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RESEARCH ARTICLE

Thermal Monitoring and Modelling of Electrical Machine – A Mini Review

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ABSTRACT - The temperature of an electrical machine can affect its performance and lifespan, as high temperatures can lead to thermal stress, material degradation, and reduced efficiency. Therefore, thermal monitoring and modelling of electrical machines are crucial for ensuring their optimal operation and maintenance. This paper provides overview of the recent studies and developments in these two areas, highlighting their advantages, challenges, and applications. Focuses on two aspects of thermal management in electrical machines: monitoring temperature response and modelling temperature response. The paper also identifies some future research directions and opportunities for improving thermal management in electrical machines.

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1.0 INTRODUCTION

Electric machines are devices that convert electrical energy into mechanical energy. The reverse process, which involves the conversion of mechanical energy into electrical energy, is performed by an electric generator. This generator shares many similarities with a motor. The majority of electric motors function through the interaction between the motor's magnetic field and winding currents, which generates force. Electrical machines are frequently incorporated into equipment and utilized in various manufacturing processes, industrial applications, and automotive actuators and facilities [1].

According to prominent standardization organizations, insulation failure accounts for 30% of motor failures, with 60% of these failures [2] being caused by overheating [1]. Overheating in electrical machines can be attributed to several factors such as overloading [3], which forces the machine to work harder than its design permits. Environmental temperature [4], as a high ambient temperature makes it more difficult for the machine to effectively dissipate heat. And material properties, as some materials are better at conducting heat away while others may insulate the machines and trap heat within them. Overheating can lead to various issues in electrical machines such as demagnetization of permanent magnets [1], thermal aging insulation [3], and winding short circuits [1].

These failures highlight the importance of thermal management in electrical machines. To address thermal issues, strategies such as condition monitoring and thermal modeling of electrical machines can be employed. Therefore, this review paper will focus on the thermal aspects of electrical machines based on recent studies.

2.0 THERMAL INSTRUMENTATION IN ELECTRCIAL MACHINES

Condition monitoring in electrical machines involves overseeing the health status of these machines to detect anomalies and anticipate potential failures. Once a fault is detected, fault diagnosis comes into play to pinpoint the root cause. This monitoring is vital for maintaining optimal performance and longevity of the machines. The machine's temperature significantly influences its health and performance. Elevated temperatures can induce thermal stress, degrade materials, and diminish efficiency. Over time, these conditions can shorten the machine's lifespan and escalate maintenance costs. Various methods, such as thermocouples and thermal imaging, can be employed to monitor the temperature of an electrical machine.

2.1 System Architecture

A thermocouple instrument is a tool that measures temperature by leveraging the thermoelectric effect. It comprises two different metal wires, referred to as the thermocouple, joined at one end to create a junction. Various types of thermocouples, such as J or K type, use distinct metal combinations in the wire. The millivolt value given by the thermocouple at the cold junction compensation end signifies the temperature difference between the sensing end and the cold junction compensation end.

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Thermocouples are widely used in industries as they can measure a broad temperature range with a relative error of 1-2% [5]. In terms of motor condition monitoring, a thermocouple instrument can gauge the temperature of motor components like the winding, permanent magnet, rotor, casing, and bearing. This data can shed light on the motor's condition and performance issues such as overheating [6] or mechanical faults [7]. It can be utilized to optimize motor performance and ensure it operates within its recommended temperature range.

In summary, a thermocouple instrument is an invaluable asset for monitoring motor condition. It provides accurate and precise data for proactive maintenance and is extensively used in harsh conditions [8] due to its affordability, robustness, and reliability [6]. Due to robustness and reliability researchers used thermocouple as tool in data acquisition for the study. In Figure 1 shown the location of thermocouples implement in the induction motor by Quispe et al. [8] in order to measure temperature response of stator and rotor.

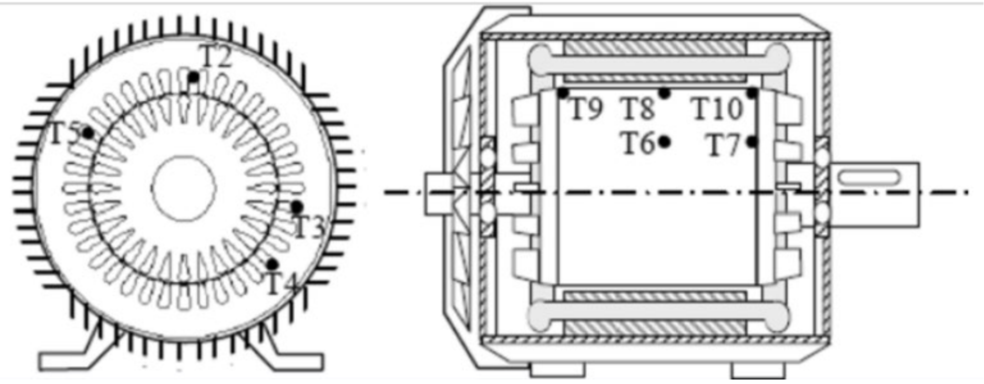

Figure 1. Stator and rotor thermocouple location.

Dong et al. [6] and Khan et al. [7] have proposed methods for detecting hotspots and functional abnormalities in induction motors. Quispe et al [8] have conducted an analysis and estimation of the derating performance of an induction motor under varying voltage conditions. In a separate study, Ganchev et al. [9] has discussed the design and development of rotor temperature monitoring. Thermocouples, known to have an average lifespan of 5 to 10 years that can be shortened if used in harsh environments, are a key focus of these studies. Fedosov [5] has proposed an algorithm for thermocouple condition monitoring based on variations in thermocouple resistance. Table 1 summarizes the research on the placement of thermocouples as data acquisition tools in electrical machines.

Table 1. Summary of application thermocouple in electrical machine.

Author	Application	Type of Motor
Quispe et al [8]	Rotor Winding	Induction Motor
Ganchev et al. [9]	Rotor	Induction Motor
Dong et al. [6]	Winding	Permanent Magnet Synchronous Motor
Khan et al. [7]	Winding	Induction Motor

2.2 Thermal Image

Thermal imaging is a non-contact, non-destructive method for measuring an object's temperature [10]. It uses the infrared (IR) radiation emitted from an object to create a visual temperature profile of the scene. The infrared spectrum is divided into different sub-bands based on their wavelength, which determines the intensity of the emitted IR. Thermal imaging technology uses this energy intensity to generate a temperature map of the captured scene. The primary component of a thermal imaging system is the thermal detector or sensor, which maps the incident IR to an appropriate temperature value. Thermal detectors are classified into three types based on their operating principle: pyroelectric, thermoelectric, and bolometer sensors. Thermal imaging-based sensors are even used in games to identify the effect of moral decisions based on the user's facial heat map [11].

In terms of motor condition monitoring, a thermal image instrument can be used to identify hot spots or areas of increased temperature on the motor and its components [10]. The instrument captures an image of the motor and displays it in a color-coded format, where different temperatures are represented by different colors [12]. But it is unable to detect the inside temperature if the inspected object is separated by a nontransparent for IRT radiation medium such as glass or other covers [13]. Overall, a thermal image instrument is a powerful tool for monitoring motor condition [12]. It provides a non-invasive and efficient way of assessing temperature variations on the motor's components and its surrounding environment [14]. Cause of great advantage from thermal image, Badoni et al. [10] extract the value of maximum temperature (T_{max}), minimum temperature (T_{min}) and average temperature(T_{avg}) from capturing the thermal images of the induction motor as Figure 2.

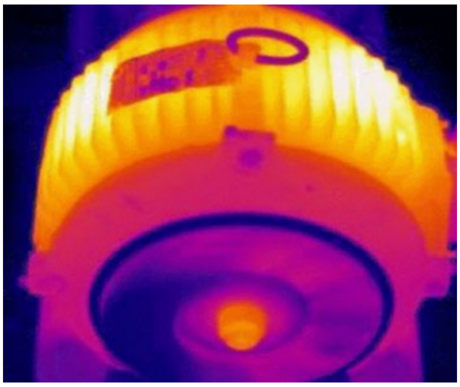

Figure 2. RGB image of induction motor.

Khamisan et al. [14] has proposed a histogram-based method to classify the variation in temperature behavior of bearings. Chaturvedi et al. [12] has studied fault detection and monitoring by presenting a color-based segmentation technique. Meanwhile, Chou et al. [13] and Ibrahim et al. [15] have proposed feature extraction and an optimization algorithm-based feature for an automatic diagnosis system. However, Badoni et al. [10] used infrared thermography to detect hotspots and analyze the thermal efficiency of a three-phase induction motor. Table 2 summarizes studies on monitoring electrical machines using thermal imaging with some feature extraction.

3.0 MODELING CONDITION OF ELECTRICAL MACHINES

Modeling the temperature response of electrical machines involves simulating the behavior of intricate thermal systems within these machines. The goal of this process is to forecast the distribution of temperature and the resulting stresses during operation. This is accomplished by employing numerical methods such as the finite element model and the lumped parameter thermal network (LPTN).

3.1 Finite Element Model

The Finite Element Method (FEM) is a numerical technique used to determine the electromagnetic parameters of electric machines. It uses the machine's geometry dimensions and material properties to provide results that are often more accurate than analytical analysis [3], [16]. FEM estimates the electromagnetic field [4] distribution and takes into account the machine's nonlinear effects to determine parameters such as electromagnetic field distribution, flux linkage, electromagnetic torques, flux density, and inductance.

In terms of temperature response, finite element modeling can predict temperature distribution and subsequent stresses during a process. It solves various physical problems using governing differential equations. The fundamental concept of FEM is to break down a large, complex geometry (like an electrical motor) into smaller, simpler elements [17]. Each of these elements is then individually analyzed, considering its specific material properties, geometry, and boundary conditions [3]. The results from all elements are combined to provide a comprehensive view of the temperature distribution and stresses within the entire motor. FEM is particularly useful for problems where analytical solutions are not available and is primarily used in complex geometries, loadings, and material properties [17]. However, it requires substantial computational resources and time. Despite these requirements, it enables a comprehensive examination of the motor thermal behavior. As depicted in Figure 3, Xie et al. [4] conducted a simulation of the winding at steady-state temperature. The temperature of the winding was found to be around 69 °C.

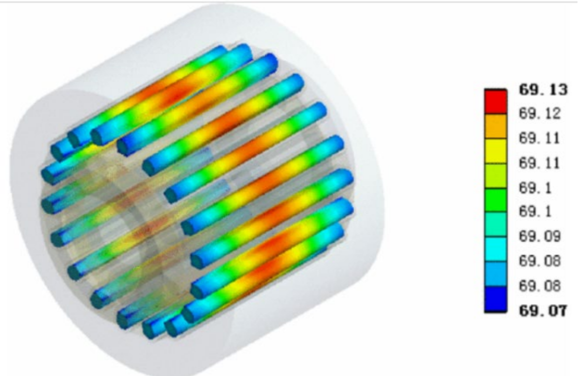

Figure 3. Temperature distribution of winding.

Xie et al. [4] and Zhao et al. [3] have proposed an estimation of the temperature rise in induction motors under rated load and overload conditions using a three-dimensional temperature model. Meanwhile, Anoop et al. [17] has proposed a thermal analysis method for monitoring the temperature of each part of the induction motor under healthy conditions using ANSYS Maxwell software. Chaieb et al. [16] and Wang et al. [18] have conducted an analysis and estimation of the thermal behavior and characteristics of permanent magnet motors under different conditions. Table 4 summarizes studies on the use of finite element models in modeling the temperature response of electrical machines.

Table 3. Summary of finite element model in electrical machine.

Author	Method	Type of Motor
Anoop et al.[17]	Thermal Analysis Method	Squirrel Cage Induction Motor
Chaieb et al.[16]	Analytical Model	Permanent Magnet Motor
Xie et al.[4]	Finite Element Method	Induction Motor
Wang et al.[18]	Finite Element Method and Heating Mechanism	Permanent Magnet Linear Motor
Zhao et al.[3]	Finite Element Method and Computational Fluid Dynamics	Induction Motor

3.2 Lumped Parameter Thermal Network

A Lumped Parameter Thermal Network (LPTN) model is a mathematical depiction of a physical system, such as an electric motor. It comprises interconnected thermal resistances, capacitances, and heat sources. This model presumes that the system can be divided into a finite number of discrete thermal nodes, each with a unique temperature and thermal capacity. These nodes are connected by thermal resistances, symbolizing the heat transfer between them. The term "lumped" in the lumped parameter model refers to the simplification of the complex distribution of temperature and heat flow in the system into discrete nodes. Liang et al. [19] has constructed a Lumped Parameter Thermal Model (LPTM) for a Permanent Magnet Synchronous Motor, as shown in figure 4. Figure 4(a) is used to understand the heat dissipation from the rotor to the stator, while figure 4(b) shows the complete construction of the LPTM for a Permanent Magnet Synchronous Motor.

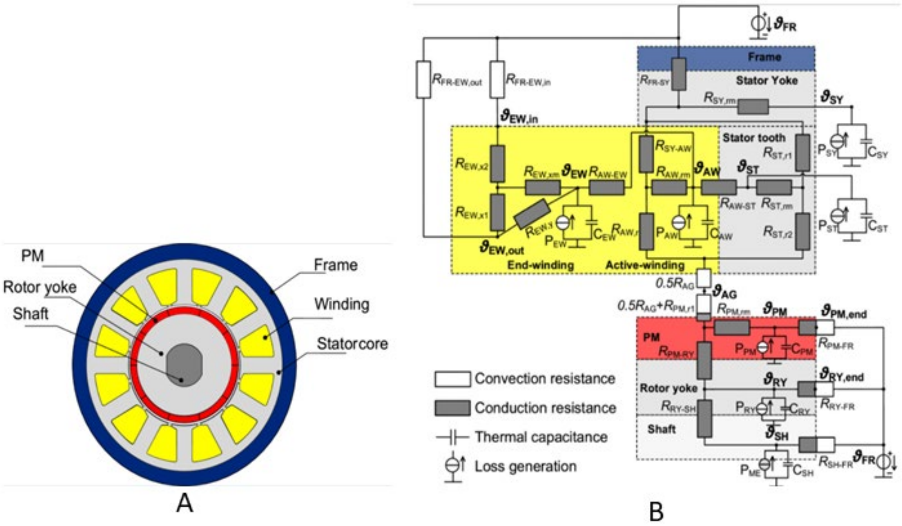

Figure 4. A) Cross section of PMSM, B) Complete T-type based LPTM for PMSM.

There are three methodologies for designing a Lumped Parameter Thermal Network (LPTN) for electric motor applications. Dark Gray-Box LPTNs utilize thermal networks of the lowest order (2–5 nodes) to model dominant heat paths and require minimal physical knowledge [20]. Light Gray-Box LPTNs model significant motor components at low local discretization levels based on heat transfer theory, with typical model orders ranging from 5–15 nodes [21]. White-Box LPTNs are modeled solely on material and geometrical motor data, with critical motor parts modeled at very high local discretization levels [22]. While white-box LPTNs allow for accurate modeling and hot-spot temperature estimation [23], they lead to large differential-algebraic-equation systems, making real-time execution infeasible for many cost-sensitive applications. Gray-box LPTNs estimate the component average temperature and lack hot-spot information [23], but their small node amount and reduced computational demand make them suitable for real-time temperature monitoring in many applications.

Several researchers have used LPTN as a thermal model in their studies. Wallscheid et al. [24] proposes an LPTN consisting of four nodes designed to estimate critical temperatures in permanent magnet synchronous motors. Liang et al. [19] presents a synergized approach that combines lumped-parameter thermal models and sub-domain thermal models for hotspot detection. Gaona et al. [1] proposes a combination of LPTN with speed-dependent Gopinath style in estimating permanent magnet and winding temperatures for permanent magnet synchronous motors. Meanwhile, Phuc et al. [25] studies the estimation of rotor temperature by proposing a virtual sensing strategy that combines an LPTN with stator windings temperature measurement. Paar et al. [26] develops an LPTN for real-time analysis and monitoring of the temperature of critical components of interior permanent magnet motors. Table 5 summarizes research on the use of Lumped Parameter Thermal Networks in modeling the temperature response of electrical machines.

Table 4. Summary of lumped parameter thermal network in electrical machine.

Author	Method	Type of Motor
Wallscheid et al. [24]	Four nodes LPTN	Permanent Magnet Synchronous Motor
Liang et al. [19]	LPTN and Sub-Domain Thermal Model	Permanent Magnet Synchronous Motor
Phuc et al.[25]	LPTN and Virtual Sensing Strategy	Induction Motor
Gaona et al. [1]	LPTN and Speed Dependent Gopinath-Style Flux	Permanent Magnet Synchronous Motor
Paar et al.[26]	Real-time LPTN	Interior Permanent Magnet Motor

4.0 CONCLUSION

The article highlights the benefits, challenges, and applications of these methods and techniques. In the monitoring method, the thermal characteristics can be classified and recorded due to the fast response from the instrumentation. However, there are challenges to face, such as the shortened lifespan of the thermocouple due to its use in harsh environments and the need for expert manpower in handling thermal images. The researcher focuses on detecting hotspots and monitoring thermal efficiency in electrical motors under varying load conditions. Meanwhile, the complex geometric areas in electrical motors can be estimated and studied for thermal behaviour through modeling methods. However, the success of the experiment requires substantial computational resources and time. The researcher focuses on estimating thermal characteristics using the FEM, while combining LPTN with other models to reduce computational time in estimating part temperatures in synchronous motors.

5.0 ACKNOWLEDGEMENT

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