Design and Analysis of Slotless Permanent Magnet Brushless DC (PMBLDC) motor

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BS Thesis

In Electrical (Power) Engineering

COMSATS University Islamabad

Abbottabad Campus-Pakistan

Spring 2023

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A Thesis Presented to

COMSATS University Islamabad- Abbottabad Campus

In partial fulfillment of the requirement for the degree of

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DEDICATION

First of all we dedicated this thesis to Almighty ALLAH and then thesis is dedicated to our parents, who have provided us with so much financial and moral support in order to meet all of our needs while we were developing our system, to our most honorable faculty, particularly our Supervisor "Dr. Faisal Khan" and Co-Supervisor “Wasiq Ullah” who has supported us at every stage, as well as to our subordinates and all those who believe in the fertility of education.

This degree is dedicated to our parents, family, friends, and respected faculty members who have supported us throughout our life

ACKNOWLEDGMENTS

I would like to express my deepest appreciation and gratitude to my Supervisor, Dr. Faisal khan, Associate Professor Department of Electrical Engineering, COMSATS University Islamabad, Abbottabad, for his support, advice, guidance and encouragement throughout my study duration and research work.

It has been an honor for me to work under a mentor with such graciousness. We are highly thankful to Mr. Wasiq Ullah, who is our senior, a talented researcher and a good friend, for his time and effort in teaching us JMAG (simulation software) and helping us throughout this study. His encouragement and critical support from the first day made our research a lot easier for us I acknowledge the support of technicians in the Engineering workshop and my lab mates for their great help during my work.

I would like to thank for the love, moral support and encouragement from my family and friends throughout my life. From you, I will always find an unwavering source of support to strive forward. Above all, I would like to thank ALLAH Almighty for having given me the courage, patience, and the intellectual power to overcome all difficulties that I have faced during my graduate studies.

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ABSTRACT

This thesis presents a new Design and Analysis of Slotless Permanent Magnet Brushless DC (PMBLDC) motor, which is mainly designed for growth in necessity for industrial and domestic use. The structure of this motor is not only reduces the motor cost but also increases the flux controllability. In order to increase its flux distribution we are designing a slotless stator. A parametric study of both stator and rotor pole arcs is carried out, targeting maximum generated EMF, and minimum cogging torque. Using the finite element method, the performance of the final design is analyzed. Finally, a prototype will be manufactured and experimented to prove its validity for domestic and commercial purposes.

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ABBREVIATIONS

PMBLDC	Permanent Magnet Brushless DC
DC	Direct current
AC	Alternate current
PMs	Permanent magnet
SM	Synchronous motor
RMF	Rotating Magnetic field
EMF	Electro motive force
ECMs	Electronically commutated motors

Chapter 1

Introduction

1.1. Introduction

Brushless Direct Current (BLDC) motors are one of the motor types speedily gaining acceptance. BLDC motors are used in industries such as Appliances, Automotive, Aerospace, Consumer, Medical, Industrial Automation Equipment and Instrumentation. Common domestic appliances which use electric motors include air conditioners, refrigerators, vacuum cleaners, washers and dryers. These appliances have relied on traditional electric motors such as single-phase AC motors including capacitor- start, capacitor- run motors, and universal motors. However, consumers now demand better performance, reduced acoustic noise and higher efficient motor for their appliances. Hence, BLDC have been introduced in order to fulfill these requirements. Brushless DC motors (BLDC) are usually small horsepower control motors that provide various advantages such as high efficiency, noiseless operation, high reliability, squeezed form and low maintenance.

A brushless DC motor (known as BLDC) is a permanent magnet synchronous electric motor which is driven by direct current (DC) electricity, and it accomplishes an electronically controlled commutation system (commutation is the process of producing rotational torque in the motor by changing phase currents through it at appropriate times) instead of a mechanical commutation system. BLDC motors are also referred as trapezoidal permanent magnet motors. Distinct conventional brushed type DC motor, wherein the brushes make mechanical contact with a commutator on the rotor so as to form an electric path between a DC electric source and rotor armature windings, BLDC motor employs electrical commutation with permanent magnet rotor and a stator with a sequence of coils. In this motor, a permanent magnet (or field poles) rotates and current-carrying conductors are fixed.

BLDCs are controlled using a microcontroller that powers a three-phase power semiconductor bridge. This semiconductor bridge provides power to the stator windings based on the control procedure. The motor is electronically commutated, and the control technique/ procedure required for commutation can be achieved either by using a sensor or a sensor less approach.

To achieve a desired level of performance in various applications that require the motor to operate at constant speed over various loads, the motor has to be operated using a suitable velocity control loop. These types of controllers are achieved by using a conventional proportional-integral (PI) controller.

Listed below are some of the main advantages of BLDCs:

- High efficiency
- Long operating life
- Low Noise
- Variable High-speed ranges

The BLDCs main disadvantage is its cost.

1.2. Motivation

Brushes eventually wear out, sometimes causing dangerous sparks, limiting the lifespan of a brushed motor. Brushless DC motors are more cost-effective, when we take into consideration the need to at times replace brushes in Brushed DC Motors (due to wear and tear). Our needs are to design such a motor which can consume less power and has an impact on our monthly bill i.e. BLDC motor. Brushless DC motors are quiet, lighter and have much longer lifespans. Brushless DC motors are often used in modern devices where low noise and low heat are required, especially in devices that run continuously. Smaller size, lesser noise, enhanced heat dissipation and higher speed also make BLDC Motor a preferred choice for motorized applications. BLDC motors are required for high-speed application. Brushed and brushless DC systems provide flat torque over a wide speed range while AC motors often lose torque as speed increases. Brushless DC motors normally have an efficiency of 85-90%, while brushed motors are usually only 75-80% efficiency.

1.3. Objective

Following are the main objectives of the proposed Project.

- To design the slotless BLDC motor for the residential and commercial areas.
- To investigate the performance BLDC motor that include cogging torque, back EMF, phase flux and voltages at no load condition and torque, efficiency, speed at load condition using JMAG software.
- To fabricate proposed slotless stator and analyze the machine performances experimentally.

Chapter 2

Literature Review

2.1. Background

The prospective growth in necessity for industrial and domestics uses the demand for BLDC Motor has increased. The stator of BLDC motor is of two types slotted and slotless. Our project is to design the slotless BLDC motor. Slotless motors are designed to optimize smoothness and create predictable torque output with minimal non-linear effects. Commonly referred to as slotless motors when rotary and air core motors when linear, slotless motor designs place only copper phase coils in the air gap of the motor. These coils, when placed properly, interact with the permanent magnetic flux to create force or torque. Cogging torque is eliminated because the discontinuous iron teeth are removed from the motor air gap. Slotless technology is especially effective with direct drive precision systems because all torque is a function of phase current and there are no unwanted or uncontrolled torque disturbances from the motor.

2.2. Classification of motors

Multiple types of AC&DC motors are being used for domestic purposes such as synchronous motor, induction motors, brushed and brushless DC motors (BDC&BLDC). Recently, the interest in brushless dc (BLDC) motor has been increasing due to its suitability for various applications such as varying load, constant load, fan application, drones industrial control, automotive, aviation, and health care equipment.

2.3. Synchronous Motor

A synchronous motor is a synchronous machine which converts AC electrical power to the mechanical power. A synchronous motor (short for synchronous electric motor) is an AC motor where the rotation of the rotor (or shaft) is synchronized with the frequency of the supply current. That is, the rotation period of the rotor is equal to the rotating field of the machine it is inside of. A synchronous motor can be either single or poly phase, generally three phase motor.

2.4. Working principle of Synchronous Motor

The synchronous motor working principle is based on the principle of magnetic locking between stator and rotor poles. To understand the working of synchronous motor, let the stator of the synchronous motor be wound for two poles. Let the rotor also produces two poles when they are excited by the external DC source.

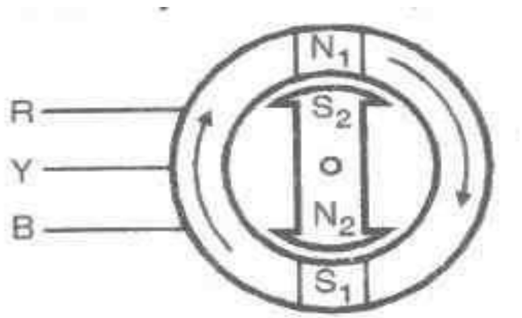


Figure 2.1: synchronous motor

As the three-phase AC supply is connected to the stator winding, a rotating magnetic field (RMF) is produced. This field rotates at the synchronous speed Ns. The two poles produced are N1 and S1, as shown in the Figure1. These stator poles (N1 and S1) rotate in the air gap between stator and rotor at synchronous speed in the clockwise direction. The rotor is then excited by the external DC source. It produces two poles N2 and S2, as shown in the Figure. The rotor is accelerated, to rotate in the clockwise direction by some external engine. This is because the synchronous motor is not self-starting. If unlike poles N1 – S2 and S1 – N2 come close to each other, then due to the strong force of attraction, magnetic locking takes place between them. Once the stator and rotor poles are locked magnetically with each other, the rotor will continue to rotate at synchronous speed along with the rotating magnetic field. Then external engine coupled to the rotor can be decoupled.

2.5. Induction motor

An induction motor is a generally used AC electric motor. In an induction motor, the electric current in the rotor needed to produce torque is obtained via electromagnetic induction from the rotating magnetic field of the stator winding. The rotor of an induction motor can be a squirrel cage rotor or wound type rotor. Used in different applications, induction motors are also called Asynchronous Motors. This is because an induction motor always runs at a slower speed than synchronous speed. The speed of the rotating magnetic field in the stator is called synchronous speed. Induction machines are the most frequently used type of motor used in residential, commercial, and industrial settings so far. The characteristic features of this three phase AC motors are:

- Simple and rough construction
- Affordable and low maintenance

- High reliability and highly proficient
- No requirement of additional starting motor and necessity not be synchronized

2.6. Types of Induction Motors

Generally, there are two types of induction motor.

- Single phase induction motor
- Three phase induction motor

2.7. Single phase induction motor

The single-phase induction motor does not self-start. The main winding carries a sporadic current when the motor is attached to a single-phase power supply. It is quite logical that the cheapest, most reduced upkeep sort engine ought to be used most regularly. Based on their way of starting, these machines are categorized differently. Those types are shaded pole, split phase, and capacitor motors. Also, capacitor motors are started with capacitor, run with capacitor and have permanent capacitor motors.

In these single-phase types of motors, the start winding can have a series capacitor and a centrifugal switch. When the supply voltage is applied, current in the main winding holdups the supply voltage because of the main winding impedance. And current in the start winding leads/lags, the supply voltage depending on the starting mechanism impedance. The angle between the two windings is sufficient phase difference to provide a rotating magnitude field to produce a starting torque. The point when the motor reaches 70% to 80% of synchronous speed, a centrifugal switch on the motor shaft opens and disconnects the starting winding.

2.8. Three-Phase Induction Motor

Being self-starting, the three-phase induction motors use no start winding, centrifugal switch, capacitor, or other starting device. Three-phase AC induction motors have various uses in commercial and industrial applications. The two types of three-phase induction motors are- squirrel cage and slip ring motors. The features which make the squirrel cage motors widely applicable are mainly their simple design and rugged construction. With external resistors, the slip ring motors can have high starting torque. Three-phase induction motors are used extensively in domestic and industrial appliances because these are rugged in construction requiring little to no maintenance, comparatively cheaper, and require supply only to the stator.

2.9. Working Principle of an Induction Motor

The motor which works on the principle of electromagnetic induction is known as the induction motor. Electromagnetic induction is the phenomenon in which the electromotive force induces across the electrical conductor when it is placed in a rotating magnetic field. The stator and rotor are two essential parts of the motor. The stator is the stationary part, and it carries the overlapping windings while the rotor carries the main or field winding. The windings of the stator are equally displaced from each other by an angle of 120°. The induction motor is the single excited motor, i.e., the supply is applied only to the one part, i.e., stator. The term excitation means the process of inducing the magnetic field on the parts of the motor. When the three-phase supply is given to the stator, the rotating magnetic field is produced on it. The figure below shows the rotating magnetic field set up in the stator.

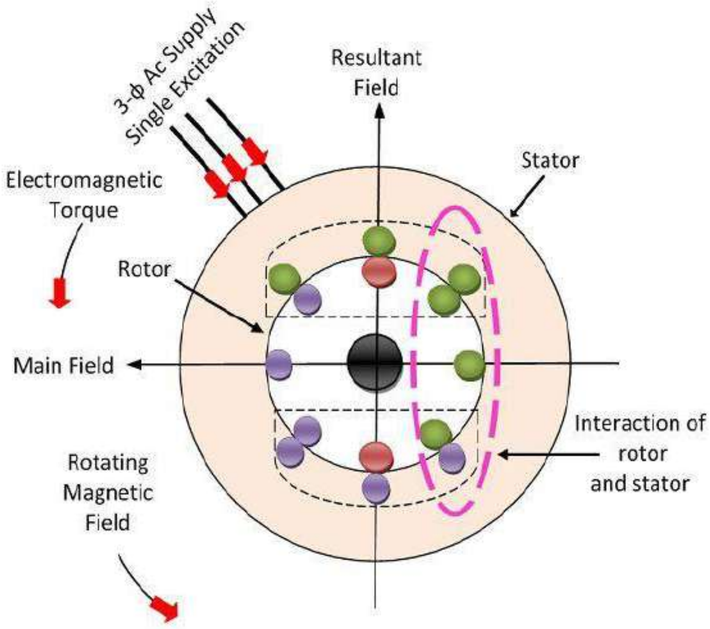


Figure2.2 Three phase induction Motor

Consider that the rotating magnetic field induces in the anticlockwise direction. The rotating magnetic field has moving polarities. The polarities of the magnetic field vary by concerning the positive and negative half cycle of the supply. The change in polarities makes the magnetic field rotates. The conductors of the rotor are stationary. This stationary conductor cut the rotating magnetic field of the stator, and because of the electromagnetic induction, the EMF induces in the rotor. This EMF is known as the rotor induced EMF, and it is because of the electromagnetic induction phenomenon. The conductors of the rotor are short-circuited either by the end rings or by the help of the external resistance. The relative motion between the rotating magnetic field and the rotor conductor induces the current in the rotor conductors. As the current flows through the conductor, the flux induces on it. The direction of rotor flux is the same as that of the rotor current.

Now we have two fluxes, one because of the rotor and another because of the stator. These fluxes interact with each other. On one end of the conductor the fluxes cancel each other, and on the other end, the density of the flux is very high. Thus, the high-density flux tries to push the conductor of the rotor towards the low-density flux region. This phenomenon induces the torque on the conductor, and this torque is known as electromagnetic torque. The direction of electromagnetic torque and the rotating magnetic field is the same. Thus, the rotor starts rotating in the same direction as that of the rotating magnetic field. The speed of the rotor is always less than the rotating magnetic field or synchronous speed. The rotor tries to run at the speed of the rotor, but it always slips away. Thus, the motor never runs at the speed of the rotating magnetic field, and this is the reason because of which the induction motor is also known as the asynchronous motor.

2.10. DC Motors

A DC motor is defined as a class of electrical motors that convert direct current electrical energy into mechanical energy. From the above definition any motor that is operated using direct current or DC motor is called DC motor.

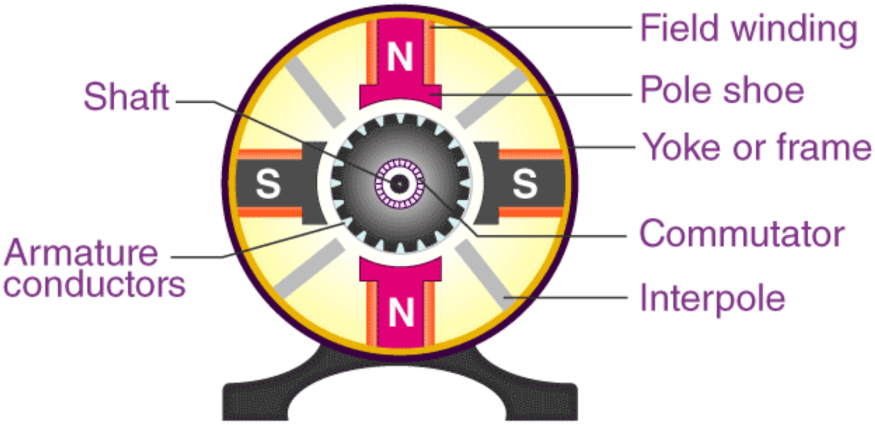


Figure 2.3 DC motor construction

2.11. DC Motor Working

A magnetic field arises in the air gap when the field coil of the DC motor is energized. The created magnetic field is in the direction of the radii of the armature. The magnetic field enters the armature from the North Pole side of the field coil and “exits” the armature from the field coil’s South Pole side.

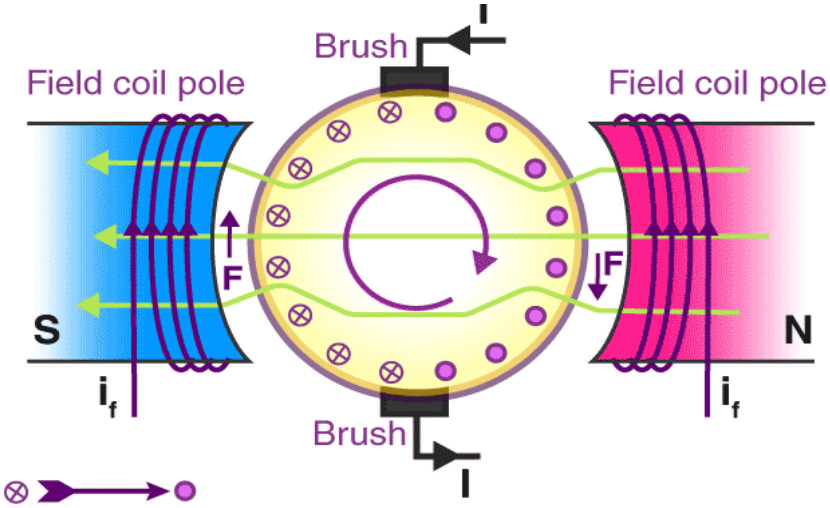


Figure 2.4 Production of torque in a DC motor

The conductors located on the other pole are subjected to a force of the same intensity but in the opposite direction. These two opposing forces create a torque that causes the motor armature to rotate.

2.12. Types of DC Motor

DC motors have a wide range of applications ranging from electric shavers to automobiles. To cater to this wide range of applications, they are classified into different types based on the field winding connections to the armature as:

- Self-Excited DC Motor
- Separately Excited DC Motor

2.13. Self-Excited DC Motor

Self-excited DC motors have an armature and field coil that is connected in series or partly in series, in parallel or partly in parallel. They also have a single source of power. There are two types of self-excited DC motors- Series DC motor and Shunt DC motor.

2.14. Separately Excited DC Motor

A separately excited dc motor is a motor whose field circuit is supplied from a separate constant voltage power supply, while a shunt dc motor is a motor whose field circuit gets its power directly across the armature terminals of the motor.

2.15. Brushed DC Motor (BDC)

Brushed DC motor is a type of DC motor which uses the carbon brush mechanism for supplying the electrical power to its armature circuit. The brushed motor is mechanically commutated DC motor. A brushed DC motor consists of two parts − armature (rotor) and magnetic field system (stator). Since, the armature winding is placed on the rotor, therefore a mechanism is necessary for providing the electric input to the rotating armature. This mechanism is provided by the help of commutator and carbon brushes. In a brushed DC motor, the commutator is a split ring which is mounted on the rotor shaft and provides the internal commutation, and the carbon brushes are made to slide over the commutator surface. The DC electric input is connected to the carbon brushes, which is further supplied to the armature winding through the commutator. Therefore, by the interaction of electric current in the armature winding and the magnetic field of stator, an electromagnetic torque is produced in the rotor which rotates it to drive the mechanical load.

2.16. Working principle of Brushed DC Motor

A BLDC Motor is made up of two. magnets facing the same direction, surrounding two coils of wire that lie in the middle of the Motor and around a rotor. The coils are set to face the magnets which causes electricity to flow to them. This builds a magnetic field, ultimately pushing the coils away from the magnets they are encountering which finally makes the rotor turn. The current cut off at the rotor makes a turn of 180 degrees. This makes each rotor to face the opposite magnet. Once the current starts over again, the electricity flows oppositely and sends another pulse having the rotor turned once again. By transferring the electricity from the rotor, brushes that exist within the motor turn it off and on.

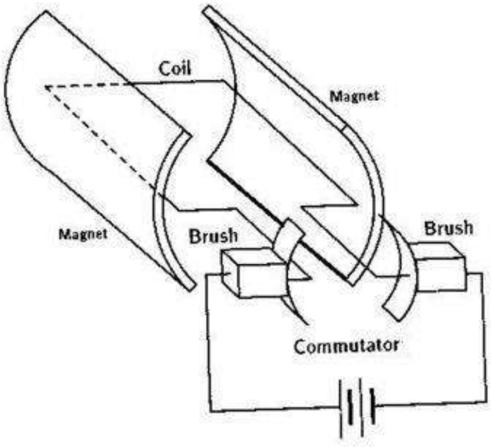


Figure 2.5 Brushed DC Motor interior

2.17. Brushless DC Motor (BLDC)

Brushless DC electric motors also known as electronically commutated motors (ECMs, EC motors). Primary efficiency is a most important feature for BLDC motors. Because the rotor is the sole bearer of the magnets, and it doesn't require any power. i.e., no connections, no commutator and no brushes. In place of these, the motor employs control circuitry. To detect where the rotor is at certain times, BLDC motors employ along with controllers, rotary encoders or a Hall sensor.

2.18. Construction of BLDC Motor

In this motor, the permanent magnets attach to the rotor. The current-carrying conductors or armature windings are located on the stator. They use electrical commutation to convert electrical energy into mechanical energy. The main design difference between a brushed and brushless motors is the replacement of mechanical commutator with an electric switch circuit. A BLDC Motor is a type of synchronous motor in the sense that the magnetic field generated by the stator and the rotor revolve at the same frequency.

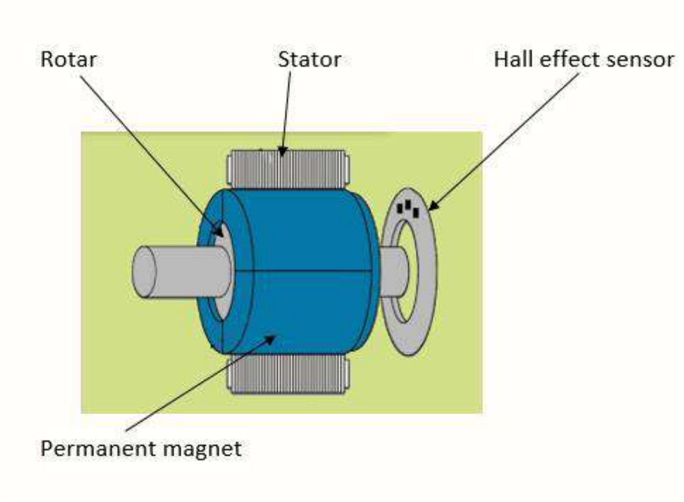


Figure 2.6 Construction of BLDC Motor

Brushless motor does not have any current carrying commutators. The field inside a brushless motor is switched through an amplifier which is triggered by the commutating device like an optical encoder. The layout of a DC brushless motor can vary depending on whether it is in “Out runner” style or “In runner” style.

- Out runner – The field magnet is a drum rotor which rotates around the stator. This style is preferred for applications that require high torque and where high rpm isn’t a requirement.
- In runner – The stator is a fixed drum in which the field magnet rotates. This motor is known for producing less torque than the outrunner style but is capable of spinning at very high rpm.

2.19. Principle of operation of BLDC motor

Stator windings of a BLDC motor are connected to a control circuit (an integrated switching circuit). The control circuit energizes proper winding at the proper time, in a pattern that rotates around the stator.

The rotor magnet tries to align with the energized electromagnet of the stator, and as soon as it aligns, the next electromagnet is energized. Thus, the rotor keeps running.

The commutator helps in achieving unidirectional torque in a typical dc motor.

Obviously, commutator and brush arrangement are eliminated in a brushless dc motor. And an integrated inverter/switching circuit is used to achieve unidirectional torque.

2.20. BLDC Motor with Slotted Stator

Traditional slotted stator designs use teeth to focus electromagnetic flux towards the rotor magnets and decrease the total air gap in the magnetic circuit. There are typically multiple teeth per phase. Slotted motors are the predominant motor topology as they provide a good balance between torque output, efficiency, motor constant, and manufacturability. Slotted motors usually yield the maximum motor constant (torque/watt$^{1/2}$) for a given motor size. They also offer high efficiency and high acceleration rates with the lowest inertia.

As mentioned above, the spaces between stator teeth allow for electromagnetic phase wire to be inserted. The slots are the main cause of cogging torque as they create a discontinuous permeability as the magnets travel past each slot. It is standard practice to skew or stagger stator teeth or rotor magnets to reduce the fundamental frequency of the cogging torque.

Figure 2.7 Slotted Stator

Cogging torque in slotted motors usually ranges from 1 to 5% of a motor's rated torque based on the design of the motor. In applications with heavier payloads, the cogging torque is small compared to the driving torque and has a minor impact on system performance. However, in applications with lighter payloads or where smooth motion is a critical necessity, the cogging torque normally results in velocity ripple, which can have unfavorable effects on performance.

Cogging torque frequency is a function of the motor's slot count and pole count. The important frequency of this cogging is the least common multiple between the pole and slot count. However, because of manufacturing variability and 3D effects, there are also lower and higher harmonic attributes to the cogging torque profile with angle. Slotted stators also experience magnetic saturation with growing current. This is also denoted as torque constant (Kt) linearity. To improve the motor size and output, it is common for the iron to be near magnetic saturation at the continuous thermal limit of the motor. In certain motors, as much as 10% Kt linearity error is embedded into the continuous output rating.

2.21. BLDC Motor with Slotless Stator

The ideal permanent magnet brushless motor has sinusoidal torque output with angle without any higher harmonic distortion. The slotless motor is the closest approximation to this goal. The slotless stator does not have stator teeth or their corresponding slots. Phase coils are spatially oriented around the stator to create the electromagnetic phase relationship needed for motor operation. When energized, the coils form an electromagnetic field like the slotted motor but result in a torque versus angle curve that is sinusoidal. There is zero cogging torque as there are no teeth with corresponding slots.

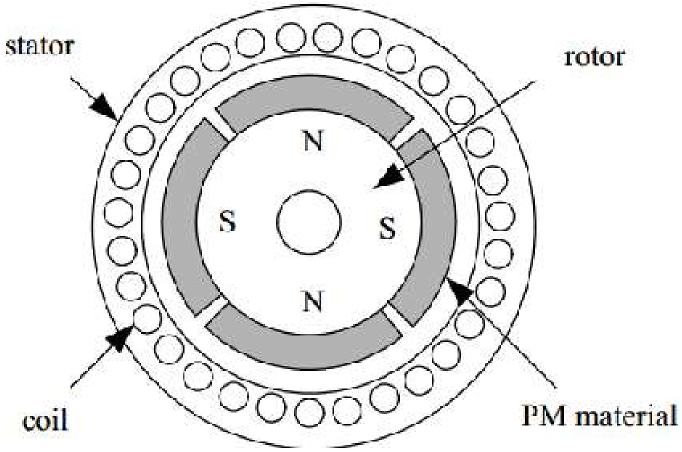


Figure 2.8 Slotless Stator

With a slotless motor, all torque is a function of current applied to the winding. This streamlines the servo control system and allows for smoother running. The motor also has considerably better Kt linearity over its slotted counterpart.

One consideration with slotless designs is the large magnetic air gap between the rotor and stator because of the removal of stator teeth. This results in lower flux density and correspondingly lower torque output for a particular size motor. The torque output of a slotless design is usually 70-75% of an equivalently sized slotted motor and Celera motion can improve many Agility Series motor designs to attain up to 85%. If smoothness is critical, the slotless technology is favored, but slotted motors are probably a better solution if continuous torque is the most critical need.

Chapter 3

Design Methodology and Results

3.1. Initial Design

In this project, Design and Analysis of Slotless Permanent Magnet Brushless DC (PMBLDC) motor for Ceiling Fan application is designed by using JMAG Designer Version 18. This software is released by japan research institute is a FEA tool used for electromagnetic simulations. The project implementation is divided into two parts that are Geometry Editor and JMAG Designer. Geometry editor is used to design each part of machine separately such as rotor, stator, FEMcoil, and armature windings while the condition setting and simulation are developed by using JMAG Designer. JMAG is simulation software for development and design of electrical devices and drive motors for electric vehicles. The initial motor configuration and dimensions are illustrated in Figure 3.3 and Table 3.1 respectively.

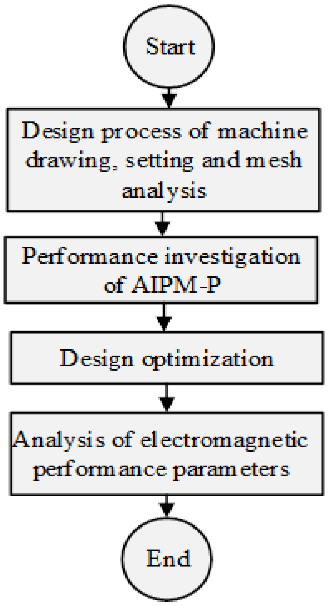


Figure 3.1: Flow chart of Methodology

As shown in Figure 3.2 (a) and (b), the Slotted motor can be regarded as an integration of an outer-rotor and inner-stator. The windings imbedded in the stator, namely armature windings.

The Design methodology of a 14-pole and 12-slot slotted permanent magnet brushless DC (PMBLDC) motor for ceiling fans, with the magnet placed on the rotor and utilizing Nippon steel in the core of the stator, is fundamental for achieving optimal performance. The construction methodology focuses on designing a motor with a stator containing 12 slots to accommodate the winding coils. The stator core is constructed using high-quality Nippon steel, renowned for its superior magnetic properties and efficient flux conduction. The rotor is equipped with permanent magnets positioned to interact with the stator poles, ensuring smooth rotation. The windings methodology involves meticulous winding of the stator coils within the 12 slots, employing appropriate insulation materials and techniques.

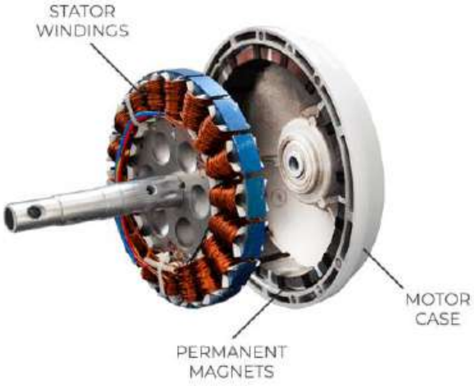


Figure 3.2 (a) Slotted Motor Design

Figure 3.2 (b) Slotted Motor Windings Arrangement

Design topology of the proposed Slotless Permanent Magnet Brushless DC (PMBLDC) motor is shown in Figure 3.3. Proposed design of slotless permanent magnet brushless DC (PMBLDC) motor for ceiling fans, with the magnet placed on the rotor, featuring a coreless (Epoxy) stator and ferrite magnets, is essential for achieving optimal performance. The construction methodology involves designing a motor with a coreless stator, where the traditional laminated iron cores are replaced by an epoxy material. This coreless design provides structural support and efficient magnetic flux distribution. The rotor is equipped with permanent magnets made of ferrite material, known for its strong magnetic properties. The windings methodology involves carefully winding the stator coils in a slotless configuration, ensuring precise current flow and effective magnetic field generation.

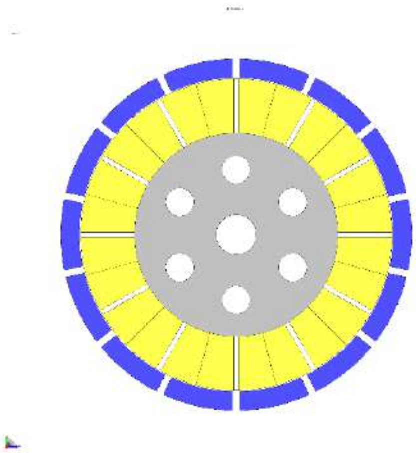


Figure 3.3Initial Design

Various winding techniques can be employed in the construction of slotless PMBLDC motors.

Table 3.1 Machine Dimension Parameters

Parameters	**Symbol**	**Value**
Outer radius	R_o	60 mm
Stator outer radius	R_{so}	51.5 mm
Stator inner radius	R_{si}	21.5 mm
Stator yoke width	w_{sy}	8 mm
Stator inner slot depth	h_{sis}	14.6 mm
Stator outer slot depth	h_{sos}	10.6 mm
Armature winding width	w_{aw}	9 mm
Field winding width	w_{fw}	4 mm
Inner airgap length	βin	0.4 mm
Outer airgap length	βout	0.4 mm
Inner rotor yoke width	$wiry$	4 mm
Inner rotor slot depth	$hirs$	4 mm
Outer rotor yoke width	$wory$	4 mm
Outer rotor slot depth	$hors$	4 mm
Stack length	L	50 mm

These techniques include concentrated winding and toroidal winding. Concentrated winding in which basically a single coil is wound on each stator tooth as shown in 3.2 (b). Toroidal Windings are based on the concept of a toroidal coil, where the wire is wound around a ring-shaped core.

3.2. Geometry Editor

Geometry Editor is used to design the machine parts such as rotor, stator, coils (armature winding) and permanent magnet.

The design requirements, restrictions and specifications for proposed PMBLDC Motor is Slotless and 14 poles. The corresponding electrical restrictions for armature coils current are 3A. Dark grey color is assigned to stator and dark magenta to stator tooth to differentiate it from other parts. First, the geometry of the stator is drawn according to the given parameters.

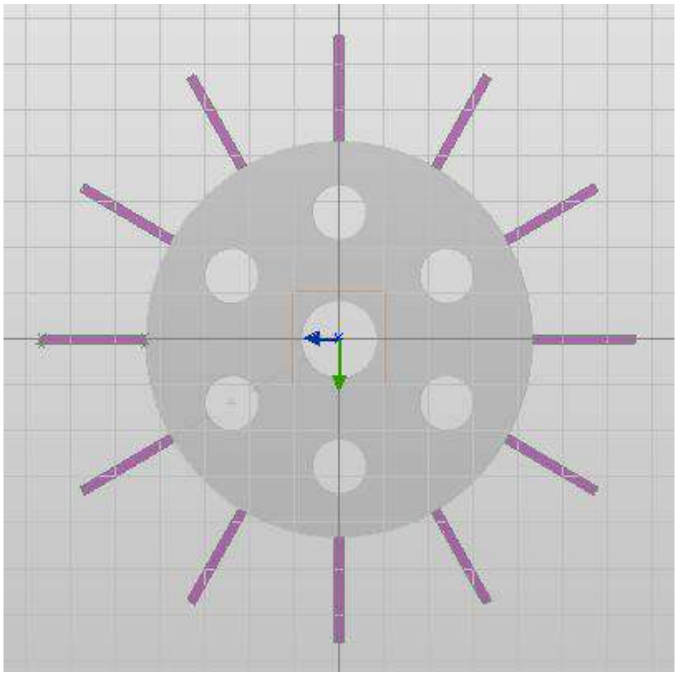


Figure 3.4 Stator

Now here is the Armature winding. The armature windings wound on the stator between teeth. The armature winding is typically formed by placing concentrated coils directly on the stator. Red color is assigned to differentiate it from other part

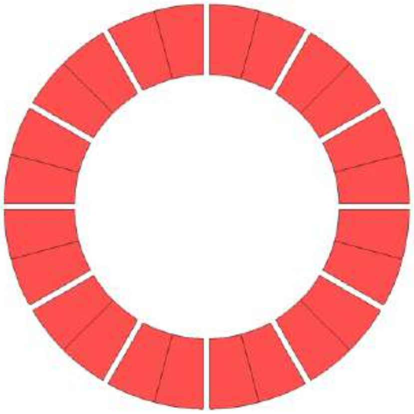


Figure 3.5 Armature Windings

The rotor mechanism consists of 14 permanent magnets arranged in a circular pattern around the rotor's circumference. Each permanent magnet represents one pole of the rotor. Blue color is assigned to differentiate it from other parts.

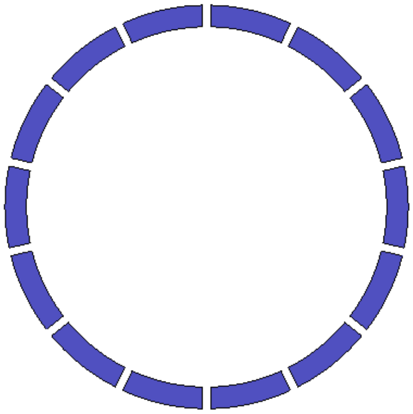


Figure 3.6 Rotor

By implementing the aforementioned process for each specific part, the entire structure shown in Figure 3.10 is acquired.

3.3. JMAG Designer

JMAG Designer is used to set the materials, conditions, mesh setting, study properties and circuit for the machine. After drawing the geometry of the machine, update this model into the JMAG Designer. Where we create our study i.e. magnetic transient analysis.

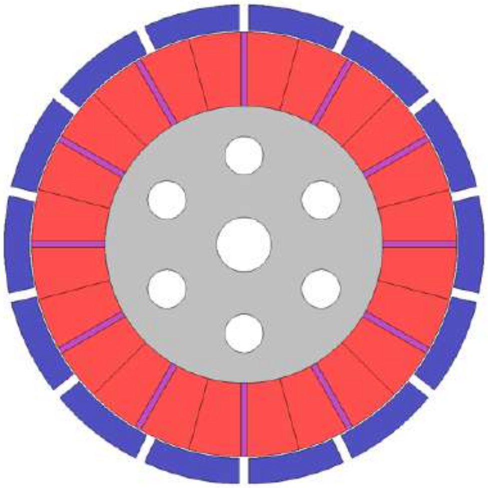


Figure 3.7 Complete Geometry

Set material properties and conditions as given in the following table 3.2

Table 3.2 Materials and Conditions

Parts	Materials	Condition
Rotor	Ferrite, Br = 0.4T	Motion: Rotation Torque: nodal force
Stator	Nippon Steel 35H210	———
Armature Coil	Conductor Copper	FEM Coil

Then a new study is created by selecting magnetic, transient analysis. The materials are set for each part of the motor that has been designed in the Geometry Editor. The materials are set by clicking on material on the toolbox at the right-hand side, as shown in figure 3.10. The materials are assigned by dragging into each part of the motor.

The conditions are set by clicking the condition on toolbox, as shown in figure 3.11. Each condition is dragged into the corresponding parts.

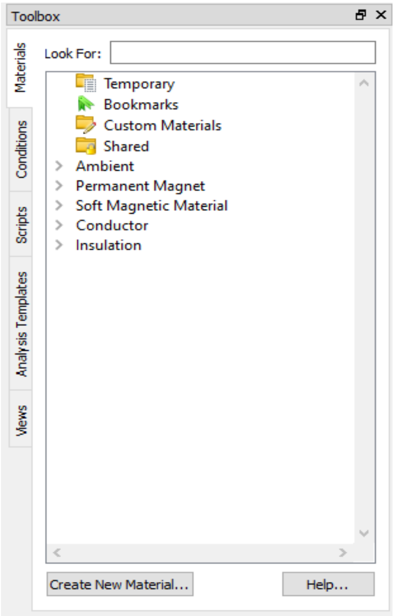
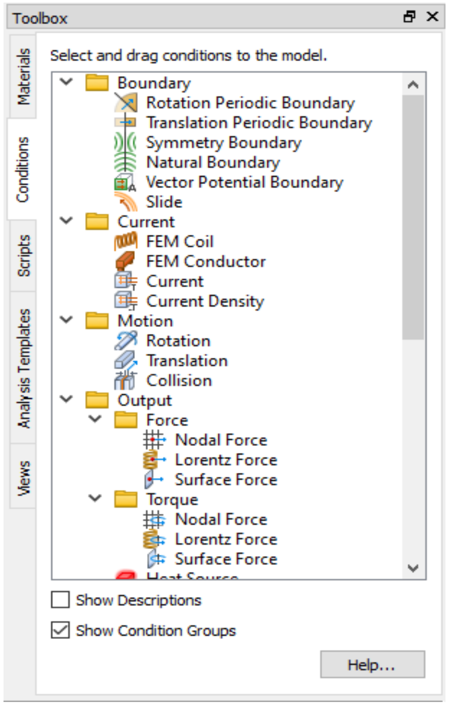


Figure 3.8 Material tool box



Select and drag conditions to the model.

☐ Show Descriptions

☑ Show Condition Groups

Figure 3.9 Condition Toolbox

The circuit is constructed to be linked with the armature coil. Choose FEM coil in circuit toolbar and connect with the ground. Linked all armature coils with the corresponding as shown in figure 3.12.

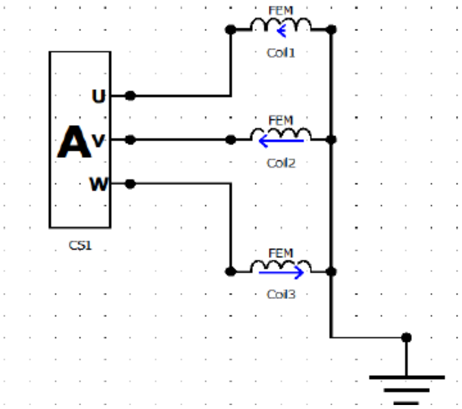


Figure 3.10 Armature winding Circuit

Create the mesh. On project manager toolbar, right click on mesh, choose add size control, choose part, select all part of the drawing and click Ok. Click properties, choose slide mesh and click generates. As shown in the below figure

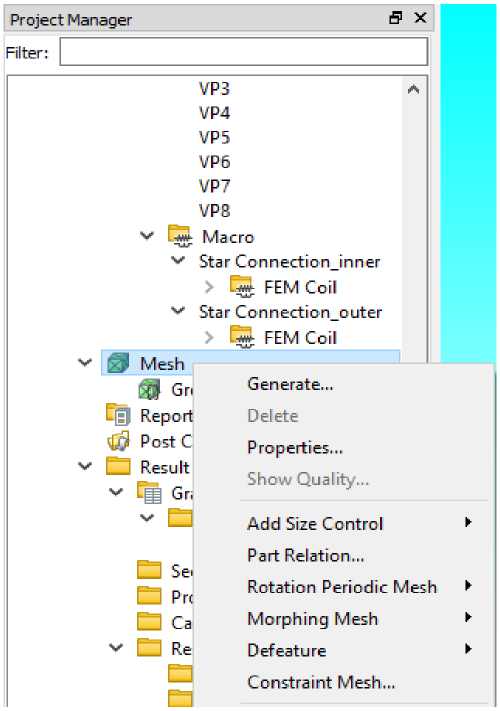
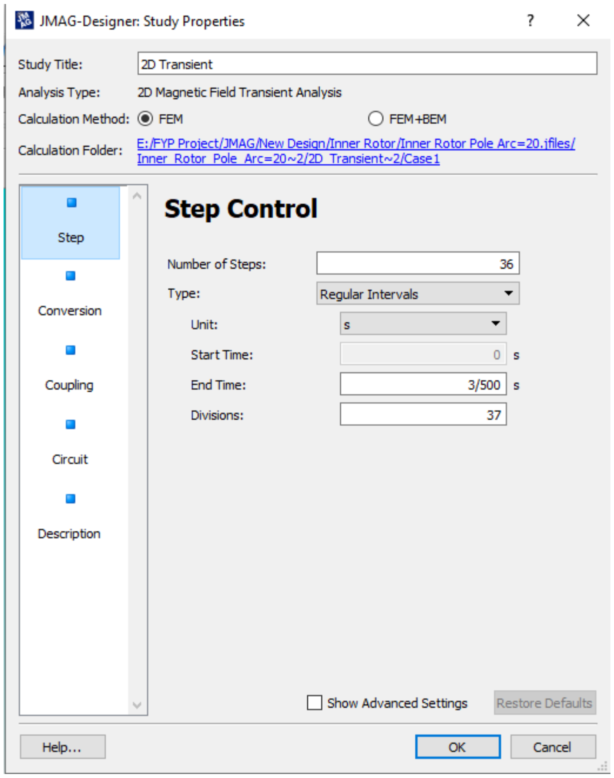


Figure 3.11 Creating Mesh

Set the magnetic study and properties. Click on study, magnetic transient, properties. Click the step control to set the steps, end time and division while click the full model conversion to set the stack length.as shown in figure 3.15 and figure 3.16 respectively.


JMAG-Designer: Study Properties

Study Title: 2D Transient

Analysis Type: 2D Magnetic Field Transient Analysis

Calculation Method: ● FEM ○ FEM+BEM

Calculation Folder: E:/FYP Project/JMAG/New Design/Inner Rotor/Inner Rotor Pole Arc=20.jfiles/Inner_Rotor_Pole_Arc=20~2/2D_Transient~2/Case1

Step Control

Number of Steps: 36

Type: Regular Intervals

Unit: s

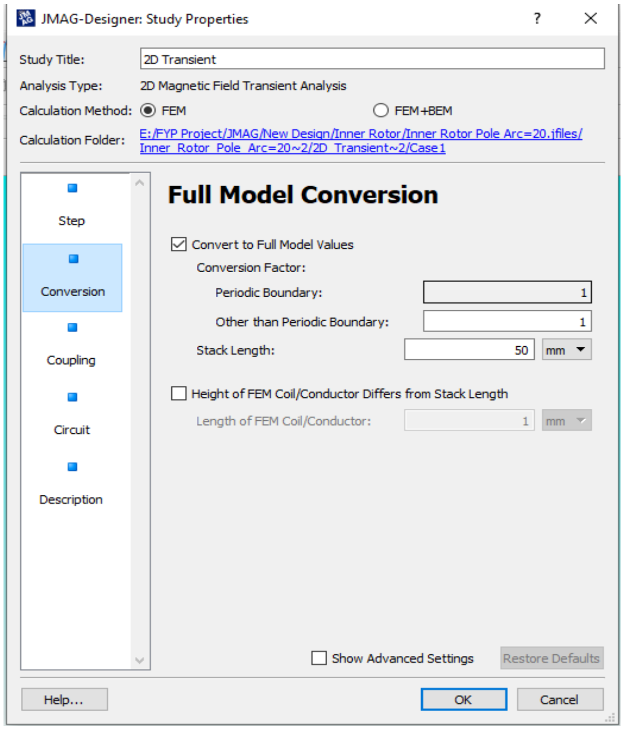
Start Time: 0 s

End Time: 3/500 s

Divisions: 37

☐ Show Advanced Settings

Figure 3.12


JMAG-Designer: Study Properties

Study Title: 2D Transient

Analysis Type: 2D Magnetic Field Transient Analysis

Calculation Method: ● FEM ○ FEM+BEM

Calculation Folder: E:/FYP Project/JMAG/New Design/Inner Rotor/Inner Rotor Pole Arc=20.jfiles/Inner_Rotor_Pole_Arc=20~2/2D_Transient~2/Case1

Full Model Conversion

☑ Convert to Full Model Values

Conversion Factor:

Periodic Boundary: 1

Other than Periodic Boundary: 1

Stack Length: 50 mm

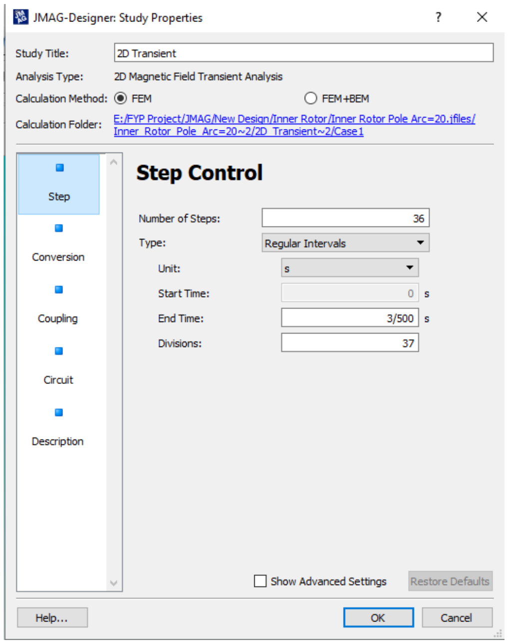
☐ Height of FEM Coil/Conductor Differs from Stack Length

Length of FEM Coil/Conductor: 1 mm

☐ Show Advanced Settings

Figure 3.13

The file is saved and analyzes the motor. On study toolbar, click run active case. Wait until the simulation finish. Check the result, right click graph, and choose magnetic flux of FEM coil. Plot the graph in Microsoft Excel and analyze the findings. And draw circuit (coils, grouping, and power source) and link it with the winding drawn in geometry.



JMAG-Designer: Study Properties

Study Title: 2D Transient

Analysis Type: 2D Magnetic Field Transient Analysis

Calculation Method: ● FEM ○ FEM+BEM

Calculation Folder: E:/FYP Project/JMAG/New Design/Inner Rotor/Inner Rotor Pole Arc=20.jfiles/Inner_Rotor_Pole_Arc=20~2/2D_Transient~2/Case1

Step Control

Number of Steps: 36

Type: Regular Intervals

Unit: s

Start Time: 0 s

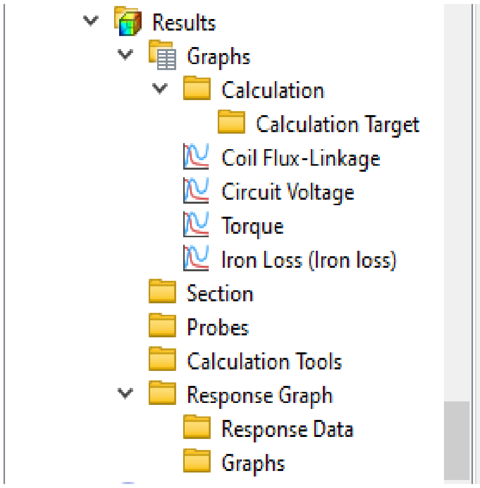
End Time: 3/500 s

Divisions: 37

☐ Show Advanced Settings

Figure 3.14 Study Properties editor.

Then we set other conditions like step size, end time, mesh size for FEA Analysis as shown in figure 3.17. After running the simulation, results can be seen in the result section as shown in figure 3.18.



- Results
  - Graphs
    - Calculation
      - Calculation Target
    - Coil Flux-Linkage
    - Circuit Voltage
    - Torque
    - Iron Loss (Iron loss)
  - Section
  - Probes
  - Calculation Tools
  - Response Graph
    - Response Data
    - Graphs

Figure 3.15 Results

3.4. Results:

The findings, from the design and analysis of the slotless Permanent Magnet Brushless DC (PMBLDC) motor have been very promising. By removing the slots in the stator we've managed to reduce cogging torque and eddy losses resulting in more efficient motor performance. Additionally the increased slot fill factor has significantly improved power density allowing for torque output in a lighter motor package. This also means that the motor is more responsive and controllable due to its inertia and reduced rotor losses. These advancements make it suitable for applications that require quick changes in speed and torque. Overall these results demonstrate that slotless PMBLDC motors are a solution, with potential to drive innovation across various industries while improving efficiency and reliability of electrical machines.

3.5. Phase Flux Linkages:

The flux linkages in a slotless permanent magnet brushless DC (PMBLDC) motor refer to the magnetic linkage between the stator windings and the rotor's permanent magnets. These flux linkages are crucial for the generation of electromagnetic torque and the overall motor performance. In the figure flux linkages of slotted and slotless PMBLDC motor is compared.

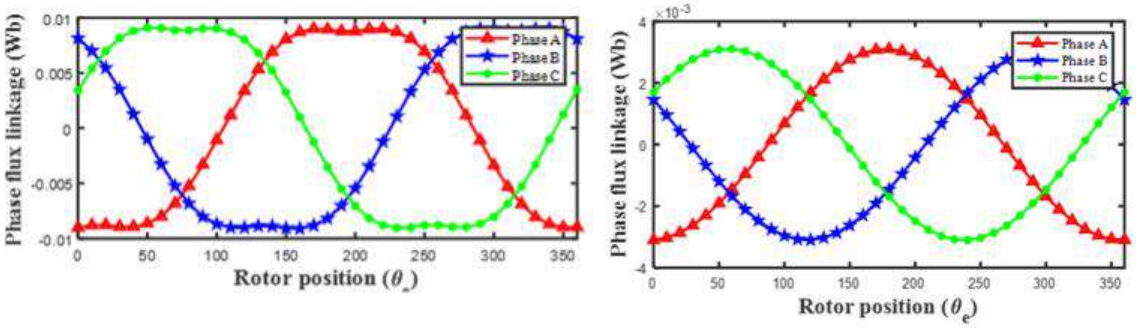


Figure 3.16 Comparison of Slotted and slotless PMBLDC motor

3.6. Phase Voltage:

The winding configuration and electrical characteristics of the motor determine the phase voltage of both slotted and slotless permanent magnet brushless DC (PMBLDC) motors. However, there are certain differences between slotted and slotless PMBLDC motors in terms of the phase voltage. The phase voltage for each type of motor is described as follows:

1. Slotted PMBLDC Motor:

- The stator core of a slotted PMBLDC motor is normally laminated and has slots that contain the stator windings.
- The distributed winding arrangement, in which the windings are dispersed over the stator slots, is the winding layout that is often used in slotted PMBLDC motors.
- The applied voltage, the winding arrangement, and the stator winding turn number significantly affect the phase voltage in a slotted PMBLDC motor.
- The phase voltage can be calculated using the formula: Phase Voltage = (Applied Voltage) / (Number of Turns per Phase).

2. Slotless PMBLDC Motor:

- In a slotless PMBLDC motor, there are no slots in the stator core, and the winding is typically concentrated or formed in a coil-like shape.
- The winding configuration used in slotless PMBLDC motors is often concentrated windings, where the windings are concentrated in specific areas of the stator.
- The phase voltage in a slotless PMBLDC motor is determined by the number of turns in the concentrated windings and the applied voltage.
- The phase voltage can be calculated using the formula: Phase Voltage = (Applied Voltage) / (Number of Turns per Phase).

In figure phase voltages of slotted and slotless PMBLDC motor are shown below

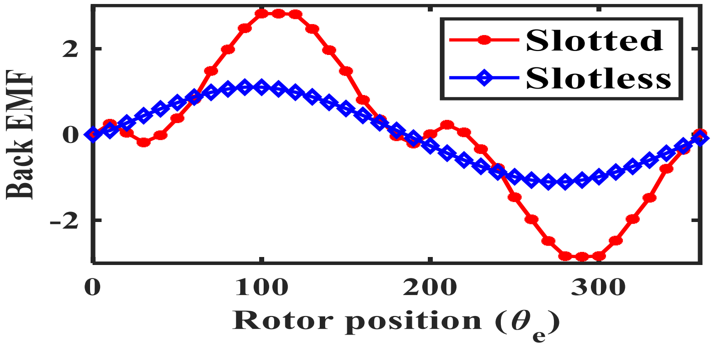


Figure 3.17 Phase Voltage of slotted and slotless PMBLDC motor

3.7. Cogging torque

Cogging torque is a phenomenon that occurs in both slotted and slotless permanent magnet brushless

DC (PMBLDC) motors. It refers to the torque variations experienced by the motor as the rotor moves past the stator teeth or concentrated windings. However, the presence and characteristics of cogging torque differ between slotted and slotless PMBLDC motors.

3. Slotted PMBLDC Motor:

- In a slotted PMBLDC motor, the stator core has teeth or slots that accommodate the stator windings.
- The presence of teeth in the stator structure introduces variations in the magnetic field as the rotor rotates.
- Cogging torque in slotted PMBLDC motors is primarily caused by the interaction between the permanent magnets on the rotor and the stator teeth.
- The cogging torque in slotted PMBLDC motors can result in torque ripple and can adversely affect the motor's smooth operation and efficiency.

4. Slotless PMBLDC Motor:

- In a slotless PMBLDC motor, the stator core does not have teeth or slots. The winding is typically concentrated or formed in a coil-like shape.
- The absence of teeth in the stator core reduces the variations in the magnetic field as the rotor rotates.
- Slotless PMBLDC motors exhibit significantly reduced or even eliminated cogging torque compared to slotted motors.
- The absence of teeth in slotless PMBLDC motors results in smoother torque production and improved overall motor performance.

Here is the comparison of both motor in the figure

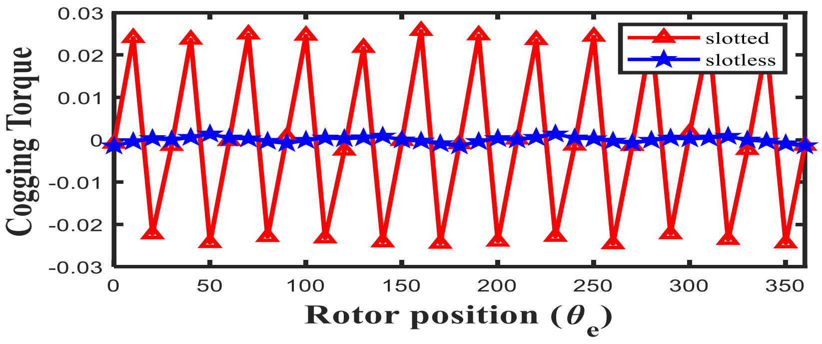


Figure 3.18 cogging torque of slotted and slotless PMBLDC motor

3.8. Air Gap Flux Density:

The air gap flux density describes the strength of the magnetic field in the area between the rotor magnets and the stator windings in a slotless permanent magnet brushless DC (PMBLDC) motor. It is essential in determining the performance of the motor, including torque production, effectiveness, and cogging torque. Factors including magnet properties, air gap dimensions, and stator winding arrangement all affect the air gap flux density.

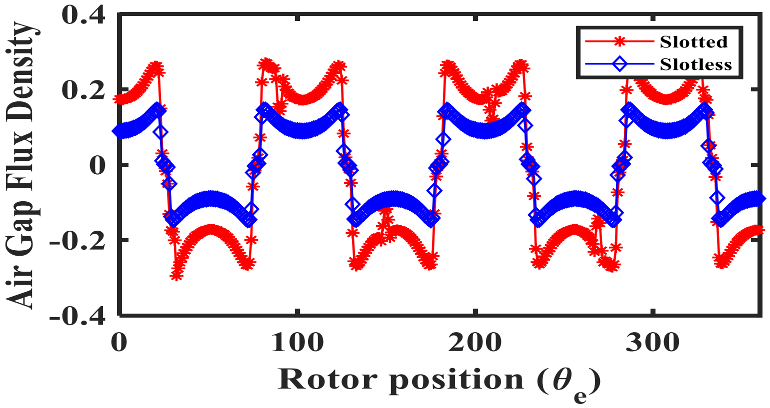


Figure 3.19 air gap flux density comparison

3.9. Rated Torque

The interaction between the magnetic fields generated by the stator windings and the rotor magnets is the process that causes the torque to be produced in both slotted and slotless permanent magnet brushless DC (PMBLDC) motors. But there are differences between slotted and slotless PMBLDC motors in terms of their torque characteristics. Here is a description of how each type of motor generates torque:

5. Slotted PMBLDC motor:

The stator core of a slotted PMBLDC motor is made up of slots that house the stator windings. Torque is produced by the interaction of the rotor magnets and stator windings. A magnetic field is created when the stator windings are energised by current, and it interacts with the permanent magnets on the rotor. The torque produced by the resulting electromagnetic force drives the rotor. However, due to the interaction between the rotor magnets and the stator teeth, which causes torque ripple and may have an impact on smooth operation, slotted PMBLDC motors are more vulnerable to cogging torque.

6. Slotless PMBLDC motor:

In a slotless PMBLDC motor, there are no slots in the stator core, and the winding is typically concentrated or formed in a coil-like shape. The absence of teeth in the stator core reduces cogging torque and improves torque smoothness. Slotless PMBLDC motors generally exhibit smoother torque production and reduced torque ripple compared to slotted motors. The interaction between the concentrated stator windings and the rotor magnets generates torque. The magnetic field produced by the stator windings interacts with the rotor magnets, creating an electromagnetic force that drives the rotor. The specific torque characteristics of a PMBLDC motor depend on various factors, including the number of turns in the windings, the strength and magnetization pattern of the rotor magnets, the winding configuration, and the motor control strategy. So here is the comparison of torque of slotted and slotless PMBLDC motor:

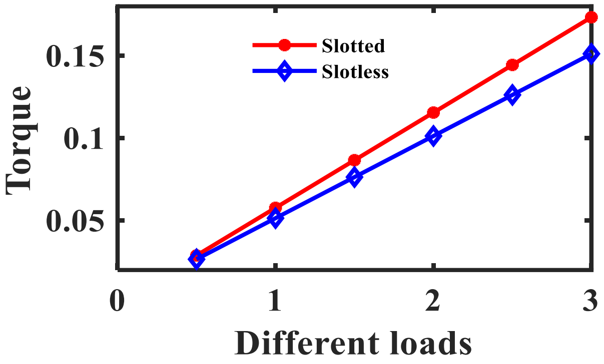


Figure 3.20 Rated Torque of Slotted and Slotless PMBLDC motor

Conclusion

The design and performance characteristics of slotted and slotless PMBLDC motors are influenced by factors such as winding configuration, flux linkages, cogging torque, air gap flux density, and torque generation. Each motor type has its advantages and considerations, and specific design optimizations and analysis techniques are employed to enhance motor performance based on the desired application requirements.

CHAPTER 4

Prototype Development and Experimental Tests

4.1 Introduction:

To validate the theoretical concept, prototype for Slotless PMBLDC motor were fabricated and tested experimentally, and the detail is included in this chapter. The Fabrication process, experimental setup and experimental analysis are discussed here.

4.2 Prototype Fabrication and Assembling:

The discussion in the previous chapter investigates the detailed electromagnetic performance of the initial and optimized design of Slotless PMBLDC motor. The effectiveness of the proposed Slotless PMBLDC motor design and concept is validated with a test prototype. Detailed prototype fabrication process is shown. It is worth noting that the prototype is developed with help of Epoxy. In order to make core hard and coreless Epoxy is used. To separate the windings we used small aluminum tooth in making a prototype.

4.3 Consideration on Manufacturing Approach:

Construction of proposed Slotless PMBLDC motor for practical implementation for fan application is presented in this section. The proposed motor was first design in JMAG before fabrication to examine its electrical properties. A stator with stack length of 25mm and a small aluminum tooth was developed.

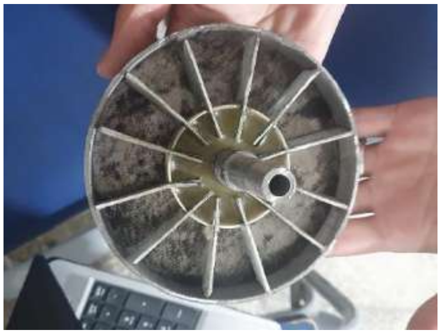


Figure 4.1 stator with aluminum tooth

The above mentioned figure 4.1 is the stator with aluminum separator of a propose motor which has no slots. Aluminum separator is used for separating the two copper windings.

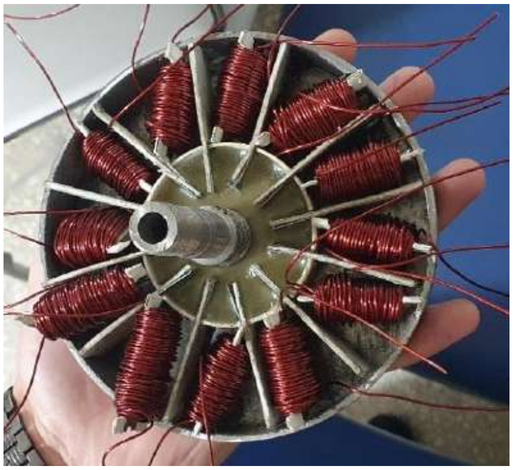


Figure 4.2 Copper Winding of Stator

The above mentioned figure 4.4 is copper winding of stator of a propose motor which has an aluminum separator between two armature winding.

Figure 4.3 Rotor

The above-mentioned figure 4.3 is the rotor of a proposed motor which has fourteen (14) rotor poles. The above-mentioned figure 4.3show assembly of the machine of having 132mm of outer diameter with which outer rotor is fixed with the assembly.

Figure 4.4 Prototype and Complete Assemble Model

The above mention figure 4.4 shows the prototype and the complete assembled model with complete circuitry and connections of proposed machine.

CHAPTER 5

Conclusion

Conclusion:

In conclusion, the design and analysis of a slotless PMBLDC motor have been thoroughly explored, providing valuable insights into its performance, advantages, and limitations. The slotless configuration eliminates the presence of teeth or slots in the stator core, resulting in several notable benefits. First off, the lack of slots results in a decrease in cogging torque, which leads to smoother operation and increased effectiveness. This is especially helpful in fields like robotics, medical technology, and electric cars where precision control and low-speed operation are essential. The reduction in cogging torque also reduces torque ripple, improving overall performance and resulting in a quieter operation of the motor. Additionally, the lack of slots makes manufacturing simpler and makes winding easier, which lowers production costs. A slotless PMBLDC motor's winding procedure is often simpler and doesn't require special slot insulating materials because there are no teeth. By reducing the manufacturing process, the motor becomes more affordable for mass production. It's essential to remember that slotless PMBLDC motors have some drawbacks as well. A motor's efficiency and performance at greater speeds may be affected by increased winding inductance and phase resistance, which may result from the absence of slots. In order to optimise the motor's performance qualities, the design must be carefully thought out, including the choice of suitable winding configurations and materials. The design and analysis of a slotless PMBLDC motor present numerous advantages, including reduced cogging torque, smoother operation, improved efficiency, simplified manufacturing process, and higher power density. Due to these features, slotless PMBLDC motors are particularly well suited for a variety of applications, especially those that call for precision control, low-speed operation, compactness, and lightweight design. To improve the design parameters and maximise the performance of slotless PMBLDC motors for particular application needs, additional research and development activities are necessary

CHAPTER 6

References

[1] Shastri, S. and Singh, B., 2022, August. Design of Fractional Slot Concentrated Windings of PM Brushless Motors for Ceiling Fan Application. In *2022 IEEE 2nd International Conference on Sustainable Energy and Future Electric Transportation (SeFeT)* (pp. 1-5). IEEE.

[2] Karnavas, Y.L., Chasiotis, I.D. and Gkiokas, A.D., 2018, August. An Investigation Study Considering the Effect of Magnet Type, Slot Type and Pole-Arc to Pole-Pitch Ratio Variation on PM Brushless DC Motor Design. In 2018 5th International Conference on Mathematics and Computers in Sciences and Industry (MCSI) (pp. 7-13). IEEE.

[3] Dong, B., Wang, K., Han, B. and Zheng, S., 2019. Thermal analysis and experimental validation of a 30 kW 60000 r/min high-speed permanent magnet motor with magnetic bearings. IEEE Access, 7, pp.92184-92192.

[4] Islam, M.S., Mikail, R. and Husain, I., 2021. Field Weakening Operation of Slotless Permanent Magnet Machines Using Stator Embedded Inductor. IEEE Transactions on Industry Applications, 57(3), pp.2387-2397.

[5] Gambhir, R. and Jha, A.K., 2013. Brushless DC motor: Construction and applications. Int. J. Eng. Sci, 2(5), pp.72-77

[6] Burnand, G., Thabuis, A., Araujo, D.M. and Perriard, Y., 2019. Novel optimized shape and topology for slotless windings in BLDC machines. IEEE Transactions on Industry Applications, 56(2), pp.1275-1283.

[7] Burnand, G., Araujo, D.M. and Perriard, Y., 2018, October. Optimization of shape and topology for slotless windings in BLDC machines. In 2018 21st International Conference on Electrical Machines and Systems (ICEMS) (pp. 31-36). IEEE.

[8] Jufer, M. and Radulescu, M.M., 1991, September. Comparative study of slotted and slotless electronically commutated permanent-magnet dc servomotors. In 1991 Fifth International Conference on Electrical Machines and Drives (Conf. Publ. No. 341) (pp. 131-135). IET.

[9] W. Cheng, G. Cao, Z. Deng, L. Xiao and M. Li, "Torque Comparison Between Slotless and Slotted Ultra-High-Speed AFPM Motors Using Analytical Method," in IEEE Transactions on Magnetics, vol. 58, no. 2, pp. 1-5, Feb. 2022, Art no. 8101805, doi: 10.1109/TMAG.2021.3081175.

[10] Shastri, Sharankumar & Sharma, Utkarsh & Singh, Bhim. (2020). Design of Fractional-Slot Concentrated Winding Consequent Pole Motor for Ceiling Fans. 10.1109/ICCCA49541.2020.9250755.

[11] Sakunthala, S., Kiranmayi, R. and Mandadi, P.N., 2017, August. A study on industrial motor drives: Comparison and applications of PMSM and BLDC motor drives. In 2017 International Conference on Energy, Communication, Data Analytics and Soft Computing (ICECDS) (pp. 537-540). IEEE.

[12] S. Dunkl, A. Muetze and G. Schoener, "Design Constraints of Small Single-Phase Permanent Magnet Brushless DC Drives for Fan Applications," in IEEE Transactions on Industry Applications, vol. 51, no. 4, pp. 3178-3186, July-Aug. 2015, doi: 10.1109/TIA.2015.2406856.

[13] Bhasme, N.R. and Durge, M.P., 2015. Comparative study of electrical motors for ceiling fan application. Journal Impact Factor, 6(5), pp.08-13.

[14] Manikandan, Boopathi. (2020). Optimized design of Permanent Magnet Brushless DC Motor for Ceiling Fan Applications.

[15] R. P. Praveen, M. H. Ravichandran, V. T. Sadasivan Achari, V. P. Jagathy Raj, G. Madhu and G. R. Bindu, "A Novel Slotless Halbach-Array Permanent-Magnet Brushless DC Motor for Spacecraft Applications," in IEEE Transactions on Industrial Electronics, vol. 59, no. 9, pp. 3553-3560, Sept. 2012, doi: 10.1109/TIE.2011.2161058.