ENGINEER

international scientific journal

ISSUE 3, 2026 Vol. 4
E-ISSN
3030-3893
ISSN
3060-5172



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Tashkent state transport university

ENGINEER

A bridge between science and innovation

E-ISSN: 3030-3893

ISSN: 3060-5172

VOLUME 4, ISSUE 3

SEPTEMBER, 2026

engineer.tstu.uz

TASHKENT STATE TRANSPORT UNIVERSITY

ENGINEER

INTERNATIONAL SCIENTIFIC JOURNAL
VOLUME 4, ISSUE 3 SEPTEMBER, 2026

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The “Engineer” publishes the most significant results of scientific and applied research carried out in universities of transport profile, as well as other higher educational institutions, research institutes, and centers of the Republic of Uzbekistan and foreign countries.

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Tashkent State Transport University had the opportunity to publish the international scientific journal “Engineer” based on the **Certificate No. 1183** of the Information and Mass Communications Agency under the Administration of the President of the Republic of Uzbekistan. **E-ISSN: 3030-3893, ISSN: 3060-5172.** Articles in the journal are published in English language.

Journal Engineer ISSN: 3030-3893 Volume:4| Issue:3| 2026

Received: 14 July 2026 | **Accepted:** 25 August 2026 | **Published:** 30 September 2026

Improving the reliability of the TD802 direct-current traction generator of the ChME3 shunting diesel locomotive through insulation replacement

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Abstract: This paper presents an analysis of the design and insulation system of the TD802 (TO802) direct-current traction generator installed on ChME3 shunting diesel locomotives operated on the railways of Uzbekistan, and substantiates a technology for improving its reliability through the replacement of that insulation. The study was carried out in three stages: an assembly-by-assembly analysis of the factory insulation system (armature winding, main and commutating pole coils, commutator, brush apparatus); identification of the physical mechanisms of insulation ageing and of their cumulative interaction; and development of a technological regulation for insulation replacement using modern heat-resistant materials. The proposed solution comprises vacuum-pressure impregnation (VPI) of the armature winding, replacement of asbestos gaskets with glass-mica and aramid-fibre materials, renewal of the commutator insulation, transition to a monolithic insulation system for the pole coils, and an upgrade of the insulation thermal class to H (180 °C). A quality-control procedure based on insulation resistance, absorption coefficient, polarization index, high-voltage testing, partial discharge monitoring and infrared thermography is proposed, together with a methodology for quantitative evaluation of the effect through the mean time between failures. It is shown that the proposed measures do not alter the design scheme of the machine and modernize only the insulating materials and the technology of their application, which makes them practically feasible at depot level.

Keywords: ChME3 shunting diesel locomotive, TD802 traction generator, insulation system, armature winding, vacuum-pressure impregnation, commutator, thermal ageing, insulation thermal class, reliability, mean time between failures

1. Introduction

Modernization of railway transport and improvement of the technical readiness of the traction rolling stock fleet are among the priority areas of state policy in the Republic of Uzbekistan. ChME3-series locomotives continue to occupy a significant share of the shunting locomotive fleet used for switching operations on the railways of Uzbekistan. These locomotives are equipped with a K6S310DR diesel engine rated at approximately 1350 hp, which converts mechanical energy into electrical energy through a TD802 traction generator — a ten-pole, self-ventilated direct-current machine with independent excitation rated at approximately 885 kW. The current produced by the generator is supplied to six TE-006 traction motors of 134 kW and 283 V each. The TD802 generator is therefore the central electrical machine of the locomotive traction system, and its technical condition directly determines the operational capability of the locomotive.

The majority of ChME3 locomotives have been in operation on the railways of Uzbekistan for more than 25–40 years. Over such an extended service period the electrical insulation system of the generator — in particular the armature winding, the main and commutating pole coils and the commutator insulation — gradually deteriorates under the combined effects of heat, vibration, moisture and mechanical loading. Depot maintenance experience shows that a substantial share of the unscheduled repairs of the TD802 generator is directly related to insulation faults: inter-turn short circuits, ground faults, and a drop of insulation resistance below the permissible threshold. Such failures usually occur unexpectedly and take the locomotive out of service for an extended period, since a complete generator rewind is a time- and resource-intensive operation.

The problem of maintaining the technical condition of locomotive equipment has been addressed in a number of studies. Intelligent and condition-based approaches to the diagnostics of traction electrical equipment have been developed for traction transformers and traction systems [1–7], including online monitoring architectures built on Internet of Things technologies [8]; the influence of insulation resistance and temperature on the condition of an electrical machine has been investigated using neural network models [9]. For diesel locomotives, fault analysis and diagnostic methods for power plant components have also been developed by the authors of this work [14–17]. However, these studies concentrate on the diagnostics of an existing insulation system rather than on the technology of its renewal, whereas for a machine that has been in service for several decades the decisive question is which materials the insulation is replaced with and by what technology.

For this reason, replacing the insulation system of the TD802 generator with modern materials and technologies, and thereby improving its reliability, is a matter of considerable scientific and practical importance for the railways of Uzbekistan. The aim of this paper is to analyze the factory insulation system of the TD802 generator, to identify the

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causes of its deterioration, and to develop technological solutions for improving the reliability of the generator through the replacement of its insulation with modern heat-resistant materials.

The objectives of the study are as follows: to analyze the design and the factory insulation system of the TD802 generator for each major assembly (armature winding, main and commutating pole coils, commutator, brush apparatus); to substantiate the physical and technical mechanisms of insulation ageing; to develop a technological sequence for replacing the insulation with modern materials; to propose a methodology for quality control of the renewed insulation; and to assess the effect of the proposed solutions on the reliability and economic indicators of the machine.

2. Research methodology

The study was performed as an engineering-analytical investigation and is based on three groups of sources: the factory design documentation of the TD802 (TO802) generator, which provides the design dimensions of every assembly and the composition of its insulation; the regulatory documents governing the repair of locomotive traction electrical machines and the aggregated fault records of depot repairs, which make it possible to establish which assembly the insulation faults occur in; and the technical literature on traction electrical machines and on the diagnostics of locomotive equipment [1–17].

The analysis was carried out in three stages. In the first stage the factory insulation system was examined assembly by assembly — the main poles, the commutating poles, the armature core and winding, the commutator and the brush apparatus — and for each of them the insulating material, its method of application and its characteristic weak point were determined. In the second stage the physical mechanisms of insulation ageing (thermal, vibration, moisture and contamination, electrical, and mechanical wear) were identified, and their mutual reinforcement was evaluated rather than each factor being considered in isolation. In the third stage, on the basis of the weak points established in the first two stages, a technology for replacing the insulation with modern materials was developed, together with a technological regulation, a quality control procedure and a methodology for the quantitative assessment of the effect.

The criterion adopted for evaluating the effectiveness of the proposed solutions is the reliability of the generator in operation, expressed through the mean time between failures (MTBF) and the failure rate $\lambda = 1/\mathrm{MTBF}$, supplemented by the trend of the insulation resistance R60 and of the polarization index PI = R10/R1 recorded at successive inspections. A further condition imposed on the solution was that it must not require any change to the design scheme of the machine, so that it can be implemented within the existing depot repair process.

3. Results and Discussion

3.1. Design and factory insulation system of the TD802 generator

The TD802 generator (also referred to as TO802 in the factory documentation) is a ten-pole, self-ventilated direct-current machine with independent excitation and a starting winding. The generator frame is welded from steel sheet; one end is flange-mounted to the diesel engine housing, while the other is bolted to the locomotive frame by means of feet. The results of the assembly-by-assembly analysis of the factory insulation system are summarized in Table 1.

The generalized technical parameters of the generator and of the associated traction equipment are as follows: diesel engine — type K6S310DR, approximately 1350 hp; traction generator — TD802 (TO802), ten-pole, independently excited, self-ventilated, approximately 885 kW; traction motor — type TE-006, 134 kW, 283 V, six units per locomotive; auxiliary generator — type DT-701-4; exciter — type DT-706-4. These parameters determine the requirements placed on the insulation system, in particular the working voltage level and the current density, and must be taken into account when selecting insulating materials. The main dimensions of the commutator–armature assembly (a commutator diameter of 595 mm with 405 segments and 135 slots in the armature core) indicate that the machine operates at a relatively high surface speed at the commutator, which places particular demands on the commutator–brush assembly and the insulating elements adjacent to it: they must be resistant not only to electrical stress but also to mechanical and thermal loading.

Table 1

Factory insulation system of the TD802 generator by assembly and its characteristic weak points

№	Assembly	Factory insulation system	Characteristic weak point
1	Main poles (starting and independent excitation windings)	Riveted core of 1 mm electrical steel; 4 turns of 1×95 mm copper strip and ≈ 63.5 turns of 4.0×7.5 mm rectangular wire in eight stepped layers; layer-by-layer epoxy varnish coating	The varnish film becomes brittle under heat and vibration, cracks and delaminates — risk of inter-turn short circuits
2	Commutating poles (interpoles)	Coils of 2.2×50 mm copper busbar in two layers (5 and 4.5 turns, ≈ 9.5 turns in total); asbestos interlayer gaskets; coil filled with cast epoxy compound	Asbestos embrittles, accumulates dust, absorbs moisture and loses thermal conductivity; does not meet modern occupational safety requirements
3	Armature core and winding	Core of 0.5 mm varnished sheets, 135 slots, 72 ventilation holes; lap winding with equalizers, sections of six 2.8×9.0 mm conductors; five layers of mica tape in the slot and six layers of glass tape in the end portions; micanite sleeves	Multi-layer hand-applied insulation retains air voids between layers, which accelerates depletion of service life through partial discharges and moisture absorption

https://doi.org/10.56143/3030-3893-2026-3-118-124 A bridge between science and innovation

№	Assembly	Factory insulation system	Characteristic weak point
		and spacers; 2 mm steel wire banding, textolite wedges	
4	Commutator	Diameter 595 mm, 405 copper segments separated by 0.8 mm micanite spacers; risers silver-soldered; sleeve insulated by split-mica collars, clamped through a pressure ring	Mechanical wear together with the working surface and thermal cycling; the mica protrudes above the segments, causing poor brush contact and sparking — periodic undercutting required
5	Brush apparatus	Ten brush-holder yokes, five double brushes each (fifty double-brush positions); spring pressure 1.5–1.8 kgf; brush size 2(32×10×40) mm	Not an insulating element itself, but moisture and commutator dust penetrate through the brush-holder insulators and reduce the overall insulation resistance

3.2. Mechanisms of insulation deterioration

Under long-term operating conditions the factory insulation system described above deteriorates as a result of the following main factors:

– thermal ageing — the operating temperature of the generator, especially under high-load conditions, gradually breaks down the binding components of the insulating varnishes and of the mica tape; according to Montsinger's rule the insulation life is roughly halved for every 8–10 °C increase in operating temperature;

– vibration fatigue — locomotive motion and diesel engine vibration cause micro-movements between the insulation layers of the armature winding and of the pole coils, which leads to delamination;

– moisture and contamination — moisture and commutator dust entering the generator housing reduce the insulation resistance, particularly because asbestos gaskets and aged micanite readily absorb moisture;

– electrical ageing — partial discharges occurring in the air voids within the insulation layers gradually erode the insulating material from within;

– mechanical wear — wear of the commutator mica insulation together with the working surface, and accumulation of brush dust between the commutator segments, which results in surface tracking paths.

The combined effect of these factors causes the insulation resistance of the TD802 generator to fall below the normative threshold, which is typically required to remain above 1.5–2.0 MΩ, with the exact value specified in the depot regulatory documents; the machine may then be barred from operation or suffer an emergency shutdown.

Aggregated depot repair records allow the insulation-related faults of the generator to be grouped into three characteristic categories: inter-turn and ground faults in the armature winding, which occur mainly in the end windings owing to moisture accumulating under the banding; insulation breakdown in the pole coils, most often in the commutating pole coils, owing to embrittlement of the asbestos gaskets; and defects of the commutator insulation, namely undercutting problems and surface tracking paths between the segments. Each group has characteristic diagnostic signs, and recognizing them makes it possible to determine in advance which assembly requires particular attention during repair.

It should be emphasized that the ageing factors listed above do not act in isolation but reinforce one another. A contaminated ventilation system raises the internal temperature of the generator and thereby accelerates thermal ageing; thermally embrittled insulation cracks more readily under vibration; and cracked insulation admits moisture and dust more deeply, which accelerates electrical ageing through partial discharges. As a result of this chain reaction, the actual service life of the insulation is often considerably shorter than the theoretical value calculated from thermal ageing alone. This is precisely why insulation replacement must be approached comprehensively, taking all ageing factors into account together rather than addressing a single factor such as the heat-resistance class in isolation — this is the underlying logic of the solutions proposed below.

3.3. Technology for replacing the insulation

Replacing the generator insulation, whether partially or completely through rewinding, is a complex technological process carried out at the depot or at a repair plant, and its quality determines the reliable operation of the machine over the following eight to ten years or more.

The first stage of rewinding the armature is to remove the old winding from the core completely, clean the slots and inspect the core for mechanical and electrical defects such as inter-lamination short circuits. New conductors are then wound with modern glass-mica tape, a material that at equal thickness provides greater electrical and thermal strength than the traditional combination of mica tape and glass tape. After the winding has been placed in the slots, vacuum-pressure impregnation with a monolithic thermosetting resin is recommended instead of the traditional drip impregnation method. In the VPI process the winding is first evacuated in a vacuum chamber in order to remove air and moisture, after which the resin is forced under pressure into every microscopic void within the insulation layers and is then cured in a heating chamber. The result is a fully monolithic, non-hygroscopic insulation layer, which eliminates the air voids that give rise to partial discharges, increases resistance to moisture and to oil and fuel vapours, improves thermal conductivity so that heat is dissipated more efficiently from the conductor to the core, and prevents movement of the conductor within the slot under vibration together with the resulting abrasion of the insulation. For securing the end windings, glass-fibre banding tape is recommended in place of the traditional steel wire banding, and glass-fibre composite wedges in place of textolite wedges in the slot portions, since these materials are considerably more resistant to ageing and moisture.

When the main pole coils are rewound it is recommended to wrap the conductors with glass-mica tape and to impregnate the entire coil by the VPI method, which produces a more uniform and continuous insulation layer than the traditional layer-by-layer epoxy varnish coating applied by hand. In the commutating pole coils the asbestos gaskets should be replaced by modern glass-mica or aramid-fibre insulating materials of the Nomex type, which offer superior heat resistance and mechanical strength while producing no hazardous fibre residue. After the coil has been assembled it should be filled with monolithic resin under vacuum pressure rather than by casting epoxy compound, since this eliminates the microscopic air bubbles that typically form during compound pouring.

The insulation-related operations performed when repairing the commutator are the complete replacement of the micanite spacers between the segments if the commutator is fully reassembled, or the renewal of worn micanite by undercutting it 1.0–1.5 mm below the working surface; the replacement of the sleeve-to-commutator insulation, traditionally made of split mica collars, with monolithic glass-mica or epoxy-glass collars, which improves the mechanical strength and moisture resistance of the sleeve insulation; and thermal stabilization of the assembled commutator in a heating chamber, which relieves the internal stresses in the insulating materials and prevents the commutator from losing its roundness in service. After reassembly, precision turning and grinding of the commutator surface followed by mica undercutting ensures good commutator–brush contact from the moment the generator is returned to service.

The factory insulation system of the TD802 generator generally corresponds to thermal class B (130 °C) or F (155 °C). During rewinding it is recommended to replace all insulating materials with class H materials rated up to 180 °C. Even without any change to the actual operating temperature of the machine, this creates a thermal margin relative to the temperature limit of the material and substantially extends the service life of the insulation — an important consideration in the hot summer conditions of Uzbekistan, when both the ambient and the depot temperatures are elevated.

In order to realize the benefits of insulation replacement in full, a number of supplementary measures are also recommended: installing dust-protective filters in the ventilation channels so as to reduce contamination-related ageing; readjusting the brush spring pressure and the brush material, using electrographite-grade brushes matched to the new insulation system; and dynamically balancing the rotor in order to reduce the dynamic loading placed on the newly wound winding.

3.4. Technological regulation for insulation replacement

Replacement of the TD802 generator insulation at a depot or repair plant is recommended to follow the sequence of stages set out below. This regulation ensures that insulation quality is controlled at every stage of the repair and reduces the likelihood of random technological errors (Fig. 2).

– Stage 1. Remove the generator from the locomotive, clean external contamination and perform initial diagnostics — insulation resistance measurement and visual inspection;

– Stage 2. Disassemble the generator into its components — armature, pole coils, brush apparatus, bearing shields — washing and drying each assembly separately;

– Stage 3. Remove the old windings completely and inspect the core and the coil frames for mechanical and electrical defects;

– Stage 4. Prepare new conductors and wrap them with modern glass-mica insulating tape (armature sections, pole coils);

– Stage 5. Place the windings in their respective locations, install the micanite sleeves and spacers and fit the mechanical securing elements — banding and wedges;

– Stage 6. Impregnate the assembled windings in a vacuum-pressure chamber and cure them in a heating chamber according to the specified temperature–time regime;

– Stage 7. Reassemble the generator — mounting the pole coils to the frame and the armature to the bearing shields — inspect the commutator and renew its insulation if necessary;

– Stage 8. Turn and grind the commutator surface and undercut the mica;

– Stage 9. Install the brush apparatus, adjust the brush spring pressure and dynamically balance the rotor;

– Stage 10. Perform final diagnostics — insulation resistance, polarization index, high-voltage test and partial discharge monitoring;

– Stage 11. Run the generator under load on a test bench, perform thermographic monitoring, record the results in the technical passport and authorize installation on the locomotive.

The work performed and the measurement results obtained at each stage should be recorded in a repair log, which makes it possible to trace the insulation history of a particular generator in the future and to diagnose faults more rapidly should a problem arise.

3.5. Quality control and assessment of reliability indicators

Before a rewound generator is returned to service, the quality of its insulation system must be verified using the following indicators: the insulation resistance R60 and the absorption coefficient R60/R15 measured with a megohmmeter; the polarization index PI = R10/R1, which provides a deeper assessment of moisture content; a high-voltage test at 1.5–2 times the rated voltage, which reveals hidden defects; partial discharge monitoring, which characterizes the internal uniformity of the insulation; and infrared thermography during load testing, which identifies local hot spots such as poorly impregnated areas. These test results are entered in the technical passport of the generator and serve as a baseline for comparison during subsequent inspections.

The quantitative assessment of the effectiveness of insulation replacement should be based on reliability indicators derived from the operating statistics of the machine. The most widely used indicator is the mean time between failures (MTBF), defined as the total operating time between failures divided by the number of failures; the failure rate is its reciprocal, $\lambda = 1/\mathrm{MTBF}$. Calculating these indicators separately for the periods before and after insulation replacement and comparing them makes it possible to substantiate the real effectiveness of the proposed technological solutions. In addition, tracking the trend of the insulation resistance and of the polarization index over time, by recording in graphical form the values obtained at each inspection, is a practical method of forecasting the remaining insulation life. If the rate of decline of the insulation resistance per unit time between measurements exceeds a set threshold, this serves as a diagnostic indication that the generator requires an unscheduled inspection or repair. Unlike a strictly time-based repair schedule, this approach allocates maintenance

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resources according to the actual technical condition of the machine, which is consistent with the condition-based diagnostic principles developed for traction electrical equipment [8; 9; 17].

Comparative Analysis

The differences between the factory insulating materials used in each major assembly of the TD802 generator and the modern materials proposed to replace them, together with the expected effect, are summarized in Table 2.

Table 2

Comparison of the factory and the proposed insulation systems of the TD802 generator

Aspect	Factory (existing) system	Proposed system	Expected effect
Armature winding	Mica tape (5 layers in the slot, 6 in the end portion) with glass tape; drip impregnation; steel wire banding; textolite wedges	Glass-mica tape; monolithic vacuum-pressure impregnation (VPI); glass-fibre banding tape; glass-fibre composite wedges	Higher resistance to partial discharges, sharply reduced moisture absorption, greater mechanical strength
Main pole coils	Layer-by-layer, hand-applied epoxy varnish coating in a stepped configuration	Continuous glass-mica insulation with VPI impregnation of the whole coil	Uniform insulation thickness, reduced dependence on manual technique
Commutating pole coils	Asbestos gaskets, cast epoxy compound	Glass-mica or aramid-fibre insulation (Nomex-type), VPI filling	Elimination of hazardous fibre residue, improved heat and moisture resistance
Commutator	0.8 mm micanite spacers, split-mica sleeve collars	Renewed micanite spacers or, in a full rebuild, monolithic glass-mica sleeve insulation; periodic mica undercutting	More stable commutator–brush contact, reduced sparking
Insulation thermal class	Class B (130 °C) or F (155 °C)	Class H (up to 180 °C)	Thermal margin relative to the temperature limit; important in the hot climate of Uzbekistan
Quality control	Mainly insulation resistance measurement	R60 and absorption coefficient R60/R15, polarization index R10/R1, high-voltage test, partial discharge monitoring, infrared thermography	Detection of hidden defects, a recorded baseline for tracking the ageing trend
Maintenance planning	Strictly time-based repair schedule	Condition-based planning using the trend of insulation resistance and polarization index, MTBF and failure rate $\lambda = 1/MTBF$	Repair resources allocated according to the actual technical condition of the machine

The comparison shows that the proposed changes do not fundamentally alter the design scheme of the generator but modernize the insulating material and the technology of its application in each assembly, which makes the solution relatively practical and economically justified for implementation at depot level. The key qualitative difference lies in the transition from a multi-layer, hand-applied insulation system, whose properties depend heavily on the skill of the operator, to a monolithic system formed under vacuum pressure, whose properties are determined by a controlled technological regime.

The economic effectiveness of replacing the insulation with modern materials consists of two main components: a reduction in the cost of unscheduled repairs owing to the extended fault-free operating life of the generator, and a reduction in the shunting work lost through locomotive downtime. Although modern insulating materials such as glass-mica tapes and VPI resin systems, as well as the vacuum-pressure equipment itself, require higher initial costs than the traditional materials, these costs are recouped over the full service life of the machine through its extended lifespan and the reduced number of emergency shutdowns. In order to assess the economic effectiveness accurately it is

recommended that each depot pilot the proposed technology on a limited number of generators and then compare their operating results — the number of failures, the intervals between repairs and the repair costs — with those of generators repaired using the traditional technology. On the basis of such a comparative analysis, a unified, technically and economically substantiated regulatory document for the repair of TD802 generators could be developed for use across the railways of Uzbekistan.

Replacing the insulation system of the TD802 generator with the modern materials and the VPI technology described above is expected to yield the following results: stabilization of the insulation resistance and polarization index values, with sustained readings above the normative thresholds; a reduction in the number of unscheduled repairs related to insulation faults; an extended mean time between failures owing to the upgraded thermal class; a lower probability of emergency shutdowns during seasonal transitions, particularly in high-humidity periods, owing to the improved moisture and dust resistance; and reduced sparking together with an extended commutator life owing to more stable commutator–brush contact. These results in turn contribute to a higher technical readiness rate for the ChME3 locomotive fleet equipped with TD802 generators, to optimized repair costs and to uninterrupted shunting operations.

4. Conclusion

Analysis of the design and of the factory insulation system of the TD802 (TO802) traction generator has shown that the traditional insulating materials used in its armature winding, pole coils and commutator — mica tape, micanite and asbestos gaskets — are subject to thermal, vibration-related and electrical ageing over long-term operation and constitute the primary cause of the unscheduled repairs of the machine. It has been established that these ageing factors do not act independently but reinforce one another, so that the actual service life of the insulation is shorter than the value calculated from thermal ageing alone; insulation replacement must therefore be approached comprehensively.

Complete replacement of this insulation with modern glass-mica materials, vacuum-pressure impregnation technology and materials of a higher thermal class can substantially improve the reliability of the generator, and the proposed eleven-stage technological regulation together with the quality control procedure makes it possible to implement the change within the existing depot repair process without altering the design scheme of the machine. Practical implementation of the proposed technological solutions at the depots of the railways of Uzbekistan, quantitative evaluation of their effectiveness on the basis of real operating statistics, and the subsequent development of unified technical guidelines for the repair of TD802 generators constitute the main direction of further research.

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