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IMPROVING THE RELIABILITY OF ASYNCHRONOUS MOTORS: ANALYSIS OF STATOR WINDING FAILURES AND ELECTROMECHANICAL MAINTENANCE METHODS

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Annotation. This paper analyzes the common failure modes in asynchronous (induction) motors, focusing on stator winding faults, bearing degradation, and insulation breakdown under maximum load conditions. A classification of faults into mechanical, electrical, and thermal categories is presented, with statistical data indicating that stator winding burnout due to overloading accounts for 31% of all failures, inter-turn short circuits for 15%, and bearing damage for 12%. The effects of maximum loading on stator windings are examined, including Joule heating, partial discharge phenomena, and electrodynamic stress. The paper further discusses modern electromechanical maintenance and repair strategies, including real-time monitoring and diagnostics, CNC-based machining of commutators, advanced insulation materials, and automated lubrication systems. The results demonstrate that systematic application of these methods significantly extends motor service life and improves energy efficiency.

Keywords: asynchronous motor, stator winding, insulation reliability, maximum load, electromechanical maintenance, bearing failure, overload protection, induction motor diagnostics.

Annotatsiya. Ushbu maqolada asinxron (induksion) dvigatellarda kuzatiladigan asosiy nosozlik turlari, jumladan, stator chulg‘amlaridagi nosozliklar, podshipniklarning eskirishi hamda maksimal yuklama sharoitida izolyatsiyaning buzilishi tahlil qilingan. Nosozliklar mexanik, elektr va termik toifalarga ajratilib, statistik ma’lumotlarga ko‘ra ortiqcha yuklama natijasidagi stator chulg‘amining kuyishi barcha nosozliklarning 31 foizini, o‘ramlararo qisqa tutashuvlar 15 foizini, podshipniklarning shikastlanishi esa 12 foizini tashkil etishi keltirilgan. Maksimal yuklamaning stator chulg‘amlariga ta’siri, jumladan Joul-Lensa qonuni asosidagi qizish, qisman razryad hodisalari va elektrodinamik kuchlanishlar ko‘rib chiqilgan. Shuningdek, real vaqt rejimida monitoring va diagnostika, kollektorlarni CNC-asbob-uskunalarida qayta ishlash, zamonaviy izolyatsion materiallar hamda avtomatlashtirilgan moylash tizimlari kabi elektromexanik

xizmat ko‘rsatish va ta’mirlash usullari yoritilgan. Tadqiqot natijalari ushbu usullarni tizimli qo‘llash dvigatel xizmat muddatini sezilarli darajada uzaytirishi va energiya samaradorligini oshirishini ko‘rsatadi.

Kalit so‘zlar: asinxron dvigatel, stator chulg‘ami, izolyatsiya ishonchliligi, maksimal yuklama, elektromexanik xizmat ko‘rsatish, podshipnik nosozligi, ortiqcha yuklamadan himoya, induksion dvigatel diagnostikasi.

Аннотация. В данной статье анализируются распространённые виды отказов асинхронных (индукционных) двигателей с акцентом на повреждения статорных обмоток, износ подшипников и пробой изоляции в условиях максимальной нагрузки. Представлена классификация отказов на механические, электрические и тепловые категории, при этом статистические данные показывают, что выгорание статорной обмотки вследствие перегрузки составляет 31 % всех отказов, межвитковые короткие замыкания — 15 %, а повреждения подшипников — 12 %. Рассмотрены воздействия максимальной нагрузки на статорные обмотки, включая нагрев по закону Джоуля–Ленца, явления частичных разрядов и электродинамические напряжения. В работе также обсуждаются современные методы электромеханического обслуживания и ремонта, включая мониторинг и диагностику в реальном времени, обработку коллекторов на станках с ЧПУ, перспективные изоляционные материалы и автоматизированные системы смазки. Результаты показывают, что системное применение этих методов существенно продлевает срок службы двигателя и повышает энергоэффективность.

Ключевые слова: асинхронный двигатель, статорная обмотка, надёжность изоляции, максимальная нагрузка, электромеханическое обслуживание, отказ подшипника, защита от перегрузки, диагностика индукционных двигателей.

INTRODUCTION.

Asynchronous (induction) motors are the most widely used type of electric machines in industrial, agricultural, and municipal applications due to their simple construction, high reliability, and relatively low cost [1, 2]. However, during operation, these motors are subject to various types of faults, including mechanical, electrical, and thermal failures, which degrade power quality, reduce efficiency, and may cause unplanned shutdowns [3, 4].

Statistical analysis reveals that stator winding burnout caused by overloading accounts for approximately 31% of all motor failures, followed by inter-turn short circuits at 15% and bearing damage at 12% [5]. These figures underscore the importance of understanding failure mechanisms and developing effective maintenance strategies to ensure reliable motor operation.

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The increasing complexity of modern industrial systems, combined with the growing integration of renewable energy sources, demands higher reliability and adaptability from electric drive systems. Conventional maintenance approaches, primarily based on periodic inspections, often fail to detect incipient faults before they lead to catastrophic failures [6, 7].

This paper presents a comprehensive analysis of common fault types in asynchronous motors, examines the effects of maximum loading on stator winding reliability, and proposes modern electromechanical maintenance methods aimed at improving motor efficiency and extending service life.

LITERATURE REVIEW.

The reliability and fault diagnosis of asynchronous motors have been extensively studied in the international scientific literature. Benbouzid [1] provided a foundational review of induction motor signature analysis as a medium for fault detection, establishing the framework for current-based diagnostic methods. Bonnett and Soukup [3] presented a comprehensive analysis of the causes and mechanisms of stator and rotor failures in three-phase squirrel-cage induction motors, demonstrating that overloading and inter-turn faults are the dominant failure modes.

Thorsen and Dalva [5] conducted statistical analyses of high-voltage induction motor failures in the petrochemical industry, providing valuable empirical data on failure distributions. Stone et al. [10] addressed the electrical insulation of rotating machines, covering design, evaluation, aging, testing, and repair aspects. Nandi, Toliyat, and Li [8] reviewed condition monitoring and fault diagnosis methods for electrical motors, while Tavner [9] systematized condition monitoring approaches for rotating electrical machines.

In the post-Soviet scientific tradition, Rustamov [2] and Usmonov [4] elaborated the theory and practice of asynchronous motor service and diagnostics in the local engineering context. Recent publications [6, 7] emphasize the transition from periodic inspections to condition-based and predictive maintenance, supported by real-time sensor data and machine-learning-based fault classification. The analysis of these sources reveals that while individual aspects of motor diagnostics have been thoroughly investigated, a consolidated approach that integrates failure statistics, the physical mechanisms of stator winding degradation under maximum load, and modern electromechanical maintenance strategies remains underexplored, which defines the scientific novelty of the present work.

RESEARCH METHODOLOGY.

The research methodology of this study combines statistical analysis of failure data, physical-mathematical modeling of stress factors acting on stator

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windings, and a comparative review of modern maintenance technologies. The faults encountered in asynchronous motors during operation are classified into three main categories: mechanical, electrical, and thermal [1–5]. Mechanical faults include rotor shaft deformation, bearing wear and seizure, loosening of stator core fixation, and contamination of rotating parts. Electrical faults encompass inter-turn and phase-to-phase short circuits, winding open circuits, insulation degradation, and phase loss. Thermal faults arise from overheating due to overloading, inadequate ventilation, or ambient temperature increase.

External causes of failure include power supply interruptions, voltage deviations, phase asymmetry, and improper connection to the network. Internal causes are subdivided into mechanical failures (bearing damage, rotor deformation, brush holder loosening) and electrical failures (inter-turn faults, winding burnout, insulation aging) [5, 8].

Maximum load refers to the condition where the motor operates above its rated power for a limited duration. During this regime, the current through the stator windings increases significantly, leading to several adverse effects [2, 9]. The first effect is thermal stress: according to the Joule–Lenz law, heat dissipation in the windings increases proportionally to the square of the current. Practical experience confirms that every 8–10 °C rise in operating temperature approximately halves the insulation service life, following the Arrhenius relationship [10, 11].

The second effect is electrical stress: increased current causes non-uniform distribution of electric field intensity, particularly at the inter-turn and inter-phase insulation boundaries. This creates conditions for partial discharge initiation, which accelerates insulation degradation through micro-crack formation [12]. The third effect is mechanical stress: the increase in electrodynamic forces results in enhanced vibration and displacement of winding conductors, causing friction-induced damage to the insulation layers. The combined action of thermal, electrical, and mechanical stresses leads to accelerated complex aging of the insulation system [9, 13].

For motors operating under variable load conditions, the equivalent power method is used to verify the correct motor rating [2, 14]. The equivalent power is calculated as:

$$Peqv = \sqrt{\frac{P_1^2 t_1 + P_2^2 t_2 + P_3^2 t_3 + P_4^2 t_4}{t_1 + t_2 + t_3 + t_4}} \qquad (1)$$

Where P_1, P_2, P_3, and P_4 represent the motor power at different load levels, and t_1, t_2, t_3, and t_4 are the corresponding durations. The condition $P(eqv) \leq P(nom)$ must be satisfied, and additionally, $M(max) < \lambda \cdot M(nom)$, where λ is the overload coefficient [14].

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Several overload protection methods are employed in practice. Current-based protection using automatic circuit breakers and current relays monitors the stator current and disconnects the motor when permissible limits are exceeded. Thermal protection employing bimetallic relays and thermistors (PTC, NTC) monitors the actual temperature of the windings. Modern microprocessor-based protection systems simultaneously monitor current, voltage, temperature, and vibration parameters, enabling predictive fault detection and preventive shutdown [6, 7, 15]. Soft starters and variable frequency drives (VFDs) limit starting currents and provide smooth transitions to maximum load regimes, thereby protecting the stator winding insulation [16].

DISCUSSION AND RESULTS.

The statistical analysis of fault data in asynchronous motors reveals a clear distribution of failure modes by frequency of occurrence. The systematized results are presented in Table 1.

Table 1

Distribution of failure types in asynchronous motors [5]

No.	Failure type	Percentage	Category
1	Stator winding burnout due to overloading	31 %	Electrical
2	Inter-turn short circuit (insulation degradation)	15 %	Electrical
3	Bearing damage	12 %	Mechanical
4	Mechanical damage to stator winding insulation	11 %	Mechanical
5	Non-uniform air gap between stator and rotor	9 %	Mechanical
6	Single-phase operation (phase loss)	8 %	Electrical
7	Short-circuited rotor bar damage	5 %	Electrical
8	Loosening of stator core fixation	4 %	Mechanical
9	Non-uniform load distribution on rotor	3 %	Mechanical
10	Rotor imbalance	2 %	Mechanical

The results indicate that electrical faults collectively account for 59 % of all failures, while mechanical faults account for 41 %. Stator winding-related

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issues (burnout, inter-turn faults, and insulation damage) together represent 57 % of total failures, confirming that stator winding reliability is the critical factor in motor longevity. To better visualize this distribution by main categories, a generalized summary is presented in Table 2.

Table 2

Generalized distribution of failure categories in asynchronous motors [author's calculations based on 5]

No.	Failure category	Total share, %	Number of types
1	Electrical faults (winding burnout, inter-turn, phase loss, rotor bar)	59 %	4
2	Mechanical faults (bearings, core fixation, air gap, imbalance, etc.)	41 %	6
3	Stator-winding-related failures (combined)	57 %	3

Based on the obtained failure analysis, the following modern maintenance approaches are recommended for improving asynchronous motor reliability. Condition-based monitoring and diagnostics: real-time sensors for vibration analysis, temperature monitoring, stator current signature analysis (MCSA), and acoustic emission detection enable early identification of incipient faults. Predictive maintenance based on these data reduces unplanned downtime and extends component life [6, 7, 17].

Material modernization: replacement of worn components with high-temperature-resistant enamel coatings and laminates for windings, and corrosion-resistant materials for bearings and mechanical parts, significantly enhances operational reliability [10, 18]. Precision machining: CNC-based grinding and polishing of commutators and contact rings eliminates surface irregularities, reduces friction and sparking, and extends the service life of these components [5].

Thermal and chemical treatment: controlled drying of windings and insulation, application of electro-insulating varnishes, and chemical removal of corrosion and oxide layers preserve insulation integrity [11, 18]. Automated lubrication and cooling: installation of forced lubrication systems for bearings and sensor-controlled ventilation channels ensures adequate cooling even under maximum load conditions, preventing thermal degradation [4, 9].

Traditional maintenance approaches, while effective for routine repairs, are insufficient for addressing the challenges posed by modern industrial

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environments with variable loads and high duty cycles. The integration of condition monitoring, advanced materials, and automated systems represents a paradigm shift toward reliability-centered maintenance that can substantially reduce failure rates and improve energy efficiency.

CONCLUSIONS AND SUGGESTIONS.

This study analyzed common failure modes in asynchronous motors and their statistical distribution, with particular emphasis on stator winding faults under maximum load conditions. The following key findings were established.

First, electrical faults, primarily stator winding burnout and insulation degradation, constitute the majority (59 %) of asynchronous motor failures. Stator winding-related issues alone account for 57 % of all faults, which confirms that the stator winding insulation system is the most vulnerable element of an induction motor and should be the primary focus of reliability-centered maintenance.

Second, maximum load operation accelerates insulation aging through the combined action of thermal, electrical, and mechanical stresses. The Arrhenius relationship confirms that every 8–10 °C temperature increase halves the insulation life, which makes thermal stress the dominant aging factor among the three.

Third, modern electromechanical maintenance methods, including real-time monitoring, advanced insulation materials, CNC machining of commutators, and automated cooling and lubrication systems, significantly improve motor reliability and extend service life compared to conventional periodic maintenance approaches.

Fourth, the equivalent power method provides a reliable framework for verifying motor rating selection under variable load conditions, ensuring that the motor operates within safe thermal limits and that both $P(eqv) \leq P(nom)$ and $M(max) < \lambda \cdot M(nom)$ conditions are satisfied.

Practical recommendations following from this analysis are: introduction of MCSA-based online diagnostic systems for critical motors; gradual replacement of conventional starting equipment with soft starters and VFDs to limit electrodynamic stress during start-up; transition from time-based to condition-based maintenance schedules; and use of advanced enamel insulation systems for motors operating in overload-prone regimes.

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