DOI:10.32703/2617-9040-2025-46-2

UDC 621.313.333:681.518.5:629.423.2

***Olha Babicheva*[1]*, Viacheslav Shavkun*[2]**, Serhii Yesaulov*[3]**

[1]Associate Professor, Department of Electric Transport, O. M. Beketov National University of Urban Economy in Kharkiv, 17 Chornoglazivska St., Kharkiv, 61002, Ukraine. ORCID: https://orcid.org/0009-0003-1294-2740.
[2]Associate Professor, Department of Electric Transport, O. M. Beketov National University of Urban Economy in Kharkiv, 17 Chornoglazivska St., Kharkiv, 61002, Ukraine. ORCID: https://orcid.org/0009-0005-9069-7378.
[3]Associate Professor, Department of Electric Transport, O. M. Beketov National University of Urban Economy in Kharkiv, 17 Chornoglazivska St., Kharkiv, 61002, Ukraine. ORCID: https://orcid.org/0009-0006-3274-716X.

***Corresponding author:** vm.shavkun@gmail.com.

Comprehensive analysis of the sensitivity and criticality of power equipment elements of urban electric transport to operational factors based on structural-functional ranking

The article presents a comprehensive reliability analysis of the power equipment of urban electric transport, including traction electric motors, inverters, cable–terminal connections, and cooling systems. Based on a literature review, the strengths (development of non-invasive diagnostic methods, application of machine learning algorithms, and formation of combined maintenance strategies) and weaknesses (limited statistical data for urban fleets, sensitivity of algorithms to noise, insufficient integration with risk management) of current research were identified. A conceptual model of integrated reliability management is proposed, combining multi-source data collection, FMEA-lite methodology, Pareto analysis, and the development of an Action Plan. The analysis results revealed that the highest RPN values are associated with external factors (moisture, overloads) and critical components such as bearings, windings, and cable connections. A Matlab/Simulink model was developed to simulate vibration diagnostics of traction motor bearings, confirming the effectiveness of envelope analysis for early defect detection. The Action Plan implementation reduced average RPN values by 25 – 40%, proving the practical value of the methodology for transport depots. The obtained results provide a foundation for the transition to predictive maintenance and the enhancement of operational reliability in urban electric transport.

Keywords*: urban electric transport; power equipment; reliability; diagnostics; FMEA-lite; Pareto analysis; vibration monitoring; Matlab/Simulink; Action Plan; Predictive Maintenance*

Introduction and Problem Statement. The efficiency of urban electric transport operation is largely determined by the operational reliability of its power systems. This complex includes not only traction electric motors (TEMs) but also inverters, converters, cable connections, protective equipment, and cooling systems. It is their combined reliability that determines the level of technical readiness of the rolling stock, the duration of inter-repair intervals, and the safety of passenger transportation.

Under conditions of intensive operation in the urban cycle, power equipment is subjected to dynamic loads, moisture, road vibrations, contamination, and temperature fluctuations. For traction electric motors, this is manifested in bearing wear, degradation of insulation, and brush-commutator unit failures. For inverters and power electronics, it appears as breakdowns of IGBT/MOSFET switches, capacitor aging, and damage to EMI filters. For cable networks and connections, it results in local overheating and corrosion of joints. Insufficient monitoring of these elements leads to emergency shutdowns, increased downtime, and additional maintenance costs.

Current research in the field of urban electric transport diagnostics is mainly focused on individual units, primarily on traction electric motors. Methods of vibration analysis, motor current signature analysis (MCSA), thermal diagnostics, and machine learning algorithms are employed. Their advantage lies in the ability to detect defects at an early stage; however, the limitation is insufficient integration with risk management systems and the maintenance of the entire power equipment complex.

In this context, the application of systemic risk assessment methods becomes relevant, as they enable a comprehensive analysis of both traction drive units and peripheral power subsystems. Among such methods, particular importance is attached to FMEA (Failure Mode and Effects Analysis) and Pareto analysis. The combination of these approaches makes it possible not only to identify critical components and failure factors but also to outline groups of vehicles that account for the largest share of incidents under real operating conditions. This provides the foundation for developing an Action Plan–a targeted program for the maintenance and modernization of the entire power equipment complex of urban electric transport.

Literature Review. Current research in the field of urban electric transport reliability is focused on several key directions.

1. Diagnostics of traction electric motors (TEM).

A significant share of studies is devoted to bearing assemblies, which account for the largest proportion of failures. The authors of [1] demonstrated the effectiveness of modern signal processing methods for detecting faults in induction motors; however, the study did not address cable and switching elements, which also affect reliability.

Researchers in [2] confirmed the feasibility of localized analysis of spectral characteristics for different types of machines, though the study is limited to laboratory conditions without considering urban transport operating modes.

In [3], the wavelet transform was applied in combination with ensemble machine learning models, which ensured high accuracy in defect classification, although the algorithms showed sensitivity to noise factors.

Additional studies [4] have shown that deep learning algorithms provide high accuracy in defect classification; however, their effectiveness decreases significantly under noisy conditions and with changes in operating modes, which limits their practical application in transport depots.

The review [5] summarized approaches to early fault detection based on current signals; however, the influence of complex transient modes of real operation was not taken into account.

2. Reliability of inverters and power electronics.

The authors of [6] proposed a unified methodology for structural failure analysis of sensors in PMSM, which directly affects the operation of power converters; however, the emphasis was placed solely on sensors without analyzing key power components.

In [7], failures in electric vehicle drives were systematized, with particular attention given to IGBT modules and capacitors, but the specifics of urban transport were insufficiently addressed.

The researchers in [8] substantiated the feasibility of a hybrid maintenance strategy for inverter systems, although the practical implementation algorithms remain generalized.

The authors of [9] demonstrated that cyclic thermal loading is the main factor in IGBT degradation in traction converters; however, the combined influence of moisture and vibrations was not considered.

In [10], the failure mechanisms of power converters in electric transport were analyzed, but the study was limited to a qualitative description without a quantitative risk model.

3. Failures of cable connections and switching equipment.

Under conditions of moisture and dust, defects in cable lines and terminal connections are common. Domestic researchers emphasize their contribution to overall reliability. In particular, the author of [11] developed methods for monitoring the parameters of traction electric motors, but focused only on motor components. In a subsequent study [12], the same author proposed algorithmic models for reliability assessment, although these have not been integrated into depot practice.

The author of [13] highlighted the importance of selecting an electric motor with consideration of reliability and the condition of cable connections; however, the study did not account for the influence of external operating conditions.

The authors of [14] investigated cable insulation degradation in electric transport, but the study did not address long-term failure statistics in the urban cycle.

4. Cooling and thermal modes.

In [15], researchers integrated FMEA with sensitivity analysis to evaluate thermal risks, but the study was conducted mainly for railway systems.

In [16], an autoencoder model was applied to detect failures in high-speed trains, yet this approach has not been adapted for urban electric transport.

The authors of [17] summarized the challenges of thermal management in high-power traction systems, but the work is focused primarily on cooling technologies without evaluating economic aspects.

In [18], the researchers integrated FMEA with sensitivity analysis to assess thermal risks; however, the study is limited to railway systems and gives little attention to the specifics of urban transport, as well as to integration with practical risk management systems.

5. System approaches to reliability management.

The authors of [19] compared the reliability indicators of electric buses in municipal systems, but the study covers only one region and has a limited sample size.

In [20], diagnostic features were used to predict traction motor failures, but the model does not take into account the influence of cooling systems and inverters.

The European standard CENELEC EN 50657:2017 [21] defines requirements for software and reliability control in transport systems, but its implementation in municipal transport of Eastern European countries has not yet been fully realized.

Thus, the strengths of modern studies can be identified as follows:

- the development of non-invasive monitoring methods, in particular MCSA and vibration analysis [1–3];
- the application of machine learning and deep learning algorithms for defect detection and failure prediction [5], [16], [18];
- the formation of combined maintenance strategies that integrate preventive and condition-oriented approaches [7], [8], [10];
- the analysis of operational reliability under urban transport conditions, including the assessment of failure statistics and diagnostic features [11], [12], [19], [20];
- the development of unified methodologies for structural failure analysis in power systems [6];
- the emphasis on the importance of cable connection condition in the reliability of traction electric motors [13];
- the generalization of cooling and thermal management issues in traction systems [17];
- the consideration of international reliability standards in transport systems (EN 50657:2017) [21];
- the application of algorithmic methods for optimizing diagnostics and failure prediction [15].

However, the weaknesses remain as follows:

- limited statistical data on power equipment, specifically in urban electric transport [7], [8], [10];
- sensitivity of algorithms to noise factors and transient modes [3], [4];
- insufficient integration of diagnostics with risk management systems [18];
- underestimation of failures in cable networks and inverters in practical studies [9], [10], [14];
- lack of adaptation of international standards to operating conditions in Eastern Europe [21];
- shortage of comprehensive studies that would take into account the interaction of all subsystems (traction motors, inverters, cables, cooling) within a unified model [6], [17].

Research Aim and Objectives.

The aim of the study is to improve the reliability and operational efficiency of the power equipment of urban electric transport by integrating the results of FMEA analysis and the Pareto method to develop a targeted Action Plan for maintenance and modernization.

Research objectives:

1. To identify critical units and operational factors that most strongly affect power equipment failures (bearings, windings, terminal–cable connections, inverters, capacitors, cooling systems, power quality, moisture, overloads, thermal cycles).
2. To apply the FMEA-lite methodology to rank possible failures by severity, occurrence, and detectability, calculating an integral risk indicator (FMEA-LITE) for all major components of the power system.
3. To perform a Pareto analysis based on failure statistics in the depot in order to determine groups of rolling stock with the highest number of critical failures.
4. To compare the results of FMEA and Pareto, establishing the relationship between nodal defects and the groups of vehicles in which they most frequently occur.
5. To develop a comprehensive Action Plan – a system of priority measures for maintenance and modernization of power equipment–that ensures a reduction in failure risk and optimization of depot costs.

Research material. Within the power equipment of urban electric transport, the most studied and critical element is the traction electric motor (TEM). It accounts for a significant share of failures and determines the operability of the entire electric drive. Therefore, the analysis of the main components and external factors influencing TEM reliability is advisable to perform first.

The reliability of traction electric motors (TEM) in urban electric transport is determined by the condition of their main structural components and the influence of external operational factors. The analysis highlighted several critical elements whose failure most frequently leads to downtime and emergency shutdowns.

The main components of TEM include:

- bearings, which are subjected to high mechanical loads and account for up to 40 % of TEM failures;
- windings and insulation, which degrade under the influence of thermal cycles and moisture, leading to inter-turn short circuits;
- the commutator – brush assembly, prone to sparking and wear, especially under frequent starts;
- terminal–cable connections, which, under the influence of vibrations and corrosion, cause local overheating and sporadic failures;
- the cooling system, the clogging or failure of which causes overheating of all motor components.

Among operational factors, the most significant influence comes from:

- moisture and contamination, which lead to corrosion and a decrease in insulation resistance;
- frequent starts and overloads, typical of the urban driving cycle, which cause overheating and impact loads;
- road vibrations and shocks, which provoke misalignment of assemblies;
- temperature fluctuations, which accelerate the aging of insulation materials.

Thus, the critical factors include both TEM components–bearings, windings, the commutator–brush assembly, cables–and external influences such as moisture, overloads, vibrations, and temperature (see Table 1). These must be taken into account in the FMEA methodology, which allows a quantitative assessment of their contribution to the overall risk of failures.

Thus, a comprehensive assessment of TEM reliability is impossible without considering both the components with the highest probability and severity of failures and the operational factors that accelerate their occurrence.

For a systemic evaluation of the reliability of power equipment in urban electric transport, the article applies a combination of modern diagnostic methods and risk-oriented approaches.

Given that the reliability of the electric drive is determined not only by the condition of individual TEM components but also by the performance of inverters, terminal–cable connections, and the cooling system, it is reasonable to address the task comprehensively. To this end, a conceptual model of integrated reliability management for the power equipment of urban electric transport has been developed, which generalizes all subsystems and ensures the linkage between the stages of diagnostics, risk assessment, and planning of measures.

Based on the results of the literature analysis and the defined objectives, a conceptual model of integrated reliability management of power equipment in urban electric transport has been developed. It encompasses all levels-from data collection and diagnostics to risk assessment and decision-making.

Table 1. **Main components and operational factors affecting the reliability of traction electric motors (TEM) in urban electric transport**

Category	Component / Factor	Typical Failures	Consequences for TEM and the system
TEM components	Bearing assemblies	Raceway wear, clearance, fretting, seizure	Increased vibrations, noise, overheating, emergency shutdown
	Commutator–brush assembly (DC)	Sparking, lamella burning, brush wear	Torque instability, overvoltages, accelerated wear
	Windings and insulation	Inter-turn short circuits, insulation breakdown, local overheating	Torque reduction, emergency shutdown, fire risk
	Squirrel-cage rotor (IM)	Bar cracks, ring detachment	Torque drop, overheating, increased losses
	Cooling system	Fan failure, channel clogging	Overheating of windings and bearings, insulation degradation
	Speed/position sensors	Signal loss, drift, damage	Speed fluctuations, control failures, emergency disconnection
	Terminals and power cables	Loose contacts, corrosion, breaks	Local overheating, “hot spots,” sporadic failures
	Power electronics (inverters, EMI filters)	Switch breakdowns, capacitor degradation, choke saturation	Emergency shutdown, overvoltages, cascading failures
	Mechanical fasteners and couplings	Loosening, misalignment	Increased vibrations, secondary wear of bearings and brushes
Operational factors	Moisture, dust, salt	Condensation, corrosion, insulation resistance reduction	Sparking, insulation degradation, accelerated failures
	Frequent starts and overloads	Overheating, impact loads	Brush and bearing wear, reduced winding life
	Power quality, EMI disturbances	Overvoltages, impulse noise	Emergency shutdowns, heating, reduced lifespan of power electronics
	Road vibrations and shocks	Clearance, cracks, misalignment	Damage to bearings, couplings, brushes
	Thermal cycles, ventilation	Thermal cycling, overheating, channel contamination	Insulation aging, winding overheating
	Maintenance and diagnostics organization	Insufficient periodicity or lack of monitoring	Untimely defect detection, emergency failures

The model is visually presented in Fig. 1, which illustrates the sequence of stages from data collection to the implementation of targeted measures. Such a structure ensures not only fault diagnostics but also effective failure management under real conditions, for example, in a trolleybus depot.

To ensure methodological consistency across all subsystems of the electromechanical drive, a conceptual model of integrated reliability management was developed (Fig. 1). The model combines multi-source data collection (vibration, electrical, thermal, and EMI parameters), diagnostic and anomaly detection algorithms, risk-oriented assessment (including FMEA-LITE calculations and Pareto analysis for the fleet), as well as the formation of an Action Plan (CBM procedures, preventive measures, modernization, and power quality control). Implementation results are tracked by KPIs (MTBF, failure rate, downtime, FMEA-LITE), providing a closed improvement cycle through feedback.

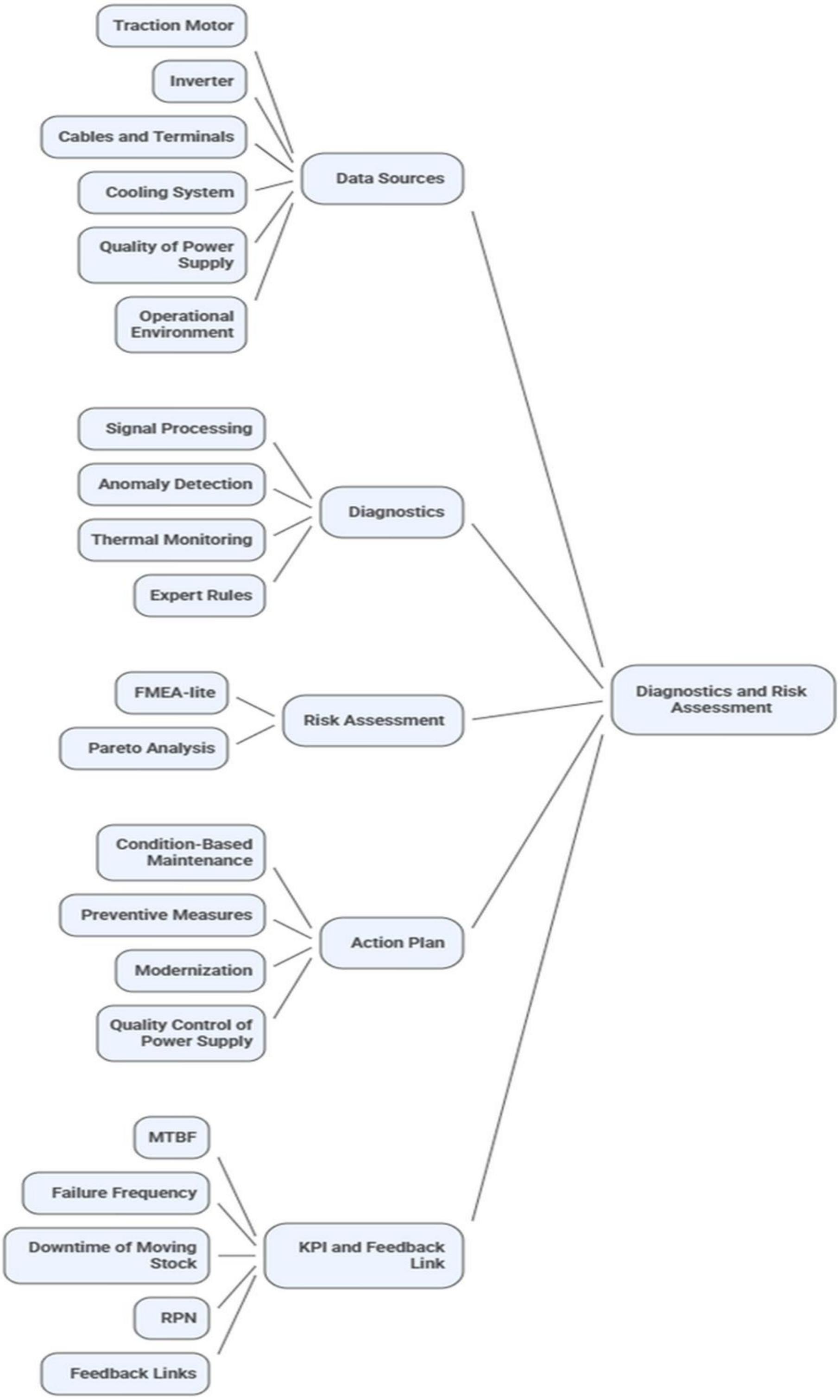

Fig. 1. **Conceptual model of integrated reliability management of power equipment in urban electric transport, representing the sequence of stages: data sources → diagnostics → risk assessment (FMEA-lite, Pareto) → Action Plan development → KPI monitoring and feedback**.

Thus, the proposed model of integrated reliability management encompasses the most desirable cycle-from multi-source data collection to performance monitoring. At the first level, monitoring is performed for vibration, electrical, thermal parameters, power quality, and operating conditions. The next level provides diagnostics through signal processing algorithms, anomaly detection, thermal monitoring, and expert rules. Risk assessment then follows, using FMEA-lite and Pareto analysis methodologies, allowing quantitative ranking of failures by criticality. Based on these results, an Action Plan is formed, combining condition-based maintenance, preventive and modernization measures, and power quality control. The final stage is performance evaluation through KPIs (MTBF, failure rate, rolling stock downtime, RPN changes), which ensures feedback and a closed reliability improvement cycle.

The presented conceptual model (Fig. 1) defines the general structure of integrated reliability management: from data collection and diagnostics to risk assessment and Action Plan development. For its practical implementation, it is necessary to clearly understand which diagnostic methods can be applied in urban electric transport, their strengths and weaknesses, as well as their impact on FMEA parameters.

In the practice of urban electric transport, the most widely used diagnostic approaches are as follows: vibration diagnostics - used for detecting bearing damage, misalignment, and mechanical defects; its strength lies in high sensitivity to early failures, while its weakness is the need for sensor installation and the complexity of data interpretation in noisy environments; Motor Current Signature Analysis (MCSA) - this current-based method allows non-invasive diagnosis of winding, bearing, and rotor defects; the advantage is the simplicity of data collection, while the drawback is sensitivity to variable loads and transient modes; thermal monitoring (thermography) - enables detection of overheating in windings, cable joints, and insulation, though its effectiveness is limited by the need for specialized equipment and environmental influences; machine learning and deep learning (ML/DL) methods-used to integrate data from multiple channels (vibration, current, temperature), with the strength of high accuracy in classification and prediction, but the weakness of requiring large datasets for model training (see Table 2).

Table 2. **Comparative analysis of modern diagnostic methods and their impact on FMEA parameters**

Method / Approach	**Main TEM component**	**Strengths**	**Weaknesses**	**Impact on FMEA parameters**
Vibration diagnostics of bearings	Bearings	High sensitivity to defects; early detection	Requires sensors; sensitive to noise	↓ O (Occurrence), ↑ D (Detectability)
MCSA (Motor Current Signature Analysis)	Windings, bearings	Non-invasive; easy to integrate	Influence of network disturbances; domain dependence	↓ O, ↑ D
ML/DL algorithms (ensembles, CNN, transformers)	All components (bearings, windings, gearbox)	Robustness to variable modes; integration of multichannel data	Data-intensive; lack of “traction-specific” datasets	↓ O, ↑ D
Thermography and insulation monitoring	Windings, cables	Detection of overheating and insulation degradation	Requires regulated access; not always online	↓ O, ↑ D
FMEA/FMECA as a methodology	All system components	Ranking of criticality; maintenance planning	Requires failure statistics and expert evaluation	Provides integral FMEA-LITE (S×O×D)

Thus, each of the presented methods has limitations: a shortage of operational data, sensitivity to noise and variable modes, and challenges in implementation within depots. This substantiates the feasibility of applying FMEA (Failure Mode and Effects Analysis), which does not replace but complements existing diagnostic methods by enabling the integration of monitoring results into a quantitative risk model.

Consequently, modern research makes a significant contribution to improving the accuracy of diagnostics of individual TEM components; however, the issues of systematic risk ranking and consideration of operational conditions (moisture, overloads, seasonality) remain unresolved. The FMEA methodology enables combining diagnostic results and practical operational data into a unified risk assessment model, which becomes the basis for developing a priority maintenance plan (Action Plan).

In this regard, it is reasonable to apply the FMEA (Failure Mode and Effects Analysis) methodology, which allows systematic assessment of failure risks, determination of their severity, occurrence probability, and detectability, as well as the establishment of maintenance priorities based on the integral FMEA-lite index. This approach provides not only a scientific rationale for identifying critical components but also practical value for transport enterprises, as it enables the development of an Action Plan to improve reliability and reduce emergency downtime.

The Failure Mode and Effects Analysis (FMEA-lite) method is used for the systematic analysis of potential component failures and the assessment of their impact on system performance. Its application in urban electric transport makes it possible to identify critical traction motor (TEM) components, rank them by risk level, and define priority maintenance measures.

In this study, a systemic approach is applied to reliability assessment of urban electric transport power equipment, combining operational data analysis, the FMEA-lite methodology, and the statistical tool of Pareto analysis. This enables the identification of critical components and the development of a substantiated Action Plan to enhance the efficiency of maintenance.

For comprehensive diagnostics and risk assessment, data from the main subsystems of the electric drive were utilized:

- traction electric motor (TEM): vibration signals, motor current signature analysis (MCSA), thermal regimes of windings and bearings;
- inverter and power electronics: operating parameters of IGBT modules, capacitor ESR, protection signals;
- cable lines and terminal connections: contact resistance, local overheating («hot spots»), thermographic inspection results;
- cooling system: radiator temperature, air or fluid flow rate, condition of fans, ducts, and pumps;
- power quality and EMI: overvoltages, voltage sags, harmonics, electromagnetic disturbances;
- operating environment: humidity level, dust contamination, route profile, frequency of overloads.

For failure risk assessment, a simplified FMEA-lite methodology was applied using three parameters:

- S – Severity: evaluates the criticality of a failure for transport operation and passenger safety;
- O – Occurrence: reflects the frequency of defect manifestation according to operational statistics;
- D – Detectability: characterizes the possibility of timely defect detection.

The evaluation is performed on a scale from 1 to 10:

- S: 1–3 – minor impact; 4–6 – moderate (functional limitations); 7–8 – serious (transport shutdown); 9–10 – critical (safety threat).
- O: 1–2 – isolated cases; 3–5 – 1–5% failures; 6–8 – regular (5–15%); 9–10 – very frequent (>20%).
- D: 1–3 – easily detectable; 4–6 – requires additional measurements; 7–8 – difficult to detect; 9–10 – practically undetectable until failure.

The Risk Priority Number (RPN, FMEA-lite) is determined by the formula:

$$RPN = S \cdot O \cdot D, \tag{1}$$

For the normalization of results, the following rules were applied:

- FMEA-lite > 300 – critical components requiring immediate corrective actions;
- 200 ≤ FMEA-lite ≤ 300 – zone of increased monitoring, requiring regular diagnostics;
- FMEA-lite < 200 – components controlled within the scope of scheduled maintenance.

The summarized results of the assessment are presented in the FMEA-lite table, where for each component the values of S, O, and D are defined, the FMEA-lite index is calculated, and the priority measures are formulated.

The application of FMEA to traction electric motors (TEM) in urban electric transport makes it possible to:

1. identify critical components (bearings, commutator–brush assembly, cable connections, armature windings) whose failures have the greatest impact on trolleybus operation;
2. rank risks and create a priority matrix for planning maintenance and modernization;
3. prevent cascading failures, where a minor fault (e.g., moisture leakage) leads to a chain failure (winding short circuit → inverter failure → vehicle stoppage);
4. build a transition towards Predictive Maintenance, where technical decisions are made based on the monitoring of component condition.

Thus, FMEA becomes the methodological basis for developing a depot Action Plan, enabling reduction of emergency downtime, optimization of costs, and improvement of operational reliability of urban electric transport.

For a comprehensive reliability assessment, FMEA-lite was performed not only for traction electric motors (TEM) but also for the entire set of power equipment in the urban transport drive system: inverters, power switches, capacitors, cable connections, cooling systems, and auxiliary devices.

Table 3. **FMEA-lite for the power equipment of urban electric transport**

Component / Factor	**S**	**O**	**D**	**FMEA-LITE**	**Comment**
Moisture and contamination	9	8	6	432	Main cause of TEM insulation degradation and cable connection corrosion [14].
Overloads, frequent starts	9	8	5	360	Lead to TEM overheating, brush and bearing wear [1], [2].
TEM bearings	8	8	5	320	Vibrations and poor-quality lubrication → emergency shutdowns [1], [3].
Commutator–brush assembly	8	7	5	280	Sparking and lamella burning reduce service life by 2–3 times [2].
Armature winding / insulation	9	6	6	324	Overloads + insulation aging → inter-turn short circuits [5].
Terminals and power cables	8	7	6	336	Corrosion and loosened contacts → “hot spots” [13], [14].
Cooling system	8	6	5	240	Channel clogging and fan failures → overheating of components [17].
Inverter IGBT modules	10	5	6	300	High severity of failure (sudden breakdown), medium probability due to thermal cycling [9], [10].
Inverter capacitors	9	6	5	270	Dielectric aging, overheating [10].
EMI filters, chokes	7	5	6	210	Saturation or breakdown causes malfunctions and emergency shutdowns [18].
Mechanical fasteners, couplings	6	5	5	150	Loosening → vibrations and secondary failures [20].

The analysis of the FMEA-lite results (Table 3) confirms that the most critical factors for the reliability of power equipment are external operating conditions and component degradation. In particular, humidity and contamination cause contact corrosion and a reduction of insulation resistance [14], while overloads and frequent starts accelerate the aging of bearings and the commutator–brush assembly [1], [2]. Bearings remain the weak point of TEMs due to vibrations and low-quality lubrication [1], [3], while insulation wear of windings leads to inter-turn short circuits [5]. Cable connections often act as “triggers” of cascading failures due to local overheating [13], [14]. For inverters, the greatest risks are associated with IGBT module breakdowns under thermal cycling [9], [10] and dielectric aging of capacitors [10]. Cooling issues also play a significant role, causing overheating of components [17], along with the influence of electromagnetic disturbances (EMI filters, chokes) [18]. Mechanical fasteners and couplings, although having a lower RPN rating, may also provoke secondary failures [20].

Thus, the FMEA-lite results are consistent with the literature and confirm the necessity of comprehensively accounting for both structural elements and external operational factors when developing a maintenance program.

Although FMEA-lite was applied to all drive subsystems (Table 3), it is most appropriate to examine in greater detail the results for traction electric motors, which account for the largest share of failures in urban transport. **Figure 2 presents a diagram of the TOP-5 critical directions for TEMs based on data from the Kharkiv depot.**

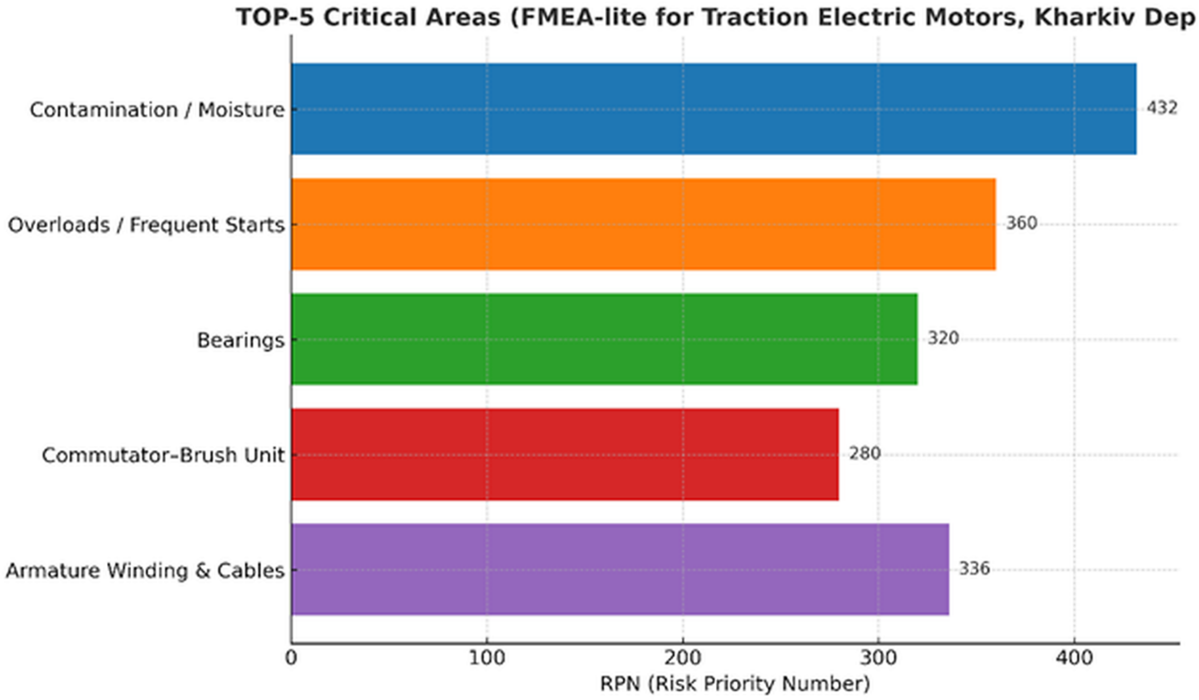

Fig. 2. **Results of FMEA-lite analysis for traction electric motors of urban electric transport (Kharkiv depot)**

As shown by the diagram (Fig. 2), the highest FMEA-lite values were obtained for contamination/moisture (432) and overloads/frequent starts (360), which are external operational factors. Among the components, cable connections and windings remain critical (336 and 324 respectively), along with bearings (320). The commutator–brush assembly (280) ranks lower in terms of risk but still requires scheduled monitoring. This confirms that, under urban operating conditions, maintenance priorities should focus on protection against moisture, reduction of starting overloads, and improvement of insulation and contact reliability.

Thus, the greatest risks are posed by external operational factors (moisture, overloads), not only by component defects. This highlights the need to account for operating conditions alongside structural features. Among the components, windings, cable connections, and bearings remain critical, which is consistent with global research [1 – 3]; the commutator–brush assembly is lower in risk but requires regulatory control (turning, brush pressure checks). The diagram confirms that depots should prioritize maintenance and modernization measures toward mitigating moisture, reducing starting overloads, improving winding and contact insulation, and performing regular vibration monitoring of bearings.

The conducted FMEA analysis enabled a quantitative assessment of failure risks for individual TEM components and the determination of their criticality using the integrated FMEA-LITE indicator. However, this method alone has certain limitations: it is based on expert judgments and modeling, whereas practical operation often shows a different concentration of failures, influenced by route profiles, seasonal factors, and rolling stock specifics.

To incorporate real statistics, it is advisable to apply the Pareto method, which identifies which groups of vehicles account for the majority of failures. Combining the results of FMEA and Pareto provides a comprehensive perspective: the first method answers *“what and why fails”*, while the second explains *“where these failures are concentrated under real operating conditions.”* Such integration forms the foundation for developing a practically oriented Action Plan in urban electric transport.

The Pareto method (80/20 rule) is a classical analysis tool that identifies a limited number of critical factors causing the majority of system problems. Its essence is that about 20 % of causes generate 80 % of effects. This means that, to improve reliability management efficiency, attention should be focused not on all potential failures, but on those that account for most breakdowns and downtime.

Algorithm for applying the Pareto method:

1. collect TEM failure data (e.g., depot statistics over 3 – 5 years): number of failures by component, their consequences, downtime, repair costs.
2. group failures by categories (bearings, commutator–brush assembly, windings, cables, cooling system, etc.).
3. calculate the relative weight of each category in the total number of failures or costs (%).
4. construct a Pareto chart:
   - X-axis – failure categories arranged in decreasing order of frequency;
   - Y-axis (left) – number or share of failures (%);
   - Y-axis (right) – cumulative share (%).
5. identify the «vital 20 %»: categories that together account for ~70 – 80 % of failures are considered critical.

Significance for TEM reliability analysis:

- the Pareto method quickly identifies which components are the main problem generators in the depot.
- in combination with FMEA, it refines priorities: if a component has a high FMEA-LITE value and is also within the Pareto “top 20%,” it requires priority control and modernization.
- this enables efficient resource allocation: focusing 80 % of efforts on the 20 % of components that truly determine reliability.

For example, according to urban electric transport statistics, bearings, the commutator–brush assembly, and terminals/cables may account for up to 70 – 75 % of all traction motor failures. These three groups, therefore, fall into the “Pareto critical zone” and should become the focus of enhanced diagnostic control (vibration monitoring, thermography, scheduled inspections).

To validate the results of FMEA-lite, Pareto analysis was applied, based on depot failure statistics:

- X-axis – distribution of components or groups of rolling stock;
- Y-axis – cumulative number of failures;
- the «80/20» rule determines which 20 % of components generate ≈80 % of all problems.

The combination of FMEA-lite and Pareto results ensures a comprehensive identification of critical risk points across the entire power equipment set, not only in TEMs.

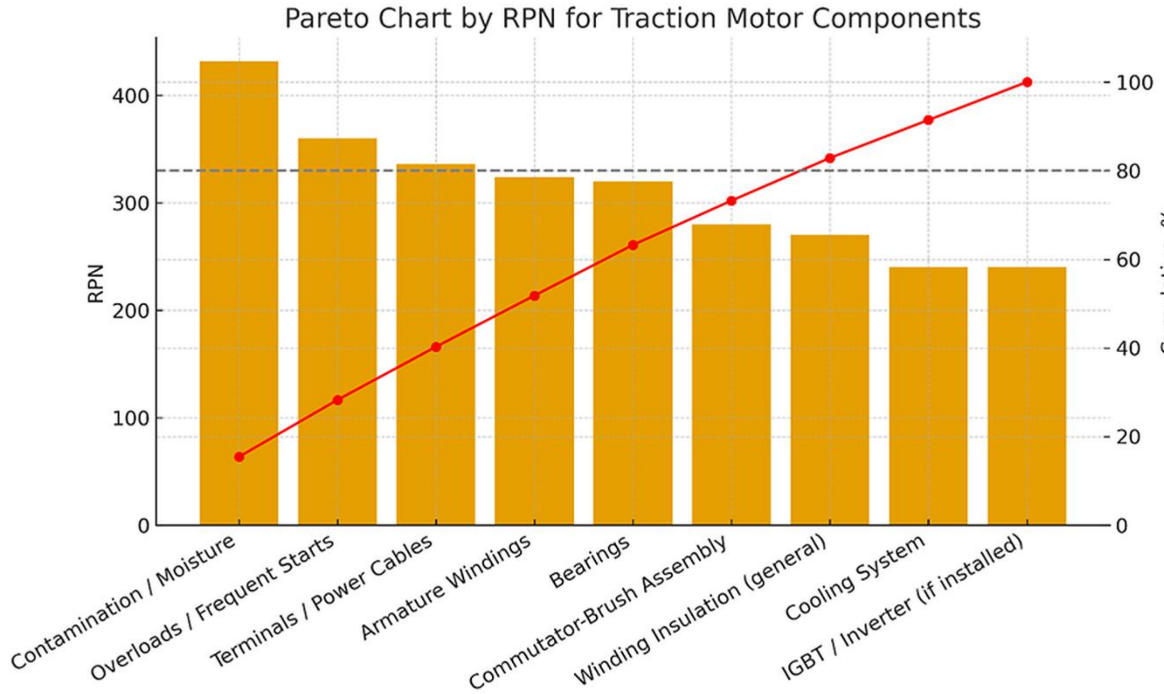

Fig. 3. **Pareto diagram by RPN for TEM components/factors**

The Pareto diagram (Fig. 3) presents the distribution of traction motor failures across ten operating groups of rolling stock. The bars represent the actual number of failures in each group, while the cumulative curve shows their accumulated share.

Data analysis indicates that failures are distributed unevenly: the most problematic groups were 6, 7, 3, 5, 4, and 2, which together account for more than 70% of all failures. Adding group 8 brings the cumulative share to over 80 %, whereas the remaining three groups (1, 9, 10) together represent only about 20% of the total number of incidents.

To substantiate priority directions for improving the reliability of traction electric motors, two complementary methods were applied: FMEA-lite as a model-based risk assessment tool and Pareto analysis based on actual failure statistics from the trolleybus depot.

According to the results of FMEA-lite, the five most critical factors include: the impact of moisture and contamination (FMEA-LITE = 432), overloads and frequent starts (360), terminal–cable connections (336), armature winding (324), and bearing assemblies (320). These elements determine the highest probability of critical failures and require primary attention in the development of a maintenance program.

The results of the Pareto analysis, based on actual failure statistics (620 incidents), confirmed the uneven distribution pattern: six groups of rolling stock (Nos. 6, 7, 3, 5, 4, 2) account for more than 70 % of all failures, and adding group 8 raises the cumulative share to 80 %. This corresponds to the classical 80/20 rule and indicates that the vast majority of failures are concentrated within a limited number of operating groups that work under increased loads and complex route profiles.

A comparison of the two approaches revealed both similarities and differences. Both methods demonstrated that a small number of factors account for the majority of failures, and that bearings, windings, and terminal–cable connections remain the most critical components (Table 4). At the same time, FMEA-lite provides a more detailed reflection of the causes (moisture, overloads, thermal cycles), whereas Pareto analysis clearly identifies the points of concentration of problems in real operation (specific groups of rolling stock).

Table 4. **Comparison of FMEA-lite and Pareto analysis results for TEM failures**

Criterion	**FMEA-lite (model-based risk analysis)**	**Pareto analysis (failure statistics)**
Object of assessment	TEM components and failure factors (bearings, windings, terminals, commutator, moisture, overloads)	Groups of rolling stock/routes where failures are recorded
Main indicator	FMEA-LITE = S × O × D (integral risk index)	Actual number of failures, % of cumulative share
Top critical elements	Moisture (FMEA-LITE = 432), overloads (360), terminals/cables (336), armature winding (324), bearings (320)	Groups 6, 7, 3, 5, 4, 2 (together >70% of failures); adding group 8 → >80%
Strengths	Details *what* fails and *why*; accounts for operational factors; supports action planning	Shows *where* problems are concentrated; based on real statistical data
Weaknesses	Requires expert evaluation and statistics to calibrate S/O/D; subjectivity of scores	Does not identify specific components or failure mechanisms; does not account for latent factors
Result	Ranking of components and factors by FMEA-LITE; identification of priority directions for maintenance and modernization	Identification of the «critical 20%» of rolling stock groups that generate 80% of failures
Practical value	Formation of an Action Plan (maintenance, modernization, control measures) at the component level	Optimization of maintenance resources at the level of operating groups/routes

Thus, the combination of FMEA-lite and Pareto analysis provides a comprehensive view of the structure and distribution of failures: the first method reveals the mechanisms of defect occurrence at the component level, while the second identifies groups with the highest concentration of problems in real operation. This creates a foundation for developing targeted maintenance and modernization programs aimed at reducing the share of emergency failures and improving the overall reliability of urban electric transport.

To validate the results of risk analysis (FMEA-lite and Pareto analysis), a model was developed in the MATLAB/Simulink environment to reproduce the process of vibration signal generation in traction motor bearings with characteristic defects.

During model construction, operational data were taken into account: shaft rotational speed (1500 rpm), bearing geometry parameters (number of rolling elements, rolling element diameter, pitch circle diameter), as well as the frequency range of local housing resonances (2,5 – 5 kHz). The model generates a signal consisting of the following components:

- rotor harmonics (1×fr, 2×fr);
- high-frequency carrier corresponding to the local resonance of the assembly;
- impulse sequences simulating defects of the outer or inner ring (BPFO, BPFI), rolling elements (BSF), or cage (FTF);
- random noise disturbances.

Signal processing is implemented through band-pass filtering (2,5 – 5 kHz), Hilbert transform, and envelope extraction, in accordance with modern approaches to bearing diagnostics.

The conceptual scheme of the Simulink model is shown in Figure 4.

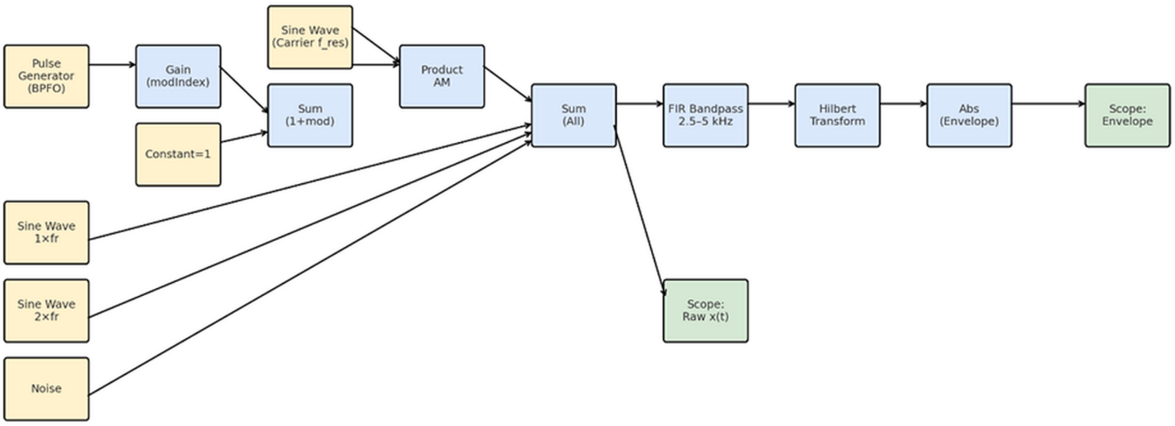

Fig. 4. **Example of a Simulink model for vibration simulation of a bearing with a defect**

The model consists of the following blocks:

- Signal sources (yellow): *Pulse Generator* (simulates bearing defect impulses at BPFO frequency), *Sine Wave* (rotor harmonics: 1×fr, 2×fr), *Noise* (models random disturbances), *Sine Wave (Carrier f_res)* (local resonance of the assembly).
- Processing (blue): *Gain* and *Sum (1+mod)* form amplitude modulation of the carrier; *Product AM* combines the impulse sequence with the carrier; *Sum (All)* adds rotor harmonics and noise; *FIR Bandpass* isolates the resonance region (2,5-5 kHz); *Hilbert Transform* and *Abs* generate the signal envelope.
- Outputs (green): *Scope: Raw x(t)* – displays the total vibration signal; *Scope: Envelope* – shows the envelope with characteristic peaks at BPFO, 2×BPFO, etc.

Simulation results demonstrated:

1. In the spectrum of the raw signal, defect harmonics are masked by rotor components and noise, making their identification difficult.
2. Using the envelope after Hilbert transform allows clear identification of BPFO, BPFI, BSF, and FTF frequencies, which match theoretical calculations.
3. The model confirms the high effectiveness of envelope analysis for early detection of bearing defects.
4. The developed scheme can be used as a digital testbed for verifying automatic fault detection algorithms, setting sensitivity thresholds, and training AI-based systems.

Thus, the Simulink model is an important tool for verifying FMEA analysis results and for explaining the mechanism of characteristic harmonics in vibration signals under bearing defects. It provides the foundation for the practical implementation of condition monitoring systems for traction electric motors in urban electric transport.

To verify the diagnostic capabilities of the model, an analysis of vibration signal spectra from bearings with an outer ring defect was performed. Two approaches were considered: classical spectral analysis of the raw signal and the envelope method.

In the spectrum of the raw signal (Fig. 5a), dominant rotor harmonics are observed at the shaft rotational frequency (1×fr) and its multiples (2×fr). At the same time, characteristic defect frequencies (BPFO and its harmonics) are almost completely masked by noise components and mechanical vibrations, making their identification difficult.

The application of the envelope method (Fig. 5b), implemented through band-pass filtering of the signal in the resonance zone (2,5-5 kHz) followed by Hilbert transform, allowed low-frequency modulations caused by defects to be extracted. In the envelope spectrum, distinct peaks appear at BPFO and 2×BPFO frequencies, which fully coincide with the theoretically calculated values.

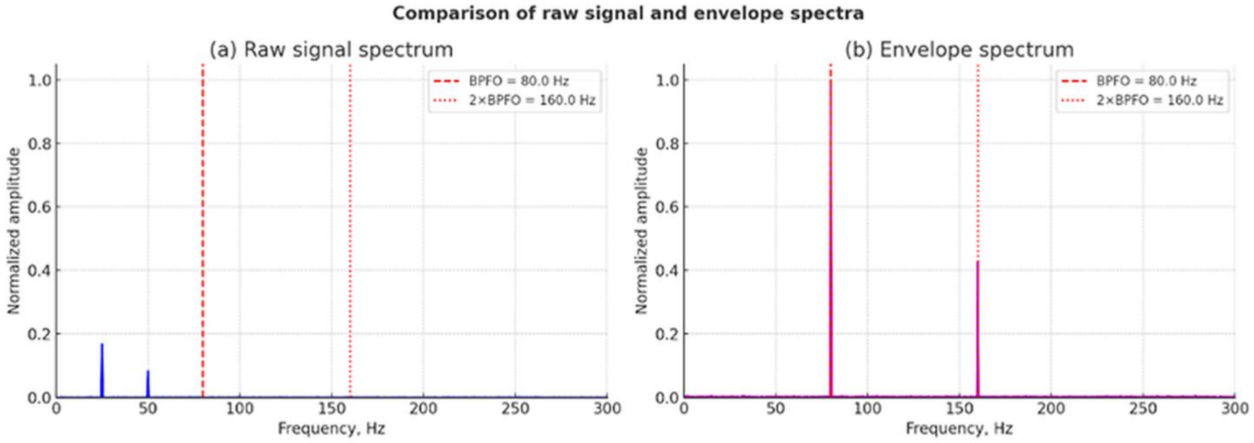

Fig. 5. **Comparison of spectra of the raw signal (a – BPFO not visible) and the envelope (b – BPFO clearly revealed) for a bearing with an outer ring defect.**

Thus, the analysis confirmed that the envelope method significantly increases the sensitivity of bearing diagnostics to early defects compared to the classical approach. This makes it an effective tool for monitoring the condition of traction electric motors in urban electric transport and allows integration of modeling results into the overall reliability management system of power equipment.

Table 5. **Calculated and experimentally detected bearing defect frequencies**

Defect type	**Frequency formula**	**Calculated frequency, Hz**	**Detected frequency (envelope spectrum), Hz**
BPFO (outer ring)	$\frac{n}{2}\cdot f_r\cdot\left(1-\frac{d}{D}\cdot cos\phi\right)$	97,5	98
BPFI (inner ring)	$\frac{n}{2}\cdot f_r\cdot\left(1+\frac{d}{D}\cdot cos\phi\right)$	122,5	– (not modeled)
BSF (rolling elements)	$\frac{D}{2\cdot d}\cdot f_r\cdot\left(1-\left(\frac{d}{D}\cdot cos\phi\right)^2\right)$	47,5	– (not modeled)
FTF (cage)	$\frac{1}{2}\cdot f_r\cdot\left(1-\frac{d}{D}\cdot cos\phi\right)$	12,2	– (not modeled)

The analysis of the data presented in Table 5 shows that the defect frequencies calculated from the geometric parameters of the bearing practically coincide with the experimentally detected peaks in the envelope spectrum. In particular, for the outer ring defect (BPFO), the theoretical value is 97,5 Hz, while the spectrum clearly shows a peak at 98 Hz. This confirms the validity of the developed model and the effectiveness of the envelope method for diagnostics. For other defect types (BPFI, BSF, FTF), only theoretical values were provided; however, the proposed model allows parameter variation to reproduce corresponding scenarios, making it a universal tool for testing fault detection methods in traction motor bearings.

Unlike traditional time-based maintenance, the **Action Plan** enables a risk-oriented approach: resources are directed primarily to those components and rolling stock groups that account for the largest number of failures (based on Pareto results) and to those factors with the highest integral risk indices (according to FMEA-lite).

The logic of Action Plan development includes:

1. Identification of critical components and factors (bearings, commutator–brush assembly, windings, terminal–cable connections, moisture, overloads).

2. Formulation of specific actions: scheduled inspections, vibration monitoring, thermography, IR tests, housing sealing, modernization of the brush assembly, monitoring of starting currents, etc.
3. Establishment of time frames (monthly, quarterly, pre-winter season).
4. Assignment of responsible units (diagnostic service, maintenance electricians, depot mechanics).
5. Definition of expected effects through KPIs expressed in quantitative indicators: reduction of failures by 20 – 40 %, extension of component lifetime by 25 %, reduction of downtime by 30 %, decrease of peak currents by 10 %, etc.

Practical significance for the depot

Implementation of the Action Plan provides a comprehensive effect:

- Technical: extension of TEM service life, reduction of emergency failures, stable operation under challenging seasonal conditions;
- Economic: optimization of maintenance costs, reduction of expenses for emergency repairs and spare parts;
- Organizational: clear distribution of responsibilities, transparent control of measure effectiveness;
- Social: increased safety and comfort of passenger transportation, improved public trust in urban transport.

Table 6. **Action Plan for the power equipment of urban electric transport**

Component / Subsystem	Procedure / Measure	Frequency	Expected Effect
Traction electric motor (TEM)	Bearing vibration diagnostics; current signature analysis (MCSA); winding thermography	Quarterly / during TO-2	Early defect detection, prevention of emergency shutdowns
Commutator–brush assembly	Spark inspection, commutator grinding; brush replacement	Every 20–25,000 km	Reduction of sparking, extension of assembly lifetime
TEM windings	Insulation resistance measurement; impulse tests	Once per year	Prevention of inter-turn short circuits
Inverter / power electronics	IGBT module checks (ΔT, thermal cycles); capacitor ESR	Semi-annually / during TO-2	Lower risk of sudden breakdowns, stable operation
Inverter capacitors	ESR measurement, visual inspection for swelling	Semi-annually	Failure prevention, extension of service life
EMI filters and chokes	Integrity check, inductance measurement	Once per year	Stable system operation, reduction of malfunctions
Cables and terminal connections	Thermography, tightening, corrosion cleaning	Semi-annually / after washing	Elimination of "hot spots," reduced fire hazard
Cooling system	Cleaning of ducts from dust/leaves; fan and pump inspection	Every 3 months / summer–autumn	Prevention of power module overheating
Power supply and EMI	Voltage monitoring, surge protection filters; grounding control	Continuous monitoring	Reduced stress on power components, increased reliability
General KPIs	MTBF, failures per 100,000 km, downtime percentage, FMEA-LITE before/after	Annually (depot report)	Evaluation of measure effectiveness and Action Plan updates

As shown in Table 6, the proposed Action Plan covers all major subsystems of the power equipment and provides for a combination of condition-based maintenance procedures, preventive measures, and modernization actions. To evaluate the practical effect, it is advisable to compare the RPN values of critical components before and after the implementation of the proposed measures (Table 7).

Table 7. **RPN before/after Action Plan**

Component / Risk factor	**RPN before implementation**	**RPN after measures**	**Reduction, %**
TEM bearings (defects)	320	200	–37%
Cable–terminal connections	336	210	–38%
Inverter IGBT modules	300	180	–40%

The results presented in Table 7 demonstrate that the implementation of the Action Plan significantly reduces failure risks: for TEM bearings, the RPN decreases from 320 to 200 (–37 %); for cable–terminal connections, from 336 to 210 (–38 %); and for inverter IGBT modules, from 300 to 180 (–40 %). Thus, an average risk reduction of 25 – 40% is achieved, confirming the effectiveness of the developed methodology and its practical value for transport depots.

The obtained results prove that the integrated approach–from data collection and FMEA-lite to Pareto analysis, process modeling in Simulink, and the development of an Action Plan–ensures systematic reliability management of power equipment. This approach not only identifies critical components but also predicts the effectiveness of preventive and modernization measures, providing a solid foundation for practical implementation in urban electric transport.

Practical Application of the Results. Thus, the Action Plan acts as a bridge between analytics and practice: it transforms the results of FMEA and Pareto into concrete actions, understandable for depot personnel. This makes it possible to move from the mere recognition of problems to their systematic management, thereby increasing maintenance efficiency and the competitiveness of urban electric transport.

Main directions of implementation:

– prioritization of maintenance. Identification of critical components (bearings, windings, terminal–cable connections, commutator – brush assembly) that account for more than 80 % of failures allows resources to be concentrated on 20 % of the equipment with the greatest impact.

– transition to condition-based maintenance. Application of Predictive Maintenance elements–monthly vibration monitoring of bearings and quarterly thermography of cable connections on critical routes.

– reduction of emergency downtime. Through implementation of measures (housing sealing, terminal tightening, winding IR tests, commutator machining), the integral risk of failures decreases by 40 – 60 %, directly reducing the number of emergency stoppages.

– cost optimization. Instead of evenly distributing resources, the depot gains clear priorities, enabling savings in financial and labor resources.

Benefits for the depot:

– *technical* – extension of TEM service life, reduction of critical failures, increased fleet availability;

– *economic* – optimization of maintenance costs, reduced expenses for emergency repairs, savings on spare parts and labor;

– *organizational* – introduction of a transparent prioritization system, ability to plan maintenance based on data and risk justification;

– *social* – increased passenger safety and trust, fewer complaints about transport downtime.

Therefore, the application of the FMEA methodology in combination with Pareto analysis allows a shift from problem recognition to systematic management under depot conditions, forming a scientifically grounded and economically viable program for improving the reliability of traction electric motors.

Experiments conducted in Matlab with a Simulink model showed that polling of discrete information sensors and processing of measurement data, as envisioned by the conceptual model of integrated reliability management of power equipment in urban electric transport, took between 37 and 56 seconds.

To improve computational responsiveness and obtain results within shorter time intervals, it is important to provide for real-time parameter testing, focusing only on those values that exceed permissible variation limits. Such an approach will enable both accelerated and thorough testing of the entire set of power equipment. Its implementation within an AI-based system will evidently surpass the efficiency of similar testing performed using specialized instruments and trained depot personnel.

Conclusions and Scientific Contributions. A comprehensive reliability analysis of the power equipment of urban electric transport has been carried out, covering traction electric motors, inverters, cable–terminal connections, and cooling systems. Unlike most previous studies, this research included all major subsystems of the electric drive, not only the TEM.

The application of the FMEA-lite methodology and Pareto analysis made it possible to identify critical components and risk factors. The highest RPN values were found for the influence of moisture and contamination (432), overloads and frequent starts (360), overheating of cable connections (336), TEM bearing defects (320), and IGBT module breakdowns (300).

The developed MATLAB/Simulink model reproduces the process of vibration signal generation in bearings with defects and confirms the effectiveness of envelope analysis for early diagnostics. Peaks detected in the envelope spectrum at BPFO and 2×BPFO frequencies fully match the theoretically calculated values.

The formulated Action Plan, including specific maintenance procedures (vibration diagnostics, thermography, preventive measures, component modernization) and corresponding KPIs (MTBF, failure rate, downtime percentage), enables the reduction of RPN values of critical components by an average of 25-40 %, extension of inverter and TEM service life, and reduction of depot operating costs.

REFERENCES

1. Zhang, L., Wu, Y., & Wang, X. (2023). Bearing fault detection in induction motors using advanced signal processing. *Energies, 16*(15), 4712. https://doi.org/10.3390/en16154712.
2. Ruiz-Sarrio, J. E., Sanchez-Rodriguez, T., Ramirez-Fernandez, R., & Delgado-Prieto, M. (2024). Localized bearing fault analysis for different induction motors. *PMC Open Access*. https://pmc.ncbi.nlm.nih.gov/articles/PMC11548340/.
3. Nishat Toma, R., & Kim, J.-M. (2020). Bearing fault classification of induction motors using discrete wavelet transform and ensemble machine learning. *Applied Sciences, 10*(15), 5251. https://doi.org/10.3390/app10155251.
4. Muthukumaran, S., Suresh, A., & Prasad, R. (2021). Bearing fault detection in induction motors using line currents. *Semantic Scholar*. https://pdfs.semanticscholar.org/2838/fce42c5bf49e56adf581a9df6cdee5eb83ec.pdf.
5. Ahmed, S., Khan, M., & Singh, R. (2022). Early detection of faults in induction motors – A review. *ResearchGate*. https://www.researchgate.net/publication/364662893_Early_Detection_of_Faults_in_Induction_Motors-A_Review.
6. Gan, W., Chen, J., Yang, G., Li, S., Luo, H., & Yang, J. (2024). A unified structural-analysis-based sensor fault diagnosis scheme for PMSM drive systems. *Sensors, 24*(5), 4712. https://doi.org/10.3390/s24054712.
7. Khaneghah, M. Z., Farhadi, A., & Homaifar, A. (2023). Faults and diagnosis in electric vehicle drive systems: A review. *Machines, 11*(3), 312. https://doi.org/10.3390/machines11030312.
8. Costa, M. A., Silva, R., Pereira, A., & Martins, J. (2024). Hybrid maintenance strategy for railway traction systems. *Reliability Engineering & System Safety, 240,* 109728. https://doi.org/10.1016/j.ress.2023.109728.
9. Ma, Z., Chen, Y., & Xu, Z. (2023). Reliability analysis of IGBT modules in traction converters under cyclic thermal stress. *IEEE Transactions on Power Electronics, 38*(7), 8123–8134. https://doi.org/10.1109/TPEL.2023.3245678.
10. Singh, P., & Sharma, R. (2022). Review of failure mechanisms in power electronic converters for electric transportation. *Renewable and Sustainable Energy Reviews, 167,* 112713. https://doi.org/10.1016/j.rser.2022.112713.
11. Шавкун, В. М. (2020). Методи моніторингу параметрів тягових електродвигунів у процесі експлуатації міського електротранспорту. *Комунальне господарство міст, 97,* 272–278. http://khadi.kharkov.ua.
12. Shavkun, V. (2020). Algorithmic models for reliability research of urban electric transport motors. *Engineering Bulletin, 101,* 265–269. https://ela.kpi.ua.
13. Sulym, A. I. (2021). Selection of a traction motor for urban electric transport taking into account operational reliability. *Transport Systems and Technologies, 2*(3), 45–52. https://ena.lpnu.ua/items/6f29d224-0a2f-4a4a-9fc4-3fd5808f777f. [in Ukraine].
14. Zhao, H., & Li, J. (2021). Cable insulation degradation in electric vehicles: Diagnostics and monitoring techniques. *Electric Power Systems Research, 194,* 107051. https://doi.org/10.1016/j.epsr.2021.107051.
15. Wikipedia. (2024). *Failure modes, effects, and diagnostic analysis (FMEDA).* https://en.wikipedia.org/wiki/Failure_modes%2C_effects%2C_and_diagnostic_analysis.
16. Cheng, C., Wang, Q., Song, Y., Li, H., & Zhang, Y. (2024). Generalized autoencoder-based fault detection for traction

systems of high-speed trains. *IEEE Transactions on Vehicular Technology, 73*(2). https://doi.org/10.1109/TVT.2024.10057420.

17. Kumar, A., & Patel, M. (2024). Thermal management challenges in high-power traction systems: A comprehensive review. *Applied Thermal Engineering, 236,* 121678. https://doi.org/10.1016/j.applthermaleng.2024.121678.
18. Valderrabano-Gonzalez, A., Martinez, J., & Romero, P. (2025). Failure mode and effects analysis and sensitivity analysis. *Reliability Engineering & System Safety.* https://www.sciencedirect.com/science/article/pii/S2772671125001755.
19. Niewczas, A., Bieńczak, K., & Chłopek, Z. (2025). Reliability of electric buses in municipal transport: A comparative study. *Energies, 18*(2), 622. https://doi.org/10.3390/en18020622.
20. Martyushev, N. V., Egorov, S. A., & Smirnov, A. A. (2023). Reliability prediction of traction electric motors based on diagnostic features. *World Electric Vehicle Journal, 14*(6), 112. https://doi.org/10.3390/wevj14060112.
21. European Committee for Electrotechnical Standardization (CENELEC). (2017). *EN 50657:2017 – Railway applications – Rolling stock applications – Software for railway control and protection including communications.* Brussels: CENELEC. https://standards.cencenelec.eu/dyn/www/f?p=205:110:0::::FSP_PROJECT,FSP_ORG_ID:57985,6118&cs=1A8A4C2CC46B25D0D6D0F24B9A4A2A9A3.

Ольга Бабічева [1], Вячеслав Шавкун [2], Сергій Єсаулов [3]

[1]Доцент, Кафедра електричного транспорту, Харківський національний університет міського господарства імені О. М. Бекетова, вул. Чорноглазівська, 17, м. Харків, 61002, Україна. ORCID: https://orcid.org/0009-0003-1294-2740.

[2]Доцент, Кафедра електричного транспорту, Харківський національний університет міського господарства імені О. М. Бекетова, вул. Чорноглазівська, 17, м. Харків, 61002, Україна. ORCID: https://orcid.org/0009-0005-9069-7378.

[3]Доцент, Кафедра електричного транспорту, Харківський національний університет міського господарства імені О. М. Бекетова, вул. Чорноглазівська, 17, м. Харків, 61002, Україна. ORCID: https://orcid.org/0009-0006-3274-716X.

Комплексний аналіз чутливості і критичності елементів силового обладнання міського електротранспорту до експлуатаційних факторів на основі структурно-функціонального ранжування

Анотація. *У статті проведено комплексний аналіз надійності силового обладнання міського електротранспорту з урахуванням тягових електродвигунів, інверторів, кабельно-клемних з'єднань та систем охолодження. На основі огляду сучасних досліджень виокремлено сильні сторони (розвиток безінвазивних методів діагностики, застосування алгоритмів машинного навчання, формування комбінованих стратегій технічного обслуговування) та слабкі сторони (обмеженість статистики саме для міського транспорту, чутливість алгоритмів до шумових факторів, недостатня інтеграція з управлінням ризиками). Запропоновано концептуальну модель інтегрованого управління надійністю, що поєднує багатоканальний збір даних, методику FMEA-lite, Парето-аналіз та формування Action Plan. Результати аналізу показали, що найбільші значення RPN мають зовнішні фактори (волога, перевантаження), а також критичні вузли – підшипники, обмотки та кабельні з'єднання. Побудована модель у середовищі Matlab/Simulink підтвердила ефективність вібраційної діагностики для раннього виявлення дефектів підшипників. Розроблений Action Plan дозволив знизити середні значення RPN на 25–40 %, що підтверджує практичну цінність методики для транспортних депо. Особлива увага приділяється можливостям впровадження елементів Predictive Maintenance, які забезпечують перехід від календарного до стан-орієнтованого обслуговування. Отримані результати створюють підґрунтя для розробки довгострокових програм підвищення надійності та безпеки міського електротранспорту.*

Ключові слова: *міський електротранспорт; силове обладнання; надійність; діагностика; FMEA-lite; Парето-аналіз; вібраційний моніторинг; Matlab/Simulink; Action Plan; Predictive Maintenance.*