostics by active and reactive power

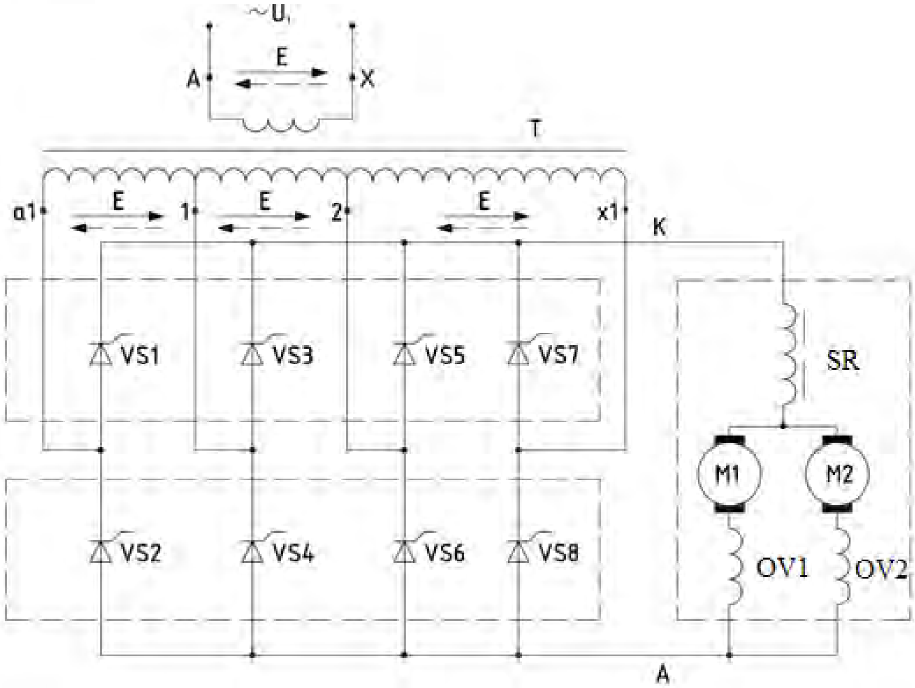
AC electric locomotives with reversible converters have a typical electrical circuit (Pic. 7) [18–24]: the primary winding of the power transformer of the electric locomotive U_1 = 25 kV feeds two groups of secondary windings (only one group is shown in Pic. 7) with a voltage of 300 V, 300 V, 600 V,



Pic. 6. Dynamics of changes in active and reactive power of the section (blue dotted line – W_a, red continuous line – W_r) (compiled by the authors).

which is fed to the input of the RC (VS_1–VS_8). A smoothing reactor SR and two parallel operating DC traction electric motors with sequential excitation M1, M2 are connected to the output of RC. All RC at VL80R receive control signals for opening thyristors from a single control unit, implementing control algorithm according to Pic. 8.

The presence of reactive power is due to the presence of inductive loads in the electric locomotive circuit [29]: it is a power transformer, a smoothing reactor and the traction motors themselves (Pic. 7). Additionally, a thyristor control, which allows controlling the rectified voltage only «on the left» – for opening, produces the current delay from the voltage

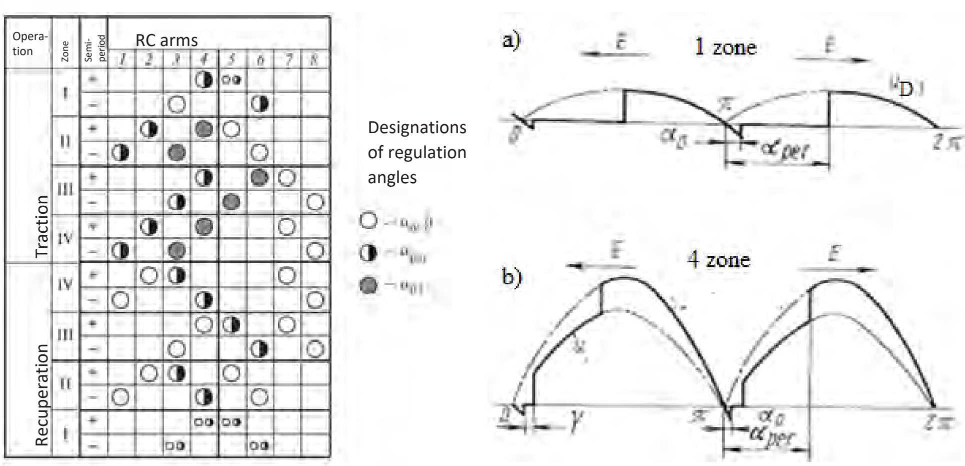


Pic. 7. Principal power circuit scheme of an electric locomotive VL80R [20–24].

(Pic. 8) [24]. Therefore, for AC electric locomotives with RC, the rated power factor is lower and is $K_m = 0,84$ [19]. In the studies performed for a serviceable locomotive, the mathematical expectation is $K_m = 0,69$ at $\sigma = 10$ and unimodality is of 3 %. The maximum value did not exceed $K_m \leq 0,83$.

Traction electric motors (TEM) can give maximum spread, but permissible dispersion of their characteristics does not exceed 3 %. For smoothing reactors, even if there is a slight scattering, it introduces a constant error.

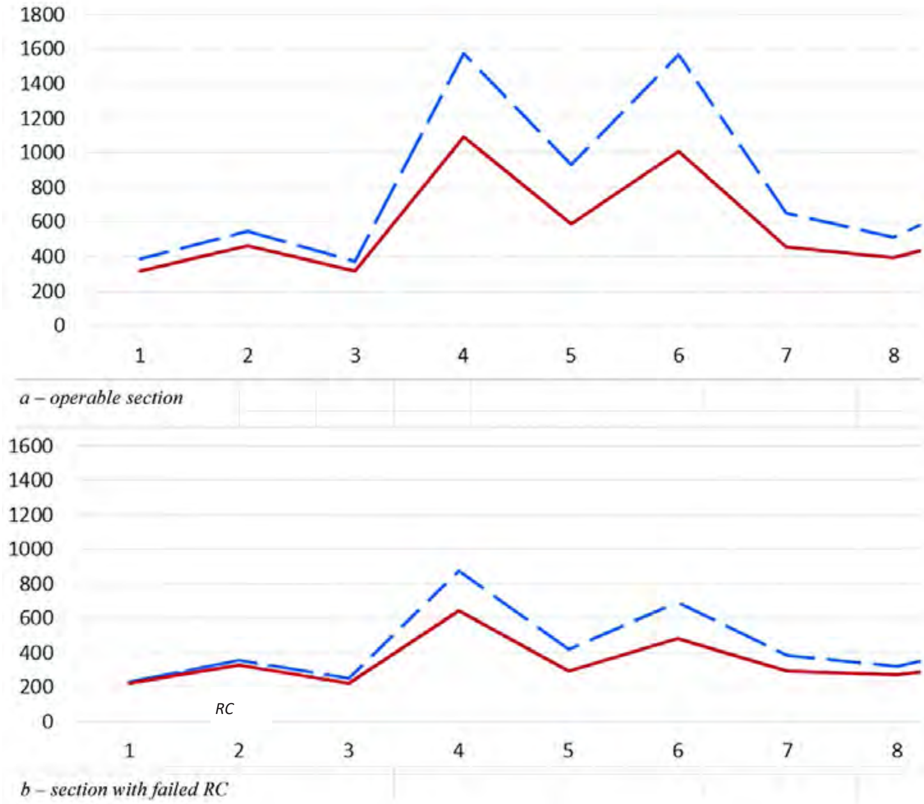
Thus, it follows from the structure of the locomotive and the design of its control system that theoretically there should not be a significant dispersion in consumption of active and reactive energy for two serviceable sections of one locomotive.



a – RC control algorithm

b – RC voltage diagram

Pic. 8. Four-zone control of RC of an electric locomotive VL80R [20–24].



Pic. 9. Active (dotted line, above) and reactive (direct line, below) components of energy of a locomotive of an operable section and section with failed RC (compiled by the authors).

There can be two reasons for changing the ratio of active and reactive power: a disproportionate change in active power and/or a disproportionate change in reactive power.

The reactive power of the locomotive takes place, first, due to the thyristor control circuit, when the opening of RC (in fact, of the rectifier bridge) occurs according to the control pulse 9° < αREG < 156°. Thus, the delay of the current from the voltage always occurs (Pic. 8b).

An additional delay of the current from the voltage is due to the thyristor switching time γ (Pic.8b), the duration of which depends on the value of the inductive load: of a smoothing reactor and two traction motors (TEM). With the same control position, a disproportionate change in the load can only be due to a change in the parameters of the traction motor, including due to disconnection. TEM has a constant inductance L_{TEM}, which is determined by its design and the variable inductance is due to the phenomena of self-induction and mutual induction [29–31].

Pic. 3 shows an example of detecting an emergency shutdown of a part of the power circuit of an electric locomotive section, which leads to a significant reduction in the section's energy consumption: when one TEM is disconnected, traction power consumption will fall by 25 %, for one RC – by 50 %. However, with proper operation of auxiliary machines (fan motors and compressors), which consume up to 20 % of the total power consumption, the drop will be approximately by 21 % and 42 %. In the example shown in Pic. 3 the drop was of 41–45 %. In this case, the ratio of active and reactive energies did not change (Pic. 9).

The main reason for change in current of one section (except for disconnecting a section, RC or TEM) is skidding of one or several wheelsets, which, with a constant voltage on the traction motor U_{TEM} = const, is accompanied by an increase in the electromotive force E (emf) and a drop in TEM current I_{TEM} [30]:

$$U_{TEM} = I_{TEM} \cdot r_{TEM} + E = I_{TEM} \cdot r_{TEM} + C \cdot n_{TEM} \cdot F_{TEM}, \quad (11)$$

where r_{TEM} – TEM resistance;

n_{TEM} – TEM speed of rotation;
F_{TEM} – magnetic flux of TEM;
C – constant.

Increased skidding occurs near the first (in the direction of travel) wheel-motor unit (WMU), near WMU with a violation of the locomotive hanging, at WMU with a smaller diameter of the tire of the wheelset D_{ws}, because with equal torque of the manual gearbox wheel set M_{KP}, the traction force F_T will be increased:

$$M_{KP} = F_т \cdot D_{ws}/2. \quad (12)$$

When skidding, the current falls, and consequently power consumption also falls. With a constant resistance and inductance of the circuit, the active and reactive power should decrease proportionally. However, this is not the case: when skidding, the inductive resistance ωL of a skidding TEM increases:

$$\omega L = (\omega_1 L_1 \cdot \omega_2 L_2)/(\omega_1 L_1 + \omega_2 L_2), \quad (13)$$

where $\omega_1 L_1$, $\omega_2 L_2$ – inductive resistance of the first and the second TEM; $\omega = 2 \cdot \pi \cdot f$; f – frequency of signal change.

Within the limit $f \to \infty$, the inductive resistance of two traction motors will double.

Thus, during skidding, power consumption decreases with an increase in the share of reactive power and a decrease in the power factor of the locomotive section. Thus, lower power consumption with decreasing power factor may be an indication of increased skidding.

Pic. 1 shows that when current is weakened, significant spreads of TEM currents can occur. A traction electric motor with a lower current will have less inductive resistance, which should also affect the laws of active and reactive power.

Thus, all the main types of faults in the power circuits of an electric locomotive with RC affect the nature of consumption of active and reactive energy.

5. Conclusion

1. To increase the efficiency of monitoring the technical condition of AC electric locomotives with reversible converters, a method for diagnosing their serviceability according to the data of electronic electricity meters transmitting data online is proposed.

2. The performed studies have shown that dynamic data on consumption of active and reactive energy, automatically collected online from domestic AC locomotives with reversible converters, can be used to diagnose the technical condition of a locomotive within the system of their monitoring. The method is based on comparison of the dynamics of consumption of active and reactive energy of two sections of a single locomotive according to the principle of functional benchmarking.

3. When monitoring the technical condition of locomotives, the term «pre-failure» can be used, which is defined as the operable condition of a locomotive when there are internal hidden defects or damage. Pre-failure is manifested in the consumption of electricity; the defect that caused it should be determined when the locomotive undergoes TMR.

4. The parameter «Significance of differences in power factor K_m», determined using Kolmogorov-Smirnov criterion, is the most sensitive to pre-failure. The parameter «Significance of differences in total energy» turned out to be the least sensitive to pre-failure.

5. In further studies, the authors intend to reveal regularities (functional relationships) will be established between the manifestations of pre-failure states according to the data on consumption of active and reactive components of energy and the faults that have arisen in the circuits of AC electric locomotive with RC.

REFERENCES

1. Monitoring of the technical condition and operating modes of locomotives. Theory and Practice [*Monitoring tekhnicheskogo sostoyaniya i rezhimov ekspluatatsii lokomotivov. Teoriya i praktika*]. Ed. by I. K. Lakin. Moscow, LLC Locomotive Technologies, 2015, 212 p.

2. Hedlund, E. H., Roddy, N. E., Gibson, D. R., Bliley, R. G., Pander, J. E., Puri, A., O'Camb, T. E., Lovelace, J. H., Steven, L. Apparatus and Method for Performance and Fault Data Analysis. US Patent 6,651,034 B1, 2003; US Patent 7,013,239 B2, 2006. Assignee: General Electric Company.

3. Lakin, I. I. Monitoring of the technical condition of locomotives according to the data of onboard hardware and software complexes. Ph.D. (Eng) thesis [*Monitoring tekhnicheskogo sostoyaniya lokomotivov po dannym bortovykh apparatno-programmnykh kompleksov. Dis... kand. tekh. nauk*]. Moscow, MIIT publ., 2016, 211 p. [Electronic resource]: https://www.miit.ru/content/%D0%94%D0%B8%D1%81%D1%81%D0%B5%D1%80%D1%82%D0%B0%D1%86%D0%B8%D1%8F.pdf?id_wm=756728. Last accessed 13.05.2020.

4. Abolmasov, A. A. Management of the technical state of traction rolling stock in the conditions of service. Ph.D. (Eng) thesis [*Upravlenie tekhnicheskim sostoyaniem tyagovogo podvizhnogo sostava. Dis... kand. tekh. nauk*]. Moscow, MIIT publ., 2017, 180 p. [Electronic resource]: https://docplayer.ru/49152812-Abolmasov-aleksey-aleksandrovich-upravlenie-tehnicheskim-sostoyaniem-tyagovogo-podvizhnogo-sostava-v-usloviyah-servisnogo-obsluzhivaniya.html. Last accessed 13.05.2020.

5. Pustovoy, V. N., Lyangasov, S. L., Lakin, I. K. Monitoring of violations of operating modes of locomotives according to MPCS data [*Monitoring narushenii rezhimov*

ekspluatatsii lokomotivov po dannym MSU]. *Transport infrastructure of the Siberian region: materials of the sixth international scientific and practical conference*. Irkutsk, 2015, pp. 354–358.

6. Pustovoy, I. V. Development of an information-dynamic model of service maintenance. Ph.D. (Eng) thesis [*Razrabotka informatsionno-dinamicheskoi modeli upravleniya servisnym tekhnicheskim obsluzhivaniem. Dis... kand. tekh. nauk*]. Omsk, OmGUPS publ., 2019, 181 p. [Electronic resource]: https://www.usurt.ru/uploads/main/065/5b97add2b36f8/%D0%94%D0%B8%D1%81%D1%81%D0%B5%D1%80%D1%82%D0%B0%D1%86%D0%B8%D1%8F_%D0%9F%D1%83%D1%81%D1%82%D0%BE%D0%B2%D0%BE%D0%B3%D0%BE_%D0%98%D0%BB%D1%8C%D0%B8_%D0%92%D0%BB%D0%B0%D0%B4%D0%B8%D0%BC%D0%B8%D1%80%D0%BE%D0%B2%D0%B8%D1%87%D0%B0.pdf. Last accessed 13.05.2020.

7. Official site of JSC TransMashHolding. Section «Enterprises». [Electronic resource]: https://www.tmholding.ru/about_us/enterprises/. Last accessed 13.05.2020.

8. Official website of LLC Ural locomotives. Section «Products». [Electronic resource]: http://ulkm.ru/produkciya/. Last accessed 13.05.2020.

9. Golovin, V. I., Nagovitsyn, V. S. ACS with safety function for electric locomotive 2ES6 [*ASU s funktsiei bezopasnosti dlya elektrovoza 2ES6*]. Website SCBIST, 2018, Iss. 4. [Electronic resource]: http://scbist.com/. Last accessed 13.05.2020.

10. Semchenko, V. V., Lakin, I. K., Chmilev, I. E. Operation and maintenance of electronic control systems for alternating current electric locomotives [*Ekspluatatsiya i tekhnicheskoe obsluzhivanie elektronnykh system upravleniya elektrovozov peremennogo toka*]. Krasnoyarsk, Publishing house of the road implementation center of Krasnoyarsk railway, 2010, 72 p.

11. GOST [State standard] 20911-89. Technical diagnostics. Terms and Definitions. [Electronic resource]: http://docs.cntd.ru/document/1200009481. Last accessed 13.05.2020.

12. GOST [State standard] 27.002-2015. Reliability in technology (SSNT). Terms and Definitions. [Electronic resource]: http://docs.cntd.ru/document/1200136419. Last accessed 13.05.2020.

13. Lipa, K. V., Grinenko, V. I., Lyangasov, S. L., Lakin, I. K., Abolmasov, A. A. [*et al*]. Method of technical diagnostics of locomotive equipment and a device for its implementation. Patent (invention), dated July 21, 2017, No. 2626168 [*Sposob tekhnicheskogo diagnostirovaniya oborudovaniya lokomotiva i ustroistvo dlya ego osushchestvleniya. Patent na izobretenie ot 21.07.2017* g. *№ 2626168*]. [Electronic resource]: https://yandex.ru/patents/doc/RU2626168C2_20170721. Last accessed 13.05.2020.

14. Lipa, K. V., Grinenko, V. I., Lyangasov, S. L., Lakin, I. K., Abolmasov, A. A. [*et al*]. Method for managing maintenance and repair of railway transport and a system for its implementation. Patent (invention), dated 24.10.2013 No. 2569216 [*Sposob upravleniya obsluzhivaniem i remontom zheleznodorozhnogo transporta i Sistema dlya ego osushchestvleniya. Patent na izobretenie ot 24.10.2013* g. *№ 2569216*]. [Electronic resource]: https://yandex.ru/patents/doc/RU2569216C2_20151120. Last accessed 13.05.2020.

15. Official website of NIITKD. Section «Locomotive economy». [Electronic resource]: http://niitkd.com/locomotivnoe/ekspluatatsiya/аппаратно-программный-комплекс-борт-detail. Last accessed 13.05.2020.

16. Ovcharenko, S. M. Improving the efficiency of the system for diagnosing diesel locomotives. D.Sc. (Eng) thesis [*Povyshenie effektivnosti sistemy diagnostirovaniya teplovozov. Dis... dokt. tekh. nauk*]. Omsk, OmGUPS, 2007, 366 p.

17. Official website of the company AVP Technology. Section «Monitoring». [Electronic resource]: https://avpt.ru/projects/monitoring-i-kontrol/. Last accessed 13.05.2020.

18. Tikhmenev, B. N., Trakhtman, L. M. Rolling stock of electrified railways. Theory of the operation of electrical equipment. Electric circuits and devices [*Podvizhnoi sostav elektrifitsirovannykh zheleznykh dorog. Teoriya raboty elektrooborudovaniya. Elektricheskie skhemy i apparaty*]. Moscow, Transport publ., 1980, 471 p.

19. Kapustin, L. D., Kopanev, A. S., Lozanovsky, A. L. Features of arrangement and operation of VL80R electric locomotive [*Osobennosti ustroistva i ekspluatatsii elektrovoza VL80R*]. Moscow, Transport publ., 1979, 175 p.

20. Gorban, V. N., Donskoy, A. L., Shabalin, N. G. Electronic equipment of VL80 electric locomotive: Repair and maintenance [*Elektronnoe oborudovanie elektrovoza VL80: Remont i tekhnicheskoe obsluzhivanie*]. Moscow, Transport publ., 1984, 184 p.

21. Electric locomotive VL80R. Operation manual [*Elektrovoz VL80R. Rukovodstvo po ekspluatatsii*]. Moscow, Transport publ., 1982, 541 p.

22. Electric locomotive VL85. Operation manual [*Elektrovoz VL85. Rukovodstvo po ekspluatatsii*]. Moscow, Transport publ., 1986, 572 p.

23. Mainline electric locomotive 2ES5K (3ES5K). Manual. Book 1. Electrical circuits [*Elektrovoz magistralniy 2ESK (3ES5K). Rukovodstvo po ekspluatatsii. Kn.1. Elektricheskie skhemy*]. Novocherkassk, 2004, 248 p.

24. Kapustin, L. D., Kopanev, A. S., Lozanovsky, A. L. Reliability and efficiency of VL80R electric locomotives in operation [*Nadezhnost' i effektivnost' elektrovozov VL80R v ekspluatatsii*]. Moscow, Transport publ., 1986, 240 p.

25. Semchenko, V. V., Vlasyevsky, S. V. Device for increasing the power factor of a reversible single-phase AC converter. Utility model patent No. 192613, dated 24.09.2019 [*Ustroistvo dlya povysheniya koeffitsienta moshchnosti vypryamitelno-invertornogo preobrazovatelya odnofaznogo peremennogo toka. Patent na poleznuyu model' № 192613 ot 24.09.2019*]. [Electronic resource]: https://yandex.ru/patents/doc/RU192613U1_20190924. Last accessed 13.05.2020.

26. Certificate of state registration of the computer program No. 2020613912 Russian Federation. Energy efficiency analysis program for AC electric locomotives with reversible converters. Semchenko, V. V., Lakin, I. K., [*et al.*]; copyright holder Joint Stock Company Railroad Centre of Technology Implementation of Krasnoyarsk Railway. No. 2019665780, app. 05.12.2019, publ. 24.03.2020, 1 p.

27. Osetrova, I. S., Osipov, N. A. Microsoft Visual Basic for Application. St. Petersburg, NIU ITMO publ., 2013, 120 p.

28. Ventsel, E. S. Probability theory: Textbook [*Teoriya veroyatnosti: Uchebnik*]. 12th stereotype ed. Moscow, Yustitsiya publ., 2018, 658 p.

29. Bessonov, L. A. Theoretical foundations of electrical engineering [*Teoreticheskie osnovy elektrotekhniki*]. Moscow, Vysshaya shkola publ., 1996, 638 p.

30. Dynamic inductance [*Dinamicheskaya induktivnost'*]. [Electronic resource]: http://www.transportine.ru/inets-455-2.html. Last accessed 13.05.2020.

31. Zakharchenko, D. D., Rotanov, N. A. Traction electric machines [*Tyagovie elektricheskie mashiny*]. Moscow, Transport publ., 1991, 343 p. ●