International Conference on Advances in Electrical-Electronics Engineering and Computer Science
9-10 November 2024, Ankara, Türkiye

SETSCI Conference Proceedings
19, 27-31, 2024

https://doi.org/10.36287/setsci.19.6.027
2687-5527/ © 2024 The Authors. Published by SETSCI

Failure Mechanisms in Enclosed Electric Motors Due to Insufficient Cooling at High Temperatures

Gizem Fırat[1*]

[1]*Koluman Otomotiv Endüstri A.Ş., University of Turkish Aeronautical Association, Ankara, Turkey*
[*](gizem.firat@koluman.com)

Abstract – This study examines the failure mechanisms of a three-phase AC induction electric motor with a closed body design, intended to provide IP protection, due to insufficient cooling under high-temperature conditions. Overheating at elevated temperatures adversely affects the motor's performance, leading to the deterioration of insulation materials and ultimately motor failures. The cooling performance of the motor, designed to rely on convection through its closed body design, has been evaluated in detail. During the experiments, temperature data were continuously recorded on both the inner and outer surfaces of the motor. The motor was operated at regular intervals under an 80% load, and its cyclic performance was monitored. The study also analyzed the effects of inadequate cooling on the motor's cycle life using analytical methods. The research findings aim to provide strategic recommendations for design and operational processes to improve the reliability of electric motors, particularly those used in military and industrial applications.

Keywords – Electric motors, Enclosed motor body, High temperature conditions, Accelerated life analysis, Overheating

I. INTRODUCTION

Electric motors are widely used in various fields, including industrial automation, transportation, and numerous engineering applications. These motors have become an essential part of modern technology due to their high efficiency and compact design advantages. However, the performance of these motors can vary significantly depending on operating conditions, particularly temperature levels. Electric motors operating at high temperatures may encounter several issues, such as wear and degradation of motor components. Insufficient cooling can lead to overheating in critical motor parts, which may trigger motor failures. High temperatures can negatively affect motor windings, insulation materials, and bearings, reducing overall efficiency and shortening the service life of the motor. Additionally, overheating due to insufficient cooling can result in electrical malfunctions, short circuits, and mechanical damage [1]. Enclosed electric motors play a crucial role in military systems, providing high durability and reliability under demanding conditions. These motors are designed to operate in harsh environmental conditions, making ingress protection (IP) ratings, particularly IP 67 and above, essential. IP protection ratings indicate the degree of protection that motors offer against external factors, particularly water and dust. Military applications often involve systems exposed to significant amounts of dust, water, humidity, and other challenging climatic conditions. Therefore, enclosed motor designs are vital to enhancing motor performance and longevity. These designs protect internal components through robust sealing features [2]. The impact of high temperatures on motor performance is a critical issue, particularly in military applications. Electric motors typically perform optimally within specific temperature ranges, depending on the operating conditions. However, high temperatures can cause thermal stress and wear in internal motor components, leading to decreased efficiency, power losses, and long-term failures. Enclosed motors face thermal management challenges under high-temperature conditions, which can result in performance loss and reduced motor lifespan. The effects of high temperatures include the degradation of insulation materials, changes in the viscosity of lubricants, and deformation of mechanical components. Therefore, understanding the impact of high temperatures on motor performance is crucial for optimizing motor design and maintenance processes [3]. Thermal management involves controlling the temperature of internal motor components and ensuring that these components remain within their optimal operating temperature range. Cooling techniques can range from passive methods, such as natural cooling, to active cooling systems. Natural cooling dissipates heat by exposing the motor's exterior surface to air, but this method is generally inadequate for high-power motors. As a result, active cooling techniques, such as fan cooling or liquid cooling systems, provide more effective solutions [4]. High temperatures can adversely affect the performance of critical components, such as windings, bearings, and other vital motor parts. The thermal properties of materials used in motor design play a significant role in thermal management. Consequently, motor manufacturers continuously research new technologies and materials to develop and optimize thermal management strategies [5]. In AC induction motors, heat generation mechanisms stem from various physical and electrical processes during motor operation. These mechanisms lead to the heating of motor components, impacting the motor's performance, efficiency, and durability. The energy loss that occurs as current passes through the resistance of the windings is one of the most significant factors contributing to motor heating. This loss, also known as Joule loss, is expressed as the square of the current multiplied by the resistance. Higher current values result in increased heat generation in the windings [1]. Magnetic losses occur in the stator and rotor cores of the motor. These losses consist of two primary components: hysteresis loss and eddy current loss. Hysteresis loss arises from the continuous change in the direction of the magnetic field, causing internal losses within the magnetic material. Eddy current loss results from circular currents induced within the core by the rotating magnetic field [6]. Mechanical losses are caused by friction between the moving parts of the motor and air resistance. Bearings, gears, and other mechanical components contribute to friction, which impacts motor performance and generates heat. Additionally, air resistance during rotor movement contributes to heat generation [7]. The insulation materials used in motor windings must operate effectively within a specific temperature range. High temperatures can cause the degradation of insulation materials, resulting in overheating of motor components. Insufficient insulation exacerbates heat generation mechanisms, leading to motor failures [8]. Motor operation under load is another critical factor that affects heat generation. When a motor operates under high load, it draws more current, which generates more heat in the windings and magnetic components. This heating can lead to motor overheating and potential failures [9]. This study aims to examine the failure mechanisms that enclosed electric motors face due to insufficient cooling at high temperatures. By addressing these issues, the study seeks to highlight the effects of these problems on motor performance and reliability, providing valuable insights into improving motor design, cooling strategies, and overall operational efficiency in various engineering and military applications.

II. MATERIALS AND METHOD

This study aims to examine the failure mechanisms encountered by enclosed electric motors under high-temperature conditions. Specifically, it focuses on the thermal stress, wear, and electrical failures that arise in the motor's internal components due to insufficient cooling. The tests are designed to assess motor performance at elevated temperature levels, analyze the effectiveness of cooling methods, and determine the durability of motor components. The materials used in the study and the methods followed are detailed below.

A. Test Motor

The motor utilized in this study is a 3-phase squirrel cage induction motor, powered by a 400V alternating current (VAC) supply. It features a 4-pole design and operates with a star connection configuration, which helps reduce the starting current, resulting in smoother operation and improved performance. The motor's rated speed is 1445 rpm, a critical parameter that directly influences its operational efficiency. Its rated power output is 1.5 kW, indicating the motor's capability to effectively manage a specified load. The motor’s torque capacity is specified at 10 Newton-meters (N·m), reflecting its ability to handle significant loads, and its high torque during start up offers a notable advantage for moving heavy objects. In terms of energy efficiency, the motor belongs to the IE3 efficiency class and has a heating rating of Class F. Additionally, its closed servo body design shields the internal components from external elements, enhancing its durability and enabling reliable, long-term operation. The motor is also equipped with two NTC (Negative Temperature Coefficient) temperature sensors, which continuously monitor its internal temperature, providing vital data for ensuring optimal performance and safety.

Figure 1 Test motor

B. NTC Sensors

NTC (Negative Temperature Coefficient) sensors are passive components that exhibit a decrease in resistance as temperature increases, and they are widely used in electric motors and various industrial applications. These sensors are made from semiconductor materials and play a crucial role in monitoring the internal temperatures of motors due to their sensitivity to temperature changes. NTC sensors are known for their low cost, fast response times, and high accuracy. The working principle is based on the reduction of sensor resistance as temperature rises, and this change is monitored through a voltage divider circuit. By continuously tracking motor temperatures, excessive overheating conditions can be prevented when temperatures exceed a certain threshold. The use of NTC sensors ensures the safe and efficient operation of electric motors while preventing damage caused by overheating [10]. Temperature measurements are carried out using NTC (Negative Temperature Coefficient) sensors. Due to their inherent structure, NTC sensors exhibit a parabolic curve at high temperatures, meaning that even the smallest changes in temperature can lead to significant variations. Specifically, calibration offsets need to be applied after reaching a temperature of 90 °C. In this study, two NTC sensors are integrated within the enclosure of a squirrel cage AC induction motor. These sensors were calibrated prior to the commencement of the testing process.

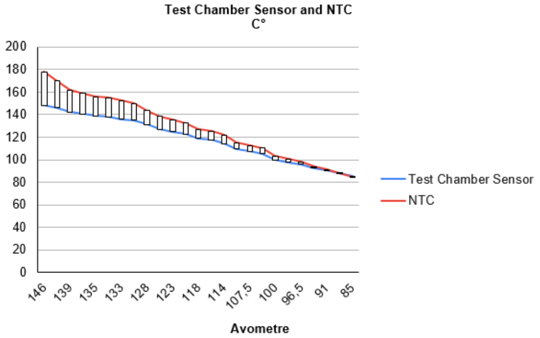

Figure 2 Test chamber sensor and NTC sensor data

C. Counter Load Test Setup

A dynamic counter load of 8 N·m has been applied to the motor during high-temperature testing conditions. A specialized test setup has been developed to impose this load on the motor, which is intended to evaluate its performance under realistic operating scenarios, simulating the actual loads the motor is expected to face. This dynamic counter load is essential for analyzing how the motor reacts to varying torque requirements, particularly in high-temperature environments. The testing apparatus is equipped with all the necessary components to monitor and assess the motor’s performance effectively. This includes load cells that continuously track the dynamic load exerted on the motor, control systems that aid in optimizing motor operation, and data acquisition devices that capture the information gathered throughout the motor's functioning, enabling a thorough performance evaluation.

D. Test Chamber

The testing was carried out in a chamber specifically designed to comply with military standards. This chamber has been certified according to MIL-STD-810G, Method 501.5, Procedure II, creating an optimal environment for thoroughly assessing the motor's performance under high-temperature conditions. This certification guarantees that the testing process adheres to international standards, thereby increasing the credibility of the acquired data. Furthermore, the chamber's control systems continuously monitor temperature and other environmental factors, ensuring that the motor operates under realistic conditions throughout the entire testing period. This configuration enables a comprehensive evaluation of the motor's functionality and resilience in extreme heat, allowing for precise analysis of its performance under the defined parameters.

E. Test Equipment

The materials used for this test include a closed-body squirrel cage AC induction motor, a thermocouple for acquiring temperature data from the motor casing, two NTC sensors located inside the motor, and control software that monitors the motor's temperature. The thermocouple continuously tracks the external surface temperature of the motor, providing critical data. The NTC sensors measure the internal temperature of the motor, supplying necessary information for performance analysis. The control software monitors the temperature throughout the test and reports an error, halting the test if a temperature above 135 °C is detected. These materials are vital for the safe and effective evaluation of the motor under high-temperature conditions.

F. Test Procedure

The test motor was assessed for functionality under high-temperature conditions following the guidelines of MIL-STD-810G Method 501.5 Procedure I for storage at a constant temperature of +63°C and MIL-STD-810G Method 501.5 Procedure II for operation at +50°C. Initially, the motor was connected to the test bench, and the procedural steps were carried out at room temperature, during which the relevant data was recorded. With no issues observed, the test chamber was adjusted to maintain a temperature of +63°C. Based on the thermocouple readings affixed to the motor casing, the temperature was stabilized at +63°C with a tolerance of 2 degrees, and a 4-hour acclimatization period was completed. Throughout this waiting phase, both the test setup and the motor remained unpowered. After the 4-hour waiting period, the temperature of the test chamber was reduced to +50°C. It was expected that the temperature reading taken from the motor casing would stabilize within a tolerance of 2 degrees. Once the temperature value was stabilized, a 2-hour waiting period was implemented. After the 4-hour waiting period, the high-temperature operation test for the motor began. The test protocol initiated with 2 minutes of operation under no load, followed by the application of a counter load of 8 N·m, which is 80% of the nominal torque capacity, for a duration of 6 minutes. This 8-minute duration was classified as one complete cycle. In total, 6 cycles were performed during the testing phase, resulting in the motor running continuously for a total of 48 minutes. Throughout this period, measurements of the motor's operating temperature, current, voltage, and torque values were recorded, allowing for close observation of the motor's performance. The collected data was then analyzed to evaluate the motor's functionality and durability when subjected to high-temperature conditions.

III. RESULTS

The operational testing commenced after a 6-hour waiting phase. For the initial 2 minutes, the motor was run without any load applied. At the beginning of the test process, the internal temperature of the motor was determined to be 50 °C based on the data obtained from the NTC sensor. Similarly, the temperature of the motor body was also measured at 50 °C according to the thermocouple data. Since the motor has an insulation class of F, the test software was set with a maximum temperature threshold of 135 °C. This setting establishes a critical limit for the safe operation of the motor. During the initial phase of the test, the motor was operated in an unloaded condition for 2 minutes. This unloaded operation is an important step for evaluating the basic functionality of the motor and for identifying any potential issues at the outset. As no problems were observed during the unloaded operation, the test progressed to the next stage. Subsequently, in order to realistically simulate the working conditions of the motor, a counter load of 8 N·m was applied, and the motor was operated for 6 minutes. During this phase, the performance of the motor under load was carefully monitored. When the motor began operating under load, the NTC sensor indicated that the internal temperature of the motor was 73 °C. This temperature serves as a significant reference point for the operational conditions of the motor at the start. At the end of the first cycle, the internal temperature of the motor reached 103 °C. Upon reaching this temperature, the rapid increase in the motor's temperature was regarded as a critical engineering concern. Therefore, it was decided to add a 1-minute waiting period at the end of each cycle in the software. This waiting period aims to help stabilize the temperature values of the motor at a more consistent level. After the waiting period, the motor began the second cycle at 99 °C and completed it at 120 °C. The motor was then allowed to rest again for 1 minute. The motor started the third cycle at 115 °C and reached a temperature of 136 °C during this cycle. This temperature indicates that the motor requires further cooling. At the end of the third cycle, the data from the motor's temperature sensor exceeded 135 °C, prompting an update in the software to raise the maximum protection limit to 155 °C. After applying a 1-minute waiting period, the motor began the fourth cycle at 121 °C and completed it at 147 °C. Following another minute of waiting, the motor started the fifth cycle at 138 °C. However, this cycle was halted by the software at the 302nd second due to the motor temperature exceeding 155 °C. Throughout the test process, the motor body temperature gradually increased to 85 °C. At this stage, the burning varnish odor emanating from the motor connector covers indicated that the motor was overheating and signaled a potential failure condition; therefore, the test was immediately halted. The test chamber was returned to room temperature, and temperature measurements from the motor body continued during this process. The test chamber reached room temperature in approximately 3 hours. By the end of this period, the surface temperature data collected from the chamber and reference samples measured 36 °C. However, the motor body's temperature was recorded at approximately 63 °C during this time. After returning to room temperature, the cooling process of the motor body was monitored. After a 1-hour waiting period, the temperature measurement indicated that the motor body temperature had decreased to 52.8 °C.

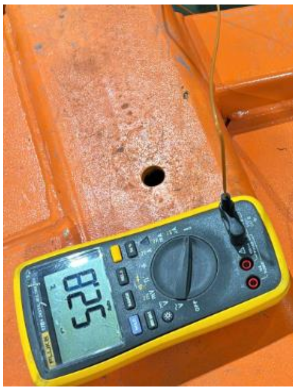

Figure 3 Motor body temperature measurement

Ultimately, following a total of 5 hours at room temperature, the motor body reached 28 °C, leading to the finalization of the test. The performance of the motor under high-temperature conditions was carefully monitored, particularly in relation to the temperature increase and the burning odor from the connectors. These observations raise questions about the effectiveness of the motor's cooling system and highlight the need for further improvements.

Table 1 High temperature test results

Phase & Waiting Time / Load Condition	**Temperature (°C)**	**Software Warning**
Initial State (No Load)	50	-
1st Cycle (Under Load: 8 N·m, 1 min wait)	73 → 103	-
2 nd Cycle (Under Load: 8 N·m, 1 min wait)	99 → 120	-
3 rd Cycle (Under Load: 8 N·m, 1 min wait)	115 → 136	Exceeded 135 °C, updated to 155 °C
4th Cycle (Under Load: 8 N·m, 1 min wait)	121 → 147	-
5th Cycle (Under Load: 8 N·m)	138 → >155	Test Stopped

IV. DISCUSSION

In this study, the performance of the motor under high-temperature conditions has been examined in detail. At the beginning of the testing process, it was observed that the internal temperature of the motor was 50 °C, which was confirmed by the data from the NTC sensors. During the first phase of the test, the motor was operated in an unloaded condition, and since no issues were observed, the performance of the motor was evaluated under realistic operating conditions. The tests conducted under load revealed the potential for the motor to overheat and provided critical data regarding the reliability of the motor. The rapid increase in the motor's temperature is a matter that must be considered from an engineering perspective. Notably, during the first cycle, the motor's temperature reached 103 °C, and it was observed that the one-minute waiting periods added at the end of each cycle were an effective method for controlling the temperature rise. However, at the end of the third cycle, the motor's temperature exceeded 135 °C, raising significant concerns about the effectiveness of the cooling system. Updating the maximum protection level in the software to 155 °C was one of the precautions taken to ensure the safe operation of the motor. Nevertheless, the motor's temperature exceeding 155 °C during the fifth cycle indicates that the motor design and cooling system require further improvements. Due to the high IP protection ratings frequently demanded in military systems, motor body designs have evolved into fully enclosed structures. While high IP protection requirements provide resistance to dust and sand and ensure leakage protection, they can negatively impact motor performance and lifespan. This study has highlighted the adverse effects of operating a fully enclosed AC induction motor solely relying on surface cooling (convective cooling). These findings assist in identifying the necessary requirements for improving the durability and performance of the motor under high-temperature conditions. Developing a more effective cooling system against overheating situations will enhance the overall efficiency of the motor.

V. CONCLUSION

In conclusion, this study has comprehensively evaluated the performance of the AC induction motor under high-temperature conditions. Throughout the testing process, the motor was operated with a starting internal temperature of 50 °C, and excessive heating tendencies were observed during load tests. The one-minute waiting periods applied at the end of each cycle helped control the temperature increase; however, the motor exceeding 135 °C during the third cycle raised concerns about the effectiveness of the cooling system. The adjustment of the software's maximum protection level to 155 °C stands out as a protective measure. It has been emphasized that fully enclosed motor designs are beneficial for meeting high IP protection requirements, yet they also introduce thermal management issues. These findings highlight the need for improved cooling solutions to enhance the durability of motors under high-temperature conditions. Future studies should focus on optimizing designs and cooling systems to ensure the reliable operation of motors in extreme conditions.

REFERENCES

[1] M. H. Rashid, "Performance Analysis of Squirrel Cage Induction Motors under Different Load Conditions," IEEE Transactions on Industry Applications, vol. 55, no. 3, pp. 2385-2392, 2019.

[2] J. Smith and R. Davis, "Induction Motors in Harsh Environments: Military Applications," Defense Technology Review, 2016.

[3] M. S. V. R. Mohan, "Electrical Failures in Induction Motors: Causes and Prevention," in Proceedings of the IEEE Industrial Applications Society Annual Meeting, pp. 1-8, 2018.

[4] S. K. Jain and K. R. Ranjan, "Cooling Techniques for Electric Motors," International Journal of Electrical Engineering and Technology, vol. 9, no. 1, pp. 15-24, 2018.

[5] T. K. Gupta, "Advancements in Cooling Technologies for Induction Motors," Journal of Electrical Engineering and Technology, vol. 17, no. 3, pp. 215-222, 2020.

[6] A. P. Singh and B. R. Sharma, "Energy Efficiency Challenges for Induction Motors in Cold Environments," International Journal of Energy Research, vol. 45, no. 9, pp. 1230-1240, 2021.

[7] K. R. Ranjan and S. K. Jain, "Challenges in the Speed Control of Squirrel Cage Induction Motors," International Journal of Electrical Engineering and Technology, vol. 9, no. 1, pp. 15-24, 2018.

[8] J. H. Wang and M. K. Li, "Thermal Analysis of Squirrel Cage Induction Motors Under Low Temperature Conditions," Journal of Thermal Engineering, vol. 6, no. 1, pp. 200-209, 2020.

[9] S. K. Jain, "Cooling Techniques for Electric Motors," International Journal of Electrical Engineering and Technology, vol. 9, no. 1, pp. 15-24, 2018.

[10] J. Lee and J. Hwang, "Performance Analysis of NTC Thermistors for Motor Temperature Control," Journal of Electrical Engineering & Technology, vol. 11, no. 2, pp. 576-582, 2016.