Development of Aluminum Winding Three Phase Induction Motor for Lightweight EV Applications

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An Undergraduate Thesis submitted to the Electrical and Computer Engineering Department as partial fulfillment of the requirement for the award of a Degree of Bachelor of Science in Electrical (Power) Engineering.

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Declaration

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DEDICATION

This project is dedicated to our parents who have never failed to give us financial and moral support, for giving us all our needs when we developed our system, and for teaching us that even the largest task can be accomplished if it is done one step at a time.

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ABSTRACT

Development of Aluminum Winding Three Phase Induction Motor for Lightweight EV Application

This project presents the topic of development of the stator winding for electric vehicles and hybrid Electric vehicles induction motors of aluminum instead of copper. The aspect of replacing the material is presented from the perspective of the producer. Copper is used widely and offers good conductivity but its weight and cost are higher so in the case of lighter-weight applications copper cannot be used such as Electric Vehicles and Hybrid Electric vehicles. It is important to obtain a new motor with the same characteristics and the same energy efficiency while decreasing conductor material price and thus the price per motor unit. The better replacement for copper was Aluminum which was considered in this study. Other materials are expensive the cheapest material with good performance which competes with copper performance is aluminum. For this purpose, two motors were analyzed, one with copper winding and one with aluminum winding. A three-phase induction motor has been taken with copper winding and tested for performance which includes torque, and efficiency. The winding material is changed to aluminum after the first tests with copper while keeping the dimensions of the motor the same to make a fair comparison. JMAG has been used to make the same three-phase induction motor with the same dimensions and then compared the results of both winding materials. From the results, it has been observed the tradeoff was less and the study can be proceeded for Electric Vehicles. A three-phase induction motor has been designed and repeated the same process to compare the results in both materials and also introduced new winding terminology i.e., hairpin winding which improved the efficiency at the end of a high performance three phase induction motor for lightweight electric vehicles has been obtained with lighter weight and lower cast. The study focuses on the mechanical characteristics, comparing the rated and starting torque values for the shaft during speed function.

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ABBREVIATIONS

EV	Electric vehicles
HEV	Hybrid Electric Vehicles
IM	Induction Motor
FEA	Finite Element Analysis
FEM	Finite Element Method

Chapter 1

Introduction

1.1 Introduction

Global warming is the absorption of CO_2, CFCs, etc. in the atmosphere and with that, the average temperature of the earth rises. CO_2 is emitted by other vehicles, and it adds 4.6 metric tons of CO_2 to the atmosphere per year which is a huge contribution to global warming. The electric vehicle is the best application for meeting the basic requirements for global warming and their emissions of CO_2 etc. are considerably lower than other vehicles. EV applications contribute to protecting the environment. The machines that are already installed and in use have copper winding on their stator like machines in mills, pumps, Autos, etc. The copper winding has many disadvantages, the major one is, that induction motors have high magnetizing inrush current which results in low voltage. The motor used in EVs has high starting torque. The copper winding is housed in the stator of the induction motor and heats up due to the excessive current flowing in the winding at the high torque region. Copper is less flexible, and this makes winding of motor a difficult task. Thus, alternate winding materials are required to be investigated for efficient and lightweight induction machines. Aluminum offers better overloading capacity than copper and a higher current can be drawn in aluminum winding than copper which results in high torque in the induction motor hence the need for high torque in the induction motor is fulfilled with aluminum winding. Aluminum is cheaper than copper and lighter in weight. Aluminum is more flexible which makes winding easier and the most interesting advantage of aluminum in the environmental aspect is that it is recyclable with steel easier than copper.

A wide variety of applications rely on three-phase induction motors, including everyday household appliances and heavy-duty industrial machinery [1][2]. The demand for efficient and high-performing electric machines has risen significantly across multiple industries thanks to the versatility and reliability offered by induction motors [3].

In the design and performance of electrical machines, copper plays a significant role as it is considered a key component among other crucial factors [4]. Under its excellent electrical conductivity, copper is highly sought after in the domain of high-performance electrical machines, as it facilitates achieving high-current density and mitigating losses from DC winding [5]. Efficient power transfer and improved motor performance are facilitated by copper's superior conductivity.

Moreover, copper's strength and durability make it the favored choice for winding applications in electric machines [6]. With its mechanical properties, the windings can endure the harsh requirements of operation, which encompass both mechanical stresses and forces experienced within the motor.

To recapitulate, the extensive usage of three-phase induction motors across industries underscores their reliability and efficiency. The importance of copper in electrical machines cannot be exaggerated, considering its remarkable electrical conductivity, capacity to facilitate high-current density layouts, and mechanical durability. The attributes exhibited by copper render it the optimal substance for windings, which in turn enables the construction of electric machines that excel in terms of both performance and durability. However, there are several potential benefits to the use of aluminum windings, [7][8]:

- Aluminum has a mass density of only 30% of that of copper, this can be beneficial in applications where low mass is important.
- Aluminum is significantly cheaper than copper, having a cost of approximately 30% of copper per unit mass, or 10% per unit volume [9].
- Aluminum can be recycled with steel, whereas copper is a considerable contaminant in the steel recycling process.

For many high-power density motor designs, it is difficult to separate the windings from the steel core without significant dismantling processes, making this an important consideration [10].

Figure 1.1: Squirrel Cage Induction Motor

Aluminum has been widely used as an electrical conductor for many years in applications such as power distribution and low-cost electrical machines, particularly in induction machine rotors [11][12]. However, its use has not been reported in high-power density electrical machines, probably due to its lower electrical conductivity than copper. The authors have previously presented a 6kW electrical machine, designed for use in an aerospace application, which used pre-compressed aluminum coils, maintaining motor losses at the required level whilst reducing motor mass by more than 10% [13]. The compression process, first presented in [14], allows a very high fill factor to be achieved (>75%) where single-stranded conductors are used. This allows the lower conductivity of aluminum, when compared to copper, to be offset whilst still retaining the benefits of low mass.

A study conducted by Sullivan in 2007 expressed worries about the financial impact of utilizing copper in electrical machines due to its expensive nature [7]. This prompted a reevaluation of copper winding's cost-effectiveness, as improving its efficiency would require additional copper, thereby increasing the motor's weight and cost. Alternatively, instead of using copper winding, this research suggests employing aluminum winding exclusively. This alternative has several potential benefits for the motor such as reduced costs, decreased weight, and noise levels along with a potential increase in overall efficiency [7].

Aluminum has become an attractive option to replace copper in recent years, with its applications expanding to include electric machines such as transformers and BLDC motors. The lower cost and good conductivity of this material make it an appealing option for electrical purposes [8]. To put it in perspective, if we compare the two metals based on equal resistance and length conditions, we find that aluminum is significantly less expensive than copper. Aluminum constitutes roughly 30% of the mass and only 10% of the cost per unit volume [5][7][9].

Evaluating the feasibility of both materials requires considering environmental factors. Although copper poses pollution risks during the recycling of steel, aluminum offers the advantage of easy recyclability when co-processed with steel, positioning it as a more environmentally friendly choice [5][9].

The weight of electrical machines holds great significance in various applications. After carrying out an extensive comparison, it was determined that copper winding trails behind in terms of weight, yet comparable performance can be reached with aluminum winding. Being around 30% the mass density of copper, aluminum becomes particularly desirable for applications that require low masses [10].

In this research, the characteristics of a three-phase induction motor featuring windings made from both copper and aluminum are explored. Investigations were performed to analyze variables like efficacy, twisting force, and sound level. The performance and weight of the windings in both aluminum and copper were compared by conducting transient analyses on them.

By thoroughly examining copper and aluminum windings, this study aimed to offer valuable insights into the trade-offs among cost, weight, efficiency, and environmental impact. By considering these factors, researchers and industry professionals can make informed decisions regarding the selection of the most suitable winding material for specific electrical machine applications.

1.2 Motivation and Needs

The motivation and needs of this project revolve around several key factors:

- Recycling Ease: Considering the ability to recycle alongside steel, aluminum outshines copper as a more environmentally friendly alternative. This coincides with the mounting relevance of sustainable practices in the sector.
- Weight Reduction: By employing an induction motor that utilizes aluminum winding, the weight of EV applications can be greatly decreased. Enhancing energy efficiency and increasing driving range are key objectives in the field of electric vehicles, making lightweight designs crucial.
- Compact Size: Induction motors with aluminum winding have an edge over permanent magnet DC motors due to their compact size. This becomes advantageous in applications that have limited space.
- Control of Torque: The induction motor with aluminum winding enables precise control of torque during acceleration. This is achieved through voltage reduction at high speeds, providing enhanced control and stability in varying operating conditions.
- Elimination of Brushes and Rotor Windings: The induction motor's rotor design removes the requirement for brushes and rotor windings. Thus, the motor experiences reduced maintenance demands and improved dependability.
- Accurate Speed Regulation: The induction motor with aluminum winding offers highly accurate speed regulation. Easily adapting to specific operational requirements can be achieved by changing the frequency and varying the motor's speed.
- Regenerative Braking: Utilizing electrical braking operations allows the induction motors to function as generators. Through this mechanism, it becomes feasible to convert kinetic energy into electrical energy and subsequently utilize it for battery charging purposes in the vehicle. The capability to apply regenerative braking contributes to improved energy efficiency and decreased dependency on traditional brakes.

With a focus on these motivations and needs, the development of the proposed model seeks to push forward electric vehicle technology. This progress can be realized through achievements such as decreased weight, heightened efficiency levels, enhanced control features, and regenerative braking capabilities.

1.3 Objectives

The proposed project aims to achieve the following objectives:

- Design a three-phase induction motor in JMAG with the dimensions of a motor available in hardware. Simulate the model with copper winding material and analyze its efficiency and torque.

- The winding material will be changed to aluminum to repeat the same analysis with the same dimensions, cross-sectional area of winding materials, and number of turns for a fair analysis.
- Conduct a comprehensive performance analysis of the designed induction motor with aluminum winding. It is important to assess how this motor performs in terms of efficiency, and torque when compared with existing induction motors in the market which have copper winding. Assess the strengths and weaknesses of implementing aluminum winding concerning its performance.
- Develop a prototype of the induction motor having aluminum winding and perform practical tests to affirm its performance and characteristics. Acquire the data from the tests regarding efficiency, torque-speed characteristics, and other relevant variables for comparison purposes with the simulation results and ongoing enhancement of the design.
- After comparing the encouraging results, a three-phase induction motor for electric vehicles will be designed with copper winding. For better performance, the necessity for Electric Vehicles will be considered.
- The same analysis will be repeated with copper winding and aluminum analysis. Then both the results will be compared for stranded winding type and an in-depth study will be carried out for the acceleration and speed of the EV.
- The induction motor for Electric Vehicles is heavy and they are larger so introducing aluminum will affect the weight with a greater portion. It will give benefits in terms of weight and better acceleration.
- To improve the efficiency and performance of the induction motor used in Electric Vehicles a new terminology of winding that is Hairpin winding will be introduced.
- The efficiency will be improved as the slot fill factor will be decreased. With hairpin winding overall the performance and efficiency will be improved and the study will be taken in layers to study the effect of the number of layers on the induction motor.
- In hairpin winding the material usage are greater so using copper in large quantity will increase the weight more. Replacing hairpin winding with aluminum will make it lighter without compromising on performance.
- From the overall study and research, a high-performance induction motor with better efficiency will be obtained for Electric Vehicles as lighter weight matters for EV applications. This study will ultimately promote the progress of EV Technology

The proposed project aims to develop a lightweight EV application-specific optimized induction motor with aluminum winding to achieve these objectives. Henceforth, the outcome would be a high-performing motor with advanced torque capacity, augmented loading potential, reduced mass, and overall improved execution. As such, this accomplishment holds considerable significance in terms of its impact on electric vehicle technology.

Chapter 2

Literature Review

2.1 Introduction

Nikola Tesla invented the asynchronous polyphase induction motor in 1882 and patented it in 1888. This invention led to an increase in the mechanization rate of the industry. The electric machine that is known today as the squirrel-cage induction motor was invented by Mikhail Dolivo-Dobrovolsky in 1891. Because of these two inventors along with the utility of power electronics, today the control of induction motors using advanced control techniques can be studied.

After considering the history of the induction motor, it is useful to give background and a basis for the following discussion. As stated earlier, the induction motor can be considered, in an electrical sense, to be a three-phase transformer with an air gap and a winding that is in motion, called the rotor. Assuming a balanced three-phase voltage set is applied to the stator, a few concepts can be obtained, namely that a magnetic field is found to be moving at synchronous speed in the motor air gap, and that this, in turn, will induce a current on the shorted rotor winding that has an angular electrical frequency associated with how much "slip" is occurring on the rotor. This induced current creates its magnetic field which interacts with the stator magnetic field to create a force that repels the stator field. Under normal operating conditions, every time the stator field attempts to line itself up with the rotor, the rotor field restores the repulsion force. It is important to note that both fields rotate at synchronous speed around the axis of the motor. It is now necessary to define synchronous speed as the "angular speed that the rotor spins multiplied by the number of poles divided by two," as shown in (1) from [19].

$$\omega_e = 2\pi f_e = {}^{p}\!/_{2}\, \omega_{rm(at\ synchronous)} \tag{1}$$

2.2 Basic Theory of Induction Motor

An electrical motor is an electromechanical device that converts electrical energy into mechanical energy. An induction or asynchronous motor is an AC electric motor in which the electric current in the rotor needed to produce torque is obtained by electromagnetic induction from the magnetic field of the stator winding. The induction motor consists of the stator, stationary windings, and the rotor as shown in Figure 2.1 and Figure 2.2. The stator is the stationary part of a rotary system, normally found in electric generators, electric motors, sirens, or biological rotors. A stator acts as the field magnet, interacting with the armature to create motion, or acting as the armature, receiving its influence from moving field coils on the rotor. The stator is made up of a series of wire windings of very low resistance permanently attached to the motor frame. As the voltage and current are applied to the stator winding terminals, a magnetic field is created in the windings. By the way, when the stator windings are arranged, the magnetic field appears to synchronously rotate electrically inside the motor housing. The rotor is a moving component of an electromagnetic system in the electric motor, electric generator, or alternator. Its rotation is due to the interaction between the windings and magnetic fields which produces a torque about the rotor's axis. The rotor is made up of several thin bars, usually aluminum, mounted in a laminated cylinder. The bars are arranged horizontally and almost parallel to the rotor shaft. At the ends of the rotor, the bars relate to a “shorting ring.” The rotor and stator are separated by an airgap which allows free rotation of the rotor. The magnetic field generated in the stator induces an electromotive force (EMF) in the rotor bars as shown in Figure 2.3 current is produced in the rotor bars and shorting ring and the magnetic field is induced in the rotor with an opposite polarity of that in the stator. The magnetic field, revolving in the stator will then produce the torque which will “pull” on the field in the rotor and establish rotor rotation.

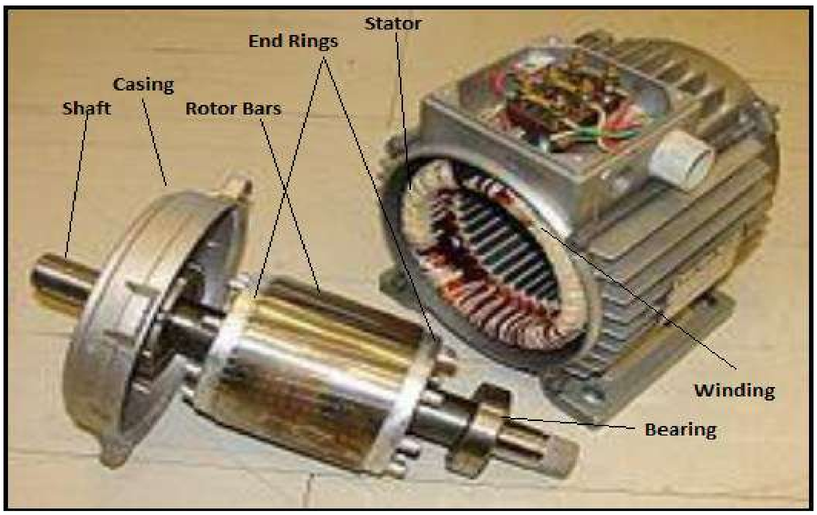


Figure 2.1: Rotor and Stator of Three-Phase Induction Motor

2.3Literature Review and Background:

IMs are characterized by three-phase AC (Alternating Current) windings arranged on the stator and short-circuited copper windings (or cast aluminum bars) on the rotor. In general, electrical machines with brushes or commutators are not preferred because of their high maintenance requirements. Therefore, squirrel-cage IMs are chosen for consideration. The widespread use of re-wound IMs causes a large decrease in efficiency. Some winders use coils that have several turns or conductor cross-sectional area that is less than or greater than the original ones [20]. These winding deviations may lead to a decrease in motor impedance, which causes an increase in motor temperature. Improving the efficiency of three-phase IMs, which is the purpose of this thesis, plays a significant role in decreasing energy consumption. Different methods have been used for performance improvement. The proposed strategy to improve three-phase IM efficiency is to replace the copper winding with Aluminum winding resulting in high torque and the same efficiency.

There are five types of losses in IM. These are stator and rotor copper loss, core loss, friction, windage loss, and stray loss. To improve the efficiency of IM at least one of the losses must be reduced. This can be achieved by improving material quality and using thin laminations. Moreover, the efficiency of IM can also be improved by increasing the core axial length [21]. In this section, the effects of increasing the core axial length along with stator inner and rotor outer diameter are studied on core loss and copper loss. Constant losses, like stray loss and friction and windage loss, are assumed to be constant.

- Copper loss: Copper loss is the I^2R loss found in the conductive materials of the IM. It is dependent on the stator resistance.
- Core loss: The core loss in IM is found in the iron parts of the machine. It is produced by the alternating flux in the iron core.

The core loss consists of two different types of losses (i) hysteresis loss and (ii) eddy current loss. Hysteresis loss is produced by the alternating magnetization of the material and eddy current is produced by the induction of circulating current within the material. [22]

It is commonly accepted that squirrel-cage IMs are renowned for their simplicity, ruggedness, cheapness, and reliability so they are used extensively in industrial drives. Their excellent field-weakening performance and low manufacturing costs make them a competitive candidate for EV motor drives. Nowadays, IMs can achieve similar torque speed control as DC motor drives. For example, the speed range can be extended beyond the base speed using field weakening as the field vector can be decoupled from the torque vector by vector control. Regarding efficiency, it can be high at the high speed and low torque range (due to reduced copper and core losses) while, at the low-speed high torque range, the efficiency reduces due to increased rotor losses [23].

An exhaustive review of EV motor drives [24] and a survey of experts' opinions [25] all concluded that induction motor drives are favored in EV applications because of their low cost, high reliability, mature manufacturing, and power converter technologies. However, their disadvantages are low efficiency, low power factor, and low inverter usage, limiting their use in large motor drives and high-speed operations of EVs. Examples of IM-driven EVs are the Silverado of Chevrolet, the Durango of Daimler Chrysler, the X5 of BMW, and the Kangoo of Renault [24].

The development of three-phase induction motors for various applications has been extensively studied in the field of electrical engineering. The exceptional electrical conductivity and high-current density machine design capabilities of copper have made it the favored material for winding in electrical machines [4][5][6]. Despite this, the high expense associated with copper has prompted researchers to reconsider its cost-effectiveness [15]. In 2007, Sullivan conducted a study that emphasized the importance of investigating alternative materials that could deliver similar performance characteristics while also reducing weight, cost, and noise levels [15].

One such alternative material is aluminum, which has gained attention in recent years for its favorable properties in electrical machines, including transformers and BLDC motors [16]. With its worldwide abundance and lower cost, aluminum offers excellent conductivity [16]. Compared to copper, aluminum exhibits a substantially decreased cost per unit mass and volume, positioning itself as an attractive option for lightweight applications [5][15][17]. In addition, aluminum can be conveniently recycled together with steel, thereby decreasing environmental worries linked to the recycling of copper [5][17].

The weight of electrical machines is crucial in numerous applications. Despite its excellent performance, copper winding is relatively heavier than aluminum winding [27]. Due to its lower mass density (which is around 30% of copper), using aluminum winding allows for achieving similar performance while reducing the weight [27]. Low-mass applications find aluminum to be a compelling option.

To investigate the performance differences between copper and aluminum winding, this study focuses on a three-phase induction motor. Tests were conducted to assess the efficiency, torque, and noise characteristics of both winding materials. Transient analyses were performed using the finite element method (FEM), specifically utilizing 2D modeling in JMAG software [26][28]. The nonlinear electromagnetic behavior of the motor, influenced by phase current and rotor positions, was accurately captured through FEM analysis [26]. The use of numerical methods, such as FEM, provides higher accuracy compared to analytical methods [28].

Additionally, the literature highlights the specific properties and challenges associated with copper and aluminum as electrical conductors. Copper exhibits superior conductivity, as per the International Annealed Copper Standard (IACS), with a rating of 98% [30]. In contrast, pure aluminum is too soft for wire manufacturing, necessitating the development of 1350 Aluminum alloy, classified under the Electrical Conductor (EC) class, with 99.50% aluminum content [29][30]. Although the electrical conductivity of the 1350 Aluminum alloy is 61.2% that of copper, it still fulfills the requirements for electrical purposes [29][30].

By exploring the advantages and considerations associated with copper and aluminum winding, this study contributes to the ongoing research on optimizing three-phase induction motors for lightweight EV applications. The comparison of performance characteristics, along with the potential for weight reduction and improved efficiency, highlights the importance of investigating alternative materials in the pursuit of advancing electric vehicle technology.

Chapter 3

Methodology and Design Development

3.1 Introduction

A detailed technique was used in the production of a three-phase induction motor for lightweight electric vehicle (EV) applications. This method consisted of several essential procedures and analyses. The first part of the investigation required the purchase of a three-phase induction motor that is already on the market and has a rating of 0.75 kW. Additionally, the motor must have a copper winding. In the laboratory, performance tests on this motor were carried out to determine its baseline characteristics.

A winding made of aluminum was subsequently installed in the motor after the original winding, made of copper, was removed. Again, the motor was put through its paces in terms of performance testing so that its operating characteristics could be evaluated considering the new material. The results of this study provide light on the performance disparities that may exist between copper and aluminum windings.

A technique that utilizes virtual design and analysis was used so that the impacts of the shift in the composition of the material could be researched further. The motor was designed and simulated by utilizing the JMAG program, which made it possible to conduct an in-depth analysis of the motor's performance characteristics using copper and aluminum windings respectively. The only impact of the material change was precisely evaluated by first ensuring that all other parameters remained unchanged.

The process of design proceeded once the comparison of the materials was completed. The motor underwent a complete overhaul to achieve the highest possible level of performance when applied to EVs. There was an investigation into both the dispersed winding and the hairpin winding layouts. In the beginning, the motor was built with dispersed winding, but later, it was changed to hairpin winding since it has several benefits over distributed winding, including better thermal performance and lower winding losses.

Several other designs of the hairpin winding, including 2, 4, 6, and 8 layers, were investigated. The motor's performance was evaluated utilizing both copper and aluminum windings in the windings of the motor. This in-depth study was conducted to identify the winding design that, in terms of efficiency, torque, and other essential characteristics, is most suited for lightweight EV applications.

This technique established a strong framework for the development and evaluation of a three-phase induction motor that could be used in EV applications. It did so by integrating experimental testing, virtual simulation, and design optimization. A comprehensive understanding of the motor's performance characteristics was made possible because of the exploration of different winding configurations and the systematic evaluation of both copper and aluminum windings. This, in turn, made it easier to identify the design decisions that were the most appropriate.

3.2 Design Development

The design development of the three-phase induction motor for lightweight EV applications involved the utilization of JMAG software, specifically JMAG Express and JMAG Designer, for modeling, analysis, and optimization purposes. These powerful tools provided a comprehensive platform for the design iteration and evaluation process.

The initial step in the design development was to create a detailed model of the induction motor in JMAG Express. The motor's geometrical parameters, such as stator dimensions, rotor dimensions, and winding configurations, were inputted into the software. By defining the material properties and electrical characteristics, a complete virtual representation of the motor was established.

Once the motor model was created in JMAG Express, various analyses were performed to evaluate its performance. The software allowed for the simulation of electromagnetic behavior, including magnetic flux distribution, induced voltages, and magnetic losses. These simulations provided valuable insights into the motor's efficiency, torque production, and other key performance metrics.

Table 3.1: General parameters and dimensions of the proposed three-phase induction motor

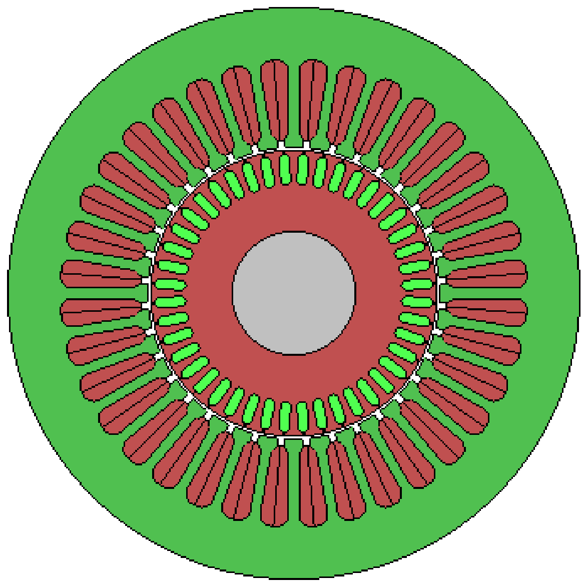
Dimensions of Stator		Dimensions of Rotor		General parameters	
Outer diameter	145 mm	Outer diameter	72.5 mm	Rated speed	1500 RPM
Inner diameter	73.95 mm	Inner diameter	31.3 mm	Rated power	750 W
Number of poles	4	Air Gap	0.725 mm	Rated voltage	400 V
Number of slots	36	Number of bars	44	Operating temperature	75 cel
Slot area	115 mm^2	Shaft	31.3 mm	Stack height	130 mm

To further refine the design, the motor model was imported into JMAG Designer. This advanced tool offered more comprehensive capabilities for motor design and optimization. Parameters such as winding layout, core materials, and magnet placement could be adjusted and fine-tuned in JMAG Designer to improve the motor's performance.

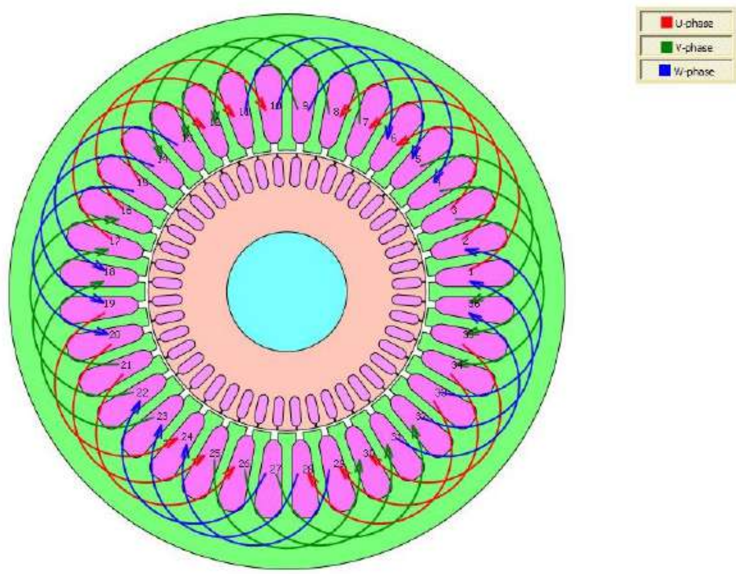
In JMAG Designer, additional analyses were conducted to assess the impact of different design parameters on the motor's efficiency, power output, and thermal characteristics.

Sensitivity studies were performed to understand how changes in key variables affected the motor's performance. Optimization algorithms within JMAG Designer facilitated the exploration of design spaces, allowing for the identification of optimal design choices.

Throughout the design development process, the motor model was thoroughly analyzed and compared using both copper and aluminum windings. By systematically evaluating the performance of the motor with different winding materials, the benefits and limitations of each material could be assessed. This analysis provided crucial information for selecting the most suitable winding material for lightweight EV applications.



(a)

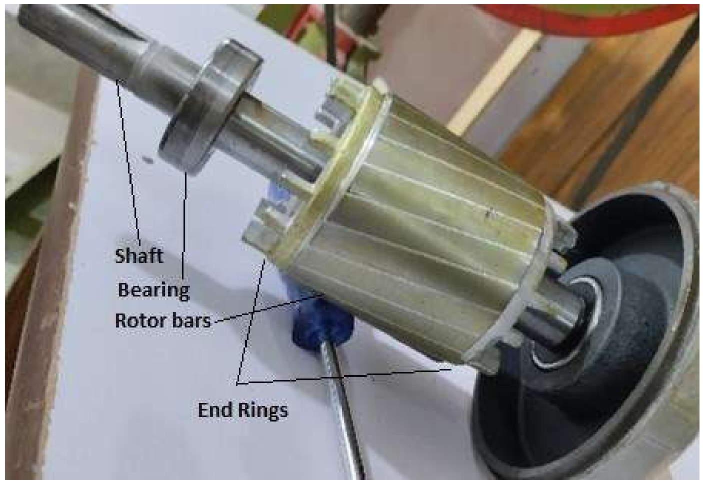


(b)

Figure 3.1: (a) Cross-sectional view of the model (b) Winding Pattern of the model

JMAG Express and JMAG Designer played a crucial role in the development of the design for the three-phase induction motor. These software tools allow for the creation of precise motor models, facilitate in-depth analyses of performance characteristics, and aid in the optimization of the motor's design parameters. JMAG's iterative design process allowed for the exploration of multiple design options and ultimately led to the development of an efficient and lightweight induction motor for EV applications.

For the hardware design of the three-phase induction motor, a 0.75 commercially available kW motor was acquired. Initially, this motor had copper winding, which is a common material in electrical machines due to its superior conductivity. The original configuration of the motor was subjected to a variety of performance tests to evaluate its efficiency, torque output, and other relevant parameters.



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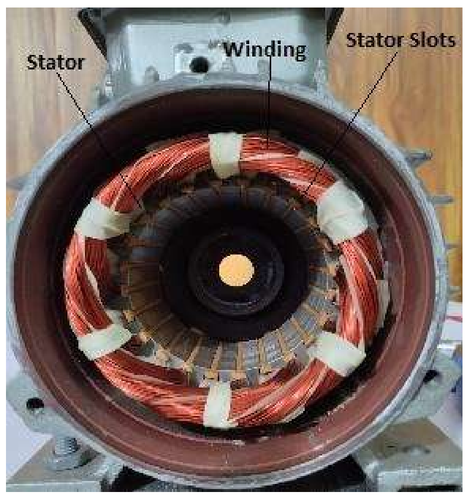


(b)

Figure 3.2: (a) Rotor of the purchased Model (b) Stator Core of the purchased Model

The copper winding in the motor was changed with an aluminum winding after first testing. This change was made to investigate the possible advantages of adopting aluminum as a winding material, such as weight and cost savings. The copper winding was removed from the motor and replaced with an aluminum winding of comparable specs.

After the modification, the motor was subjected to a fresh battery of performance tests to determine the effect of the new winding material. Efficiency, power output, and torque were tested and compared to the original copper winding's performance. This comparison enabled a thorough study of the performance differences between the two winding materials.

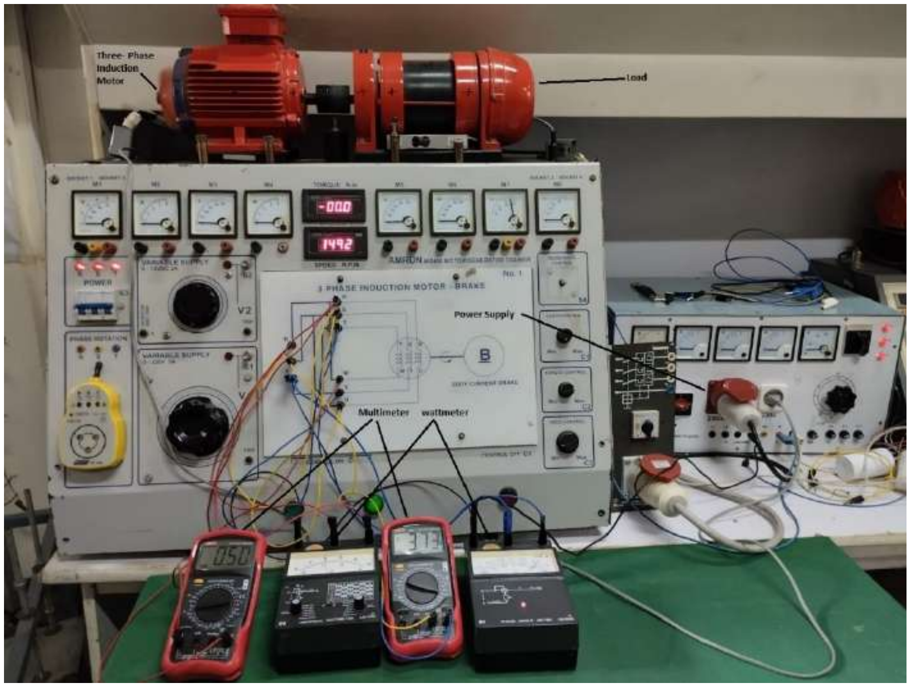
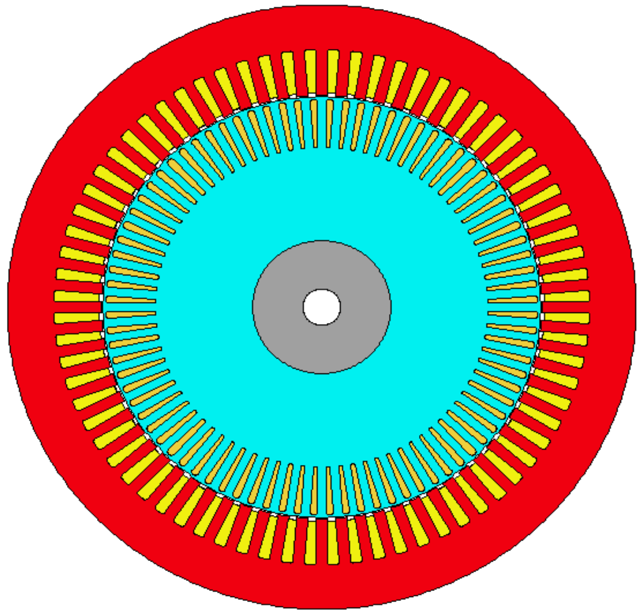


Figure 3.3: Hardware Setup for Experimental Validation

Through these hardware design alterations and subsequent performance testing, useful insights were gathered about the impact of winding material on the overall performance of the motor. This study's results gave significant considerations for the development of lightweight induction motors for EV applications, with the potential to maximize efficiency, decrease weight, and improve cost-effectiveness.

3.3 Electric Vehicle Induction Motor Design Development

Using Motor-CAD software, the design evolution of the EV induction motor was further investigated. Initially, the motor was developed with Distributed windings, which is a standard winding structure for three-phase induction motors. Motor-CAD was used to build the distributed winding design, considering the motor's specs and needs for EV applications.



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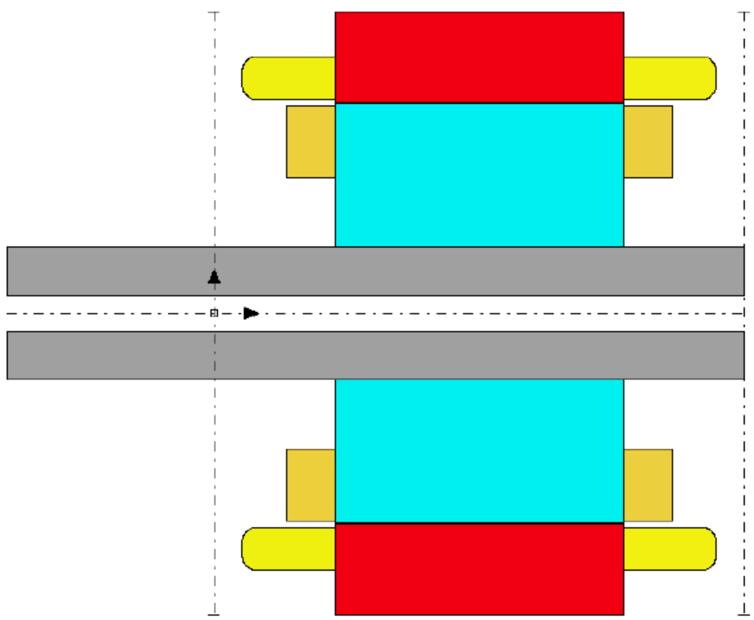


(b)

Figure 3.4: (a) Radial View of the designed model for EV (b) Axial View of the designed model for EV

To evaluate the performance of the motor, simulations were run in Motor-CAD using copper and aluminum winding materials. Simulations yielded insightful information on the motor's efficiency, power output, and other performance aspects. By comparing the findings achieved with copper and aluminum windings, it was possible to assess the benefits of aluminum, such as its lighter weight and lower cost.

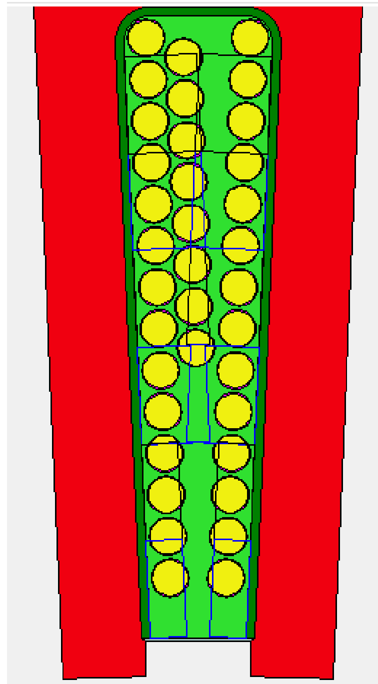


Figure 3.5: Stranded Winding in designed EV Model

As the design evolved, dispersed winding was replaced by hairpin winding. The compact and durable architecture of hairpin winding makes it appropriate for high-power density applications such as electric vehicles. The design of the hairpin winding was developed in Motor-CAD, considering many configurations with 2, 4, 6, and 8 layers.

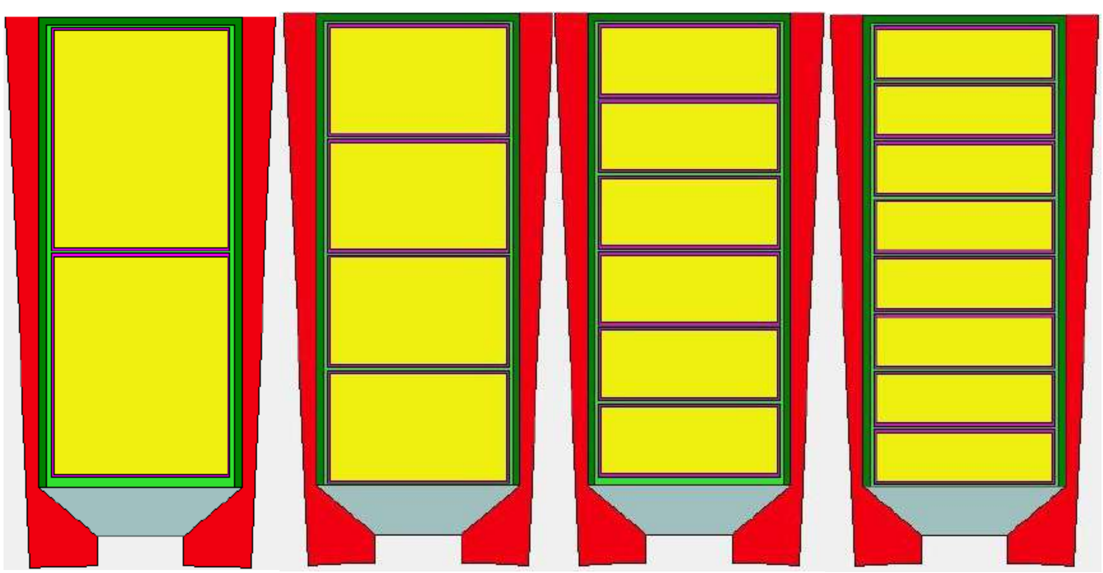


Figure 3.6: Hairpin winding with 2, 4, 6, and 8 layers in the designed Model for EV

On the improved design, simulations were run to evaluate the performance of the motor with hairpin winding. The influence of the hairpin winding on the motor's overall performance was determined by analyzing parameters such as efficiency, torque, and thermal behavior.

The findings of Motor-CAD simulations offered useful insight into the advantages of hairpin winding in terms of increased efficiency, decreased losses, and increased power output. The research of several layer designs enabled a thorough assessment of the ideal winding arrangement for the EV induction motor's unique needs.

By using the capabilities of Motor-CAD, the design development of the EV induction motor was increased, allowing the investigation of the effects of alternative winding configurations on motor performance. This data was essential in defining the optimal winding design for meeting the intended goals of lightweight and high-performance EV applications.

3.4 Winding Material and Cost Estimation

Winding is the most important part of an electrical machine, and it is made of coils. The wires in the coil are made of conductive material which is surrounded by resistive insulating material. Low electrical resistance and minimum joule losses are desired for a conductive core. The material used is generally Aluminum, copper, silver, and gold. The density of metal and alloys and electrical resistance of Commonly used materials in electricity at room temperature are given in Table 3.2 [11].

Table 3.2: Materials and Alloys Commonly Used in Electrical Applications

Main Element	**Electrical Resistivity (μΩ-cm)**	**Density (g/cm^3)**	**Cost/kg (USD)**
Pure Copper	1.7241	8.94	8.55
Pure Aluminium	2.6548	2.688	2.27
Aluminum 1350 (Electrical Alloy)	2.82	2.705	2.6
Pure Silver	1.586	10.492	752.63
Pure Gold	2.192	19.37	62,963.67

Copper and Aluminum are the most used materials in electrical equipment. According to the International Annealed Copper Standard (IACS), copper used in electrical equipment has a 98% conductivity [30]. On the other hand, pure Aluminum with good conductivity is too soft for the manufacturing processes of wires. [29][30]. Due to this reason, for electrical purposes, 1350 Aluminium alloy was developed. Its classification is under the EC (Electrical Conductor) class Aluminium, with 99.50% Aluminum content. In terms of mechanical properties, it is still soft and flexible as compared to copper, although it is for electrical purposes and has 61.2% of the conductivity of copper [29][30].

As Aluminium winding has lower electrical conductivity as compared to copper, the per unit winding length resistance value is higher, as given below in (2) [31][32].

$$\partial_R = \frac{R_{Aluminum}}{R_{copper}} = \frac{\sigma_{copper} S_{FF}^{Copper}}{\sigma_{Aluminum} S_{FF}^{Aluminum}} \cong 1.64 \frac{S_{FF}^{Copper}}{S_{FF}^{Aluminum}} \tag{2}$$

Where:

σ is the Electrical Conductivity of the winding material, S_{FF} *is* the slot fill factor, and *R* is the resistance, The electrical conductivities of Al and Cu at 20 °C are σ_{copper} =58.0 x10^6 *S/ m* and / *Al* $\sigma_{Aluminum}$ = 35.4 x10^6 *S/ m* [31][32].

By using the current (I), Resistance (RDC), and Ohmic DC (Direct Current) the copper losses in a fixed area can be calculated and given as in equation (3). [33].

$$P_{DC} = R_{DC} \times I^2 \tag{3}$$

With the current density (j*)* and specific resistance (ρ), the total losses are calculated as given in Equation (4) [33].

$$P_{DC} = \iiint \rho J^2 dV \tag{4}$$

Additionally, according to Equation (3) with an equivalent AC (alternating current) resistor (RAC*) Equation* (4) can be rewritten as given in Equation (5) [33].

$$P_{AC} = R_{AC} \times I^2 \tag{5}$$

From Table II, the densities and electrical resistances are different for copper and aluminum. The expression in Equation (6) must be fulfilled for equal resistance.

$$\rho_{Copper} \frac{l_{copper}}{S_{copper}} = \rho_{Aluminum} \frac{l_{Aluminum}}{S_{Aluminum}} \tag{6}$$

In Equation (6), *S* is the winding cross-section (m^2). ρ is the specific resistance (Ωm), and *l* is the winding length (m),

When the specific weights, cross-section diameter, and lengths of the Copper and aluminum winding used in the electric machine are substituted into Equation (7), the results will be the weight per pole of winding used. In Equation (7), *d* is the density (kg *dm)*, *m* is the weight (*kg)*, and *v* is the volume (dm^3).

$$d = \frac{m}{v} \tag{7}$$

The thermal conductivities of copper and Aluminum are 230 $Wm^{-1}K^{-1}$ and 387.7W $m^{-1}K^{-1}$ and $230W\ m^{-1}K^{-1}$, respectively. Their thermal conductivity ratio is given in Equation (8) [32].

$$\partial_k = \frac{\lambda_{Aluminum}}{\lambda_{Copper}} \cong 0.59 \tag{8}$$

When exposed to open air both aluminum and copper oxide are produced. Oxidation in Aluminum upon exposure to air occurs easily and around the metal an electrically insulating oxide forms quickly, a hard outer layer strongly bonded. On the other hand, the layer in copper is conductive and soft, but like the base metal, the oxide layer in copper is not as conductive [34].

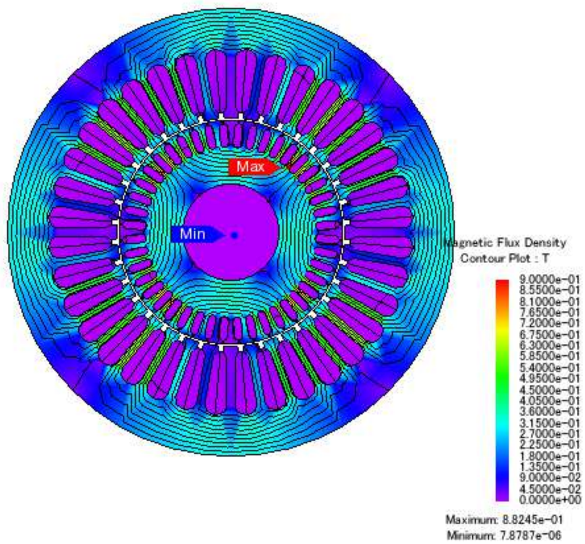
Chapter 4

Results and Discussions

4.1 Results

The results obtained from the simulations conducted in JMAG software provided valuable insights into the performance of the EV induction motor. Various parameters were analyzed, including flux density, torque, and efficiency.

The analysis of flux density distribution in the motor revealed the magnetic field strength and its distribution within the machine. This information is crucial for understanding the motor's magnetic behavior and optimizing the design for improved performance.



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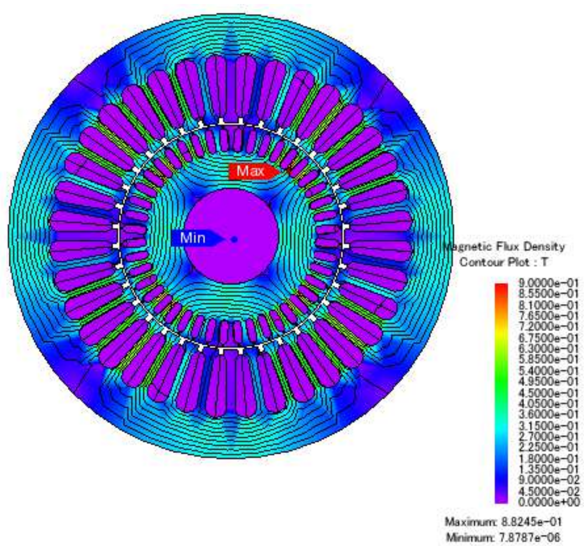


(b)

Figure 4.1: Flux Distribution of the initial model: (a) Copper Winding (b) Aluminum Winding

Torque is a key performance parameter for an induction motor, as it determines the motor's ability to deliver rotational force. The simulations in JMAG allowed for the evaluation of torque characteristics under different operating conditions. This helped in assessing the motor's capability to meet the torque requirements of EV applications.

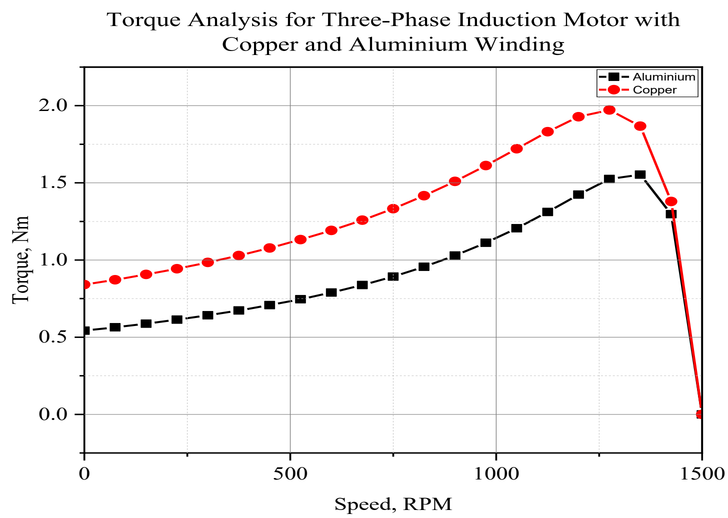


Figure 4.2: Torque vs. Speed curve for copper and Aluminum winding of the initial Model

Efficiency is a vital factor in electric motors, as it directly influences the motor's energy consumption and overall performance. The simulations in JMAG provided insights into the efficiency of the motor, allowing for comparisons between different winding materials and configurations. This information facilitated the selection of the most efficient winding design for the lightweight EV induction motor.

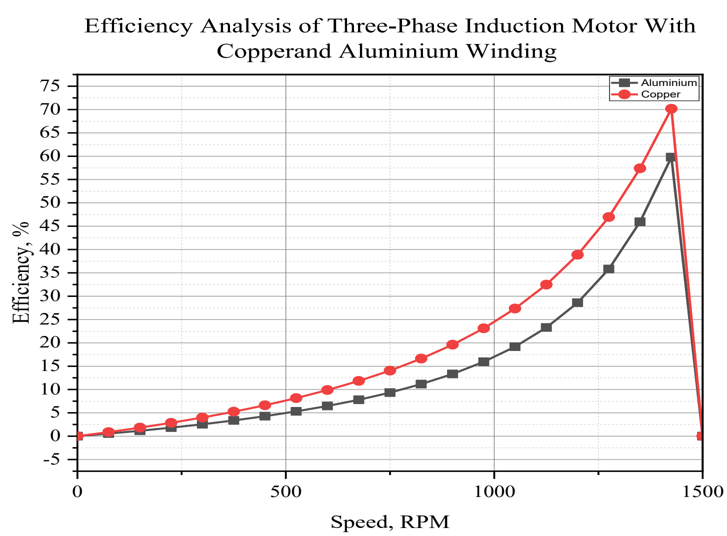


Figure 4.3: Efficiency vs. speed curve of copper vs. Aluminum winding of the initial model

Moving on to the hardware results, the initial motor with copper winding was tested in the laboratory to evaluate its performance. Parameters such as torque, power output, and efficiency were measured to assess the motor's performance under real-world conditions.

Following the hardware testing, the winding material was changed to aluminum. The same motor was reassembled with the aluminum winding and tested again to compare its performance with the copper winding. The tests provided valuable data on the motor's performance with the different winding materials, allowing for a direct comparison of their efficiency, torque, and other performance characteristics.

Table 4.1: Performance of Three-Phase Induction Motor with Copper Winding Material

Speed, Rpm	Torque, Nm	Pin, W	Pout, W	Current, I	Efficiency, %
1483	0	208	0	0.52	0
1480	0.3	227	46.50	0.53	20.48
1466	0.6	255	92.12	0.55	36.12
1457	0.9	289	137.33	0.59	47.52
1448	1.1	317	181.98	0.62	57.40
1443	1.3	331	196.46	0.64	59.35

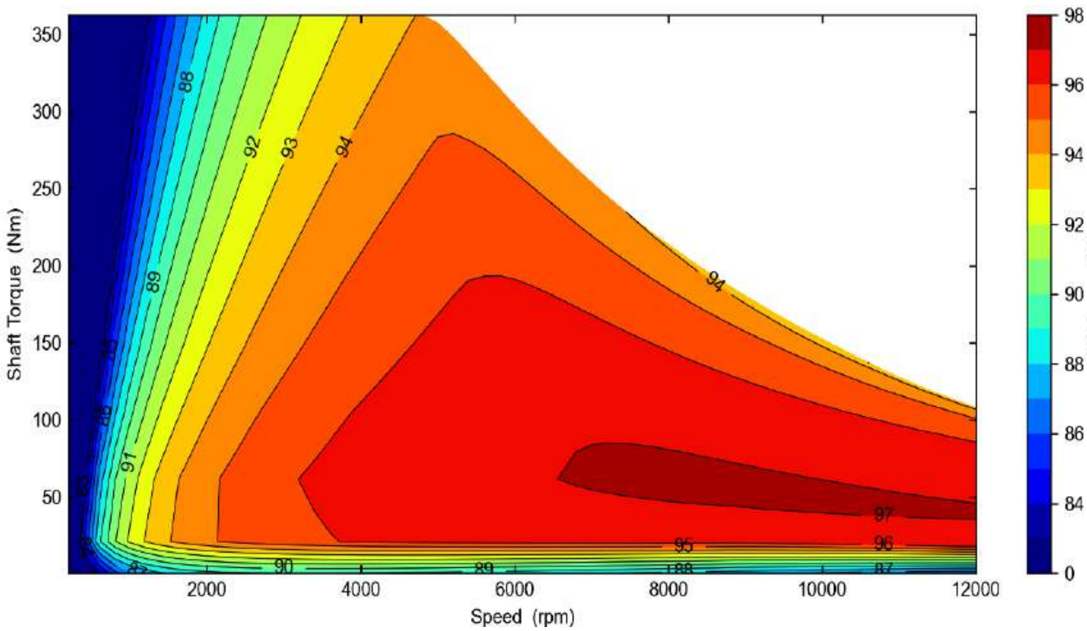
Table 4.2: Performance of Three-Phase Induction Motor with Aluminum Winding Material

Speed, Rpm	Torque, Nm	Pin, W	Pout, W	Current, I	Efficiency, %
1483	0	141.4	0	0.5	0
1480	0.1	141.78	15.50	0.51	10.93
1466	0.3	157.54	46.06	0.51	29.23
1457	0.45	176.91	68.66	0.52	38.81
1448	0.6	187.58	90.99	0.55	48.50
1443	0.7	190.87	105.79	0.58	55.42

The hardware results served as a validation of the simulations conducted in JMAG. They provided practical evidence of the motor's performance and helped in evaluating the feasibility and benefits of using aluminum winding in terms of weight reduction, cost-effectiveness, and improved efficiency.

The results obtained from both JMAG simulations and hardware testing provided valuable insights into the design and performance of the three-phase induction motor for lightweight EV applications. These results informed the design decisions and demonstrated the potential of using aluminum winding to achieve the desired objectives of lightweight, high-performance electric vehicle technology.

In Motor-CAD, the design and analysis of the EV induction motor included the evaluation of different winding configurations. The initial focus was on distributed winding, and efficiency maps were created for both copper and aluminum winding materials.



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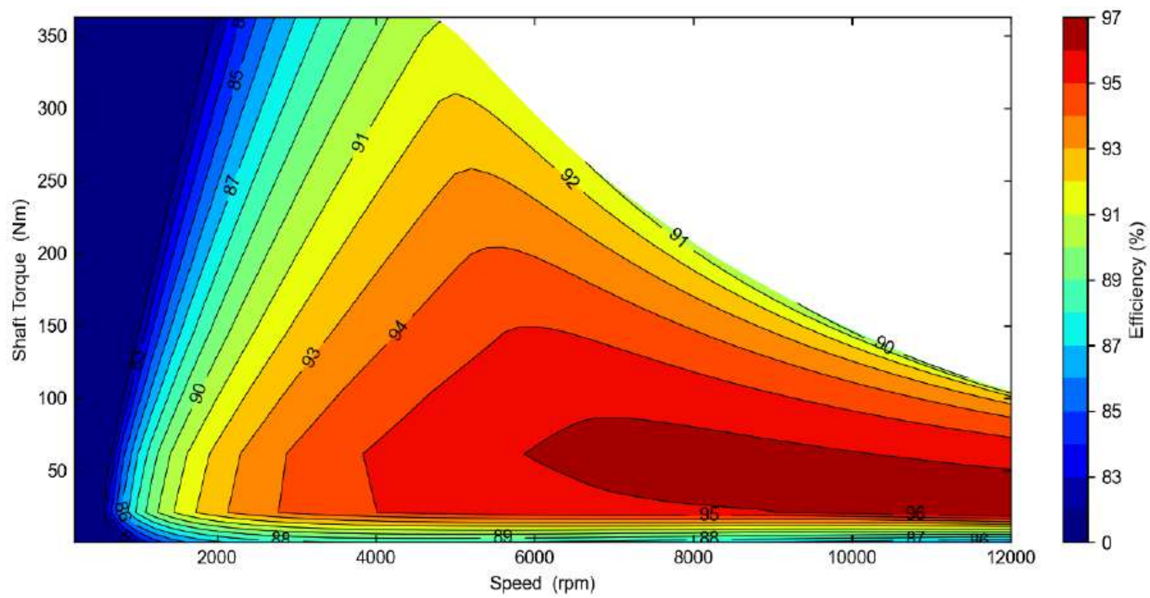

(b)

Figure 4.4: Efficiency Map of the designed EV Model (a) Copper Winding (b) Aluminum Winding

The efficiency maps provided a comprehensive understanding of the motor's efficiency across a range of operating conditions. By analyzing the efficiency distribution, it was possible to identify the optimal operating points and assess the performance of the motor concerning different load conditions for both copper and aluminum windings.

From the efficiency map it can be observed that the efficiency and torque are greater in copper winding because it is obvious that the conductivity of copper is greater than aluminum winding but from the second efficiency map, the performance in aluminum winding is also better. The performance of aluminum is just 4% to 7% less than that of copper. These results represent the induction motor which is designed for electric vehicles in stranded winding with special measures taken into consideration for EVs That's the reason its efficiency and performance are far better than an ordinary three-phase induction motor and that is what is needed for electric vehicles. By replacing copper winding with aluminum winding the results are still best and with new winding terminologies it can be enhanced more. The main objective of the study is to obtain a lightweight induction motor for EV applications with better performance and after getting encouraging results the study can be proceeded to hairpin winding in aluminum material.

Additionally, a comparison of the torque and efficiency between the copper and aluminum winding materials was conducted for the hairpin winding configuration. The efficiency comparison provided insights into the impact of the material choice on the overall performance of the motor. It helped in evaluating the benefits of using aluminum winding in terms of efficiency improvement, weight reduction, and cost-effectiveness compared to copper winding.

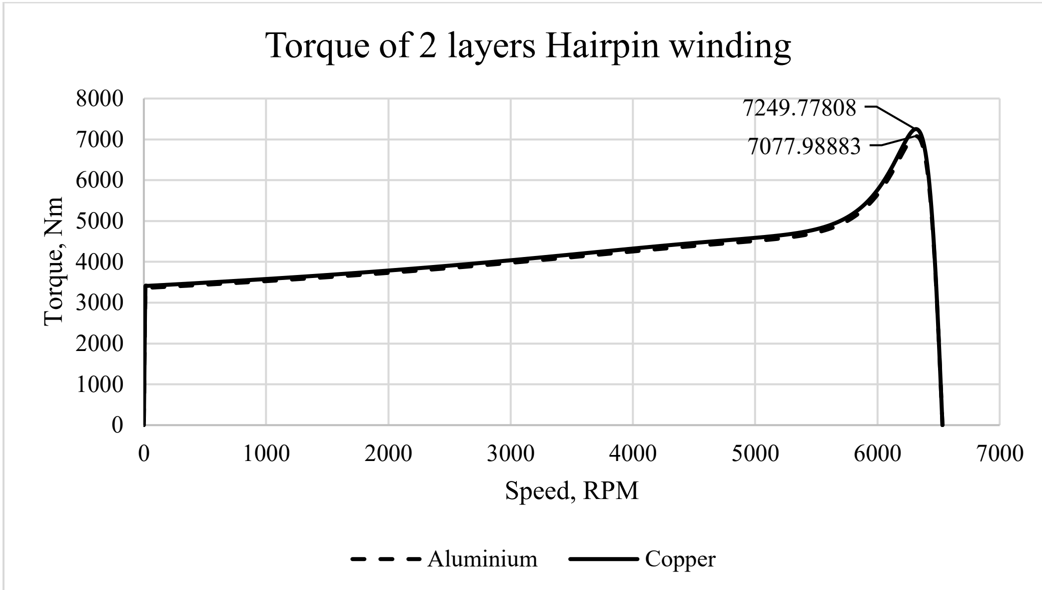

Figure 4.5: Torque Analysis of 2 layers Hairpin Winding in copper and aluminum

As the conductivity of copper is better than aluminum from figure 4.5 it can be verified that the torque in aluminum winding material is less than the copper winding. After analysis, the important fact that might be considered is the difference in torque is not greater it's just a small tradeoff and that's a good outcome in the study towards achieving the objectives.

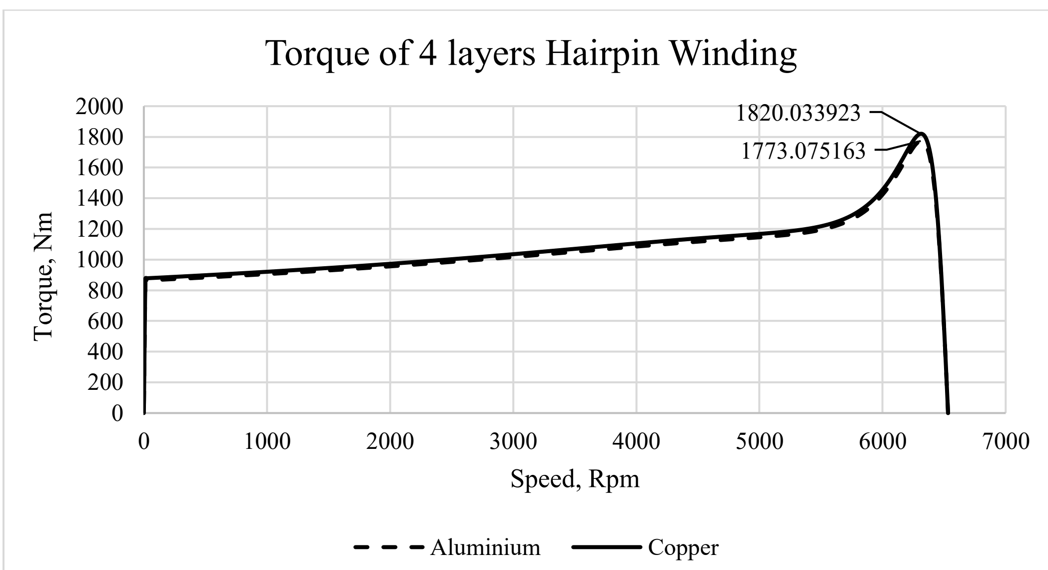

Figure 4.6: Torque Analysis of 4 layers of Hairpin Winding in copper and aluminum

Proceeding the study and the analysis of hairpin winding by adding two more layers of winding. As hairpin winding can be done in layers and as the layers numbers increase the losses also increase because the strands increase and that contributes to losses. The overall performance and torque in 4 layers are less than that in 2 layers. The difference between copper and aluminum is in the same ratio.

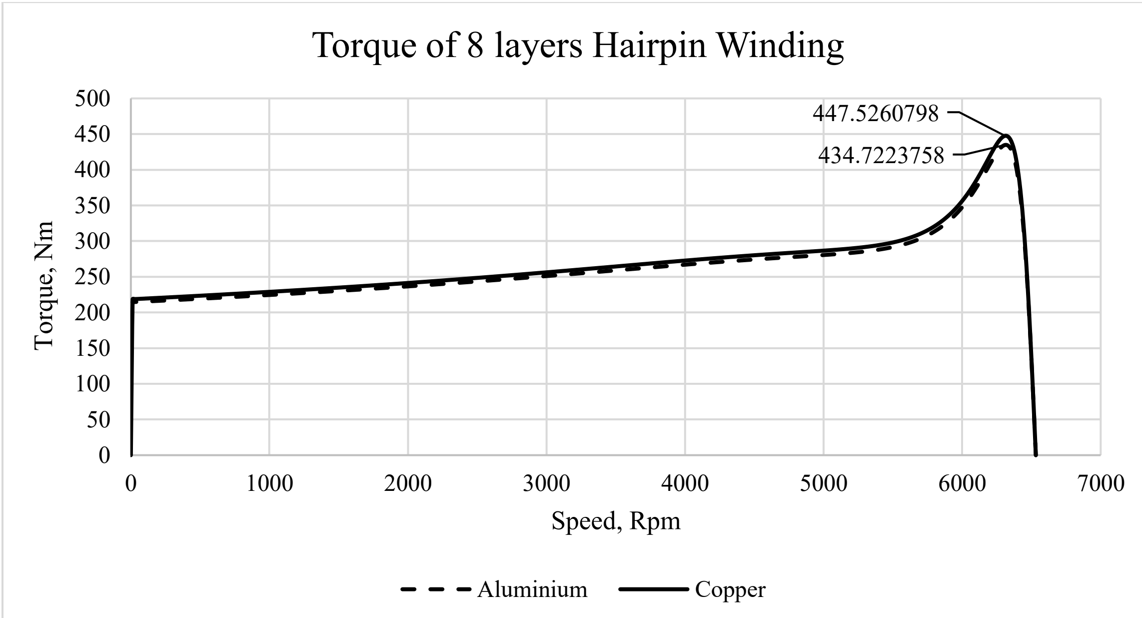

Figure 4.7: Torque Analysis of 8 layers of Hairpin Winding in copper and aluminum

The layers number has been increased to 8 and the torque dropped more. With a greater number of layers, the losses become greater and that's become a reason for lower torque than the previous analysis of 2 and 4 layers of hairpin winding. The difference between both materials remains the same as it was in previous results.

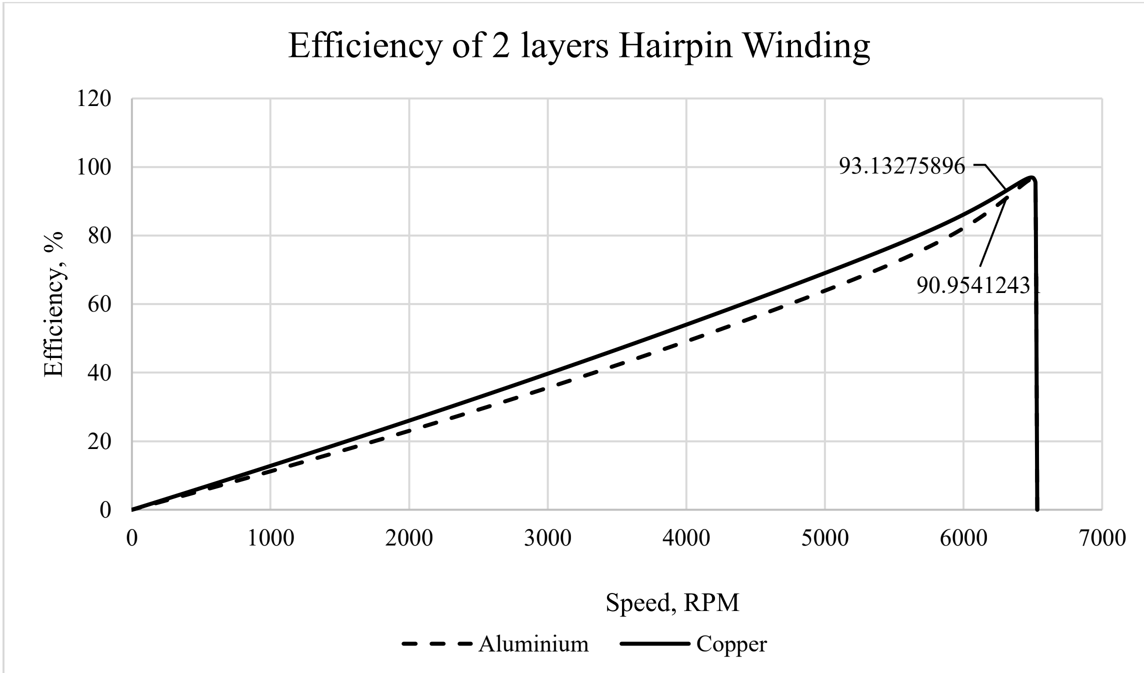

Figure 4.8: Efficiency Analysis of 2 layers Hairpin Winding in Copper and Aluminum

The efficiency of 2 layers hairpin winding was improved to the best range for electrical vehicles and the difference between copper vs. aluminum winding is just 3% which was an encouraging result towards the objective of this study.

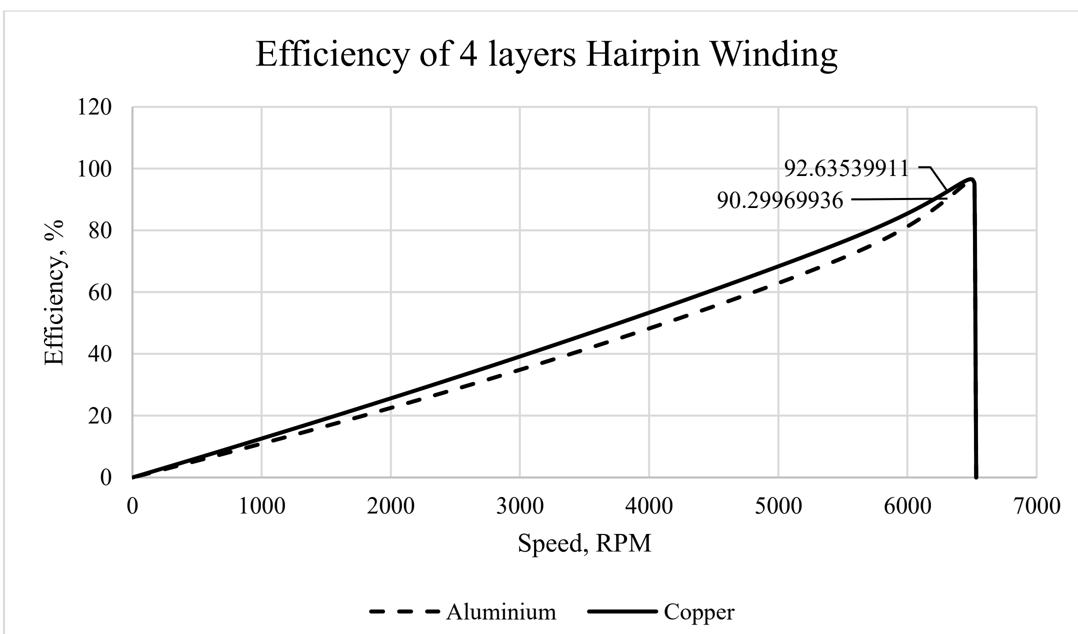

Figure 4.9: Efficiency Analysis of 4 layers Hairpin Winding in Copper and Aluminum

With the increase in number, the efficiency decreased by 1% which is not a big change while the aluminum winding efficiency decreased by 0.66%. The tradeoff between both materials is just 2.4%, which is not a big difference. Three-phase induction motor with aluminum winding having 90% efficiency is a big achievement in this study. Compared to the stranded winding copper this is far better in efficiency, performance, weight, and cost.

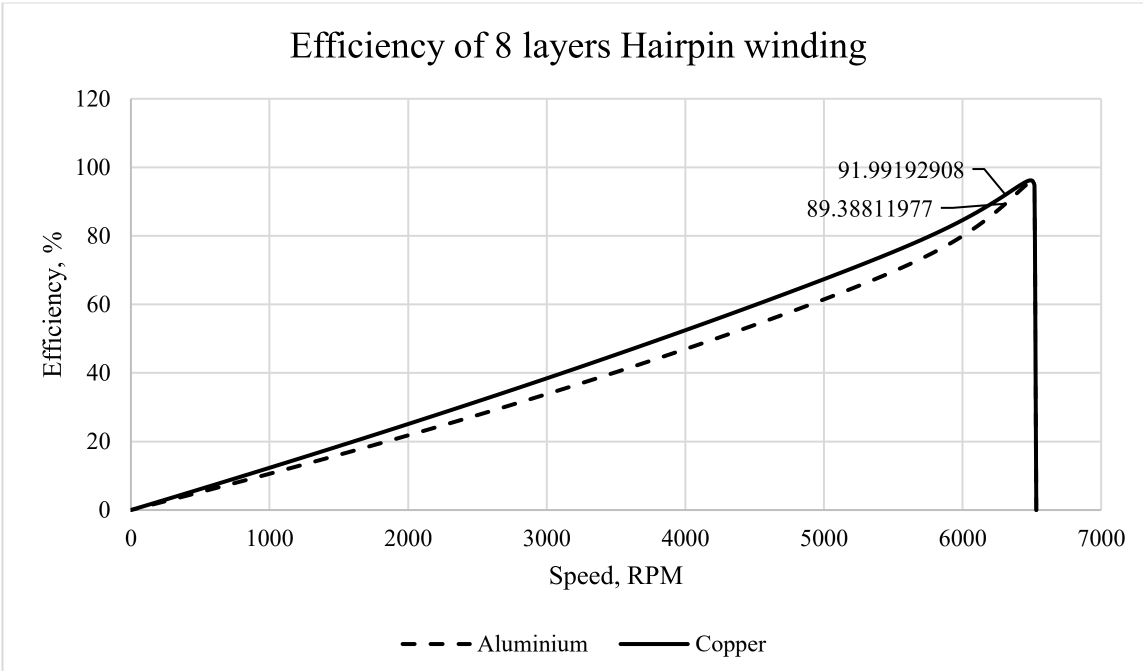

Figure 4.10: Efficiency Analysis of 8 layers Hairpin Winding in Copper and Aluminum

In 8 layers of hairpin winding the efficiency was just 74% and the aluminum winding decrease in efficiency was 90%. The ratio of the difference between both materials is the same as they were in previous results.

The results obtained from Motor CAD analysis provided valuable information for optimizing the design of the EV induction motor. The efficiency maps for the distributed winding allowed for efficient operating point selection, while the examination of flux distribution in the hairpin winding design helped in identifying areas of potential improvement. The efficiency comparison between copper and aluminum winding materials highlighted the advantages of using aluminum winding for lightweight EV applications.

Overall, the results obtained from Motor CAD analysis contributed to the development and refinement of the EV induction motor design, ensuring optimal performance and efficiency for lightweight electric vehicle applications.

4.2 Discussion

The findings of the JMAG investigation revealed that copper and aluminum winding materials differed only little in terms of efficiency, torque, and flux densities. In terms of motor efficiency and torque output, both materials demonstrated identical performance characteristics, showing that the aluminum winding was comparable to copper. It was also determined that the flux density distribution was comparable for both materials, indicating that the choice of winding material did not have a major effect on the magnetic field intensity inside the motor. These results illustrate the viability of aluminum winding as a feasible alternative to copper, enabling the possibility of cost reductions and weight reduction without sacrificing motor performance.

Next, the performance of the induction motor with the modified winding material was examined. Tests done on the hardware prototype indicated results that were compatible with simulated outcomes. Both the efficiency and torque performance of the motor with aluminum winding and the motor with copper winding were comparable. This demonstrates the practical usefulness of aluminum windings in EV applications since they provide equivalent performance while decreasing material prices and motor weight.

In the Motor-CAD research, efficiency maps were obtained for both copper and aluminum-distributed winding arrangements. The efficiency maps revealed that both materials had comparable efficiency characteristics, showing that the choice of winding material had a negligible effect on motor performance. Furthermore, the investigation of the hairpin winding design found equivalent findings between copper and aluminum winding materials, indicating that the use of aluminum did not substantially impact the distribution of the magnetic field inside the motor. These findings bolster the viability of aluminum winding as an alternative for lightweight EV applications since it delivers equivalent performance to copper winding while delivering cost and weight savings benefits.

From the study of the different layers, it has been observed that increasing the number of layers affects the torque more than efficiency. The efficiency difference between different numbers of layers is not greater. The copper and aluminum winding difference in torque and efficiency is so less that they can be considered almost the same for such a heavy induction motor in which lightweight is the main concern.

Overall, the findings from JMAG, hardware testing, and Motor-CAD analysis indicate that aluminum winding is a feasible alternative to copper winding for lightweight EV applications using three-phase induction motors. The similarities revealed in efficiency, and torque, between the two materials across several evaluations emphasize the potential advantages of employing aluminum winding, such as weight reduction, cost savings, and equivalent motor performance. By introducing hairpin winding into an induction motor for EV the performance can be outstanding and by replacing the material with aluminum winding two important factors that are cost and weight can be decreased prominently The weight of the overall motor will be decreased as aluminum has 30% of the weight copper and having almost 50% of the cost of the copper. Which makes the induction motor lighter and cheaper with improved performance.

Chapter 5

Conclusion

In conclusion, the objective of this work was the design and analysis of a three-phase induction motor using copper and aluminum windings. The fluctuating price of copper has motivated the investigation of alternate materials, such as aluminum, which provides a combination of economic advantages and desired properties. Using the finite element approach, the transient study of the motor revealed useful insights into the performance characteristics of both winding materials. To confirm the modeling findings for both copper and aluminum windings, experiments were done.

It was noticed that aluminum's increased winding resistance compared to copper resulted in somewhat reduced electrical conductivity and, therefore, decreased efficiency. However, the efficiency difference between the two materials was minimal. By adjusting the geometric dimensions and circumstances slightly, it is feasible to get comparable efficiency for copper and aluminum windings.

Moreover, this study's results have important ramifications for electric car applications. The use of aluminum winding has the potential to lower the induction motor's weight, making it more suited for lightweight EV designs. In addition, the cost-effectiveness of aluminum winding makes it an appealing alternative for electric car producers and consumers.

The research established the viability of employing both dispersed winding and hairpin winding topologies using copper and aluminum in the context of a Motor

CAD analysis. The findings demonstrated that the motor's performance parameters in terms of flux distribution and efficiency were equivalent for both winding materials. This demonstrates the adaptability of aluminum winding as an alternative to copper winding in a variety of motor designs.

From the results, the difference was not greater and this statement is validated by Finite Element Analysis and lab testing of both materials as well. Moving to Electric vehicles the designed model has improved efficiency in both models and after introducing hairpin winding the efficiency and performance have been enhanced to the best range for EVs. At last, an induction motor for EVs with aluminum winding has been obtained and the performance is approximately that of copper so it is the best alternative for replacement.

In hairpin winding increasing the number of layers decreased the torque and there was a big difference between different layers study of torque. And also decreased efficiency but there was not a big difference in the efficiency of different layer studies. The increased number of layers increased losses in the winding so in less number of layers the losses were less and the efficiency and torque were good.

This work may be expanded in the future to concentrate primarily on electric vehicle applications. For enhancing the performance and loading capacity of induction motors with aluminum windings for lightweight EVs, more studies may investigate optimization strategies. In addition, the inquiry may examine the use of Motor-CAD analysis to enhance the motor design process and maximize the performance and efficiency of induction motors for electric cars.

The study in EVs can be further modified and improved by introducing new cooling techniques to the machine which contributes to improving the performance of the machine. Another contribution can be achieving the copper performance in aluminum for household and industrial machines by changing its cross-sectional area or compressing the aluminum winding. Then with lighter weight and cheaper cost, the same performance can be achieved which will benefit the consumers

The results of this work add to the expanding body of information about the design and analysis of induction motors using various winding materials. The use of aluminum winding is a potential approach to producing lightweight, cost-effective, and high-performance applications for electric vehicles.

Chapter 6

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