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Analysis Failure Modes for Design Reliability to Improve Performance of Mechanical Equipment (Case study of a water pump)

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ABSTRACT

This paper presents a methodology for failure analysis and performance optimization of industrial components while ensuring optimal design reliability. This approach integrates Failure Pattern and Effects Analysis (FMEA) with Failure Tree Analysis (FTA) and is applied to an electric motor driving water pumps. The research aims to identify the most impactful failures, determine their causes, and propose alternatives that significantly reduce maintenance costs. An optimal distribution (exponential distribution) of the data sets was proposed using Minitab software. The design is validated using the proposed methodology to continuously evaluate the failure pattern. These results guide the intended design modifications, which are subsequently verified through iterative testing of the relevant equipment components.

1. Introduction

The development of modern technology, particularly in industry, has led to a significant increase in research related to product design to ensure reliability. Aventura and van der Wharf emphasize the importance of reliability analysis in the conceptual design phase. It has been proven that design can be improved by applying reliability analysis techniques at this stage. The risks and effects of failures can be reduced and managed by using effective and efficient maintenance procedures, even though they cannot be totally prevented [1]. Mechanical failure is any change or any design or manufacturing error that renders a component, assembly, or system incapable or performing is prevent failure due to repeated loads, the product should be designed by selecting the appropriate shape and material to ensure its strength and rigidity. This is achieved by identifying and diagnosing potential product defects [2]. The most influential and important factors can be used to describe the mechanisms of component failure that may lead to performance malfunction:

1) The loads or stress applied to the structure.

2) The kind and form of materials utilized Physical and functional failures can be identified, categorized, and their severity can be determined using fault analysis, which is based on field failure data.

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Fault Pattern, Effects, and/or Fault Pattern and Effects Analysis (FMEA) are used to do this. In order to increase system/component reliability, FMEA/FMECA analysis is usually employed as a preventative tool, especially during the design phase. It is also advantageous during the operating phase. The goal of FMEA/FMECA analysis is to give a thorough evaluation of how each fault pattern affects every system component [3].

The importance of reliability has increased significantly in recent years, primarily due to the complexity of large systems and the consequences of their failures. This leads to decreased operational efficiency, increased maintenance costs, and, most importantly, can endanger human lives, there are substantial costs associated with failures that occur during the warranty period. Reliability is defined as the probability of a system performing within the required parameters for generating output over a specific period when used under given conditions [4]. It is an indicator of a product's ability to maintain its quality over time, that is, to operate efficiently under a given set of operating conditions. It is defined theoretically as (Reliability = 1 − Probability of Failure), which is represented by R(t). Reliability is associated with availability and maintenance, which are considered to be crucial elements of it [5].

FMECA is a method known as failure pattern analysis, which assesses failure patterns, their impact, and their sensitivity. This analysis relies on the probability and severity of a failure pattern to classify failures, determine the probability and severity of the pattern, assess detectability, and identify necessary corrective actions. Overall, this leads to reduced costs and increased system and/or product reliability [6]. Fault Tree Analysis (FTA) is a logical methodology that details and graphically analyzes the various ways a specific fault pattern can occur, as well as its probability of occurrence. FTA is applied to specific fault patterns, which are constructed as a tree using symbols to represent three levels (upper, middle, and lower) of events and binary logical relationships. This allows for the different probabilities of faults to be assessed and their relative contribution to understanding overall risk [7].

Failure analysis is a cornerstone of reliability and safety engineering, contributing to the identification and classification of potential failure causes based on their impact on system performance. Given the complexity of modern engineering systems across all industrial sectors, relying on a single analytical tool is no longer sufficient to guarantee a high level of reliability. Therefore, it has become necessary to integrate multiple methodologies to leverage the advantages of each and compensate for the weaknesses of others.

Zhichao Wang et al. (2020) [8] presented a new methodology for Failure Pattern and Impact Analysis (FMEA) based on the Extended Physical Element Model and the Analysis Hierarchy Process (AHP) to assess and prioritize failure pattern risks.

In a study of a water pumping station, **Bouyaya & Chaib (2022)** [9] demonstrated that the (Structured Analysis Design Technique) tool was used to analyze the system into its components. Then, FMECA (which combines FMEA with critical factor analysis) was applied to evaluate the failure patterns associated with each component and select an appropriate maintenance plan. The study showed that assessing the availability of critical components in a pump motor system after 24 months of operation provides practical recommendations for improving reliability.

Study by **Pratama & Surya (2025)** [10], FMEA was applied to a pump motor in a water treatment plant. 430 failure cases were analyzed, and the results showed that "motor fault" was the most critical failure pattern, measured by RPN. The study also revealed that the most common failure patterns included motor cable breakage and motor burnout. The study analysis failure patterns and their effects, enabling the researcher to establish recommendations for the proposed corrective actions that led to improved engine operation, reduced damage, and consequently increased equipment reliability and overall operating efficiency.

Befekadu et al. (2026) [11] an integrated methodology combining Reliability-Centered Maintenance (RCM) and Failure Pattern and Effects Analysis (FMEA) is employed. This involves identifying key failure factors (misalignment, vibration, high rotational speeds, and excessive wear) and their impact on availability, safety, and production. The goal is to improve reliability and thus identify the causes and impact of potential failures on system production.

Fault tree analysis (FTA) focuses on identifying the conditions and elements that lead to, or contribute to, a specific peak event. A fault tree is a model that explains the relationship between operator errors, underlying system failures, and the occurrence of an event associated with the system's inability to function correctly, as illustrated in the studies presented below [12]:

Krzysztof Boryczko et al. (2022) [13] study showed that fault tree analysis can analyze the risks threatening the performance of the system operator in a selected water treatment process, because it analyzes the initial events leading to an emergency, clarifying the cause-and-effect relationships.

The results of the study presented showed **Lin CHEN and Cheng (2023)** [14] quantitative failure tree analysis, which identified the failure factors affecting the normal operation of the gears, thus revealing weaknesses and clarifying the failure patterns and mechanisms that cause gear failure in the system.

Georgi Todorov et al. (2025) [15] FTA used to determine the connections between subsystem and component failures that could impact system dependability and cause an unwanted initial event. This made it possible for the researcher to provide an approach for examining failure patterns and how they affect large-scale hydraulic devices. Given the complexity of modern engineering systems across all industrial sectors, relying on a single analytical tool is no longer sufficient to guarantee a high level of reliability. Therefore, it has become essential to integrate multiple methodologies to leverage the advantages of each and address the weaknesses of others. This has led to the integration of two approaches FMEA and FTA as shown in Table 1.

Table 1. Literature Review integration FMEA and FTA

Researcher's Name	Research Date	Sequence of Methods	Details
Peeters et al. [16]	2018	FTA-FMEA	used to assess the criticality of these modes and select only the critical ones.
Mahmood Shafiee et al. [17]	2019	FTA-FMEA	analyze and prioritize the risks of safety-critical systems.
Marianne Bogna et al. [18]	2024	FMEA- FTA	economic evaluation and the identification of critical points for improving overall device reliability and reducing production losses.
Arellano Ortega et al. [19]	2025	FMEA- FTA	Developing a specific architecture to identify critical failure patterns, and understanding the root causes among

			components to build an improved matrix for predicting and classifying failures at the system level.
Ammar Jakhrat et al. [20]	2025	FMEA- FTA	The systematic link between corrective actions and safety requirements provides a robust framework for improving reliability and mitigating risks in aviation systems that are critical to safety.

2. Methodology

Water pumps are a fundamental component of industrial pumping systems, and specifically thepump motor, which is the electromechanical nerve center of the system. Motor failures can stem from multiple and overlapping causes, including overheating, overloads, electrical faults, or mechanical problems with the bearings as shown in Figure 1.

Figure 1. Water pump motor

The main methodological problem is that Failure Pattern and Effect Analysis (FMEA) or Fault Tree Analysis (FTA) alone are insufficient for a comprehensive analysis of these failures [21]:

• FMEA uses an inductive, top-down approach, analyzing each component individually, but it cannot represent the interactions between different components.

• FTA uses a deductive, bottom-down approach, dealing with clusters of failures, but it is less effective at addressing symptoms and diagnostic signs at the individual component level, as illustrated in Figure2.

Therefore, this research proposes a four-stage methodological model to integrate the two tools, applying it to water pump motors.

Stage 1: System Analysis and Identification of Vital Functions

Stage 2: Performing a detailed FMEA analysis of the motor (At this stage, the potential failure modes for each component are identified)

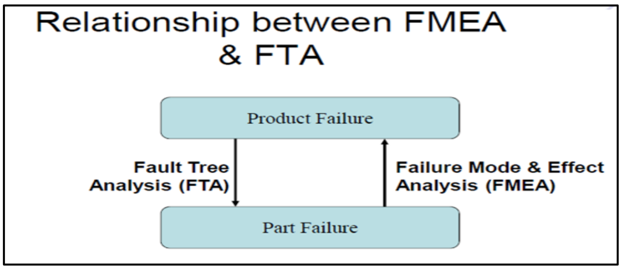


Figure 2. Relationship between FMEA [22]

Stage 3: Building a Fault Analysis Tree (FTA) for Motors

After FMEA is completed, the most impactful and highest failure rates of faults are identified, and the root causes of their occurrence are determined through FTA in a top-down manner, where the top event is selected from the FMEA outputs with the highest priority.

Stage 4: Feedback – Integrating FMEA outputs into FTA

This stage represents the core of integration. The fault sets identified by FMEA are transferred and added as "component failure modes" to the FTA. This process:

• Allows the detection of faults that only occur when two faults are present simultaneously (low oil + high temperature together leading to motor burnout).

• Transforms FMEA from a "one-dimensional" analysis tool to one that considers the system's fault causes.

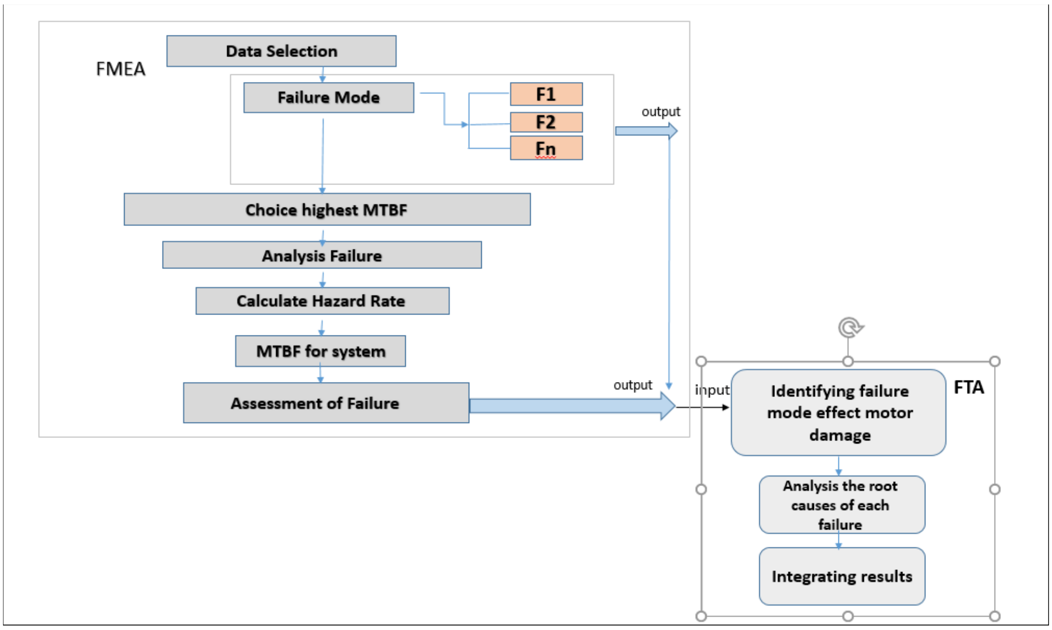


Figure 3. Experimental S-N curves of constant fatigue test for conditions

The electric motor is the mechanical product that we shall employ. Electric motors are the interface between a facility's mechanical and electrical systems; they are electromechanical devices that transform electrical energy into mechanical energy. • An essential component of any electrical system is an electric motor. They consume over 64% of all electricity produced and are utilized in all homes, offices, and manufacturing facilities. Since there are many various methods to construct a motor, there are many distinct kinds of motors, and each type has unique working characteristics. The motor can be selected for a particular application based on these features.

The most significant fault patterns considered in the electric motor can be illustrated in Figure (3). The average time between faults for the electric motor fault components in the range of (7000-25000) hours, as shown in the Table 2, and their frequency for each component (in hours), were analyzed using the Minitab software.

Table 2: MTBF Failure Mode

NO	Failure Mode	MTBF	NO	Failure Mode	MTBF	NO	Failure Mode	MTBF	NO	Failure Mode
1	bearing	25000	1	bearing	25000	1	bearing	25000	1	bearing
2	shaft & coupling	7000	2	shaft & coupling	7000	2	shaft & coupling	7000	2	shaft & coupling

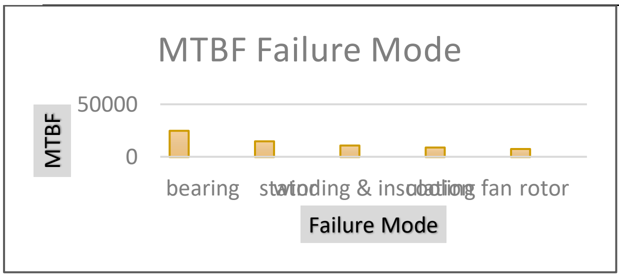
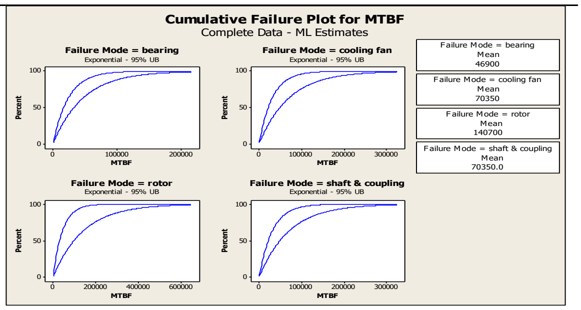
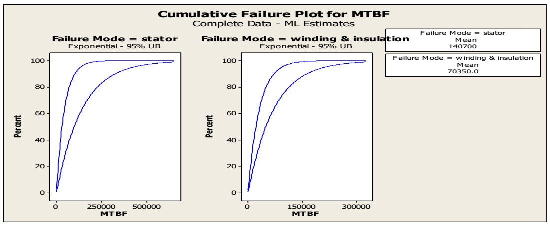


Figure 4. Pareto chart MOTOR (Failure Mode)



(a)



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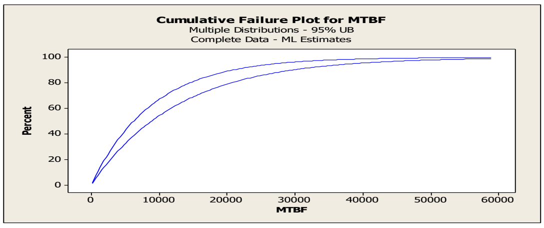

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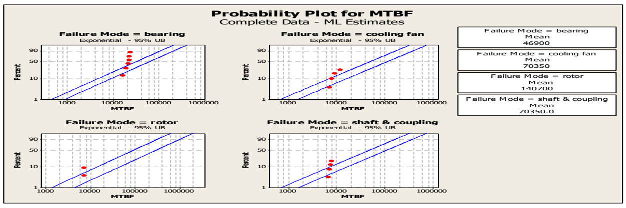
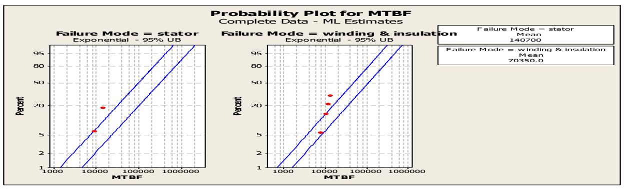
Figure 5. Probability failure plot for MTBF. (a),(b),(c)

3. Results and discussion

Figure (6) shows the probability of failure plots in an exponential distribution, illustrating the probability of the average time between failures. The average failure pattern had its highest value in the stator and rotor, while its lowest value was in the bearing.



(a)



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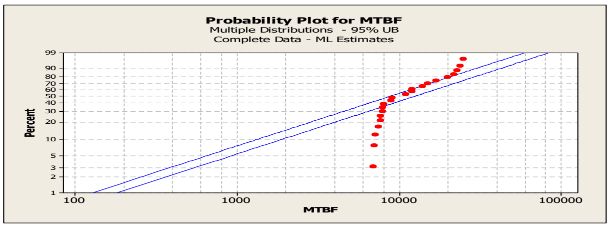

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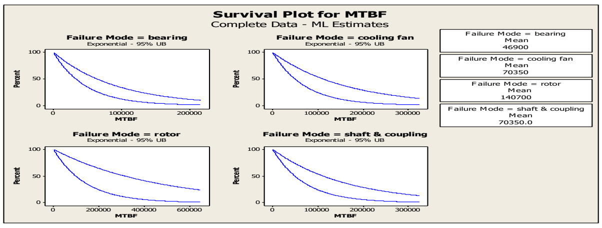
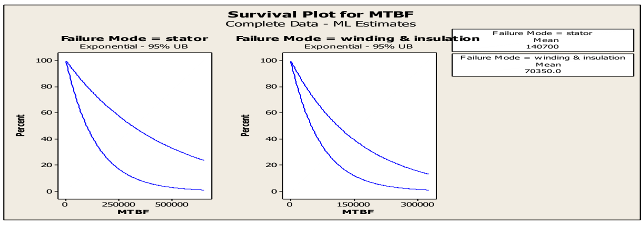
Figure 6. Parametric survival failure plot for MTBF. (A),(B),(C)



(a)



(b)

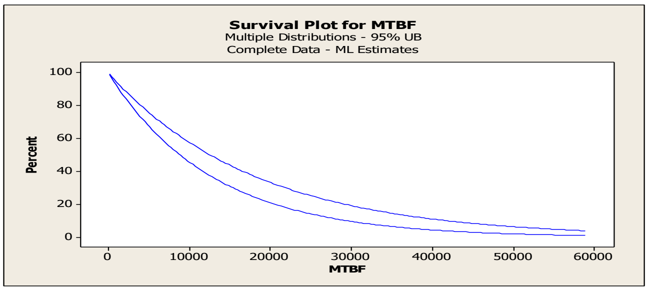


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Figure 7. Survival failure in the exponential distribution. (a),(b),(c)

Using the graphs, determine the Hazard rate **(λ)** of the components which is depend on the y-axis in the hazard plots. Then we can determine **F(t)** for each component which is depend on the hazard rate and the time (fixed time = 25000 hr.), and this is represented by this equation [23]:

$$\mathbf{F_{(t)}} = \lambda^{-\lambda t} \qquad \text{..................(1)}$$

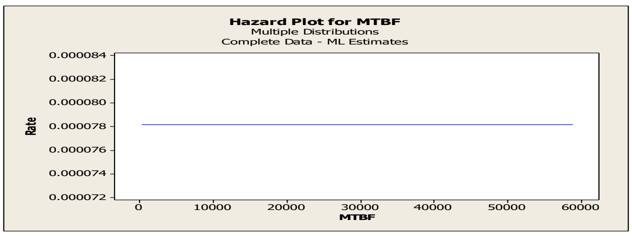

Figure 8. Parametric hazard failure plot for MTBF

When we found F(t) we can also found R(t) because it depends on F(t) of each component,

R (t) = 1 – F(t) ………………..(2)

Table 3. Data Analysis

component	Hazard rate (λ)	F(t)	R(t)
Bearing	0.000022	1.27×10^{-5}	0.9999873
Shaft	0.0000145	1.01×10^{-5}	0.9999899
Stator	0.00000715	5.98×10^{-6}	0.99999402
Rotor	0.0000072	6.01×10^{-6}	0.99999399
Winding	0.000014	9.87×10^{-6}	0.99999013
Cooling fan	0.0000140	9.87×10^{-6}	0.99999013

The R(t) value for each component was obtained, and by arranging them in a series and parallel network, the total R for each component, as well as the R for the system as a whole, was calculated.

R series = R1 × R2 × R3 × R4 × R5 × R6 …………………(3)

R series = 0.9999454712

In parallel network system we can determined R total by the equation [25]:
R parallel = 1 - Fs …………(4)
Where F(s) = F1×F2×…….Fn
R system = parallel = 4.49×10^{-31}

From Figure 8 the λ the system from the plot of the Hazard rate, to determined MTBF for the system, by this equation :

$$\mathbf{MTBF} = \frac{1}{\lambda} \quad \text{……………}\mathbf{(5)}$$

Where MTBFps is the parallel system mean time between failure and λ is the unit constant failure rate. Based on the calculations performed above, the faults of electric motors, their causes, effects, and signs that should be looked for in order to take early action to avoid them were identified and are shown in the Table (4).

Table 4 Causes, Effects Failure in Motor Pump

Problem	POSSIBLE CAUSES	EFFECT ON MOTOR	SIGNS TO LOOK FOR
Motor overload	Excessive current draw Insufficient torque	Damaged windings Broken shaft Damaged bearings	Overheating Reduced torque
Bearing current/ shaft current	Leakage current from the armature windings (DC motors) Non-symmetrical magnetic fields Induced voltage from a VFD	Bearing destruction	Noise Overheating Frosting of polished metal surfaces Premature grease darkening
High operating temperature	Inadequate motor cooling Wrong voltage supply Buildup of dirt or debris in motor fins Poor power quality Voltage imbalance Improper connections Wrong motor for application	Reduces effectiveness of lubricants Degrades windings	Motor is hot to touch Hot spots in motor windings
Voltage imbalance	Power quality issues Faulty circuits High resistance connections	Stress on each phase circuit Insulation breakdown Core losses	Excessive heat Vibration Noise Increased operating costs

From FMEA bearing is the most critical component, as it has the highest failure rate and will therefore be the first to fail over time under the same conditions and The same applies to the shaft and the stator.
Use Fault Tree Analysis (FTA) for a downward deductive analysis of faults, understand how systems fail, identify the best ways to reduce

risks, and determine (or sense) the incidence rates of safety incidents or a specific technique to rule out causes. This case study focuses on water pumps.

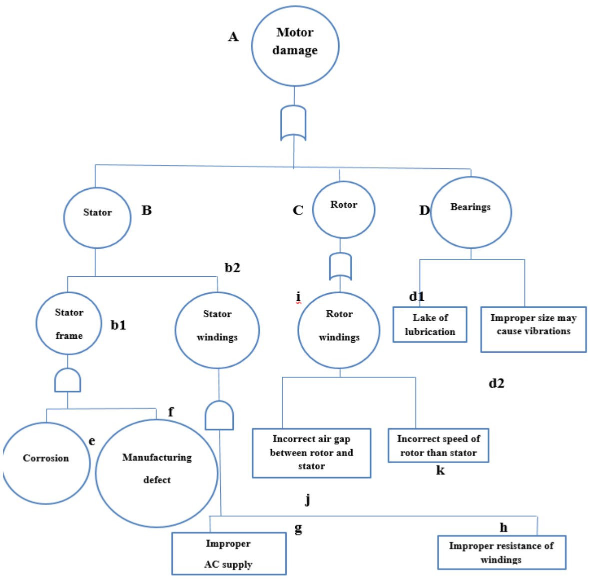

Figure 10. Fault Tree of the top events: A (Motor Damage)

4. Conclusions

The water pump motor is the core component of the pump's operation. There are numerous mechanical and electrical causes of motor failure. This research methodology investigated these failure causes by combining Failure Mode and Effects Analysis (FMEA) with Failure Tree Analysis (FTA)

By applying Failure Mode and Effects Analysis and calculating the risk level for each motor component, the most impactful faults were identified, representing the parts with the highest failure rates (Bearings being the first to fail, followed by other components Stator, Rotor).

Failure Tree Analysis (FTA) for each motor component, the most impactful failures were identified, representing the parts with the highest failure rate (bearings being the first to fail, followed by other components). The direct and indirect causes of failures and their sources were also identified using the fault tree analysis shown in Figure 10. Bearing failure is attributed to improper loading, resulting in vibrations and air gap defects. Rotor failure is caused by winding insulation leading to electrical disconnection, as well as inconsistent rotational speed. Stator failure is caused by overload and dry running, resulting in increased motor temperature.

This study aims to reduce water pump motor failures and minimize the costs associated with replacing faulty parts.

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