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Analysis of Inrush Current Loads in Electric Motors in Low Temperature Tests

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Abstract – This study examines the effects of inrush current loads on electric motors operating under low-temperature conditions. While electric motors have a wide range of applications in industrial and military environments, they face significant performance challenges in low-temperature settings. In particular, inrush current loads reduce the efficiency of the motor, leading to overheating, wear, and, ultimately, component failure in long-term use. In this study, the fluctuations in inrush current occurring under low-temperature conditions were evaluated. Experimental data reveal that when the motor operates in low temperature environments, current loads increase significantly, which, in turn, raises the motor's energy consumption. The focus is on the necessity of improvement strategies, particularly for electric motors used in harsh military applications. The research also explores strategies to manage inrush current loads at low temperatures. In conclusion, this study highlights the negative effects of inrush current loads experienced by electric motors under low-temperature conditions and suggests design and operational improvements for motors operating in such environments.

Keywords – Inrush current, Surge current, Cold environment operation, Operational enhancements, Design improvement

I. INTRODUCTION

Electric motors are widely used in various areas of industry and have an important place in military systems with the development of the defense industry. In this context, reliability is one of the most important criteria for military systems, and induction motors meet this need by offering long-term and trouble-free operating performance thanks to their robust and simple structure [1]. Their brushless construction makes them more resistant to wear, thus minimizing the need for regular maintenance [2]. Additionally, the absence of wearable components such as brushes or commutators reduces maintenance costs and frequency, which in turn allows for a reduction in maintenance time and costs in military operations [3]. Especially in applications that require low noise, such as submarines and unmanned aerial vehicles, the silent operation of induction motors offers a significant advantage, as it reduces the risk of detection [4]. Additionally, induction motors play an effective role in reducing the costs of military operations due to their high efficiency and low energy consumption. Their high starting torque supports the efficient operation of military vehicles carrying heavy loads [5]. AC motors help reduce energy consumption in military vehicles by providing high energy efficiency, which is critical, especially in battery-powered systems [6]. Squirrel cage rotor induction motors are among the most widely used types of electric motors. These motors are long-lasting because they do not contain wear-prone parts such as brushes and commutators [7]. However, the use of these motors also comes with some disadvantages. First of all, the speed control of squirrel cage induction motors is the most complex among alternating current motors. The motor speed varies depending on the supply frequency, which necessitates the use of additional systems, such as variable frequency drives (VFDs), to control the speed of the motor. Therefore, this increases both cost and system complexity [8]. In addition, squirrel cage induction motors may initially fall short in applications that require high torque. The starting torque may be insufficient under certain load conditions, which can be problematic when heavy loads need to be started suddenly [9]. In long-term operation, these motors may experience heating problems, and overheating can adversely affect their performance and increase the risk of failure. Therefore, it is crucial to design appropriate cooling systems [10]. Low temperature ambient conditions can cause some disadvantages that adversely affect the performance of these motors. For example, low temperatures increase the viscosity of the motor's oils, which raises the coefficient of friction and creates more resistance between the moving parts. As a result, the operation of the motor becomes difficult, and energy efficiency decreases [11]. Under low temperature conditions, the starting torque of squirrel cage induction motors can also be reduced. In cold weather, the motor can produce low torque while drawing more current than normal, making it difficult to operate heavy loads [12]. At low temperatures, motors usually operate by consuming more energy; this can create heating problems in the internal structure of the motor, and overheating reduces its efficiency and increases the risk of failure [13]. Low temperatures can also reduce the overall efficiency of the motors. Cold weather adversely affects their operation, leading to increased energy consumption and significant cost increases in long-term operation [14]. Finally, low temperatures can affect the physical properties of the motor's materials. In particular, insulation materials can lose their mechanical strength in cold weather, which can lead to electrical failures [15]. In this study, the performance of a 3-phase squirrel cage induction motor under low temperature conditions was investigated. The motor was subjected to a test temperature of -33°C in accordance with MIL-STD-810G, Method 502.5, Procedure II. MIL-STD-810G is a document developed within the scope of military standards, designed to ensure the durability of military equipment, systems, and materials against various environmental conditions. This standard provides a set of testing and evaluation methodologies for assessing the performance of military equipment in different climatic and environmental conditions. In this context, Method 502.5 was developed specifically to analyze material and system performance under low temperature conditions [16]. The standard establishes the criteria necessary to ensure the reliable operation of military systems in harsh conditions. These criteria cover parameters such as freezing, material deformation, functionality of internal components, and overall durability. Low temperature tests stand out as a critical requirement for adapting to the climatic conditions specific to the regions where military operations are conducted, ensuring that the equipment performs its duties effectively. The reliability and performance of electric motors are especially critical in military applications. In this context, understanding how the motor operates under low temperature conditions is essential for the design and implementation processes. The test process began with conditioning the motor at a temperature of -33°C for 6 hours. This conditioning time is critical for observing the effects of low temperature, such as the increased viscosity of engine oils, and for assessing the impact of these effects on engine performance. The inrush current can cause the current drawn by the motor at startup to be several times the rated current. This high current can lead to overheating of the windings and other components of the motor. Overheating shortens the life of the motor and can cause various malfunctions. This effect becomes even more pronounced, especially under low temperature conditions [17]. Additionally, the inrush current can place an overload on the electrical components inside the motor, which can lead to electrical faults such as short circuits in the windings or insulation breakdown. Low temperature conditions can increase the likelihood of such failures occurring [18]. Low temperature conditions can affect the mobility and efficiency of the internal components of electric motors, making it difficult for the motor to operate effectively. The motor under test is a 3-phase AC motor with a speed of 1445 rpm, a power of 1.5 kW, and a torque of 10 N·m. These characteristics make it suitable for a variety of applications, while also highlighting the performance issues that can be encountered at low temperatures. In particular, the high starting torque of the motor offers a significant advantage when heavy loads need to be moved. However, within the scope of this study, analyzing the peak currents experienced by the motor during startup is a critical component for understanding its performance under low temperature effects. During the test, the motor was driven by a counterload with a capacity of 8 N·m. This load provides a scenario that closely resembles the actual operating conditions of the motor, allowing for observation of how it performs under low temperature effects. Thus, critical parameters of the motor, such as low-temperature starting currents and torque generation, were examined. As a result, this study aims to systematically evaluate the effects of low temperature environments on the performance of 3-phase squirrel cage induction motors and to analyze inrush peak currents. The findings will provide important data for the design and use of electric motors in military and industrial applications and will contribute to future motor development processes.

II. MATERIALS AND METHOD

In this section, the materials used and the methods applied for the analysis of the inrush current loads of the 3-phase squirrel cage induction motor under low temperature conditions will be presented. In the study, a special test procedure was developed to determine the critical parameters affecting the performance of the motor. Below are the details of the materials used in the test process and the methods applied.

A. Test Motor

The test motor used in this study is a 3-phase squirrel cage induction motor powered by 400 V alternating current (VAC). The motor has a 4-pole structure and is designed with a star connection. The star connection type reduces the starting current of the motor, resulting in more stable operation and thus increasing the performance of the motor. The rated speed of the motor is set at 1445 rpm; this speed is an important parameter that directly affects the performance of the motor. The rated power of the test motor is set at 1.5 kW, which indicates the motor's ability to effectively handle a given load. The torque capacity of the motor is determined to be 10 Newton-meters (N·m). This torque value reveals the load-carrying ability of the motor, and the fact that it produces high torque at startup provides a significant advantage in moving heavy loads. In terms of energy efficiency, the motor is classified in the IE3 efficiency class and has an F class heating rating. Additionally, the motor features a closed servo body structure that protects its internal components from external factors, thereby enhancing its durability and supporting long-term operation. The motor is equipped with two NTC (Negative Temperature Coefficient) temperature sensors. These sensors continuously monitor the internal temperature of the motor, providing critical data to ensure the performance and safety of the motor.

Figure 1 Closed body design test motor

The motor is controlled by a long-delay type circuit breaker. This type of circuit breaker is activated to protect the motor when a certain current limit is reached. However, unlike traditional circuit breakers, the long-delay type circuit breaker provides a range limit that varies over time rather than a single current limit. This feature allows for tolerance against temporary current surges that occur when the motor draws high current during startup, offering more effective protection against sudden and transient load fluctuations that can affect the motor's operation. As a result, it enhances the reliability of the motor while also helping to prevent unnecessary interruptions.

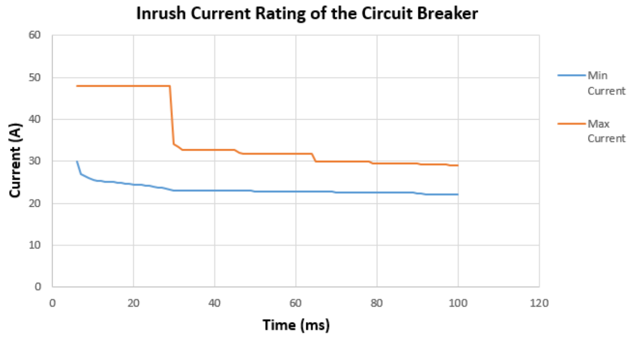

Figure 2 Inrush current rating of the circuit breaker

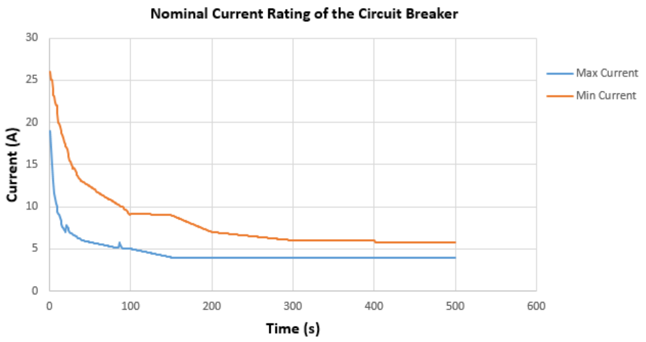

Figure 3 Nominal current rating of the circuit breaker

B. *Counter Load Test Setup*

A dynamic counter load of 8 N·m has been applied to the motor. A test setup capable of applying this load to the motor has been established. This arrangement is designed to evaluate the performance of the motor under real working conditions and simulates the load the motor will encounter during operation. The dynamic counter load allows for the assessment of how the motor responds to various torque demands and is a critical element for analyzing the motor's behavior, especially under low temperature conditions. The test setup includes all the necessary components to monitor and evaluate the motor's performance. These components consist of load cells, control systems, and data collection equipment. Load cells continuously monitor the dynamic load applied to the motor, while control systems assist in optimizing the motor's operation. Additionally, data collection equipment records the data obtained during the motor's operation, facilitating the gathering of information required for performance analysis.

C. *Test Chamber*

The test environment was conducted in a test chamber designed to meet military standards. This chamber has been accredited according to MIL-STD-810G, Method 502.5, Procedure II, providing an ideal setting for comprehensively evaluating the motor's performance under low-temperature conditions. The accreditation ensures the compliance and validity of the testing process with international standards, thereby enhancing the reliability of the data obtained. Additionally, the control systems within the chamber continuously monitor temperature and other environmental parameters, ensuring that the motor is exposed to realistic operating conditions throughout the test duration. This setup allows for a thorough assessment of the motor's functionality and durability in extreme cold, facilitating an accurate analysis of its performance under specified conditions.

D. *Test Equipment*

During the test, various equipment was used to monitor the motor's performance and record the data obtained. At the start of the test, an oscilloscope was employed to measure the motor's inrush current with greater precision. Since the inrush current is expected to be a short-lived phenomenon occurring within milliseconds, the oscilloscope was chosen for its ability to detect rapid and momentary current fluctuations with high accuracy. Once the motor's current stabilized, the initial measurements taken with the oscilloscope were followed by longer-term and steady current monitoring using a Fluke clamp meter. This process was conducted to verify the current readings under stable operating conditions. The clamp meter monitored the motor's steady-state current levels to detect any deviations in performance during the test.

Figure 4 Current measurement during the test

Thermocouples have been placed on the motor body, and inside the motor, there are two NTC (Negative Temperature Coefficient) sensors. These sensors are used to measure the external body temperature and the internal winding temperature of the motor, collecting crucial data during the test. This setup ensures continuous monitoring of the motor's thermal behavior, allowing for a detailed analysis of the temperature variations affecting both the outer surface and the critical internal components. The motor's circuit breaker box has been placed outside the environmental test chamber. This arrangement was made to prevent the circuit breaker box from being affected by temperature fluctuations, keeping it at a constant room temperature. By doing so, the impact of temperature conditions on the circuit breaker box was eliminated, allowing for a focused evaluation of the motor's performance under low-temperature conditions.

E. *Test Procedure*

The test motor was evaluated for functionality under low-temperature conditions according to MIL-STD-810G Method 502.5 Procedure I for storage at a constant temperature of -33°C and according to MIL-STD-810G Method 502.5 Procedure II for operation at a constant temperature of -32°C.

The motor was connected to the test bench and followed the test procedure steps at room temperature, during which the data collected was recorded. As no issues were observed, the test chamber was sent to -33°C. According to the thermocouple data connected to the motor body, the temperature was stabilized at -33°C with a tolerance of 2 degrees, and a 6-hour waiting period was completed. During this waiting period, the test setup and the test motor remained unpowered. Following the 6-hour waiting period, the low-temperature operation test of the motor began; the test procedure commenced with 2 minutes of no-load operation, followed by applying a counter load of 8 N·m, which corresponds to 80% of the nominal torque capacity, for 6 minutes. The total test duration of 8 minutes was considered as one cycle. A total of 6 cycles were conducted during the test, which means the motor was operated continuously for 48 minutes. Throughout the test, the motor's operating temperature, current, voltage, and torque values were recorded, and the motor's performance was observed. The obtained data was analyzed to assess the functionality and durability of the motor under low-temperature conditions.

III. RESULTS

The operation test was initiated following a 6-hour waiting period. During the first 2 minutes, the motor was operated in an unloaded condition. Throughout the test, the motor's inrush current was measured at 22 A, with a starting time of 132 ms. In preliminary tests conducted under ambient conditions, the motor's inrush current was recorded at 15 A, and the starting time was measured at 110 ms. These results indicate an increase in the motor's inrush current and an extension of the starting time under test conditions. At the 91st second of the test, the motor's fuse blew, resulting in the interruption of the supply voltage. Concurrently, at the 91st second, the current drawn by the motor was observed to be 5.1 A via a clamp meter. This situation is considered a consequence of the excessive current conditions encountered during the motor's startup process. During the test, it was observed that the current drawn by the motor gradually decreased from 8 A to 5.1 A by the 91st second. This indicates that the current value began to stabilize as the internal structure of the motor warmed up. The test setup was returned to its initial state and restarted. The first cycle was completed with 2 minutes of unloaded operation followed by 6 minutes of loaded operation. During the first cycle, the current drawn by the motor was observed to be 5.1 A. Without any interruption, the second cycle commenced. During this process, the motor casing temperature rose from -35 °C to 0 °C. The internal sensor data indicated a reading of 9.2 °C for the first sensor and 11.3 °C for the second sensor.

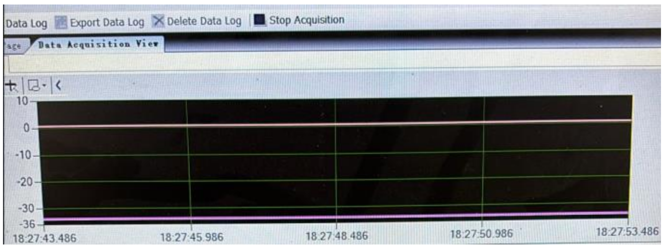

Figure 5 Motor body thermocouple temperature value

After completing the second cycle, the direction of the motor was reversed counterclockwise while transitioning to the third cycle. During the direction change of the motor, the circuit breaker tripped again. This event occurred as the motor was subjected to sudden load variations during the direction change, leading to an excessive current that triggered the protective mechanism of the circuit breaker. During the direction change of the motor, the current exceeded the fuse trip current of 24 A in conjunction with the counter load. The circuit breaker was reactivated. A 3-second waiting period was added to the test software during the motor's direction change, and the testing process continued accordingly. Starting from the third cycle, the motor successfully completed a total of 6 cycle tests, which corresponds to a duration of 32 minutes. Throughout the testing period, a significant increase in both the casing and internal temperatures of the motor was observed. At the end of the 6th cycle, the motor casing temperature reached 28 °C, while the internal temperature rose to 98 °C. These temperature increases are considered a result of the loads and environmental factors to which the motor was subjected under operating conditions. A total of 6 cycles were successfully completed in the tests conducted at room temperature. No waiting time was applied during the direction change, and the circuit breaker’s overcurrent protection limits were not exceeded. The motor’s internal temperature was measured at 68 °C, while the body temperature was recorded at 36 °C. The starting current was observed to be 16 A for 110 ms, and the maximum nominal current drawn by the motor was recorded at 3.8 A. In the low-temperature conditions, the starting current of the motor was noted to be 22 A for 132 ms. At the 91st second of the test, the circuit breaker cut off the supply due to excessive current draw without a load on the motor. Additionally, when transitioning to the third cycle, the power supply was also cut off due to excessive current during the motor's direction change. A 3-second waiting period was added during this direction change. The test under low-temperature conditions also completed a total of 6 cycles, with the internal temperature of the motor reaching 98 °C and the body temperature measured at 28 °C. During the test, the nominal current value of the motor started at 8 A and decreased to 4.6 A.

Table 1 Table 1. Test comparison data

Parameter	**Room Temperature**	**Low Temperature Condition**
Number of Cycles	6 cycles	6 cycles
Waiting Time	None	3 seconds
Circuit Breaker Status	Overcurrent limit not exceeded	Cut off due to overcurrent
Motor Internal Temperature	68 °C	98 °C
Motor Body Temperature	36 °C	28 °C
Starting Current	15 A (110 ms)	22 A (132 ms)
Nominal Current	Maximum 3.8 A	8 A - 4.6 A
Status at 91 Seconds	-	Cut off due to overcurrent
Direction Change Status	-	Cut off due to overcurrent

IV. DISCUSSION

The comparative analysis of tests conducted under room temperature and low temperature conditions reveals significant differences in motor performance and operational stability. In the tests carried out at room temperature, the motor successfully completed six cycles without any waiting time during direction changes and did not exceed the circuit breaker's overcurrent protection limits. The internal temperature of the motor was recorded at 68 °C, while the outer casing temperature was noted at 36 °C, indicating effective thermal management under these conditions. The starting current was observed to be 16 A for 110 ms, with a maximum nominal current recorded at 3.8 A, demonstrating the motor's capability to effectively handle the initial load. In contrast, the tests conducted under low temperature conditions presented distinct challenges. The starting current was recorded at 22 A for 132 ms, indicating a significant increase in electrical demand at startup. This led to an overcurrent situation at the 91st second when the motor was unloaded, resulting in the circuit breaker tripping. A similar overcurrent condition was observed during the motor's direction change before proceeding to the third cycle, necessitating a 3-second waiting time. Under low temperature conditions, the internal temperature of the motor rose to 98 °C, while the casing temperature was measured at 28 °C, indicating that the motor was subjected to significant stress. During the testing period, the nominal current decreased from 8 A to 4.6 A, which is correlated with the increase in internal motor temperature and rising electrical resistance over time. Rapid changes in internal and external temperatures during motor operation, particularly in low temperature conditions, can lead to condensation formation and short-term leakage current situations. The heating associated with low temperature conditions may cause the moisture in the air to condense, resulting in accumulation within motor components and a decrease in electrical conductivity. Condensation can lead to water pooling in critical parts, especially in the electric motor windings, triggering electrical problems such as short circuits and failures. Short-term leakage currents are directly related to this condensation, causing unwanted electrical currents to develop.

V. CONCLUSION

In conclusion, the comparative analysis of tests conducted under room temperature and low-temperature conditions has highlighted significant factors affecting motor performance and reliability. At room temperature, the motor successfully completed six cycles without any waiting time during direction changes, demonstrating effective thermal management. However, the challenges encountered under low-temperature conditions raise concerns about the operational reliability of the motor and negatively impact its performance. Notably, the increased starting current and the resulting instances of overcurrent in low-temperature conditions create stress on critical motor components, raising the potential risk of failure. Furthermore, considering the relationship between rapid temperature changes and condensation within the motor, the occurrence of short-duration leakage currents cannot be overlooked. These findings indicate the necessity for optimizing motor design and operational conditions to account for such scenarios. Thus, this research provides essential data that can guide future efforts aimed at improving motor performance and reliability. Consequently, it is critical to comprehensively evaluate environmental factors and temperature management strategies to ensure that motors can operate safely and efficiently under low-temperature conditions.

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