TALLINN UNIVERSITY OF TECHNOLOGY
SCHOOL OF ENGINEERING
Department of Electrical Power Engineering and Mechatronics

ADVANCED THERMAL SOLUTION FOR ADDITIVELY MANUFACTURED ELECTRICAL MACHINES

KOLMEMÖÖTMELISELT TRÜKITUD ELEKTRIMASINATE SOOJUSIAHENDUSE ARENDUS

MASTER THESIS

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Tallinn, 2023

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THESIS ABSTRACT

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Abstract:

Conductors within an electrical machine induces the highest heat loss and technological advances has been made to improve efficiency thereby finding solutions to reduce the heat loss for a machine.The most common and widely used method is called a water jacket but the inherent disadvantages is the thermal resistance between the conductor and cooling medium. This restriction leads designers to implement alternatives such as end cooling. The advances in additive manufacturing have unlocked new potentials for conductors end cooling. This thesis propoes an additive manufactured conductor with an integrated end turns heat exchanger which is cooled by an integrated fan in the rotor as a solution.

Keywords: Electrical machines, Additive Manufacturing, Heat Exchanger, Winding, Convection, Master Thesis

LÕPUTÖÖ LÜHIKOKKUVÕTE

Autor: Hemenseter Henry Ahure	*Lõputöö liik:* Magistritöö
Töö pealkiri: Kolmemöötmeliselt Trükitud Elektrimasinate Soojusiahenduse Arendus	
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Töö juhendaja(d): Martin Sarap	
Sisu kirjeldus: Elektrimasina juhtmed tekitavad kõige suurema soojuskao ning tehnoloogilised edusammud on tehtud efektiivsuse parandamiseks ja lahenduste leidmiseks soojuskadude vähendamiseks masinas. Kõige levinum ja laialdaselt kasutatav meetod on veekate, kuid sellel on kaasasündinud puudused, näiteks soojusresistents juhtme ja jahutuskeskkonna vahel. See piirang sunnib disainereid kasutama alternatiivseid lahendusi, näiteks lõpukülmumist. Lisandtootmise tehnoloogia edusammud on avanud uued võimalused juhtmete lõpukülmumise jaoks. Käesolev lõputöö pakub välja lisandtootmisega valmistatud juhtme, millel on integreeritud lõpupöördussoojusvaheti, mida jahutab integreeritud ventilaator rootoris kui lahendus.	
Märksõnad: Elektrimasinad, Lisandite tootmine, Soojusvaheti, Kerimine, Konvektsioon, Magistritöö	

THESIS TASK

Thesis title in English:	**Advanced Thermal Solutions for Additively Manufactured Electrical Machines**
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Student:	**Hemenseter Henry Ahure, 212304MAHM**
Programme:	**Master Thesis**
Type of the work:	**Martin Sarap**
Supervisor of the thesis:	
Co-supervisor of the thesis: (company, position and contact)	**Validity period is given by supervisor**
Validity period of the thesis task:	Choose an item. Choose an item.
Submission deadline of the thesis:	**May 18th 2023**

Supervisor (signature) Student (signature) Head of programme (signature)

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1. Reasons for choosing the topic

Electric machines has been widely used in many industries such as the transportation industry. with the rising trend in electrification in transportation, higher power density and higher efficiency electric machines are demanded therefore more rigorous thermal management requirements are needed for electrified vehicle applications because high motor temperature can prevent a vehicle from meeting set quality and safety specifications.Heat, friction, and other elements along the path can all cause energy loss. Controlling heat enhances mechanical efficiency, especially when power density is rising. The correct cooling approach can lengthen the life of the motor and enhance lifetime efficiency by reducing insulation aging, keeping magnetic material below demagnetization temperature (in permanent-magnet machines), tolerating known limitations on power electronic components and lubricants, and limiting resistance.

2. Thesis objective

The aim of the thesis is to provide a solution for an electric machine by replacing the traditional copper winding by an AM conductor with an end turn heat exchanger without disturbing the standard operation of the machine but improving the thermal performance of the machine.

3. List of sub-questions:

List 3-4 specific research goals that you intend to achieve or find and answer to.

1. What is the Best AM Material to use?
2. How to integrate the solution without affecting the overall function of the machine?
3. How is this method beneficial?

4. Basic data:

The data will be gotten from research papers and also from testing of the 3d printed model.

5. Research methods

The results will be achieve by researching other papers similar to the task online and from online references of motor designs design a model of the the winding with end turn heat exchangers with a realistsic geometry and design an axial flux motor for testing the winding. Using Ansys to analyse the thermal performance of the winding using two different material (the traditional copper material and the AlSi10mg which is the material of choice)

6. Graphical material

- Table showing different mmaterials used in AM
- chat showing the categorisation of themal management solutions
- Image of 3D model of winding
- Image of 3D printed winding

7. Thesis structure

Chapter 1 Introduction

Chapter 2 Literature Review

- Electrical machine thermal management
- Different types of cooling, advantages and disadvantages
- Why do we need better cooling?

Chapter 3 Additive manufacturing

- AM methods
- AM in electrical machines
- Advanced cooling methods with AM

Chapter 4 AM conductor with end-turn heat exchanger

- Explanation of the design choices
- Analytical calculations

- Simulations

Chapter 5 Measurements

- Describing the measurement methodology
- Measurement results
- What do the results mean?
- Conclusion

8. References

What types of sources do you use (books, research articles, reports, development plans, legislative acts, interviews)? Add 4-5 references of the main sources of literature.

[1] James Pecotich, David Klink, Greg Heins, Behrooz Bahrani: ‘Additively Manufactured Electric Machine Conductors with Integrated End Turn Heat’

[2] D. G. Dorrell, M. -F. Hsieh, M. Popescu, L. Evans, D. A. Staton and V. Grout, "A Review of the Design Issues and Techniques for Radial-Flux Brushless Surface and Internal Rare-Earth Permanent-Magnet Motors," in IEEE Transactions on Industrial Electronics, vol. 58, no. 9, pp. 3741-3757, Sept. 2011, doi: 10.1109/TIE.2010.2089940.

[3] Silbernagel, C., Ashcroft, I., Dickens, P., & Galea, M. (2018). Electrical resistivity of additively manufactured AlSi10Mg for use in electric motors. Additive Manufacturing, 21, 395–403. https://doi.org/10.1016/j.addma.2018.03.027

[4] Yinye Yang, Berker Bilgin, Michael Kasprzak, Shamsuddeen Nalakath, Hossam Sadek, Matthias Preindl, James Cotton, Nigel Schofield, Ali Emadi: ‘Thermal Management of electric Machines’

[5] Sarap, M.; Kallaste, A.; Shams Ghahfarokhi, P.; Tiismus, H.; Vaimann, T. Utilization of Additive Manufacturing in the Thermal Design of Electrical Machines: A Review. Machines 2022, 10, 251. https://doi.org/10.3390/ machines10040251

9. Thesis consultants

N/A

10. Work stages and schedule

Going through the literature, collecting basic data, writing theoretical part,(December 2022)

Designing the Model of the winding and Motor (February2023)

Printing of the Winding and motor parts, (March 2023)

Testing (March/April 2023)

Completing the final version of the thesis, sending to supervisor for corrections (April 2023)

Making Corrections and sending to Supervisor (April 2023)

Buffer Period and submission (May 2023)

CONTENTS

PREFACE

I would like to thank God for first of all the gift of life and for the grace to be able to finish this thesis work.

I will like to appreciate my supervisor Mr Martin Sarap for constantly guiding me and helping me to go improve everyday and study more and compile my thesis better. I am deeply grateful for my Family’s continued support especially after loosing my Dad during this program and for their continued prayer.

LIST OF ABBREVIATIONS AND SYMBOLS

AM - Additive Manufacturing

HT - Heat Transfer

ET - End-Turn

HEX - Heat Exchanger

DC- Direct Current

AC- Alternating current

PBF- Power Bed Fusion

IM- Induction Machines

BJ- Binder Jetting

SLA-stereolithography

FDM- fused deposition modeling

SLS-selective laser sintering

SLM- selective laser melting

EBM- electron beam melting

DMLS- Direct Metal Laser Sintering

LBPF- Laser Power Bed Fusion

UV- Ultra Violet

CAD- computer Aided Design

h_m – Convection Coefficient

R_{th} - Thermal Resistance

ρ_t- Resisitivity of material

I- current

V - Voltage

R- Resistance

Q heat power

A Area

ΔT Temperature difference

1. INTRODUCTION

Electric machines are essential in modern transportation systems, renewable energy, and industrial automation. Thermal management has become a serious concern as the power density of these machines continues to increase. Excessive heat created during operation can cause degradation of insulation materials, winding problems, and bearing failures, resulting in lower performance, increased maintenance costs, and potentially catastrophic failure. As a result, proper thermal management of electric machine is critical for their reliable and efficient operation [1]. The conductor losses accounts for most of the losses in an electric machine. This comprises of copper losses in stator conductors and, particularly, in induction motors (IM), followed by losses in rotor conductors [2]. Copper losses result from the resistance of the copper.

The advancement of Additive manufacturing allows for the production of complex designs which are difficult with conventional manufacturing used to enhance the thermal performance of electric machines. These includes AM hollow windings [3], winding heat guides [4], and heat exchanger designs. Forced convection which is the transport of fluid generated by an external source is more common than natural convection for electric machines with high power density machines. An external cooling jacket on the machine housing is the most widely used forced convection approach [5] Although cooling jacket facilitates a high rate of heat transfer, the machine is still limited by the thermal resistance between the conductor and cooling medium, which reduces the cooling capacity, regardless of the design [5].

Thermal resistance is a measurement of a materials resistance to the flow of heat. It is expressed as the reciprocal of thermal conductance, which is the ability to conduct heat [6]. The thermal resistance for convection (R_{th}) is expressed as the reciprocal of the product of the convective heat transfer coefficient(h_m) and the surface area (A) of the object that generates the heat as seen in equation (1.1) below

$$R_{th} = \frac{1}{h_m \times A} \text{ KmW}^{-1} \tag{1.1}$$

where R_{th} Thermal Resistance

h_m convective heat transfer coefficient

A surface area

Based on this equation, it can be determined that the convective thermal resistance is decreased as the surface area is increased or if the convective coefficient is increased the convective coefficient, also known as the convective heat transfer coefficient, $Wm^{-2}K^{-1}$ is a measure of the effectiveness of heat transfer between a solid surface and a fluid (liquid or gas) in motion.

AM has opened design freedom for direct conductor cooling solutions which were previously not possible, this thesis paper proposes an AM conductor with an air-cooled heat exchanger that provide a large surface area for efficient heat transfer with the integration of a fan in a rotor which improves the cooling of the winding by creating air flow thus increasing the velocity of air which in turn increases the convection coefficient which is a measure of the effectiveness of heat transfer between a solid surface and a fluid (liquid or gas) in motion as a thermal management solution.

2. LITERATURE REVIEW

2.1 Overview of Thermal Management of Electric Machine

During the operation of electrical machines losses such as copper loss, iron loss, magnet loss, and mechanical loss, are generated which are converted to heat and cause temperature increases. Thermal management is therefore crucial to ensuring the secure operation of electrical machines. Advanced thermal management solutions that increases currents capacity also help to improve the torque/power density of electrical machines since the toque of an electrical machine is proportional to armature currents [7].

2.2 Cooling Techniques

Cooling techniques can be classified according to the mode of heat transfer; conduction, natural convection, forced convection and evaporative cooling; or according to cooling fluid, water, air, oil and phase change materials or according to the parts of the machine the cooling is targeted such as stator winding, stator core, end windings and so on as seen in Figure 2. Some of these technologies can be incorporated simultaneously to minimize the temperature of various hotspots [1]. This thesis focuses on Forced air-cooled method targeted at the stator winding heat exchanger.

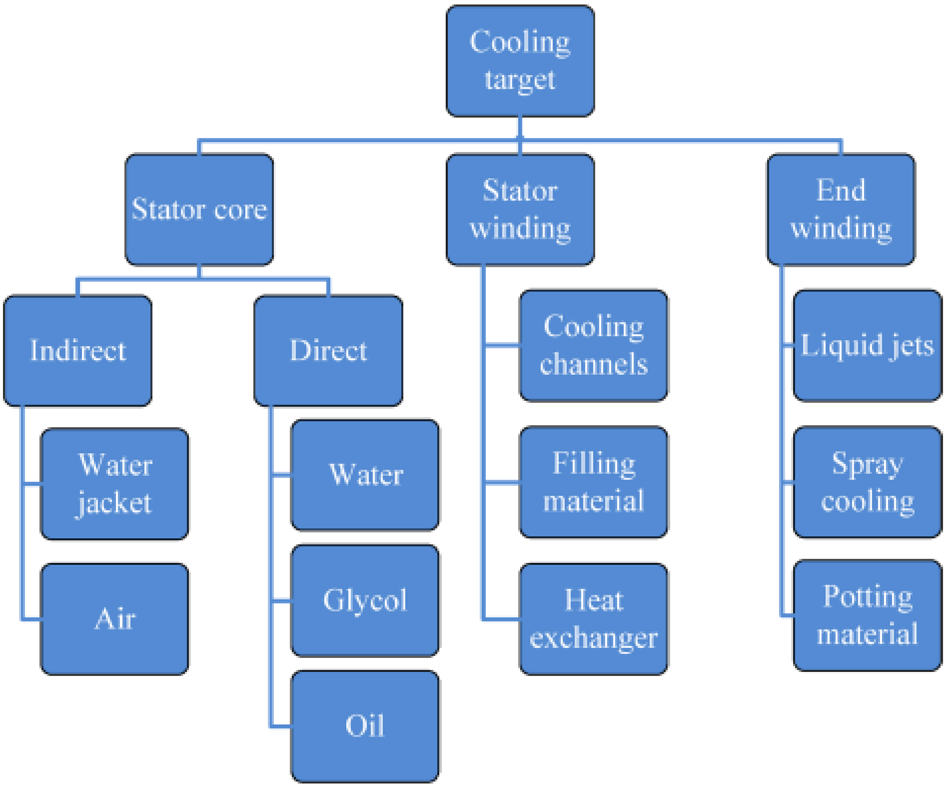

Figure 1 Showing cooling methods according to targeted parts[1]

2.2.1 Forced Air Convection

Forced convection which is the transport of fluid by an external source. Dissipating heat generated within an electric machine to ambient air in forced convection is dependent on several elements such as the effective heat transfer area and shape, the working fluid used for cooling, the flow rate and temperature of the cooling media, and so on. To boost heat dissipation, a more complex forced air-cooling system can be used [1]. The rate of heat transfer in forced air cooling depends on velocity of air, the higher the velocity the higher the rate of heat transfer

Advantages of Air Cooling incude the following;

(a) Unlike Liquid cooling, there is no pumps, hoses and filters to maintain which reduces cost of maintenance

(b) There is no problem of leakage as it is in liquid cooling, thereby increasing the reliability and lifespan of the machine

Disadvantages of Air cooling includes the following;

(a) Comparatively it is less efficient especially in high load or prolonged operation

(b) Electric machines cooled by fans used to circulate air over the heatsinks or other parts can be noisy and can be an issue in places like hospitals, libraries e.t.c.

(c) the machines are susceptible to dust and debris build up, which can clog the air channels and affect the cooling efficiency

2.3 Axial Flux Motor

Axial flux motors are a type of electric motor with a unique design that includes a disc-shaped rotor and stator, allowing for a more compact and efficient motor [8(5)]. In contrast to standard radial flux motors, which have a cylindrical rotor and stator, axial flux motors feature a flatter and wider design that allows the magnetic field to work on a larger surface area as seen in Figure 2.2. Because of the greater surface area, axial flux motors have higher torque and power density than radial flux motors, making them an excellent choice for many applications such as inwheel/hub motor configuration [9], elevators [10], e.t.c

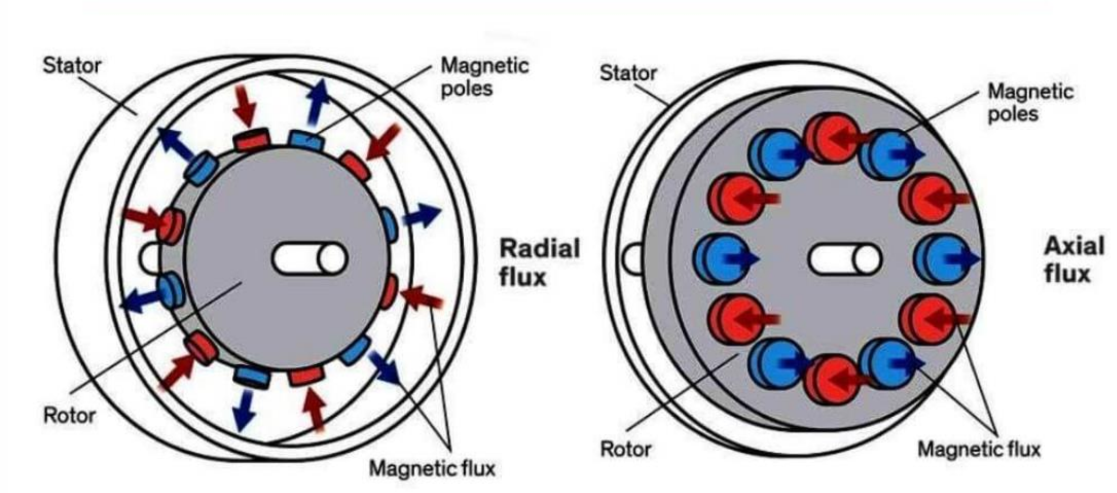

Figure 2.2 Diagram showing (a) Radial flux motor and (b) Axial flux motor [8(5)]

One of the key advantages of axial flux motors is their high efficiency, which is due to the shorter magnetic path length between the rotor and stator. Shorter iron parts mean less iron losses. Axial flux motors can also be constructed with a better power-to-weight ratio, making them excellent for situations where weight and size are crucial.

2.4 Additive Manufacturing

Additive manufacturing, often known as 3D printing, has emerged as a disruptive technology with the potential to transform the manufacturing industry. It involves using a range of materials, including metals, plastics, and ceramics to build three-dimensional objects layer-by-layer. This technique has received a lot of attention in recent years because of its ability to generate complicated geometries and functioning parts with a high degree of precision and accuracy [11].

The technological method known as additive manufacturing (AM) has both many benefits and some drawbacks. Due to its versatility and relatively low cost, it has long been widely used in quick prototyping. This technology has more recently focused on the capacity to manufacture new parts utilizing metallic materials, such as for aerospace and automotive applications, where compactness and lightweight are requirements. Each layer in the layer-based approach used by AM technology is a thin cross-section of the components produced by a CAD file. Since the invention of this technology in the 1980s, countless materials have been invented and produced using additive manufacturing (AM). Printable metals, polymers, ceramics, composites, and biological materials are just a few examples [12].

2.5 Additive Manufacturing Methods

There are seven major categories into which current AM techniques can be divided namely, Vat photopolymerization, material extrusion, material jetting, binder jetting, powder bed fusion, direct energy deposition and sheet lamination [13].

Material extrusion involves the deposition of melted or semi-molten material through a nozzle or similar tool to build up the object layer by layer. Powder bed fusion involves the use of a laser or electron beam to selectively melt or sinter powder particles to build up the object layer by layer. Directed energy deposition involves the deposition of material, usually in powder form, using a focused energy source, such as a laser or electron beam, to melt or fuse the material to the previous layer.

Binder jetting involves the use of a liquid binder to selectively bond powder particles together to build up the object layer by layer. Sheet lamination involves the layering of sheets of material, typically paper or plastic, with an adhesive to build up the object layer by layer. Vat photopolymerization involves the use of a liquid photopolymer that is selectively cured by a light source, such as a laser or UV lamp, to build up the object layer by layer [14]. Material Jetting (MJ) involves jetting droplets of liquid material that are cured by UV light to create a 3D object layer-by-layer [13].

Each technique has distinct advantages, disadvantages, and produces the three-dimensional object in a different way. The major distinctions are in the materials that can be used, as photopolymerization and extrusion techniques mostly use plastic materials, whilst PBF methods are typically used to produce metal items [13]. In this thesis focus will be on a specific type of PBF method selective laser melting.

2.5.1 Powder Bed Fusion

Powder bed fusion can be divided into two main types [15]

a) selective laser sintering

b) selective laser Melting

In this thesis focus will be on selective laser melting since it is the method that will be used to print the winding.

Selective laser melting (SLM) which was developed in 1995 [15] is a powder bed fusion technique that builds three-dimensional parts by selectively melting tiny layers of metallic powder using high-power laser as seen in Figure 2.3. The following steps make up the SLM operating principle:

1) Powder spreading: Using a recoating technique, a thin layer of metallic powder is applied to a construction platform.

2) Laser scanning: A high-powered laser beam is directed onto the surface of the powder layer, selectively melting, and fusing the particles together to form a solid layer.

3) Layer by layer building: The platform is then lowered by a distance equal to the thickness of the melted layer, and a new layer of powder is spread over the preceding layer. The laser then scans the new layer, selectively melting and fusing the powder particles to the preceding layer.

4) Cooling and solidification: The process is continued layer by layer until the final item is formed. After cooling to room temperature, the part is taken off the build platform [16].

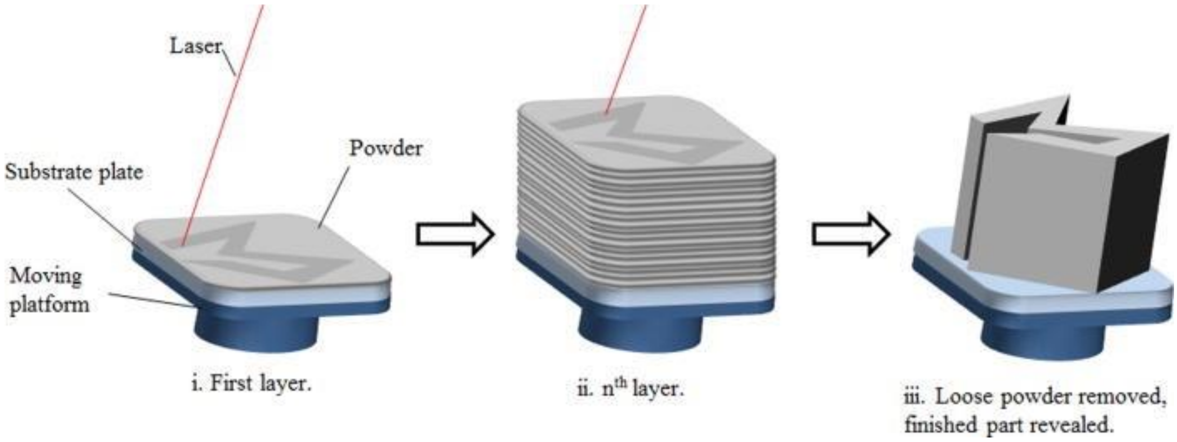

Figure 2.3 SLM process. (i) High-power laser melts selective areas of the powder bed. (ii) Process is repeats for successive layers. (iii) Loose powder removed and finished part revealed [16].

A high-power fiber laser with a near-infrared wavelength is often the laser utilized in SLM. A scanning system, which regulates the laser beam's position and intensity, directs the laser beam onto the metallic powder layer's surface. The powder particles are heated by the laser beam to a temperature that is above their melting point, which causes them to combine and create a solid layer. The final part's quality can be impacted by SLM process variables such as laser power, scan speed, and layer thickness. For instance, a high laser power and slow scan speed might raise the melt pool temperature, increasing the risks of flaws like porosity and cracking. Therefore, it is essential to optimize these parameters to produce high-quality parts with the desired attributes [17].

2.6 Additive Manufacturing in Electrical Machines

When it comes to using additive manufacturing for electrical devices, the possibilities are endless, ranging from prototyping to mass-customized production. The use of additive manufacturing (AM) in the production of electrical machines is a promising development that offers a few advantages over traditional manufacturing methods, including the realization of 3D designs (which includes electrical, mechanical and thermal considerations), recyclable constructions, and optimal material utilization. Selective laser melting, binder jet printing and fused deposition modeling technology have been identified as the AM processes that hold the greatest promise to produce electrical machinery [18].

The disadvantages or difficulties are case-specific with an emphasis on electrical machines. For example, with the windings, one issue is obtaining 100% electrical conductivity together with high fill factor [17]. For any printed object, the core magnetic material's higher permeability and reduced eddy-current losses present the most obstacles. Only a few attempts at additive manufacture of electrical devices have been made thus far. With the benefits of fast prototyping and creating designs with complicated geometries, AM is opening the door for future innovation in manufacturing different sections of electrical machines, including iron core, winding, insulation, PM, and heat exchangers and cooling systems. Additionally, these practices can be expanded to a fully additively built machine by integrating the other passive parts, such as the housing, end cover, rotor shaft, and winding frame, thanks to the benefit of lightweight integrated fabrication.

2.7 Advanced Cooling Methods with AM

Electric machines are designed to operate efficiently and to be reliable while generating a large amount power, during their operation they also generate a large amount of heat that can cause thermal stresses, material degradation, and reduced performance. Effective thermal management therefore is needed for maintaining the performance and reliability of electric machines. With the emergence of new materials and manufacturing processes such as additive manufacturing, there are opportunities to develop novel thermal management solutions that can be integrated into the machine’s design.

Additive Manufacturing offers a chance to enhance electrical systems, the capacity of machines to cool in numerous ways, including through reducing the weight, enhancing the form of the cooling system, and geometries, and decreasing the typical cooling systems' size limitations and downsides of traditional manufacturing [20]. AM allows for numerous solutions to cool down electric machines but in this thesis, focus will be on direct conductor cooling.

2.7.1 Direct Conductor Cooling

Direct conductor cooling is a method that involves running coolant directly through an electric machine's conductors, like the stator windings. The machine's efficiency, power density, and lifespan can all be increased because to this technique's efficient heat dissipation.

Most of the heat produced in a typical machine is caused by Joule losses in the conductors. Due to the thermal breakdown of the insulation, the conductors are also the most vulnerable to high temperatures. Although copper has a high thermal conductivity, the insulation, air bubbles, and contact resistances found in windings cause the conductivity of the overall winding body to be rather low [21] Additionally, heat must pass through the machine's core material, which normally has a low thermal conductivity, in a machine that uses a standard cooling system. This causes a significant thermal resistance between the motor's surface and the windings, where heat can be removed from the motor surface because greater conductor temperatures diminish machine efficiency, the negative relationship between electrical conductivity and temperature is also notable. Copper loss results from Joule heating due to the resistivity of the conductors which can be expressed as a function of temperature [2] in equation (2.1) below.

$$\rho_t = \rho_0(1 + (T - T_0)) \qquad (2.1)$$

where ρ_o is the resistivity at initial temperature Ω cm,

T_o, initial temperature °C,

a is the temperature coefficient $°C^{-1}$,

T is the final temperature °C,

ρ_t resistivity at final temperature Ω cm.

This makes extracting heat from the winding of electrical motor the primary problem when cooling them.

Wrobel et al. [4] suggested an additive manufacturing approach by using SLM to produce thermally conductive heat guides from an aluminum alloy (AlSi10Mg), which are intended to be positioned between the windings of a motor (Figure 2.4a). The heat guides help drain heat from the winding's active portion as they are positioned close to it inside the stator slots, but they also contribute to machine losses brought on by eddy currents brought on by flux leakage. Therefore, the performance benefits of a solid heat guide are minimal, but because AM makes it feasible to create various lattice patterns that resemble classic laminations (Figure 2.4b, c), it is possible to reduce additional losses while maintaining excellent thermal conductivity.

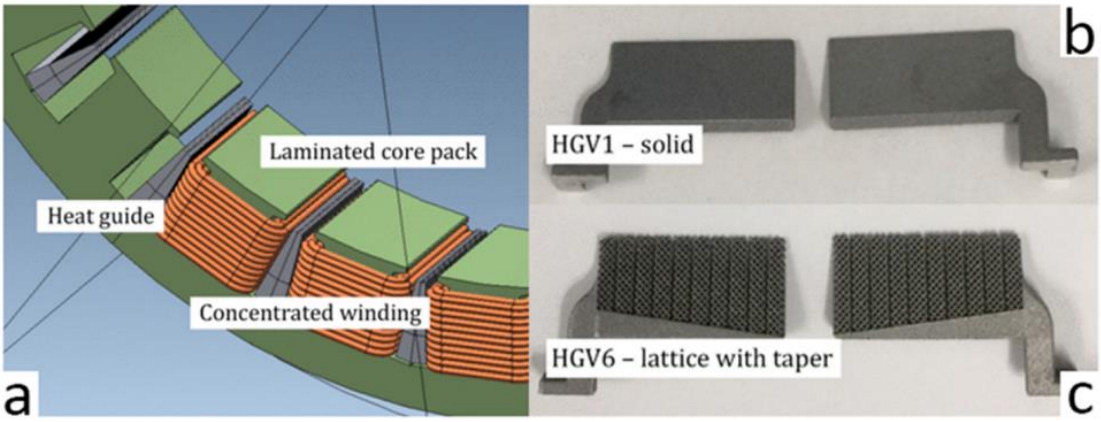

Figure 2.4 Additively manufactured heat guides places between the windings (a), a heat guide with a solid structure (b) and a heat guide utilizing a taper and a lattice structure to reduce eddy current losses (c) a heat guide utilizing a taper [4]

Laser-sintering has been employed by Wohlers et al. [3] to produce fractional-slot concentration windings of aluminum alloy (AlSi10Mg), which have a hollow structure for direct liquid cooling of each conductor (Figure 2.5). In addition to the hollow construction, the rest of the coil design is tuned for minimal losses and maximum cooling. The thermal resistance between the heat-generating conductors and the coolant is reduced by pumping coolant straight into the conductor, without the use of any interface material (for example, steel tubes inside the conductors [22]). The windings reached a current density of 70 A/mm2 with a maximum coil temperature of 180 C during testing while being cooled at a constant coolant temperature of 30 C. It should be emphasized that these values are obtained from an aluminum alloy coil, whereas using an identically shaped copper coil, the authors compute maximum current densities of around 130 A/mm2 which means the motor can get more power for same size since the torque of electric machines in proportional to current.

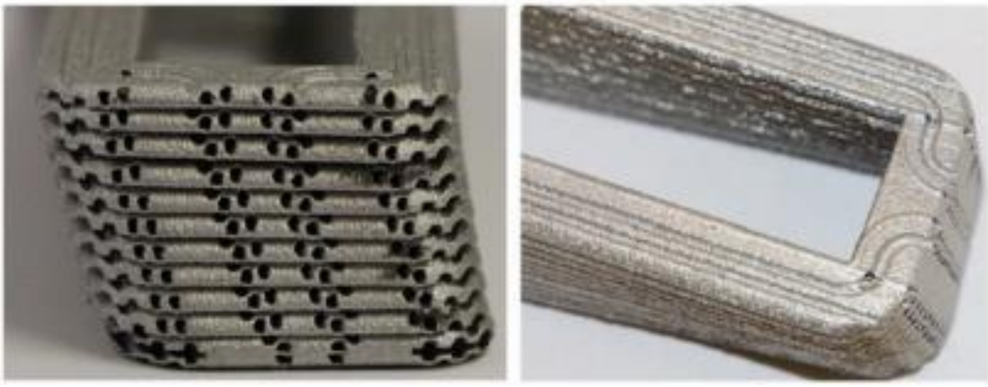

Figure 2.5 Additively manufactured aluminum alloy windings with a hollow structure for direct conductor water cooling [3].

3. AM CONDUCTOR WITH INTEGRATED END TURN HEAT EXCHANGER

3.1 Design Considerations

With the advent of additive manufacturing (AM), previously impractical cooling solutions for electrical machine conductors are now possible. Using a low thermal resistance and high surface area design methodology, the proposed solution comprises the use of an additively manufactured conductor with an air-cooled heat exchanger integrated on the end turn. The heat exchanger is intended to be cooled by a built-in fan in the rotor, increasing the system's overall heat dissipation. The use of air also eliminates the need for external cooling devices such as radiators and pumps, which add significant mass and complexity to the system.

The material chosen is AlSi10Mg which despite having lower electrical conductivity compared to copper, is a relatively good electrical conductor that does not have the same reported concerns as processing pure aluminum or copper using selective laser melting (SLM) [17]

3.1.1 Winding Design

In designing the winding for the axial flux motor stator, various considerations were considered, including the size, shape, number of turns, and thickness of the winding. The size of the winding plays a crucial role in determining its electrical and thermal characteristics. Specifically, the size of the winding can affect its resistance, as well as its ability to dissipate heat.

Moreover, the shape of the winding was designed to fit the winding slot of the axial flux motor stator. This ensures that the winding can be properly positioned and secured within the stator. The winding shape also impacts the fill factor, which is a measure of how effectively the winding utilizes the available space within the motor. As such, careful consideration was given to the winding shape during the design. The thickness of the winding was chosen according to the specification of the printing thickness and the width was modeled to have a similar width of a similar thermal solution from [4] to improve the thermal performance of the winding because it increases both the cross sectional area and overall surface area and the length of the end turn was designed to provide enough surface area for the attachment of the fins.

The 3d model of the winding can be seen in Figure 3.1 below and the geometry of the winding is shown in Table 3.1 below.

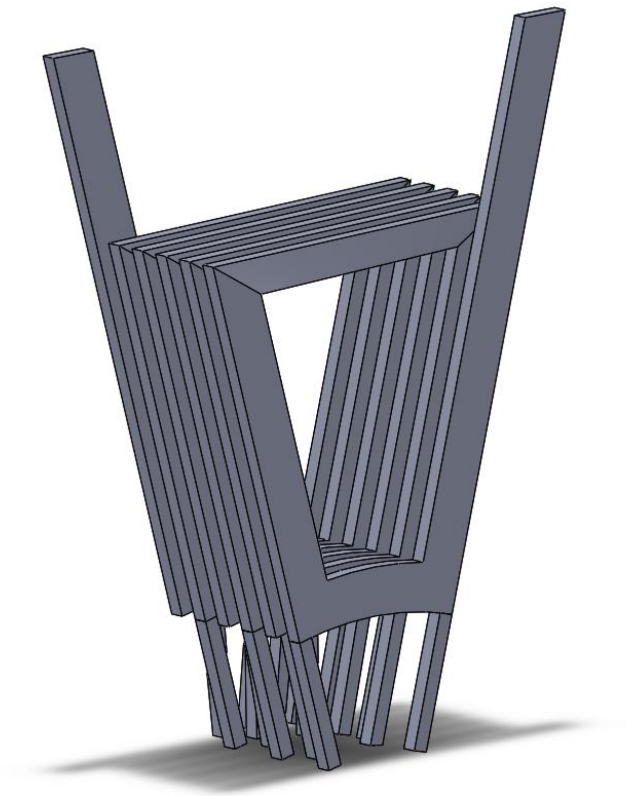

Figure 3.1 3D model of winding

Table 3.1 Showing the geometry of the winding

Parameter	Dimension(mm)
winding width	2,6
heat fins length	7
winding thickness	0,8
Longest end turn	20,8
Short end turn	18
Length of slide of winding	20,7

In the design of heat exchangers, the use of an integrated fan on the rotor is an effective method to create the airflow flowing through the heat exchanger, which improves the cooling. This is because higher air velocity leads to a lower thermal resistance, as air flows through the heat exchanger, it undergoes a reduction in temperature, with the sections of the exchanger that are first in contact with the air receiving the highest velocity and thus the most cooling. The subsequent sections of the heat exchanger receive less cooling as the air velocity decreases.

Given a fixed surface area in a heat exchanger, the rate of heat transfer will decrease as the temperature difference between the hot and cold sides decreases. This is because using fan as the air travels the temperature of the heat exchanger increases while the temperature of the winding remains constant. However, by increasing the surface area of the heat exchanger, it is possible to compensate for this reduction in temperature difference.

In the heat exchanger design, this is achieved by adding more fins to subsequent winding turns to increase the surface area of the heat exchanger as seen in Figure 3.2 below. By doing so, the rate of heat transfer can be maintained at the same level despite the decrease in temperature difference. This is because the increased surface area provides a larger contact area for heat transfer, allowing for more efficient heat exchange between the hot and cold sides.

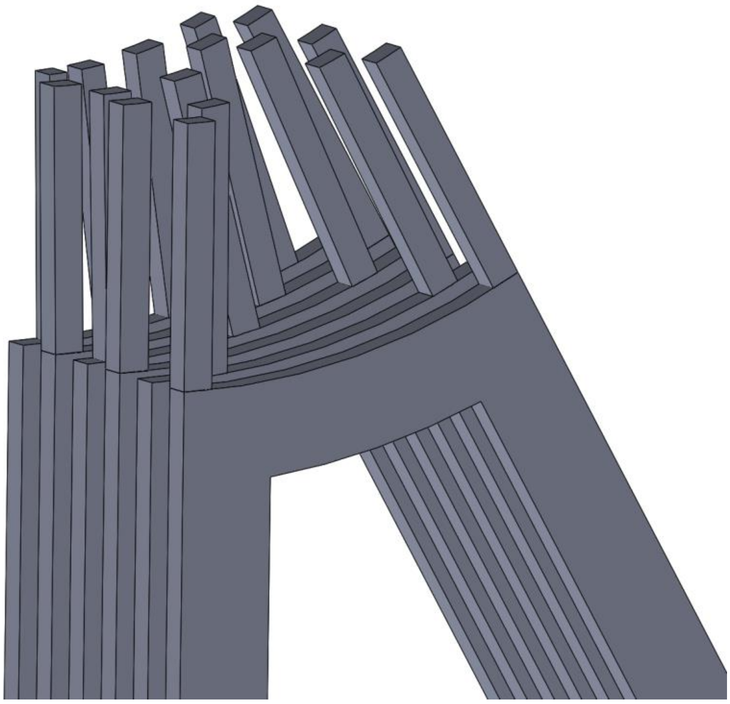

Figure 3.2 Heat sink configuration

The number of fins per winding turn and the surface area are given in Table 3.2 below in the sequence of proximity to the cooling fan

Table 3.2 Table showing the number of fins and the surface area in a sequence of proximity to the cooling fan

Sequence of winding	No of fins	Surface area(mm^2)
1	2	46
2	2	46
3	2	46
4	3	69
5	3	69
6	4	92

Convective heat transfer occurs whenever an object is either hotter or colder than a surrounding fluid Convection occurs in a moving liquid or a gas. The basic equation for the rate of convection heat transfer is known as Newton's Law of Cooling [23] seen in equation (3.1) below:

$$Q = hA(T_w - T_s) \tag{3.1}$$

where Q is the heat dissipated (W),

h is the convection coefficient ($Wm^{-2}K^{-1}$),

A is the surface area of the winding (m^2),

T_w is the temperature of the winding (K),

T_s is the temperature of the surroundings in (K).

The convective coefficient, also known as the convective heat transfer coefficient, is a measure of the effectiveness of heat transfer between a solid surface and a fluid (liquid or gas) in motion. The convective coefficient considers factors such as fluid properties, fluid velocity, temperature gradients, and the nature of the solid surface.

The speed of the rotor fan can have an impact on the convective heat transfer coefficient in the cooling systems. Increasing the speed of a fan increases the air velocity and enhances the convective heat transfer. This occurs because higher fluid velocities lead to increased turbulence and mixing, which in turn promotes better heat transfer between the solid surface and the fluid, this can be understood better by varying the convection coefficient from [23] we can see the range of free convection of air from 2.5-25 $Wm^{-2}K^{-1}$ and forced convection from 10-500 $Wm^{-2}K^{-1}$. using the range of 5-100 $Wm^{-2}K^{-1}$ the effect of convection coefficient on rate of convection heat transfer can be seen in Table 3.3. The surface area of the winding model is $A = 368\ \text{mm}^2 = 0.000368\ \text{m}^2$. Using the Surface area and the varying convection coefficient the relationship of convection coefficient and the amount of heat dissipated per kelvin can be evaluated as seen in Table 3.3 below.

Table 3.3 Table Showing how the increase in convection coefficient increases the amount of heat dissipated per unit Kelvin

Convection coefficient ($Wm^{-2}K^{-1}$)	$\frac{Q}{(T_w - T_s)} = h \times A$ (WK^{-1})
5	0,0018
25	0,0090
50	0,018
75	0,028
100	0,037

from the upward trend of the graph this shows that the increase in convection coefficient increases the amount of heat dissipated. This suggest that integrated fan on the rotor improves the cooling of the winding. From [3] which implements a similar solution the heat coefficient is around 100 $Wm^{-2}K^{-1}$, so we can assume h to be 100 $Wm^{-2}K^{-1}$ which means for every 0.037 W of losses heat sink will be 1 K hotter than the ambient air.

3.1.2 Analytical Calculation

In the calculation of motor winding Max current capacity, the convection coefficient is considered. The resistance of the winding, material property and limiting the max temperature differential to 100 K like the max temperature of a similar application from [3] making the current that produces up to 100 K temperature differential as the max current.

Resistance of the winding can be calculated from the equation (3.2) below

$$R = \rho \frac{L}{A} \ \Omega \tag{3.2}$$

where R – Resistance Ω,

ρ - resistivity of the material Ωcm,

L - length of winding cm,

A - cross surface area cm^2,

The resistivity ρ of AlSi10mg $4.91x10^{-6}$ Ω cm. The cross section is a rectangular surface and the area it can be calculated by equation (3.3) below

$$A = \ lxb \ cm^2 \tag{3.3}$$

$$A = 2.6 \times 0.8 = 2.1\text{mm}^2 = 0{,}021\text{cm}^2$$

The Length of the winding by using the dimension of the winding and multiplying the length by how many times it re occurs in the winding like the *length of the longest end turn* = 20,8 mm occurs 5 times, the *length of the shorter end turn*= 18mm occurs 6 times and the *length of the side* = 20,7 mm occurs 12 times as seen below

$$L = 12(20.7) + 5(20.8) + 6(18) = 248.4 + 104 + 108 = 460{,}4\text{mm} = 46{,}04 \text{ cm}$$

From the length L cm, cross surface area A cm2 and resistivity of the material ρ Ωcm the resistance can be calculated as below

$$R = \frac{4.91 \times 10^{-6} \times 46.04}{0.021} = 0.0109 = 10{,}9 \text{ m}\Omega$$

$$R = 10{,}9 \ \text{m}\Omega$$

The Heat Power dissipated in the winding can be calculated from equation (3.4) below

$$Q = I^2 \times R \text{ W} \tag{3.4}$$

Assuming we pass a current of I=10 A.

$$Q = 10^2 \times 10.9 \ \times 10^{-3} = 1{,}09 \text{ W}$$

The temperature differential can be calculated by using the equation (3.1) to derive the calculation of temperature differential as seen in equation (3.5) below

$$\Delta T = \frac{Q}{h \times A}\ K \tag{3.5}$$

where *h* is convection coefficient, *A* is cross section, *Q* is heat power dissipated, *ΔT* is the temperature differential

$$\Delta T = \frac{1.09}{100 \times 0{,}000368} = 29{,}62\text{ K}$$

Assuming the max Temperature differential between the exchanger and Ambient Temp to be 100 K, the heat dissipated can be calculated from the formula in equation (3.1)

$$Q = \Delta T \times h \times A\text{ W}$$

where ΔT is 100 K

$$Q = 100 \times 100 \times 0{,}000368 = 3{,}6\text{ W}$$

Using the heat power equation 3.4 the max current can be calculated be calculated as below

$$I = \sqrt{(Q/_R)}\ \text{A}$$

$$I = \sqrt{\frac{3.6}{0.0109}} = 18.17\text{ A}$$

From the max current the current density of the winding can be calculated using the equation (3.6) below,

$$J = \frac{I}{A}\ \text{Amm}^{-2} \tag{3.6}$$

$$J = \frac{18.17}{2.1} 9{,}08\text{ Amm}^{-2}$$

From the calculation the current density is 9.08 Amm^{-2} as opposed to typical electric motor from [24] which has a current density of about 3-5 Amm^{-2}. It is about 5 times higher thus can handle higher power density applications.

3.1.3 Rotor Design

The rotor is the moving part of the motor, and it rotates as a fan would, instead of making a whole fan system and attaching it to the motor thus increasing the size of the motor, the fan is integrated into the rotor and targeted at the fins to improve the cooling. As the rotor rotates the fan also rotates thus create the air flow to cool the heat sink. The rotor also comprises of magnet slots as seen in Figure 3.5 below. The dimensions of the Rotor are shown in Table 3.4 below

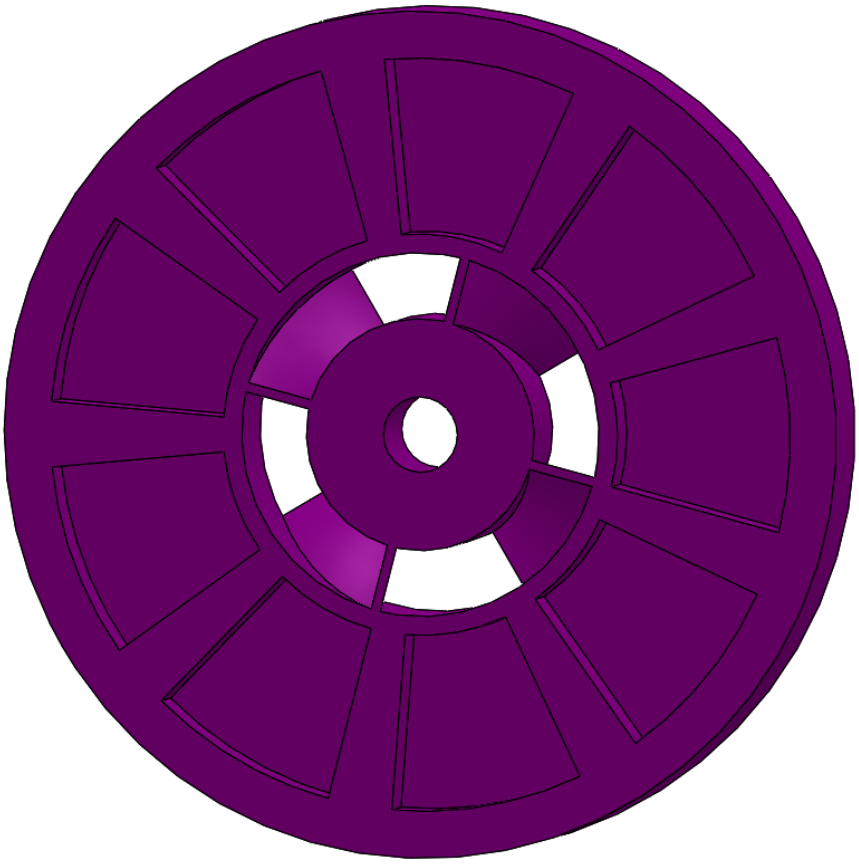

Figure 3.5 3D model of the Rotor

Table 3.4 Table showing the dimensions of the rotor

Parameter	Dimension(mm)
outer diameter	90
inside diameter	24,6
magnet slot outside diameter	80
magnet slot inside diameter	42,6
magnet slot depth	5
fan outside diameter	38,6
fan inside diameter	24,6

The integrated fan blades were designed after an axial fan so the air will flow in the direction as seen Figure 3.6. In the design target for the airflow is the heat sink.

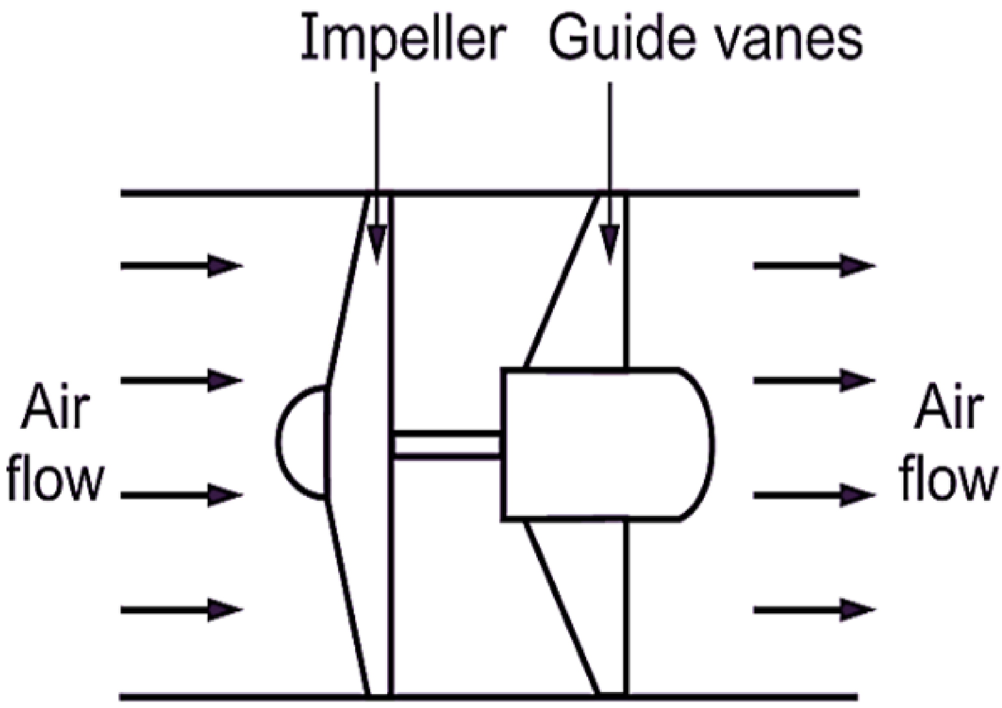

Figure 3.6 Direction of flow of the integrated fan in the rotor [24]

3.1.4 Stator Design

A stator is the stationary part of the machine that houses the winding which when excited produces an electro-magnetic field that interacts with the moving rotor to produce rotational motion. The stator is designed with airholes in the heat sink region to allow air to flow as seen in Figure 3.7 below

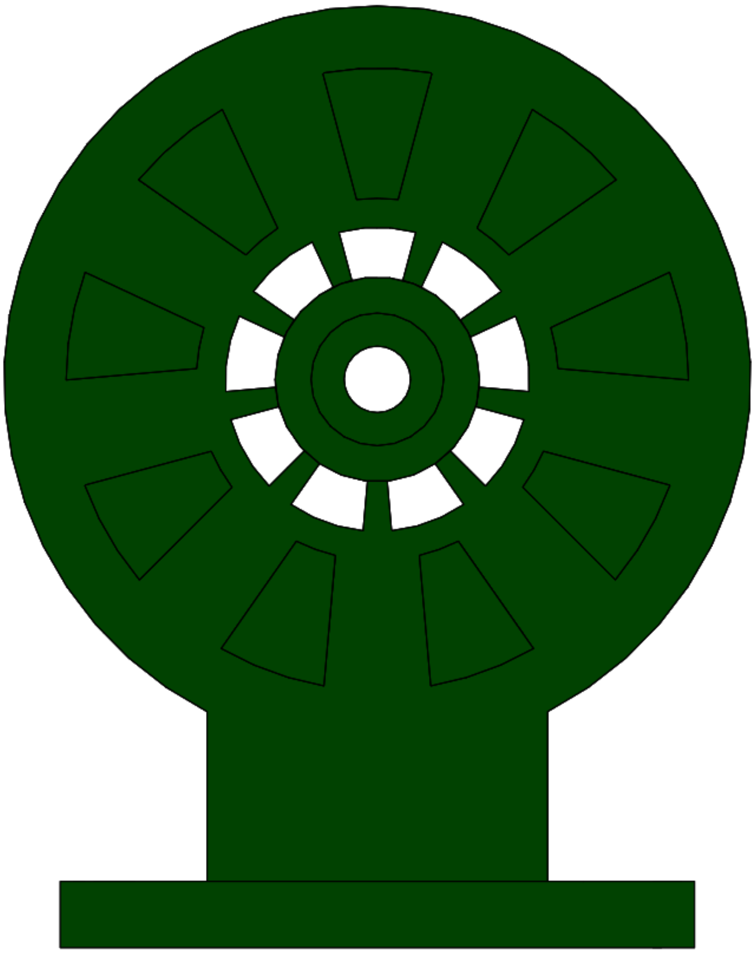

Figure 3.7 3D model of the stator

Table 3.4 Table showing the dimensions of the stator

Parameter	Dimension(mm)
outer diameter	90
inside diameter	24,6
winding slot outside diameter	75
winding slot inside diameter	46,1
Air holes outside diameter	38,6
Air holes inside diameter	24,6
bearing slot outside diameter	16

3.2 Simulation

To simulate the cooling of the winding and validating the concept of the convection coefficient *h* $Wm^{-2}K^{-1}$ affecting the cooling of the winding a simulation was done with SolidWorks to imitate the cooling concept by applying heat power to the winding and varying the convection coefficient targeted at the heat sinks.

The material used in the simulation was an aluminum alloy with similar thermal conductivity as Alsi10mg since it cannot be found in solid works and knowing the thermal conductivity of AlSi10mg from [17] to be 120 $Wm^{-1}K^{-1}$ as it is not annealed. Figure 3.8 shows the material property of the material to be 120 $Wm^{-1}K^{-1}$.

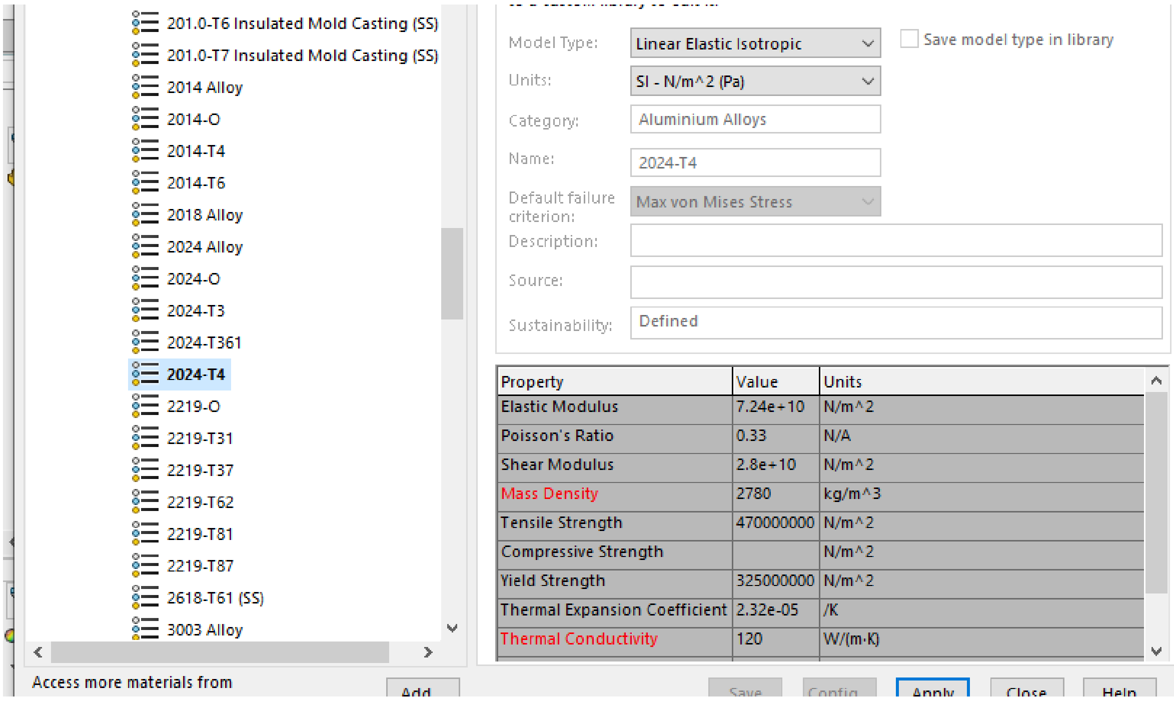

Figure 3.8 Material property of the Aluminum alloy used in the simulation

The heat power given to the winding was kept constant throughout the winding to monitor how cooling the heat sink affects the cooling of the winding the as seen in Figure 3.9 below.

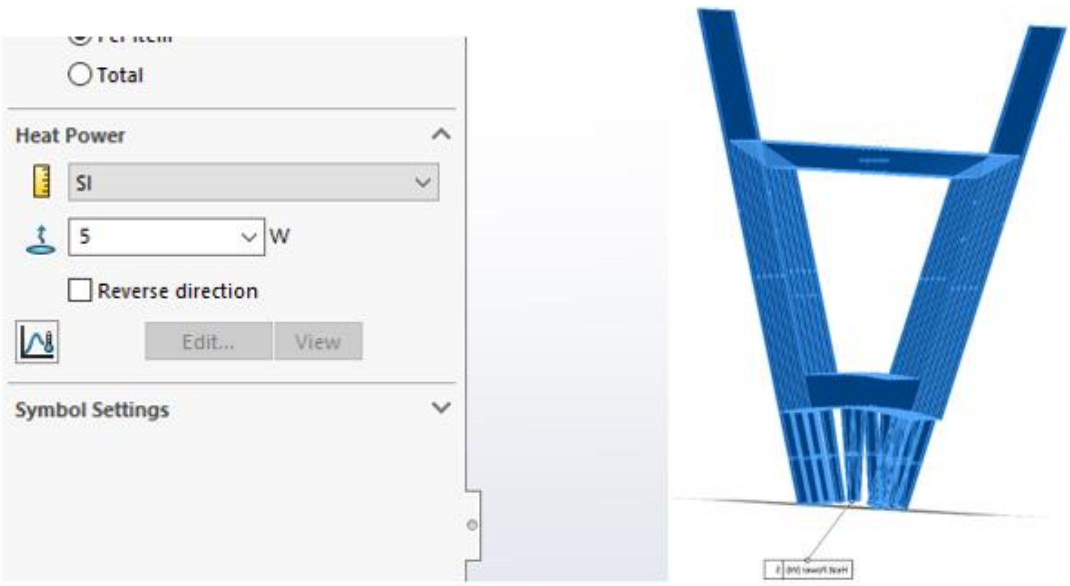

Figure 3.9 Image showing the target of heat power

The convection coefficient range from Table 3.3 will be used in the simulation to show that with increasing convection coefficient h $Wm^{-2}K^{-1}$ the winding is cooled better. the bulk ambient temperature of 293 K is kept constant throughout the variation

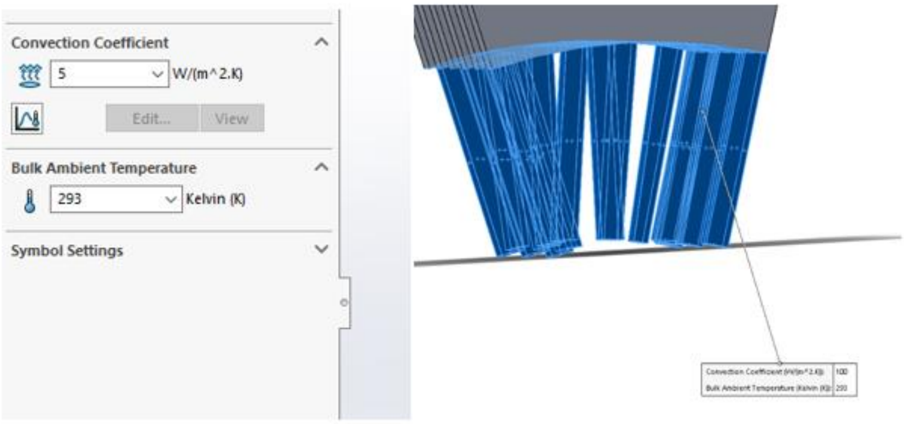

Figure 3.10 Image showing the Target of the convection coefficient

Using the power and the convective coefficient calculated 3.6 W and 100 calculated earlier we use this parameter to simulated the max temperature of the winding was 1,857 x 10^3 K as seen in Figure 3.11 which is very higher which can be due to the material properties and other simulation parameters like the meshing but the importance of the simulation is to try the concept to see how cooling the heat sink might affect the winding temperature and also to see how increasing the convective coefficient will affect the cooling which can be seen in Figure 3.12 below.

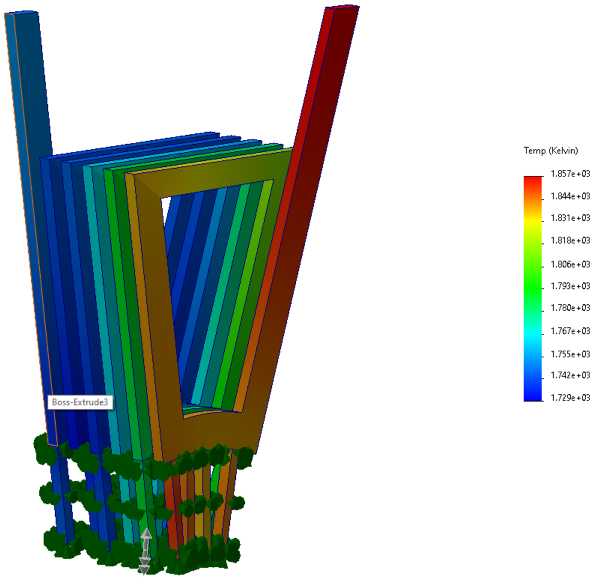

Figure 3.11 Thermal simulation of winding with heat power of 3 W and convective coefficient of 100 $wm^{-2}K^{-1}$

To get a temperature differential of about a 100 K or within 100 using the simulation the heat power simulated was about 0.03 W but it was used to also validate that with increase in convection coefficient, the winding temperature is cooler as seen from Figure 3.12 below

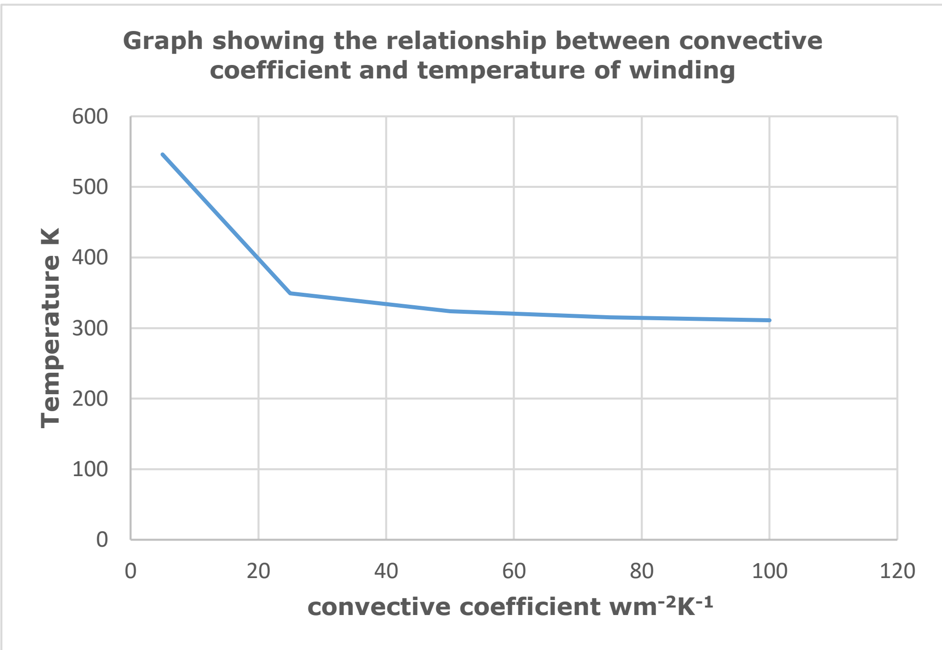

Figure 3.12 Graph showing how convective coefficient affect cooling

4. MEASUREMENTS

4.1 Experimental Set Up

To evaluate the performance of this concept, the winding was printed using an SLM machine using Alsi10mg as the material. The dimensions of the prototypes are same as the modelled design. with a scaling ratio of 1:1.

Figure 4.1 shows the image of the test set up. The stator was mounted on a 90/45 extrusion to enable the motor stay in place during testing. To evaluate one winding, an external motor was used to drive the rotor thus rotating the fan creating the air flow that improve the cooling of the winding. the use of an Arduino circuit to control the motor driving the rotor. Two power supply was used, one was used to pass current through the winding while the other was used to supply power to the external motor.

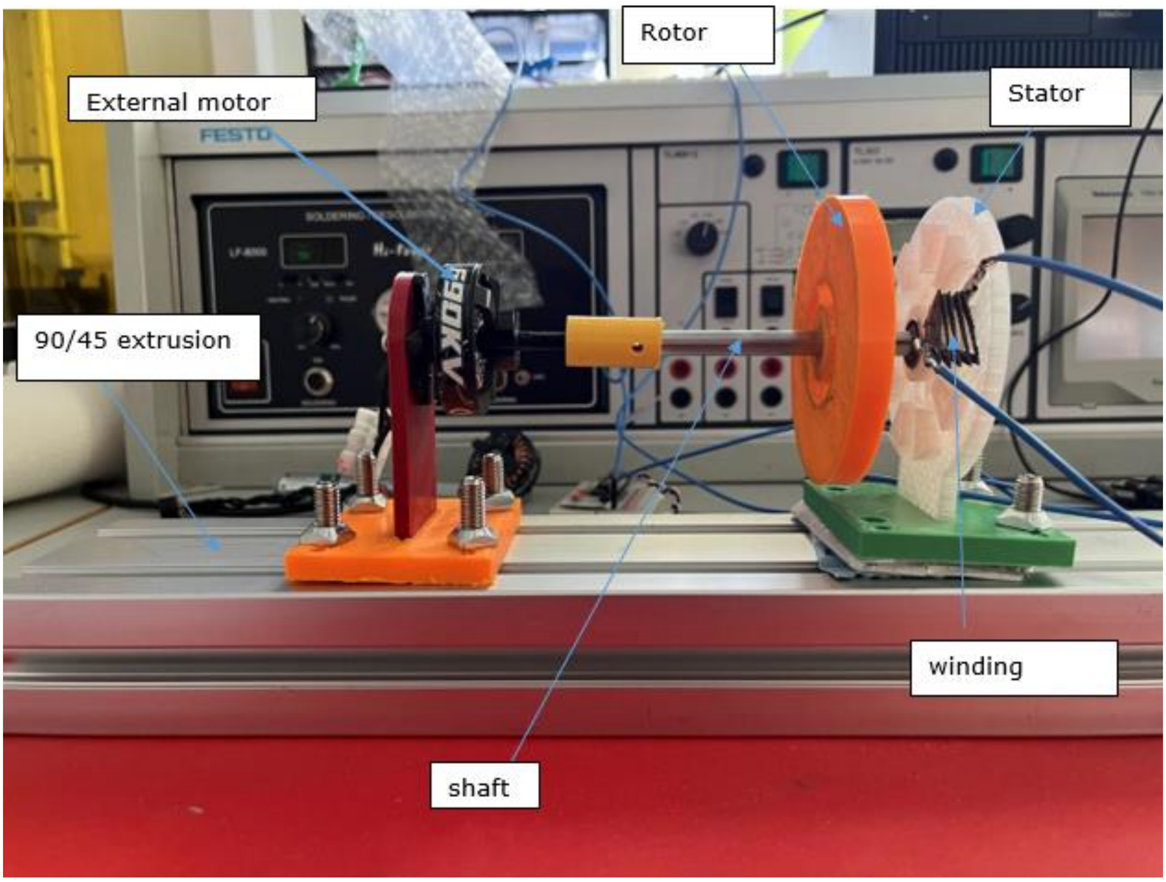

Figure 4.1 Image showing the test set up

Power was supplied to the winding. the winding was connected to the power supply using spade connectors. The windings were insulated before testing to create a barrier between the conductors ensuring safe and reliable operation thus to connect the spade connector the ends were filed to ensure the current goes through.

4.2 Measurements Methodology

The resistivity of a material depends on temperature, thus the resistance also depends on temperature, since *R* is directly proportional to *ρ*,

$$R = \rho \frac{L}{A}$$

where *R* is resistance, *ρ* is resistivity of the material, *L* is length *A* is cross-sectional area

if *A* and *L* do not change with temperature, *R* will have same temperature dependences as resistivity ρ as seen from equation (2.1). This can be expressed in the equation (4.1) below

$$R = R_0(1 + \alpha\Delta T) \tag{4.1}$$

where R_0 - Initial resistance Ω

R - The resistance after a temperature change Ω

ΔT- Temperature differential °C

A - Temperature coefficient $°C^{-1}$

With this we can measure the temperature change by passing a current through the winding and measuring the voltage drop across the winding, thus finding Resistance by Ohm's law in equation (5.2)

$$R = \frac{V}{I}\ \Omega \tag{4.2}$$

Where *V* - Voltage, V

R -Resistance, Ω

I - Current, A

The temperature differential can be calculated by using the formula from equation (4.1) to derive *ΔT* as seen in equation (4.3)

$$\Delta T = \frac{\left(\frac{R}{R_0} - 1\right)}{\alpha} \quad ^{\circ}C \tag{4.3}$$

using these methods and equations we can get results to evaluate the performances of the design. The temperature coefficient of Alsi10mg is 0.0039 $^{\circ}C^{-1}$ from [25].

4.3 Results

The set up was constructed primarily to validate the assumptions for the concepts that the integrated fan improves the cooling of the winding by (i)measuring the resistance of the winding while supplying current to the winding and running the motor (ii) measuring the resistance while supplying current without the fan (iii) reducing the speed of the fan and measuring the resistance across the windings to find the temperature differential *ΔT*.

The equation (4.3) is used to calculate the temperature differential *ΔT* from the measured resistance. R_0 is the resistance calculated from the winding properties. The increment of current increases the heat dissipated so to monitor how the integrated fan is cooling the winding it is compared to excitation of the winding without the effect of the fan and the temperature differential is calculated from the resistance and the comparison is made between the rotor of running and the temperature differential without the rotor. The value of R_0=10,9 mΩ

4.3.1 Cooling Performance

Figure 4.2 validates that the integrated fan on the rotor improves the cooling of the winding because the temperature differential of the winding with the rotor running is lower than that of without the rotor which indicates that with this design the winding can handle much higher current with the integrated fan design than without it thus allowing for more power with same size of motor.

Table 4.1 Table showing Temperature differential measurement of the winding with and without the rotor rotating.

Current (A)	Voltage (without roto) (mV)	Voltage (with Rotor) (mV)	Resistance (without Rotor) (mΩ)	Resistance (with rotor) (mΩ)	ΔT (without rotor) (°C)	ΔT (with Rotor) (°C)
2	22,67	22,08	11,33	11,04	10,11	3,29
4	46,72	45,41	11,68	11,35	18,34	10,59
6	71,52	69,92	11,92	11,65	25,41	17,64
8	98,33	94,24	12,29	11,78	32,40	20,7
10	128,91	118,9	12,89	11,89	46,81	23,29
12	163,43	146,16	13,62	12,18	63,98	30,11
15	213,15	186,01	14,21	12,4	77,86	35,29

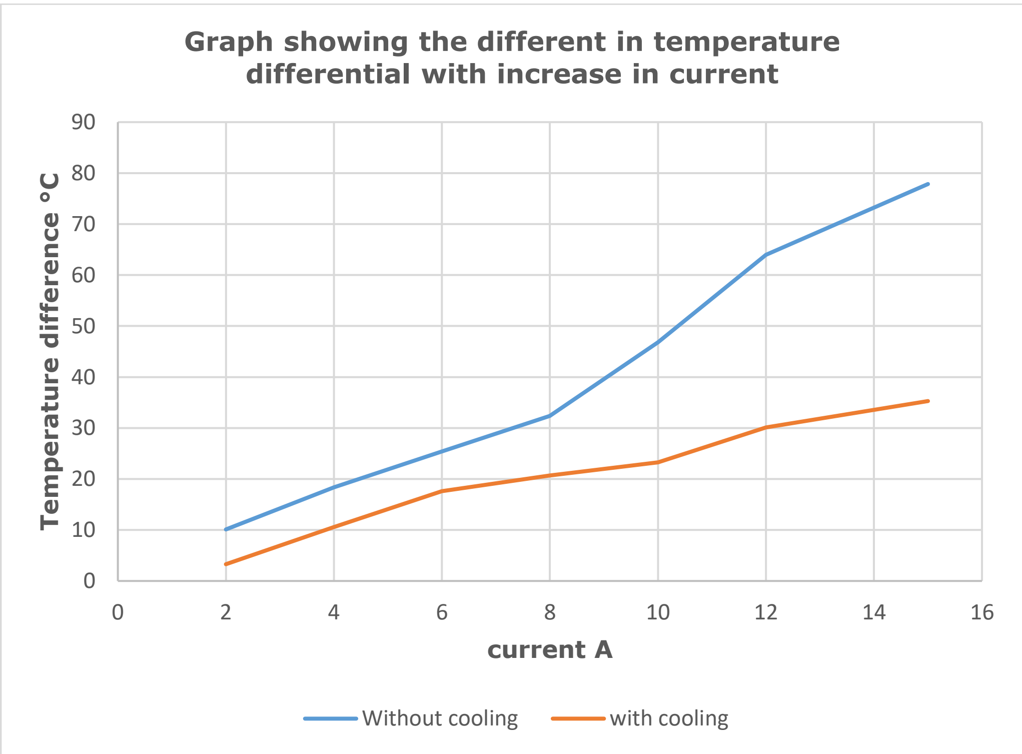

Figure 4.2 Graph showing the winding thermal performance of winding without cooling and with cooling.

Finding the difference between the two-temperature differential can evaluate how much the integrated fan cools the winding with increasing current and from Table 4.2 the graph can be plotted as seen in Figure 4.3.

Table 4.2 The difference of the Temperature differential when it is rotating and when it is not

Current (A)	ΔT (without cooling) (°C)	ΔT (with cooling) (°C)	$\Delta T = \Delta T_w - \Delta T_{wc}$ (°C)
2	10,11	3,29	6,82
4	18,34	10,59	7,75
6	25,41	17,64	7,77
8	32,40	20,7	11,7
10	46,81	23,29	23,52
12	63,98	30,11	33,87
15	77,86	35,29	42,57

Where ΔT_w is temperature of winding(without cooling) °C

ΔT_{wc} is temperature of winding (with cooling) °C

ΔT is the difference between ΔT_{wc} and ΔT_w °C

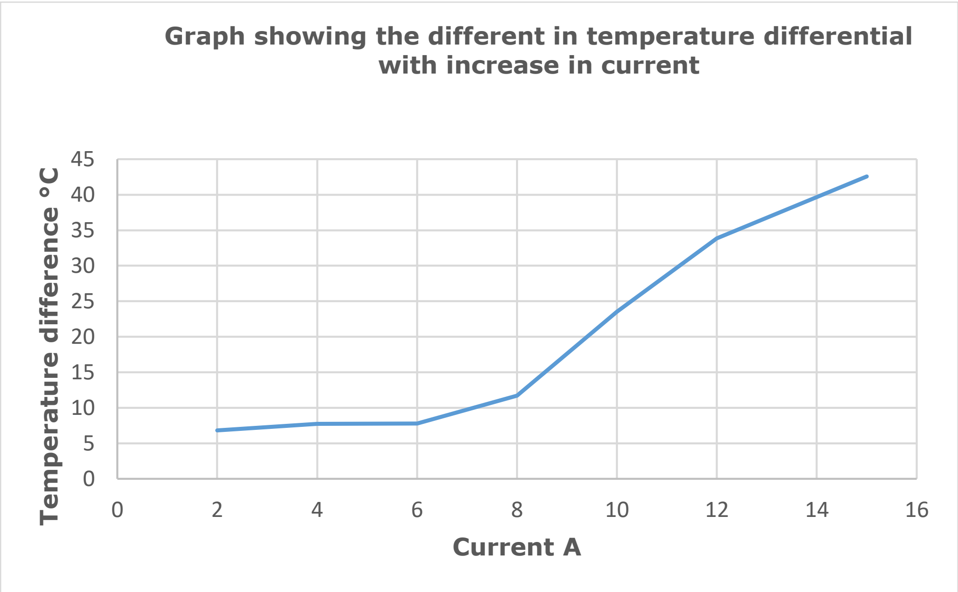

Figure 4.3 Graph showing how much the winding was cooled using the internal fan in the rotor with increase in current

4.3.2 How Does the Speed of the Rotor Affect the Cooling of the Winding

To prove the concept that the speed of the rotor affects the cooling the rotor speed was changed to a lower speed to validate this concept, thus the motor driving the rotor's speed can be varied using the voltage of the power supply and for the test, the speed of the test motor can be calculated from the *Kv* rpmV^{-1} rating and voltage level of the supply to find the speed rpm as in equation (4.4) below

$$Rpm = K_v \times V \text{ rpm} \tag{4.4}$$

Where *Rpm* is speed of rootor rpm

K_v – voltage rating of motor rpmV^{-1}

V – voltage of supply V

The external motor has a *Kv* rating of 690 rpmV^{-1}

Table 5.3 below shows both Temperature differential.

Current (A)	ΔT (At 5520 Rpm) (°C)	ΔT (At 6210 Rpm) (°C)	ΔT (At 6900 Rpm) (°C)	ΔT (At 7590 Rpm) (°C)
2	4,84	4,43	3,29	2,96
4	12,78	11,36	10,59	8,33
6	19,32	18,79	17,64	15,61
8	22,23	21,92	20,70	18,98
10	24,87	24,54	23,29	22,67
12	33,22	32,67	30,11	29,65
15	38,73	37,12	35,29	33,34

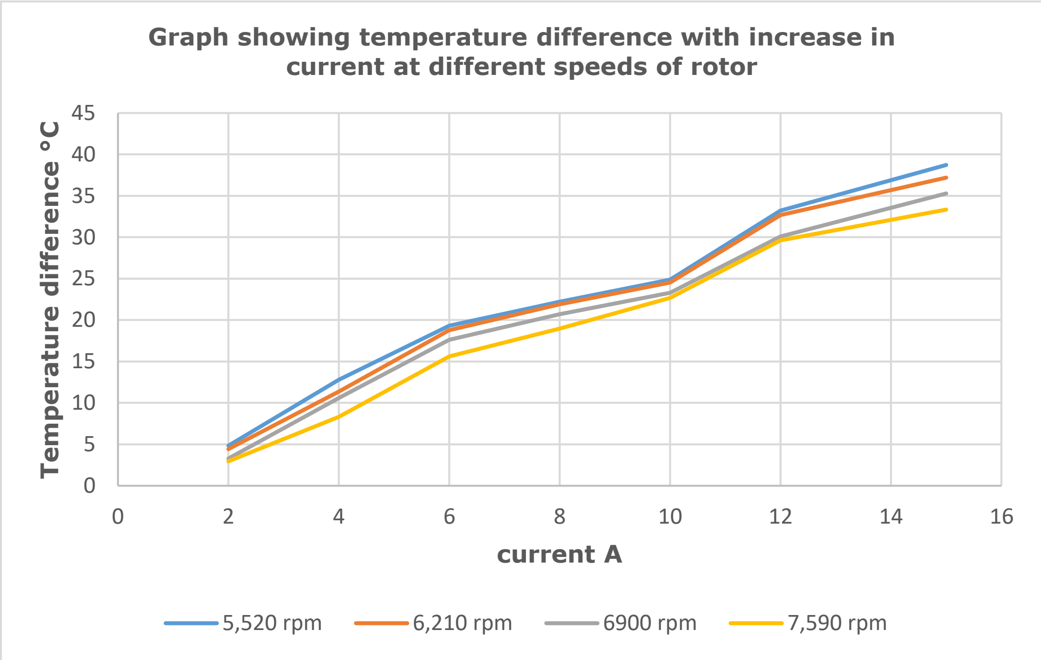

Figure 4.4 Graph showing how change in speed of the rotor affects cooling

Figure 4.4 confirms that the increase in speed of the rotor improves cooling thus the temperature differential of the higher speed has lower temperature differential.

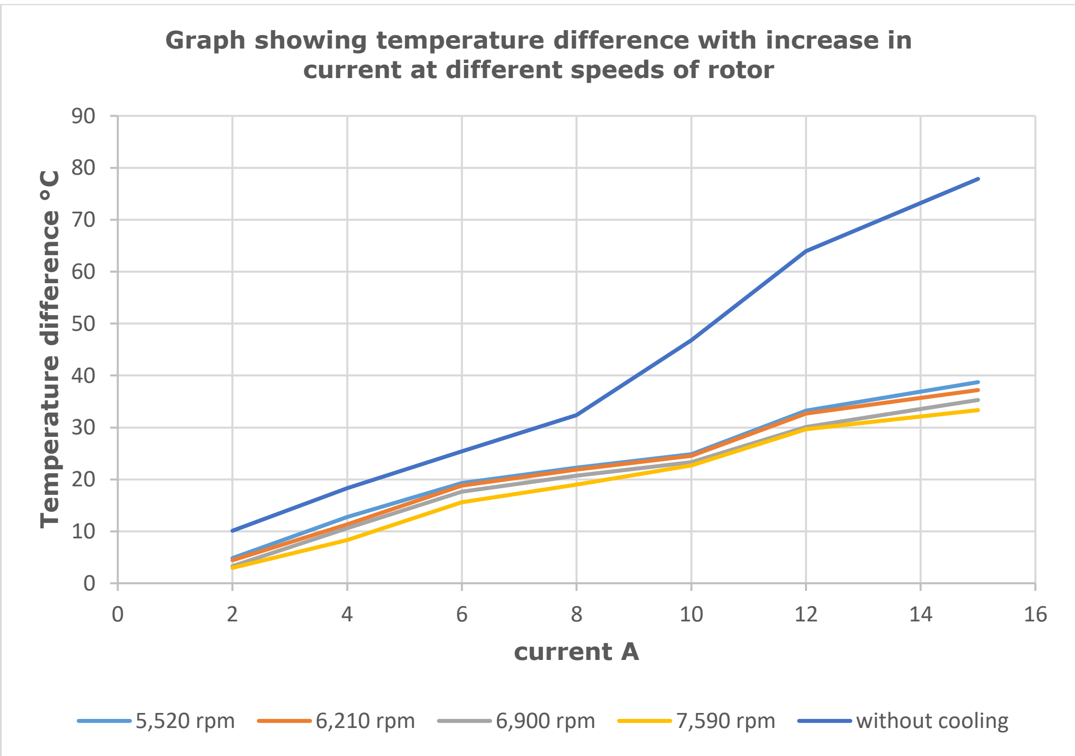

Figure 4.5 Graph showing the temperatuure differential without cooling and with cooling at diferent speed of rotor

From Figure 4.5 the integrated fan targeted at the heat sink significantly cools down the winding thus giving lower temperatuure differences compared to without cooling. The graph also confirms that increase in speed of rotor improves the cooling thus the plot of the higher speeds have lower temperatuure difference.

With the temperatuure difference of the windings at different speed the relationship between speed and convective coefficient can be evaluated using the values for current I= 15 A and R_0 = 10.9 mΩ and the surface area A of the heat sink of 0.000368 m^2 . The temperature difference of all the different speed at 15 A was used to calculate for the convective coefficient.

From equation subsituting the value of ΔT we can get h at the various speed and using to plot a graph as it is Figure 4.6 below

$$h = \frac{Q}{\Delta T \times A}$$

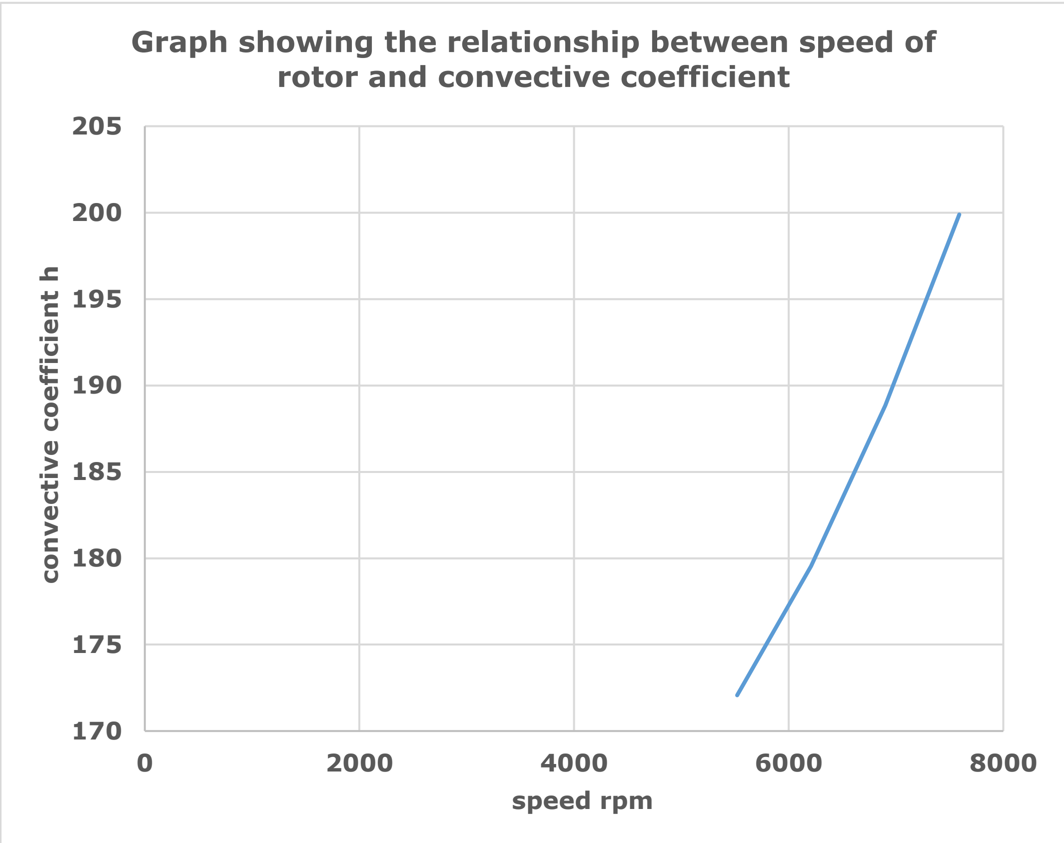

Figure 4.6 Graph showing the relationship between speed and convection coefficient.

The graph shows that with increase in speed the convective coefficient increases thus improves the cooling of the winding and from Figure 4.7 the greater the speed the greater the max current.

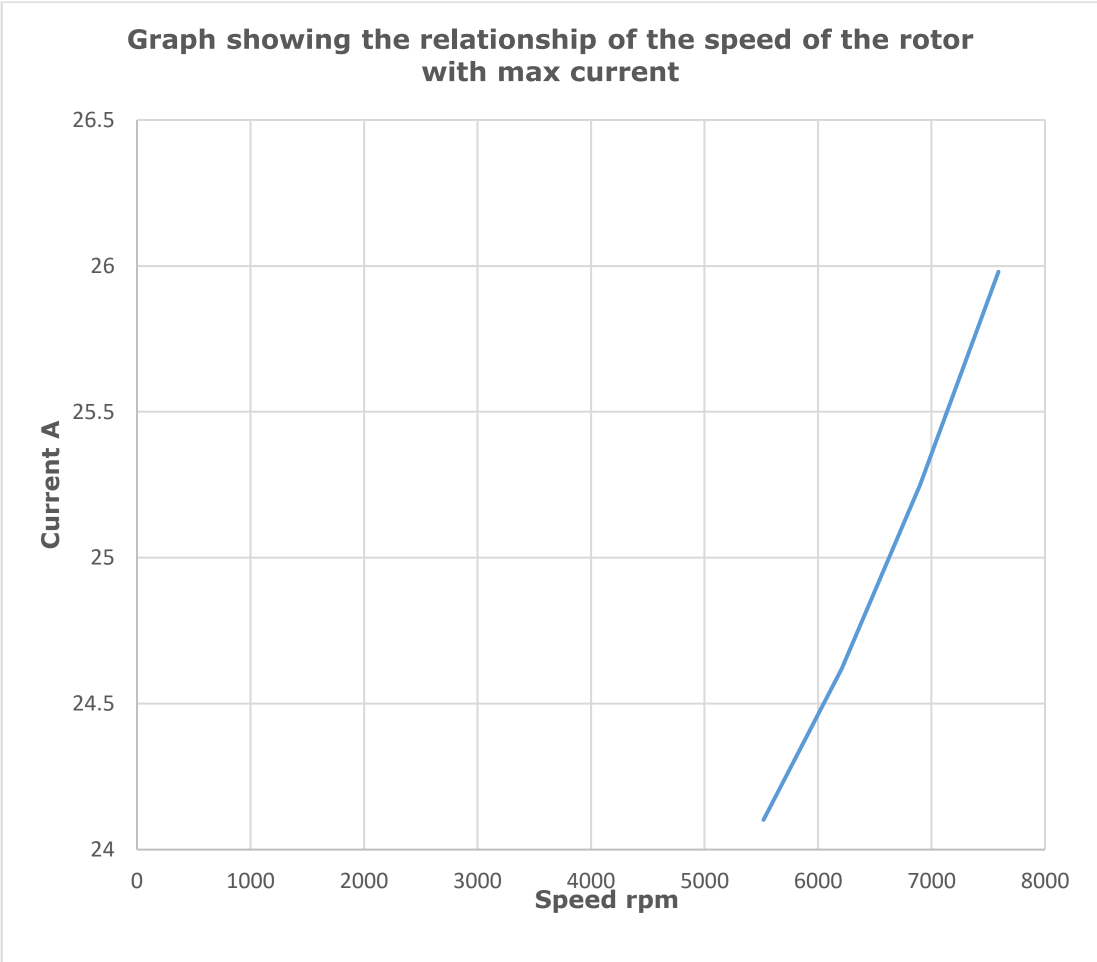

Figure 4.7 Graph showing the relationship between Max current capacity and speed of Rotor

Figure 4.7 above shows that the Max current of the motor is dependent on the speed of the rotor thus the greater the speed of the rotor, the greater the current the motor can handle.

4.4 Conclusion

The measurements and graphs although might exist some errors validates that the concept of using a winding with an end-turn heat Exchange that is cooled by an integrated fan on the rotor is an effective thermal solution. It also shows that with increased speed of the rotor improves the cooling.

Utilizing these windings in real machines will help improve the power capacity of the machines and will improve the lifespan of the conducor and also the machine. Using copper as the material might yield similar result but with diferent magnitude due to the difference in property material and printing of the winding.

The design allows for more compact and powerful applications and its being cooled during standard operation without having to adapt the machine to the cooling method like the case of water jacket adding more size to the machine and most forced convection by air incorporates a fan system to facilitate cooling but in this solution the fan is integrated in the rotor thus no additional size or fan system. From the measurements we can see that it significantly cools the winding and allows for more current thereby increasing the current density of the winding. From the Table 4.1 it shows that it cools about half of the temperature differential without cooling, which means it is possible to get double the current capacity of the winding. thus double the current density compared to typical electric machines which shows a current density of about 3-5 Amm^{-2} [24] but in this case the current density of the motor increases with the speed of the rotor and from the max speed from the test the highest current density is about 12.5 Amm^{-2} which is about 3 times more. A higher current density for same size motor not only enables the motor to generate stronger electromagnetic force which improves the performance but can be used in applications where space is limited.

From the analytical calculation which shows that the max current capacity is about 18 A when compare with the measurements which shows about 25 A, we can say the measurements are almost identical thus proving the concept and the measurements yielded more which can be due to the convection coefficient of the set up being more that the expected coefficient used for calculation.

5. SUMMARY

In this paper a reliable and efficient mode of operation of an electric machine is discussed. As studied, excessive heat created during operation of electric machines (high temperature leading to increase in resistance and losses) can cause degradation of insulation materials, winding problems, etc. An additively manufactured Method employed to solve this problem.

The additively manufacturing method that was studied in this paper can enhance the thermal performance of electric machines. This was done by designing a winding with end-turn heat exchanger that is intended to be cooled by an integrated fan in the rotor to replace traditional copper windings thus keeping the standard operation of the machine and improving the thermal performance without increasing the size of the machine.

The performance of this method was tested, and it yielded positive results to validate the concept and from Figure 5.5 the concepts allow for more current through the winding thus allowing for more power of a machine with same size. During the test factors such as speed of the rotor was considered to understand better how it affects cooling in case of future projects.

6. KOKKUVÕTE

Selles artiklis käsitletakse usaldusväärset ja tõhusat töörežiimi elektrimasina jaoks. Uurimuse tulemusel selgus, et elektrimasinate töötamisel tekkinud liigne soojus (kõrge temperatuur, mis suurendab takistust ja kadusid) võib põhjustada isoleerimismaterjalide halvenemist, mähiseprobleeme jne. Selle probleemi lahendamiseks kasutati lisandvalmistamise meetodit.

Uurimuses käsitletud lisandvalmistamise meetod võib parandada elektrimasinate termilist jõudlust. Selle saavutamiseks kavandati mähis koos otsaosa soojusvahetiga, mida kavatsetakse jahutada rootoris oleva integreeritud ventilaatori abil, asendades traditsioonilised vaskmähised, säilitades samas masina tavapärase töörežiimi ja parandades termilist jõudlust ilma masina suurust suurendamata.

Selle meetodi jõudlust testiti ja see andis positiivseid tulemusi, et kontseptsiooni valideerida. Joonisel 5.5 on näha, et kontseptsioon võimaldab mähisesse rohkem voolu, võimaldades samasuguse suurusega masinal rohkem võimsust. Katse käigus võeti arvesse ka rootori kiirusega seotud tegureid, et paremini mõista, kuidas see tulevikuprojektide korral jahutamist mõjutab.

7. LIST OF REFERENCES

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