Advanced Renewable Wind Turbine Braking System

By

Nithin Thimmaiah

Thesis

Submitted to Flinders University

for the degree of

Master of Engineering(Electrical and Electronics)

College of Science and Engineering

23/10/2023

TABLE OF CONTENTS

ABSTRACT

Significant technological progress has been made in wind turbines, the key tools for harvesting wind energy. When operating a wind turbine, safety and efficiency are of the utmost importance, especially in challenging wind conditions or in times of emergency. The use of eddy current braking devices on wind turbines is investigated in this thesis. The non-contact feature of eddy current brakes allows for effective and precise braking without the wear typically seen in mechanical systems. This thesis presents research on an eddy current braking model built from the ground up for use in vertical axis wind turbines. The goal is to develop a model that minimizes energy waste without compromising the system's ability to provide consistent and effective braking. The results of this study will aid in the ongoing effort to improve wind turbine safety and performance. This thesis contributes significantly to the effort to safely and sustainably harvest wind energy by investigating the application of eddy current braking and employing software simulations for performance evaluations. It makes a significant contribution to the field of renewable energy by laying the groundwork for the future development and application of eddy current braking systems in wind turbine technology.

DECLARATION

I certify that this thesis:

1. does not incorporate without acknowledgment any material previously submitted for a degree or diploma in any university
2. and the research within will not be submitted for any other future degree or diploma without the permission of Flinders University; and
3. to the best of my knowledge and belief, does not contain any material previously published or written by another person except where due reference is made in the text.

Signature of student....... ....

Print name of student........Nithin Thimmaiah..

Date...........23/10/2023...

I certify that I have read this thesis. In my opinion is not (please circle) fully adequate, in scope and in quality, as a thesis for the degree of Master of Electrical and Electronic Engineering. Furthermore, I confirm that I have provided feedback on this thesis and the student has implemented it minimally/partially/fully (please circle).

Signature of Principal Supervisor...

Print name of Principal Supervisor.......Dr. Amir Zanj............................

Date................23/10/2023......................

ACKNOWLEDGEMENTS

I want to extend my sincere thanks and appreciation to the many individuals and organizations who played a crucial role in the successful completion of my Masters thesis.

I would like to express my sincere gratitude to my supervisor, Dr. Amir Zanj, for his invaluable guidance and support.Your consistent support, guidance, and expertise have been priceless throughout this research journey. Your commitment to guiding and your perceptive feedback have been instrumental in the excellence and thoroughness of this work.

I would like to express my appreciation to the entire team at Flinders Engineering Services for their valuable assistance and cooperation in providing essential resources and technical support. Your collaborative spirit and willingness to share your knowledge have greatly contributed to the development and execution of this research.

To all my friends, I want to express my gratitude for your unwavering support and motivation throughout this academic journey. Your encouragement has been invaluable during the most challenging moments. I greatly appreciate the valuable discussions, insights, and feedback you have provided, which have significantly enhanced my research and contributed to my personal and professional development.

Lastly, I want to express my heartfull gratitude to my family for their constant support and understanding throughout this journey.

LIST OF FIGURES

LIST OF TABLES

Introduction

Wind power is a sustainable and eco-friendly source of energy that we harness through wind turbines to decrease our reliance on fossil fuels. The cost of building a wind turbine varies depending on a number of different aspects, some of which include the size of the turbine, the location of the installation, and the level of difficulty of the project. The installation of a wind turbine can cost anywhere from $3,000 to $8,000 per kilowatt of capacity. This is the average range. This indicates that the price of constructing a standard wind turbine with a capacity of 10 kilowatts would range anywhere from $30,000 to $80,000. Hence in order to protect the wind turbine and its utilization in an efficient way it is crucial to have a reliable braking system to effectively regulate rotor speed, protect the turbine from strong winds, facilitate maintenance, and enable emergency stops.Vertical axis wind turbines (VAWT) and horizontal axis wind turbines (HAWT) are the two main types of wind turbines used to convert wind energy into electricity. The primary components of a VAWT are positioned at the turbine's base, and the primary rotor shaft is oriented perpendicular to the wind. Since VAWTs don't have to be oriented towards the wind, wind-sensing and orientation systems are unnecessary. Braking plays a crucial role in ensuring the safety of wind turbines, particularly in VAWTs. VAWTs have a higher risk of overspeed compared to HAWTs, and they can pose a greater challenge to control during strong winds. There are several kinds of braking systems which are utilized on the VAWTs. Braking systems in VAWTs are not just limited to mechanical braking, but also make use of aerodynamic braking. Mechanical braking is often used to bring the turbine to a halt in an emergency or to regulate the speed at which the turbine rotates, whereas aerodynamic braking is typically used to slow down the rotor and prevent it from overspeeding.

There is a new way of applying a braking system towards the VAWTs i.e making use of eddy current braking. Since eddy current braking is a simple , effective and low maintenance that can be used to control the speed of the wind turbine. This report mostly covers my Master's thesis work, which involved the creation and design of an eddy current braking system for wind turbines with a vertical axis. This study will propose an innovative braking design for VAWTs and experimental data that prove its efficiency, both of which will contribute to the advancement of eddy current braking technology.

Literature Review

1.Vertical Axis Wind Turbines(VAWT)

A vertical-axis wind turbine (VAWT) operates with a unique design, featuring a rotor shaft positioned perpendicular to the wind and essential components situated at the turbine's base. This arrangement enables easy access for service and repair by placing the generator and gearbox close to the ground. VAWTs do not require wind-sensing or orientation mechanisms, as they do not need to be pointed into the wind.

Vertical-axis wind turbines (VAWTs) offer several advantages compared to traditional horizontal-axis wind turbines (HAWTs). These include:

1.Omnidirectional operation.

2.Performance in low-wind conditions.

3.Urban and rooftop installations.

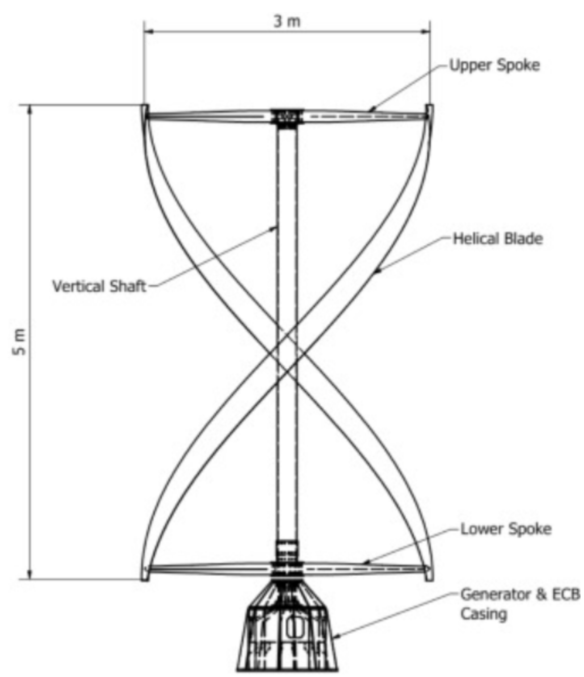
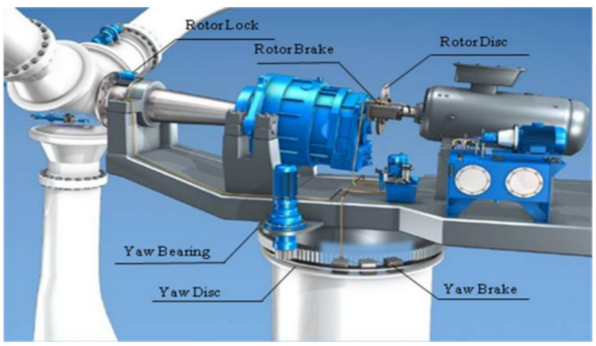


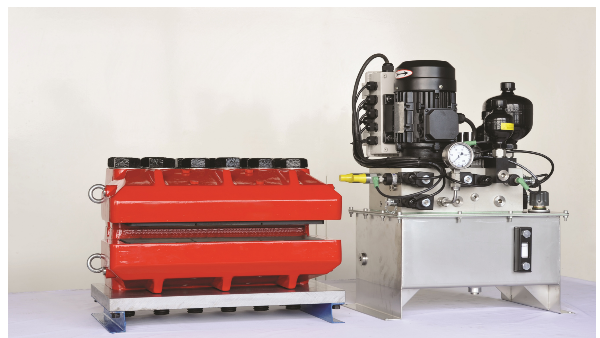
Fig1:The prototype model of VX-6 wind turbine

The figure above describes the VAWT prototype (VX-6) which was installed in the United Kingdom in 2013.Since the wind turbines are complex machines which operate under constantly changing environmental conditions, which demands the presence of reliable and efficient braking systems. In the history of the wind turbine braking systems the researchers have developed various braking techniques to control the speed of the wind turbines. Various factors, such as turbine size, design, and operating conditions, influence the selection of the wind turbine braking method.

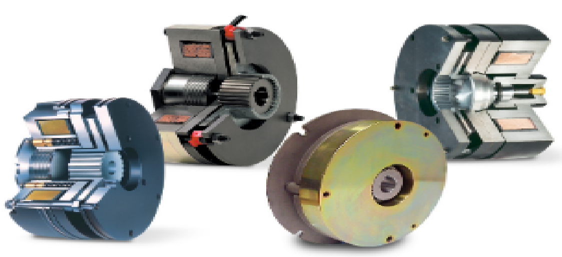
2.Existing Wind Turbine Braking Methods



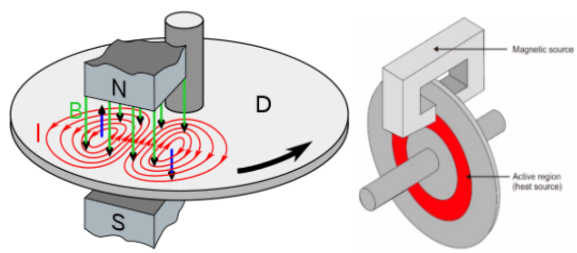
a.Mechanical Braking



b.Hydraulic Braking



c.Permanent Magnet Braking



d.Eddy Current Braking

Fig2:Different Kind of wind turbine braking methods

When we look into different kinds of braking methods there are several wind turbine braking models such as mechanical, hydraulic, permanent magnet and eddy current braking systems. Mechanical brakes are used to apply force either to the rotor shaft or directly to the blades.In mechanical braking methods they utilize the physical braking methods such as disc brakes and caliper brakes(S.V. kozlov 2018). A hydraulic braking system is quite large because of its hydraulic control unit. This size allows it to generate a significant amount of stopping force, making it capable of bringing wind turbines to a stop quickly and safely. Due to their reliability and durability, hydraulic systems are commonly employed for braking purposes in wind turbines(Rudolf limpert 1992).On the other hand the non contact form of braking systems such as permanent magnetic brake on the wind turbine operates without requiring any interaction between the braking components, which sets it apart from conventional braking methods (S.V. Gandzha 2017). A limited 5% of wind turbine manufacturers utilize permanent magnetic brakes.The cost of installing permanent magnet brakes can be higher compared to other types of braking systems(Seung-Woo Kim 2018). Moreover, the eddy current braking is a form of electromagnetic braking that is capable of decelerating the rotor. The eddy currents generate a magnetic field that counteracts the magnet's rotation, resulting in a deceleration of the rotor(W. R. Smythe 1942). Eddy current braking is a straightforward and cost-effective braking system to implement. It is highly efficient in reducing the rotor's speed, even at high velocities(K. Park 1999).

3.High Efficiency Braking Models

By analyzing braking performance from each of the braking models and as per the several journal papers and IEEE established research papers they mainly prefer the braking which works on the electrical approach due to its non contact form of braking nature(X. Wang 2022). Most of the electric vehicles braking mechanism works on the principle of eddy current braking. Most electric vehicles prefer a regenerative kind of braking mechanism(S.V. Gandzha 2017). In the case of wind turbines the mechanical kind of braking is also much more effective, especially in the case of HAWTs. The HAWTs also utilizes the eddy current form of braking which works on pitch controlling mechanisms. Eddy current forms of braking are highly reliable and much more effective in the case of VAWTs (K. Anbalagan et al 2020).

4.Emergency Brakes

The emergency braking systems are useful when there is a failure in the primary braking system. In most of the cases in the wind turbines they utilize a kind of mechanical braking system as emergency brakes. Since during the maintenance and extreme weather conditions the wind turbines are set to be in halt position during this emergency kind of braking they utilize disc brakes or the caliper brakes which are a kind of mechanical brakes. In most of the recent electrical vehicles and the modern wind turbines they are utilizing the magnetic locking mechanism with the help of permanent magnets(S .B sharma 2021). Since the magnets holding force torque is more when it is compared to the mechanical brakes.

5.Case Study of VAWT-X Energy

VAWT-X Energy is a start-up company that is registered and based in South Australia.The primary focus of the company is on the research, development, and certification of its proprietary airfoil for use in the mass manufacture of two-bladed helical VAWTs. Accelerating the research and development of VAWT-X Energy's products is a top priority for the company, and it is doing it in close collaboration with Flinders University. VAWT-X Energy is an industry involved in the production of wind turbines, such as the VX-6, which has a power output of 6 kilowatts, and the VX-80, which has a power output of 80 kilowatts. As a consequence of working together, an efficient brake model will need to be developed in order to investigate the performance of the VX-6 turbine. In addition, a prototype known as VX-6/5, which is a scaled-down version of the VX-6 turbine, was constructed at Flinders University as shown in the figure below.

Fig3:VX-6/5 VAWT prototype

6.Current braking mechanism used by VAWT-X Energy

For safety reasons VAWT-X energy includes two brakes. Comparing mechanical brakes and hydraulic brakes.In this prototype VX-6/5, they utilize hydraulic brakes. This hydraulic braking mechanism consists of brake calipers and hydraulic pressure units. The hydraulic pressure unit features a spacious reservoir with a generous 10-liter oil storage capacity. The system includes a single electric motor that is linked to a reservoir containing a hydraulic pump. A hydraulic pump generates hydraulic pressure in fluid, which is then delivered to the brake caliper through hydraulic pipe connections. The brake caliper functions through the use of a piston operated mechanism. Friction is generated on the rotating hub by a pressurized oil caliper, which is mounted on the rotating shaft. As a result of the friction between the brake caliper and the rotating shaft, the speed of the rotating shaft was controlled. During the testing phase of this prototype, due to some variations in wind energy levels caused by atmospheric changes leads to strong gusts of wind with increased atmospheric pressure. During that period, the wind turbine was spinning at a very high speed, during this situation, the time taken by the hydraulic mechanism to completely stop the turbine was excessively long. Consequently, this had a direct effect on the turbine and generator components.

Parametric model VX-6/5 includes both an aerodynamic model and a generator model, as demonstrated in the case study section. The aerodynamic model was used to control the speed of the turbine. The performance of the wind turbine blades was being negatively impacted by this braking mechanism, so our supervisor Dr. Amir Zanj proposed to build a braking model that could be integrated into the generator model using an electrical approach.

7.Research Gap

As mentioned in the case study section, the existing braking mechanism has certain limitations when it comes to achieving optimal braking performance for VAWT. This is because it was initially designed for a straight blade VAWT. The stability of the torque distribution in the straight blade VAWT model is a result of the abrupt changes in the angle of attack. As a result, the hydraulic brake proved to be highly effective during that period. According to the new design, the helical geometry of the blade in the helical blade VAWT shown in the figure above would reduce the impact of brakes. Consequently, the eddy current braking mechanism has the ability to tackle these issues, making it a viable method for improving the braking performance of the VX-6/5 turbine. The literature review makes it abundantly clear that the eddy current braking system will be significantly more effective in both achieving fail safe braking. The more research that is done on this subject, not only will it be beneficial to VAWT-X Energy, but it will also increase the understanding of the performance and applications of the eddy current braking model. The table below, based on a survey of the relevant research, provides a summary of the many reasons why eddy current braking is superior to other types of braking.

Table1:Comparison of each braking system

Types of brakes	**Hydraulic Brakes**	**Eddy Current Brakes**	**Mechanical Brakes**	**Permanent Magnet Brakes**
Size	Bigger	**Compact**	Compact	Compact
Weight	Heavy due to oil	**Medium**	Medium	Medium
Braking power	High	**Very High**	High	High
Operate	Easy to operate	**Easy to operate**	Difficult to operate	Easy to operate
Reliable	Less reliable	**Highly reliable**	Less reliable	Highly reliable
Fail ratio	Low	**Low**	Low	Low
Maintenance	High	**Very Low**	Medium	Low
Heat generation	Medium	**High**	Low	None
Life	Depends on the maintenance	**Long life**	Depends on the maintenance	Long Life
Required electricity	High	**Medium**	None	Low
Cost of Installation	High	**Medium**	Medium	High also depends on the design

8.Project Objectives:

This project's objective mainly focuses on integrating the braking model with the generator model hence the aerodynamic model is beyond the scope of the project.

There are four objectives in this project which aims to increase and optimize the braking capacity of the vertical axis wind turbine. The objectives are:

1.High efficiency braking: This aims to achieve effective braking capacity with less power usage within the short duration of time irrespective of environmental conditions.

2.Shaft locking: This objective mainly focuses on the locking of the shaft which is necessary during turbine maintenance and to stop the turbine during extreme weather conditions.

3.Controlling the speed of the wind turbine: This feature plays a major role in controlling the speed of the turbine during gust winds or the sudden changes in the weather conditions.

4.Electrical control with feedback: This objective mainly focuses on controlling the braking capacity of the turbine based on the wind speed.

5.Fail safe braking: This objective aims to design the braking model which is much more reliable and easy to maintain.

Methodology

1.Assumptions for analysis on the Eddy current braking mechanism

For the purpose of predicting the performance of eddy current braking systems, these assumptions can be utilized to construct analytical models and simulation tools.

1. The magnetic field generator is capable of producing a magnetic field that is robust enough to fulfill the requirements.
2. The magnetic field is consistent and runs in a direction that is perpendicular to the conductor's surface.
3. The magnetic field is created by either a permanent magnet or an electromagnet.
4. The conductor can take the form of either a disc or a cylinder.
5. The conductor can be either stationary or rotating.
6. The rotor design effectively dissipates heat generated during braking, ensuring efficient heat removal from the system.

2.Steps to achieve the project objectives

The flowchart given below involves conducting thorough investigations, performing detailed analysis, overseeing the manufacturing and assembly processes, and conducting rigorous testing. The project's start and finish are clearly defined through a flow chart, which also illustrates the procurement process for all required components at different stages of the schedule.The flow chart also covers a detailed analysis of conducting research on the construction of the test portion. This flowchart serves as a valuable reference during the development of the work plan. The work breakdown structure of the plan outlines the sequential steps that form the structure of the project and the order in which the components of the result are assembled.

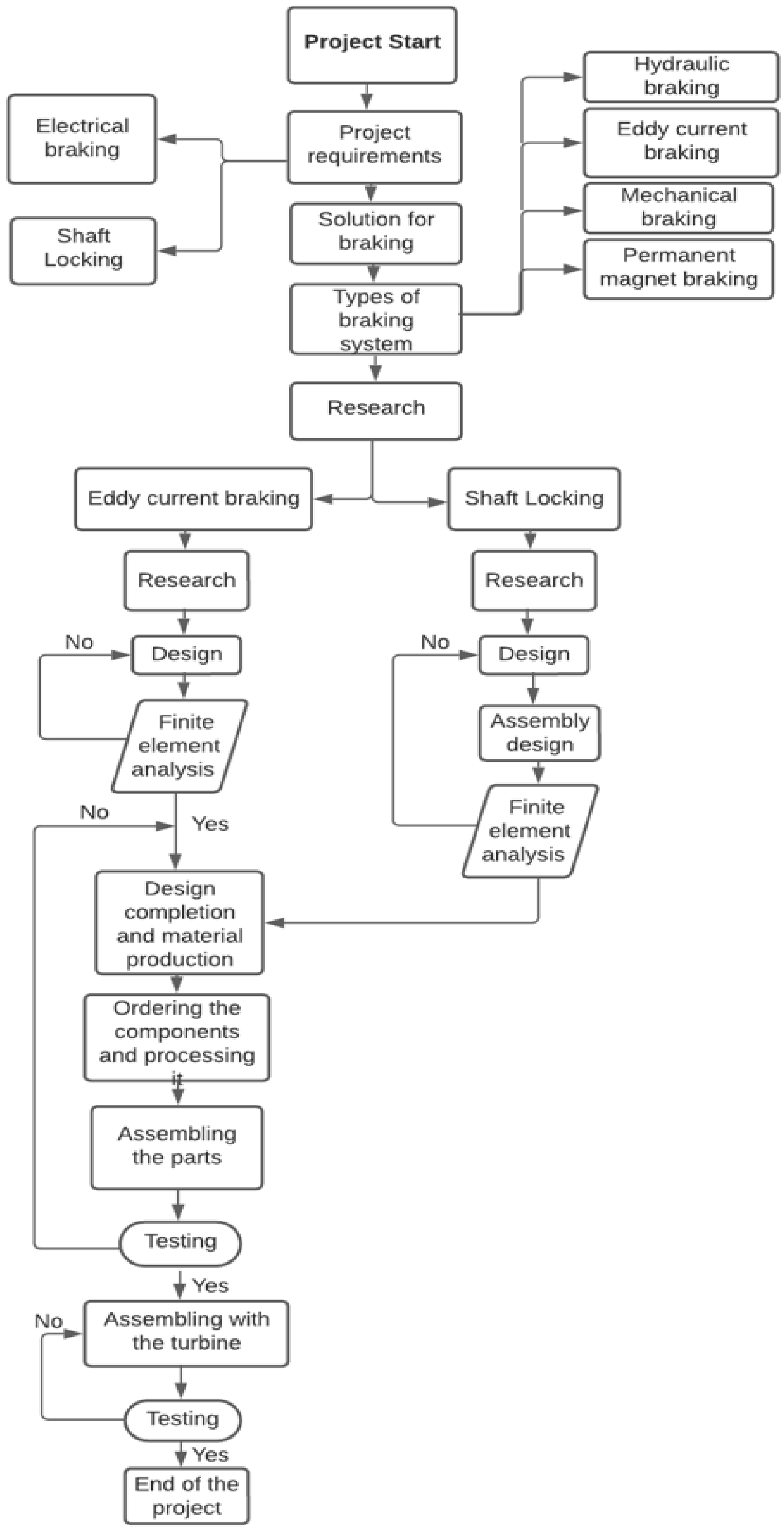


Fig4: Flowchart to achieve project objectives

3.Eddy Current Braking

Eddy current braking is a non-contact method of braking that utilizes the principle of electromagnetic induction to slow down a rotating object.

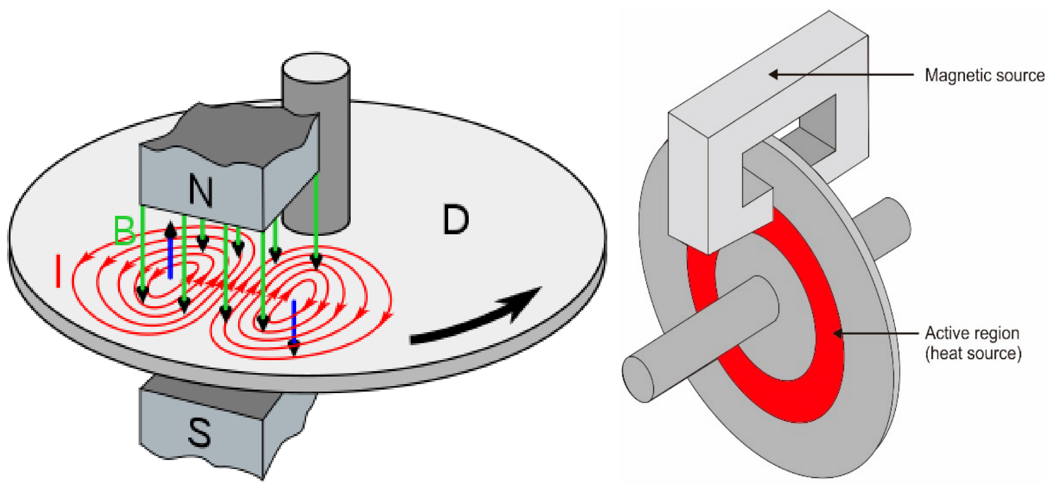


Fig5:Principle of eddy current braking

Understanding the mechanism of eddy current braking:

1. The mechanism of eddy current braking involves the generation of eddy currents in a metal disc that is positioned near a rotating magnet. Circular currents known as eddy currents are generated within a conductor when it comes into contact with a magnetic field that is undergoing changes.
2. As the metal disc comes near the rotating magnet, the magnetic field produced by the magnet undergoes changes due to the disc's rotation. Eddy currents are generated in the disc due to the varying magnetic field.
3. The magnetic field generated by the eddy currents works against the magnet's rotation. The rotation of the disc is gradually slowed down and eventually comes to a stop due to the presence of an opposing magnetic field.

Benefits of utilizing the eddy current braking for VAWT:

1. In the event of an unanticipated wind gust or other emergency, eddy current braking can be used as a preventative measure. Using this method, the rotor of a wind turbine can be brought to a stop from its rapid rotation.

2. The eddy current brake system can serve as a secondary mechanism to safeguard the wind turbine from exceeding its safe operating limits by spinning too fast.
3. Eddy current brakes can be used to control the speed of the rotor in order to maximize power output or to minimize noise and vibration.
4. There is no need for physical contact between the brake and the rotor when using an eddy current brake in wind turbines, which is one of the potential benefits of this braking method. As a result, the brake system may last longer before requiring repairs or replacement.

4.Braking Mechanism:

In accordance with the goals of the project, the braking mechanism can be realized by breaking it down into two stages.

1. Controlling the speed of the turbine.
2. Shaft locking.

4.1 Controlling the speed of the turbine

Eddy current braking is a technique implemented in order to control and completely stop the turbine blades. This technique was developed so that the speed of the turbine could be regulated. In order to check the braking performance of the eddy current braking we make use of Ansys 2D analysis software. Using this we mainly calculate the braking torque developed, in defining an air gap between the electromagnetic coil and a rotating disk, No. of turns on an electromagnetic coil.

4.1.1 Existing eddy current braking design:

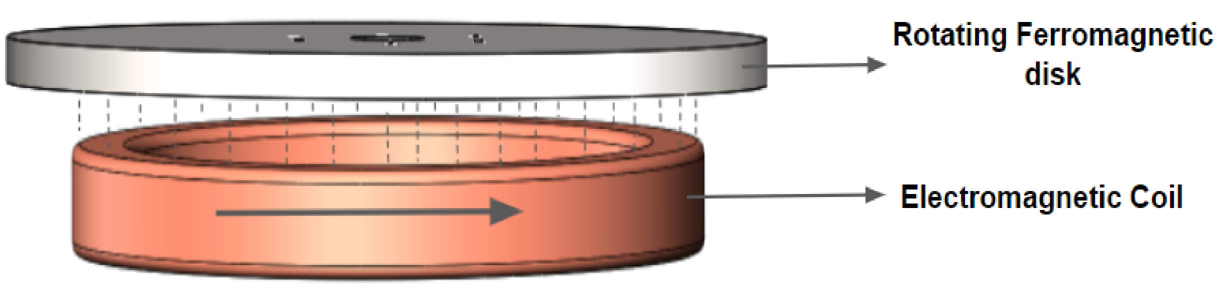


Fig6:Existing eddy current braking

The above figure gives a simple description of the eddy current mechanism.This setup includes a fixed electromagnetic coil with the current direction indicated by an arrow. The rotating ferromagnetic disc experiences eddy currents, represented by the dotted lines. In this kind of eddy current braking design are used in the applications like exercise equipment, roller coasters, electric trains. This kind of braking has very good braking performance.The major drawback of this kind of design is that it requires a greater amount of current in order to achieve excellent braking performance. This is because the length of the conductor is directly proportional to the resistance of the conductor. In this approach the current flows via a single coil that is encircled by an n-fold increase in the number of copper wires. Hence, this design requires a greater amount of current to achieve the high level of braking performance.

4.1.2 Proposed eddy current braking design:

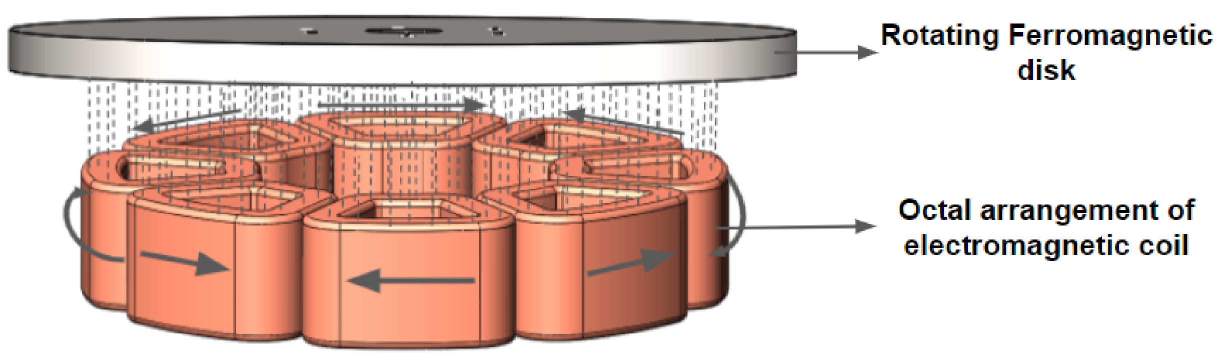


Fig7:Proposed eddy current braking

The existing eddy current braking and the proposed eddy current braking are very similar to one another. The only significant difference is that the electromagnetic coil arrangements in the proposed eddy current braking are in the form of an octal coil arrangement. This means that each coil is energized in such a way that the direction of current applied in one coil is opposite to the direction applied in the next coil. This can be achieved by supplying current on each of the individual coils separately. By arranging the coils in this fashion, we may reduce the amount of current needed to brake effectively and reduce the coil's surface area on the braking model.

4.1.3 Eddy Current Braking Analysis

Using ansys 2D analysis we mainly focus on the calculating

1. Magnetic saturation field strength exhibited by the coils on the braking plate.

2.The No. of turns on coil.

3.The supply current.

In order to analyze the braking performance of the proposed eddy current design we first simulated the existing eddy current braking design. Prior to simulation, we utilized solid works software to design the coils, taking into account the parametric measurements found in recent research documents on eddy current braking(brake disc from aluminium series of A16061 and A17075). Following this, an analysis was conducted.

a.Existing eddy current braking 2D Ansys analysis

This analysis was carried out on the electromagnetic coil which consists of 500 no. of turns with an air gap of 1 mm between the coil and braking disk.

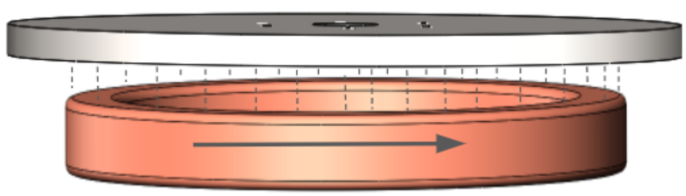


Table2: Magnetic saturation strength on existing eddy current braking design

Supply current [A]	Magnetic field saturation strength [T]
1	0.071
2	0.089
3	0.15
4	0.28
5	0.5

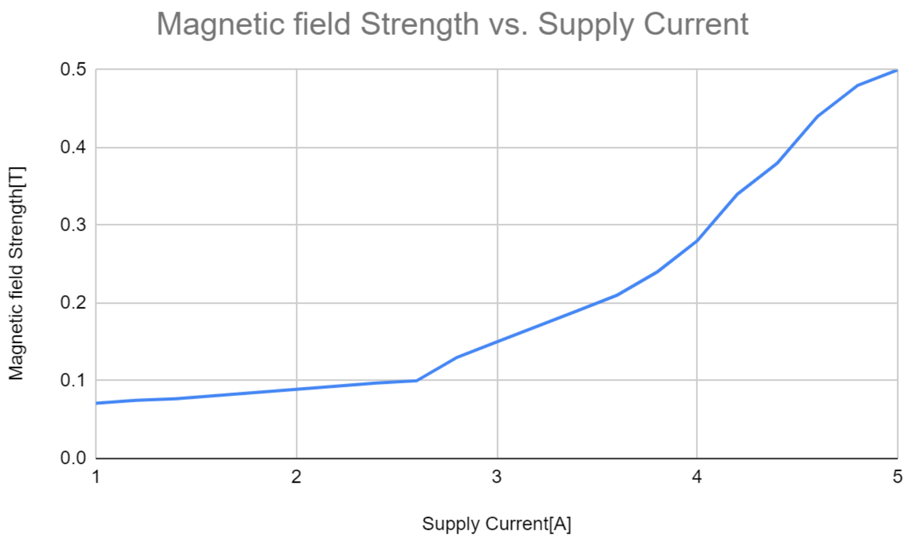
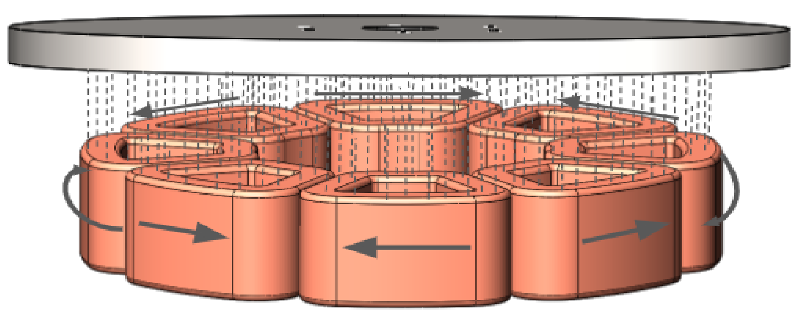


Fig8:Magnetic field strength characteristics on existing eddy current design

From the above graphical analysis the existing braking module consumes more current in order to achieve a high magnetic field strength. Generally it consumes around 5A to reach the magnetic saturation capacity of 0.5T.

b.Proposed eddy current braking 2D ansys analysis:



While performing the ansys analysis on this proposed eddy current braking design each coil was energized with different direction of current as shown in the figure above. Therefore an magnetic saturation field strength was calculated on each of the single coils consisting of 320 Turns with an air gap of 1 mm between the coil and the braking disk.

Table3: Magnetic saturation strength exhibited by the single coil on proposed eddy current braking design

Supply current [A]	**Magnetic field saturation strength [T]**
0.2	0.001
0.4	0.06
0.6	0.17
0.8	0.32
1	0.37
1.2	0.42
1.4	0.49
1.6	0.53
1.8	0.57
1.9	0.61
2	0.64

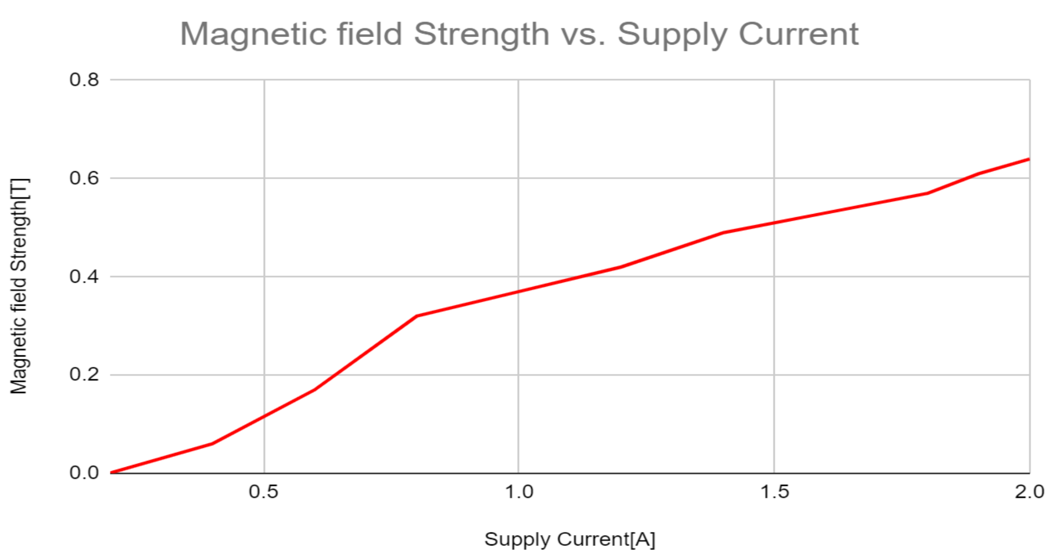


Fig9:Magnetic field strength characteristics of single coil on proposed eddy current design

From the above simulation we can observe that:

1. Number of turns for a single coil is observed to be 320 turns.
2. Supply current can be varied from 0-2A.
3. Magnetic saturation field strength on the braking plate by a single coil is found to be 0.64T.
4. The combination of 8 poles each at 0.64T is capable of stopping the entire turbine during emergency conditions.

4.2 Shaft Locking

Another type of braking used for emergency situations is called shaft locking. When the weather is particularly severe or when we are performing maintenance on the turbine, it is necessary for us to fully halt the rotation of the turbine. When this occurs, the shaft locking plays a significant role by completely stopping the turbine.

Fig10:Wind turbine maintenance

Here in order to achieve shaft locking we make use of a magnetic locking mechanism. Because the eddy current braking mechanism is most effective when the disc is rotating and it is used to totally stop the disc from rotating. When the disc is in the stationary position,we are unable to rely on its eddy current braking in this kind of scenario. We have to use magnetic locking to prevent the disc from rotating in its initial state.

In order to achieve shaft locking first we have to completely stop the rotating disk by applying eddy current brakes, when the rotating disk comes into the halt position then this magnetic locking mechanism can be utilized to achieve shaft locking objective.

This magnetic locking mechanism mainly works on the principle of magnets. As the like pole repels and the unlike poles attract. Here in our design we make use of the electromagnetic coil, permanent magnets and a spacer plate to achieve the shaft locking mechanism. Since the rotating disk will be holded by the shaft if we completely halt the disk from rotating we can achieve the shaft locking process.In order to check the performance of the magnetic locking we make use of FEMM analysis software.

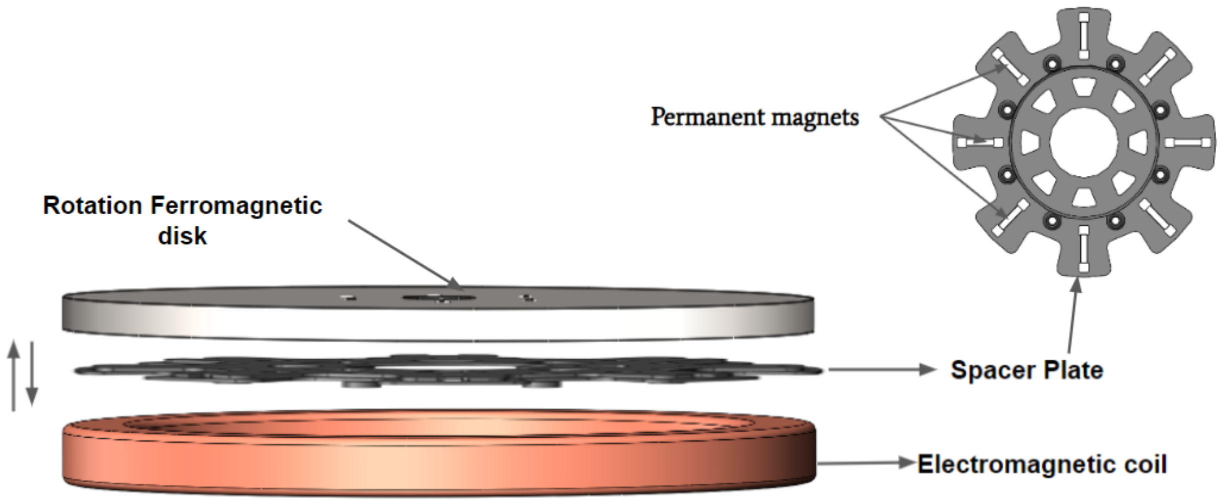


Fig11:Magnetic locking mechanism

From the above figure we can see that the permanent magnets are placed on a spacer plate which is free to move up and down. The movement of the spacer plate depends on the electromagnetic coil. As per the right hand thumb rule the direction of the magnetic force will be perpendicular to the direction of current. In a similar way by altering the polarity of the electric current that is passing through this electromagnetic coil can cause the magnets to either attract or repel to the electromagnetic coil. These permanent magnets are coupled to the spacer plate as shown in the figure above, which allows the spacer plate to move up and down.

4.2.1 Magnetic locking analysis using FEMM software

As mentioned in the previous section of the magnetic locking process will be achieved by the combination of electromagnet and the permanent magnet. By altering the electromagnet's supply current, this study using FEMM 4.2 verifies the magnetic force exerted by the electromagnet on the permanent magnet. As per the experiment first we mainly focus on the force exhibited by the electromagnet on the single permanent magnet as shown in the figure below.

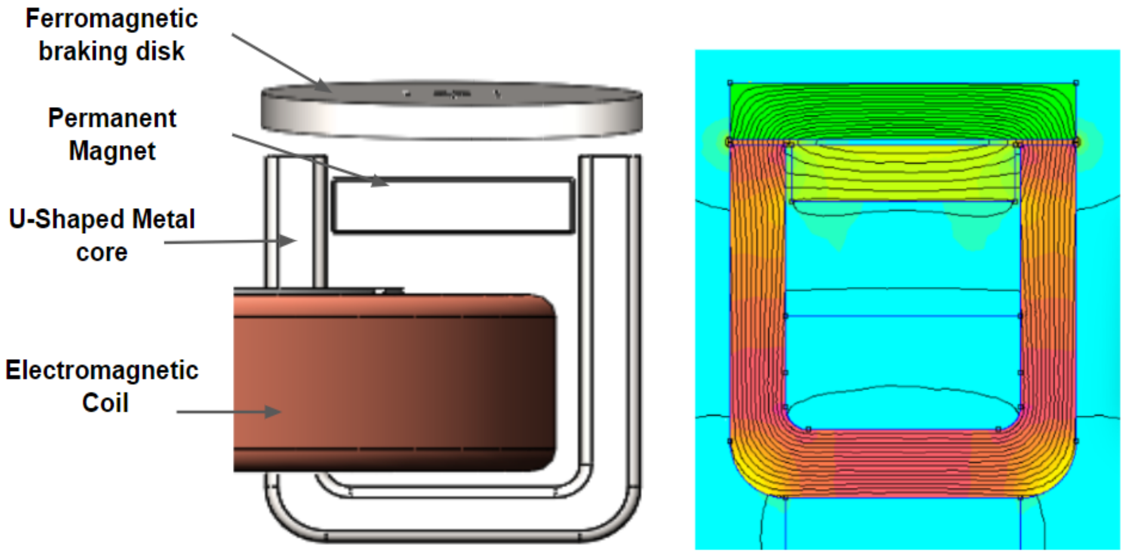


Fig12:FEMM analysis output representation

The following images are FEMM analysis output displaying the force exerted by the electromagnet at current values of 1-2A on the single permanent magnet.

1.Holding force at 0 Amps:**(-0.32N)**

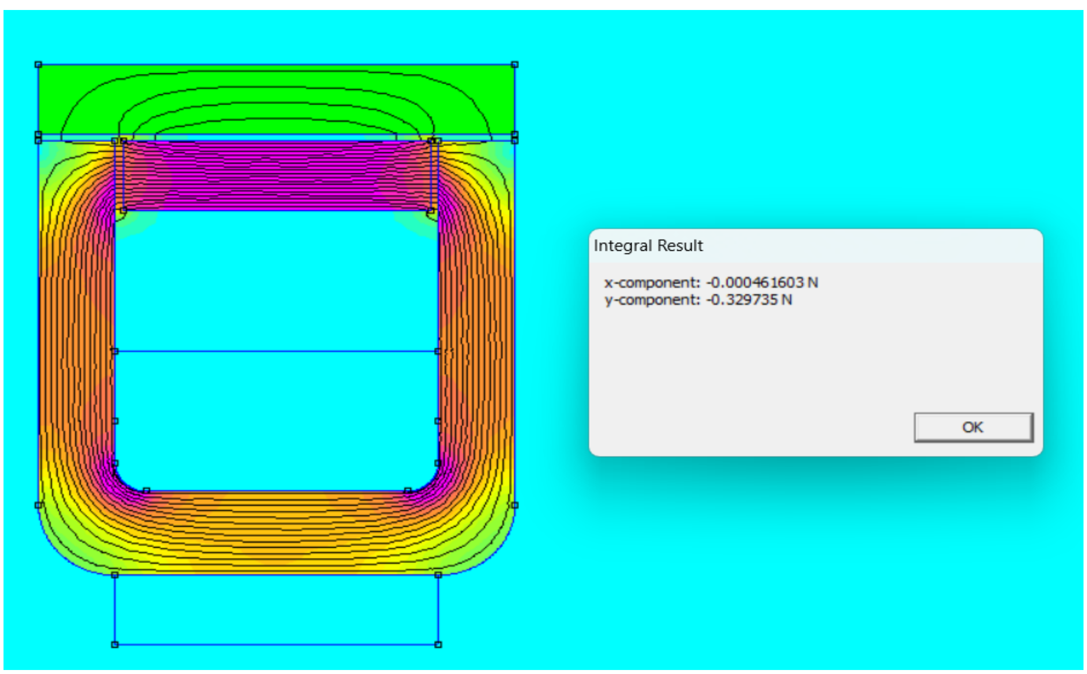


Fig13:Holding force of the electromagnet on the single permanent magnet at 0 Amps

2.At 1 Amps of same polarity:**(-0.065N)**

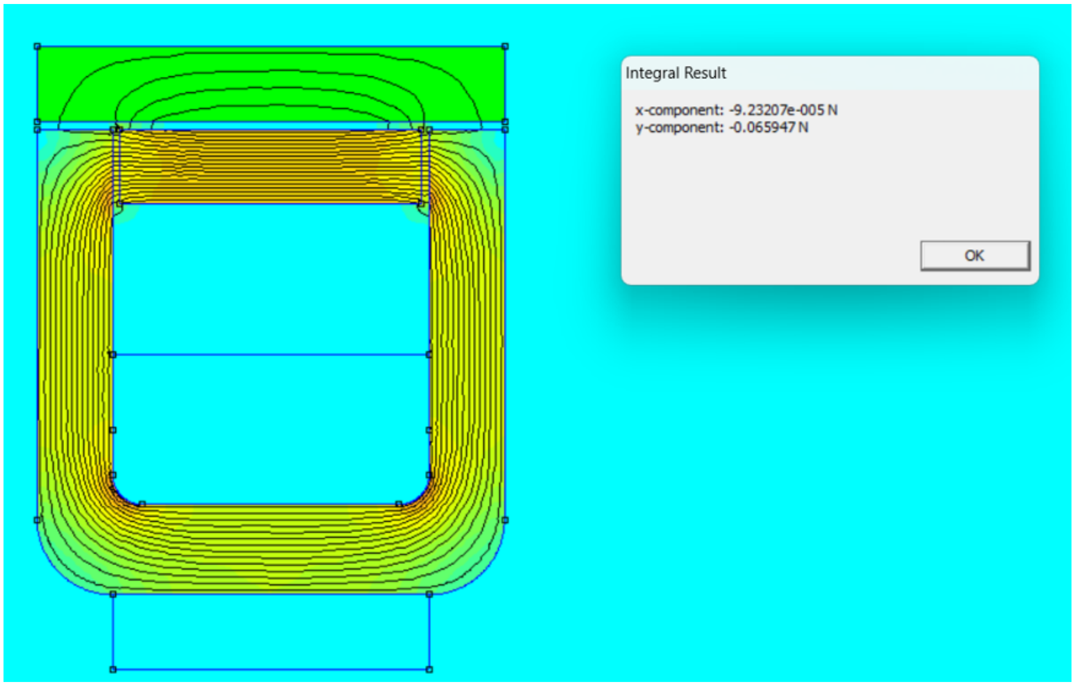


Fig14:Force exerted by the electromagnet on the single permanent magnet at 1 Amps of same polarity

3.At 1 Amps of opposite polarity:**(-15.61N)**

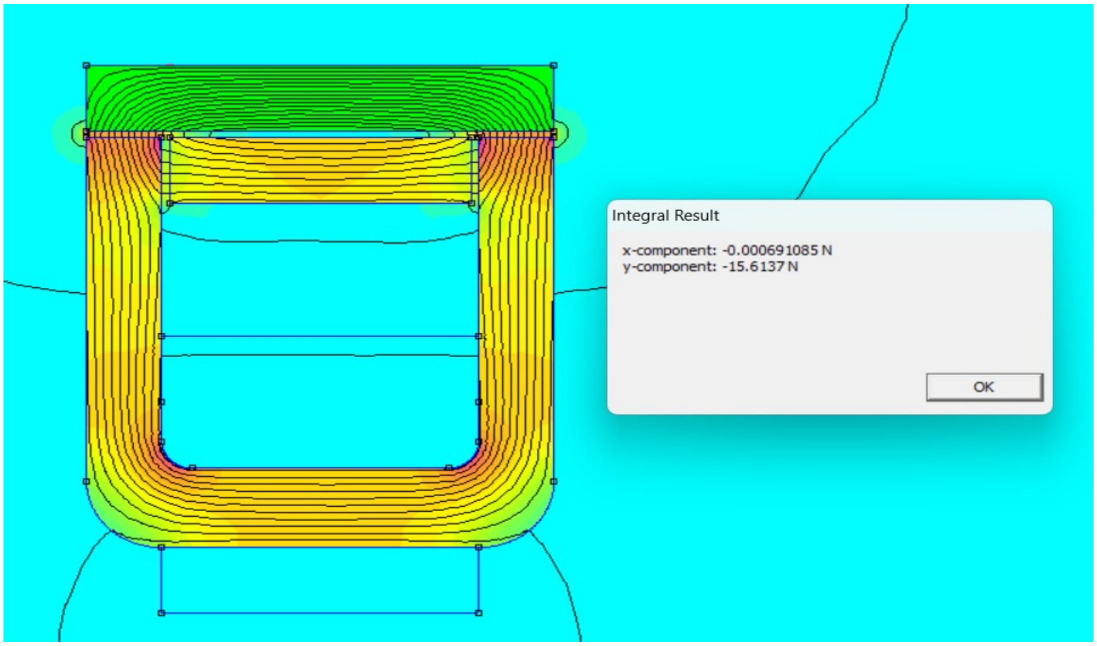


Fig15:Force exerted by the electromagnet on the single permanent magnet at 1 Amps of opposite polarity

4.At 2 Amps of same Polarity:**(-5.95N)**

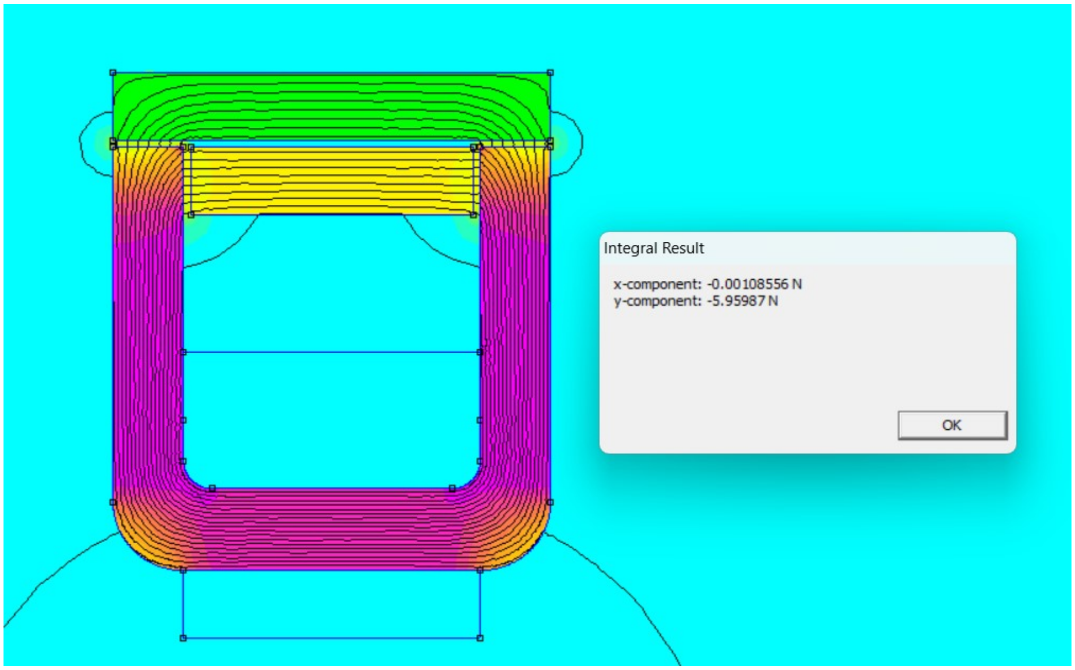


Fig16:Force exerted by the electromagnet on the single permanent magnet at 2 Amps of same polarity

5.At 2 Amps of opposing polarity:**(-9.48N)**

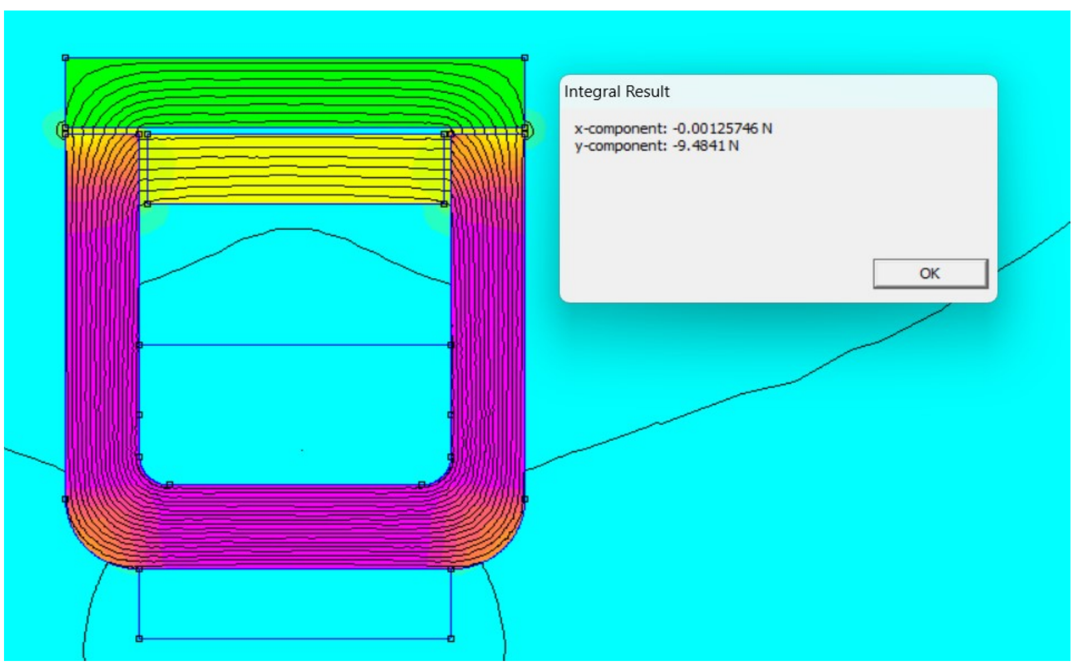


Fig17:Force exerted by the electromagnet on the single permanent magnet at 2 Amps of opposite polarity

6.Magnetic upward force at 0 Amps:**(0.284N)**

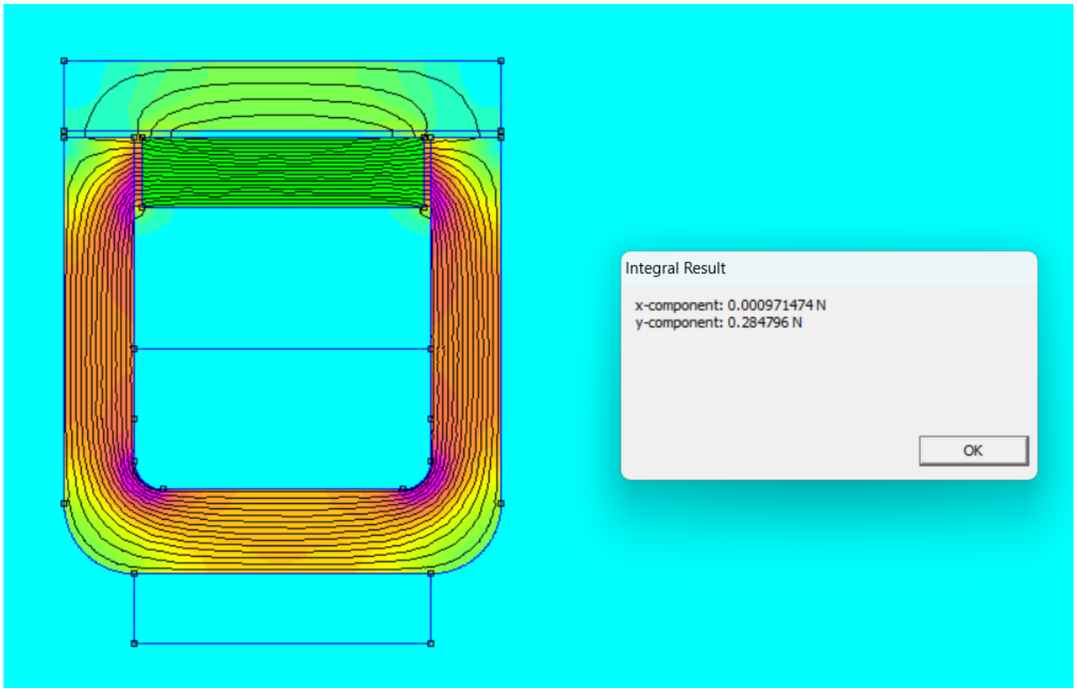


Fig18:Magnetic upward force at 0 Amps

7.Magnetic upward force at 1 Amps:**(1.56N)**

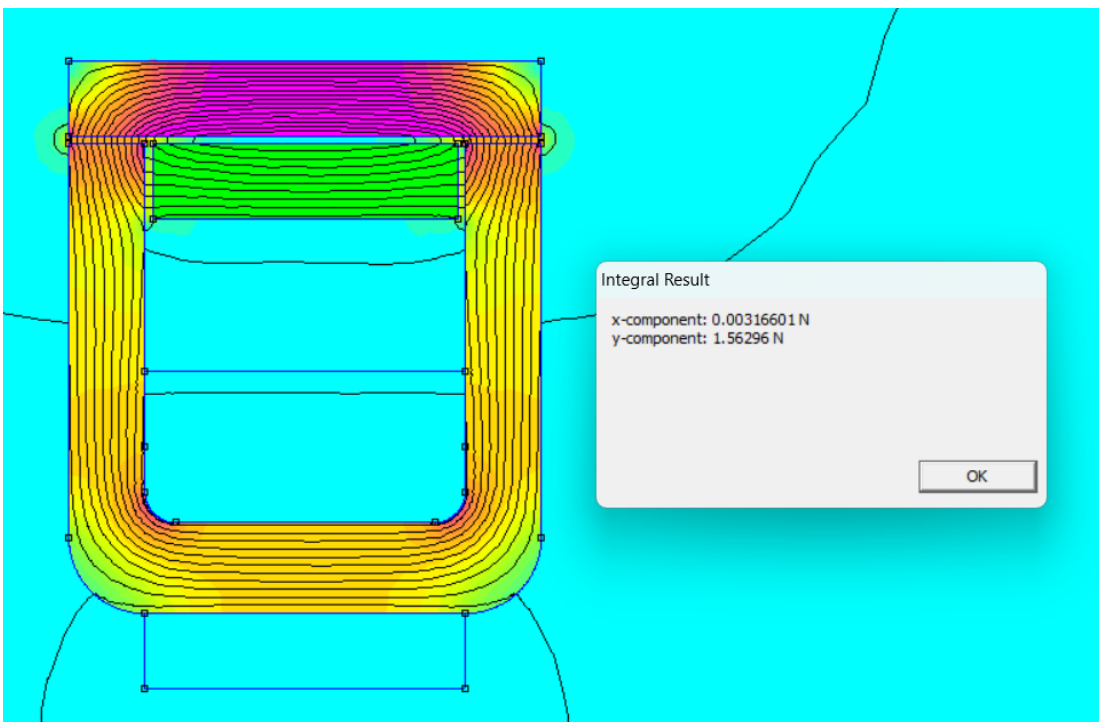


Fig19:Magnetic upward force at 1 Amps

8.Magnetic upward force at 2 Amps:**(2.18N)**

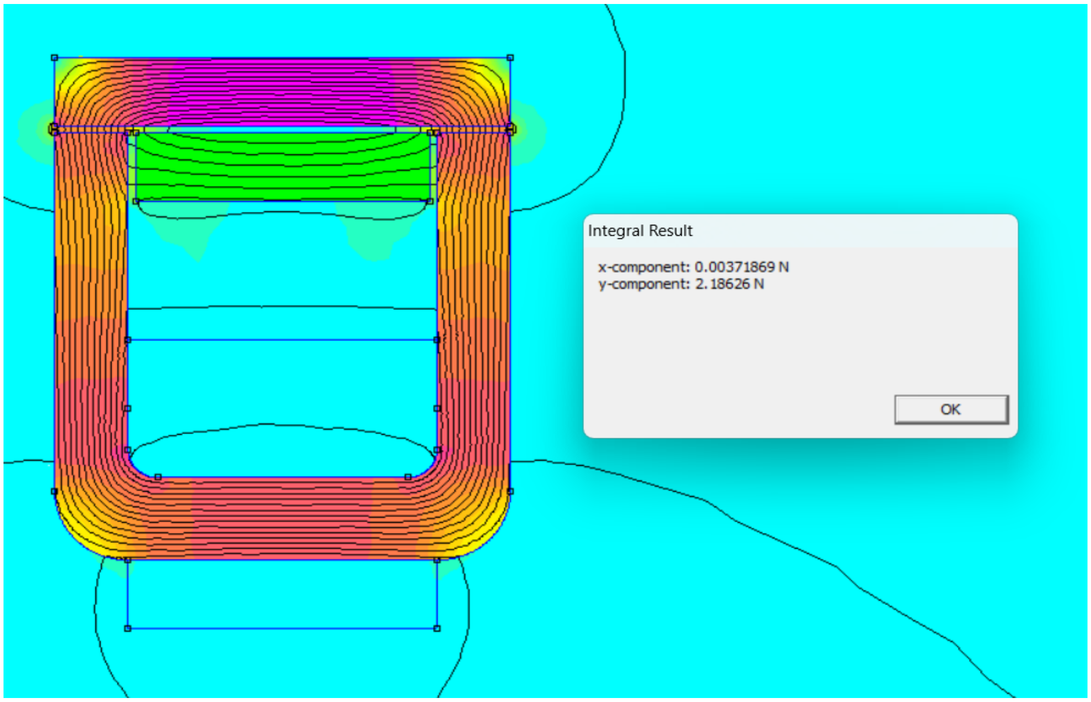


Fig20:Magnetic upward force at 2 Amps

9.Magnetic downward force at 1 Amps:**(-0.61N)**

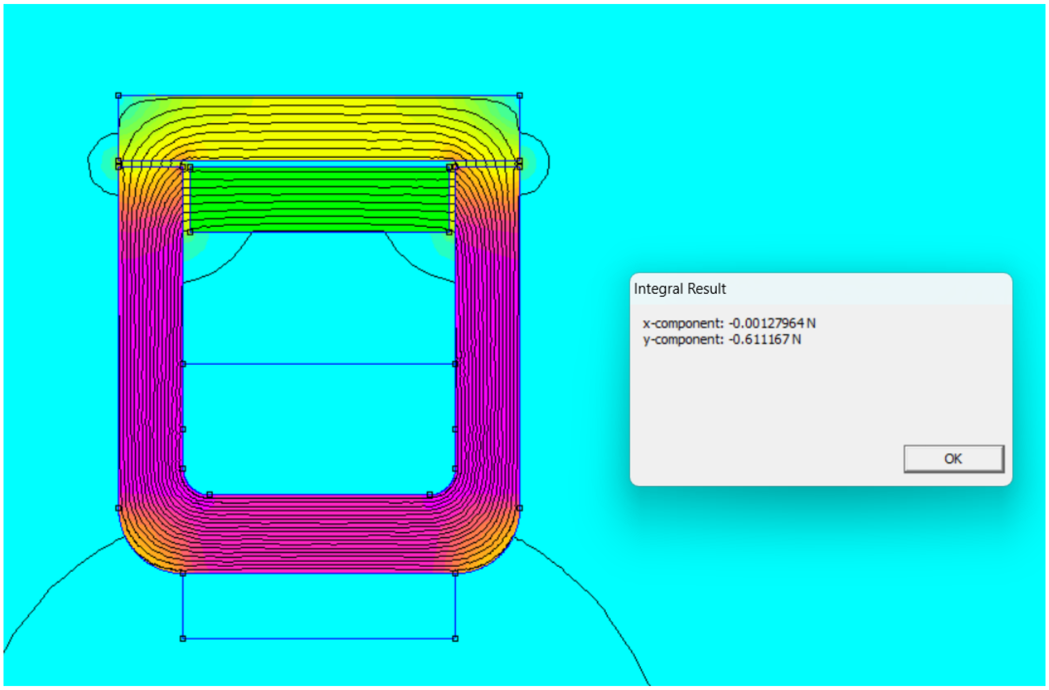


Fig21:Magnetic downward force at 1 Amps

10.Magnetic downward force at 2 Amps:**(-0.85N)**

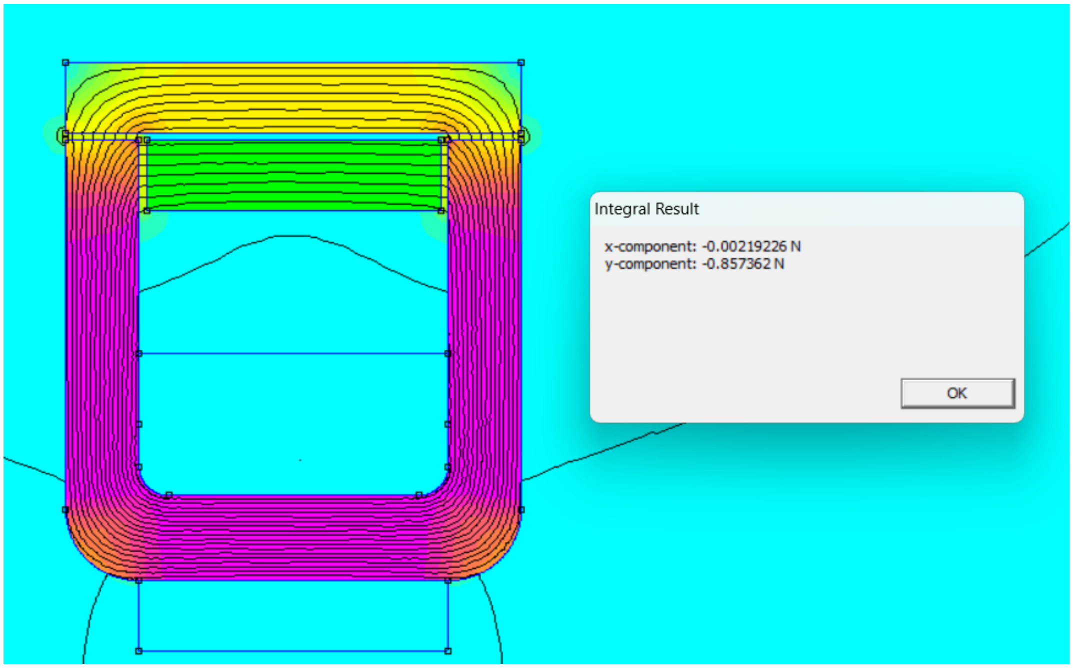


Fig22:Magnetic downward force at 2 Amps

11.Flux when the magnet is down at 0 Amps:**($4.14 * 10^{-6}$T)**

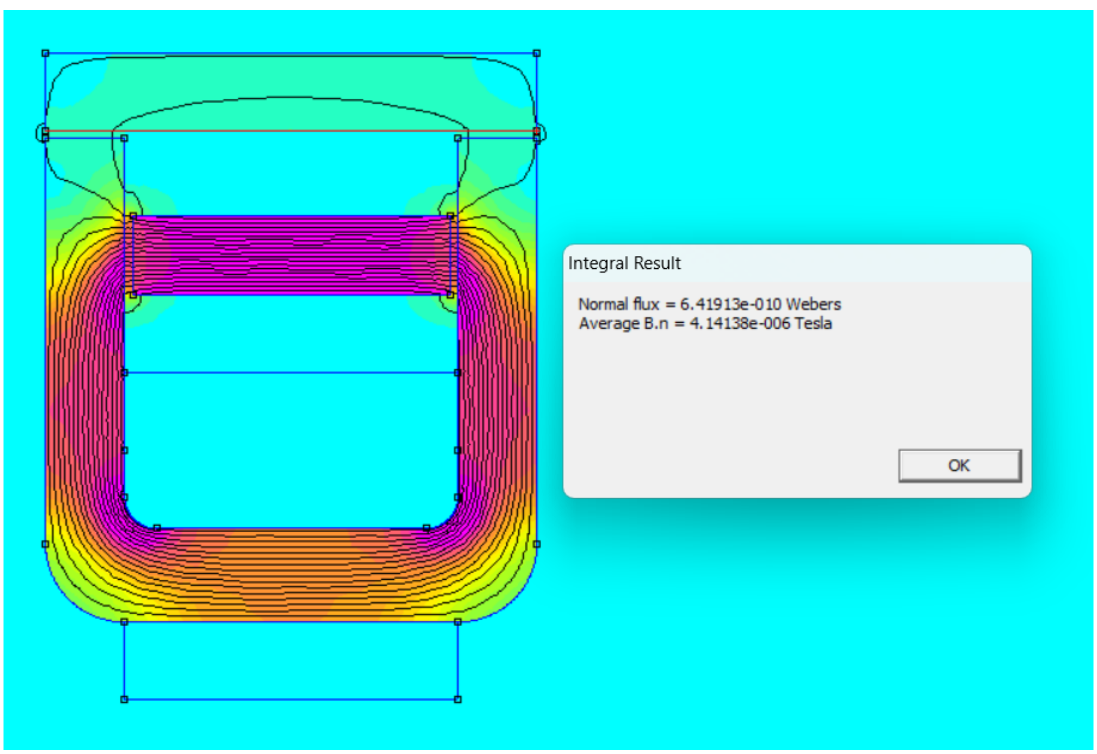


Fig23:The average magnetic flux at 0 Amps

By keeping track of all of these FEMM output analyses and the values of the force displayed by the electromagnet on the single permanent magnet, which is the same force exhibited on all the remaining 7 permanent magnets. Even when the current that is delivered to the electromagnet is 0A, there will still be some sort of repelling magnetic field that keeps the magnet away from the electromagnet. This ensures that the spacer plate does not stick to the electromagnet when the shaft locking process is not in use. Here is a graphical representation of the magnetic field's effect on the magnet when the electromagnet is activated at different current levels, ranging from 0 to 2A. The graph shown below depicts the relationship between the magnetic field and the vertical path of the spacer plate.

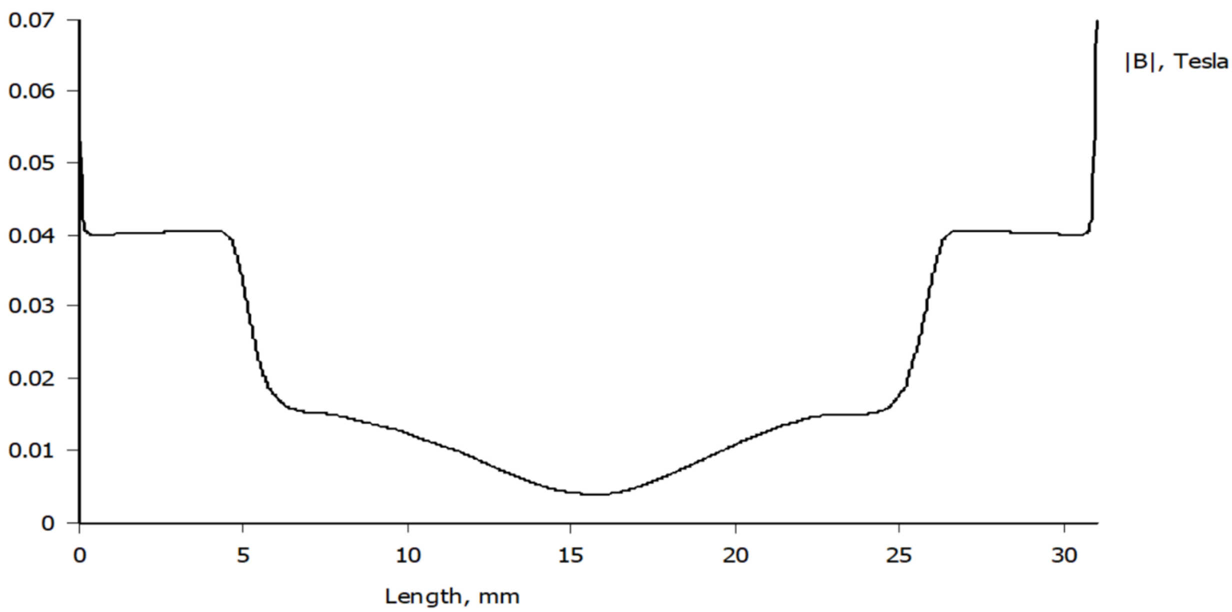


Fig24: Graphical representation of the magnetic field acting upon the single magnet.

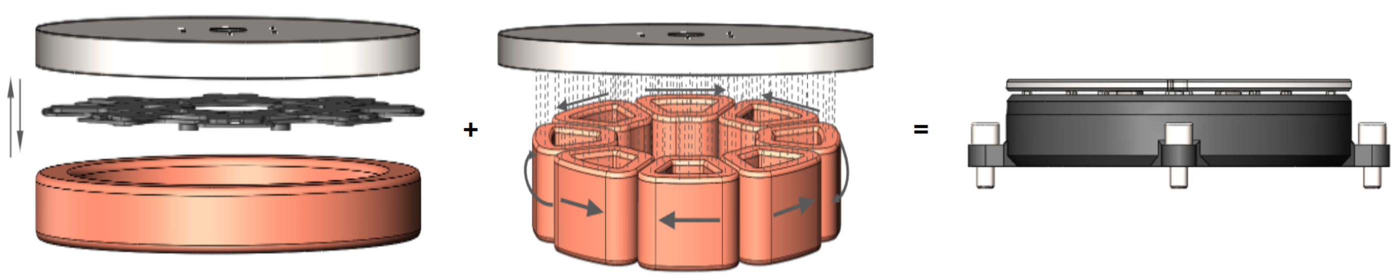
This demonstrates that by adjusting the amount of current that is given to the electromagnetic coil, which ranges from 0 to 2 A, we can easily regulate the movement of the spacer plate consisting of 8 permanent magnets to achieve the shaft locking mechanism.

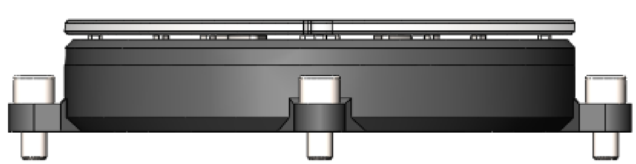
Results and Discussion

Based on the methodology results acquired from the ansys analysis on eddy current braking to control the speed of the turbine and the FEMM analysis of the magnetic locking mechanism for the shaft locking process. In the context of these findings and analyses, the software's application was extended to cover more of the project's objective as a result, a compact braking model was developed that is capable of performing both the braking mechanism needed for vertical axis wind turbines.

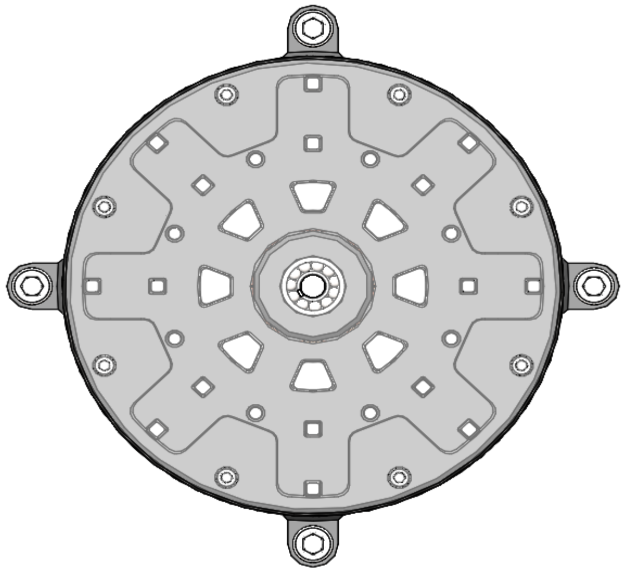
1.Compact Designed 3D Braking Model

A compact 3D braking model has been designed using the solid work software. This model includes both eddy braking and shaft locking mechanisms which fulfill the project objective requirements. This compact model consists of a freely rotating ferromagnetic disc and a stator part is composed of up of an electromagnetic coil in the shape of a circle located at the model's outer circumference and eight electromagnetic coils configured in an octal pattern located at the model's inner circumference. In addition to that, it has a spacer plate that is equipped with a permanent magnet. The compact model is shown in the figure below.

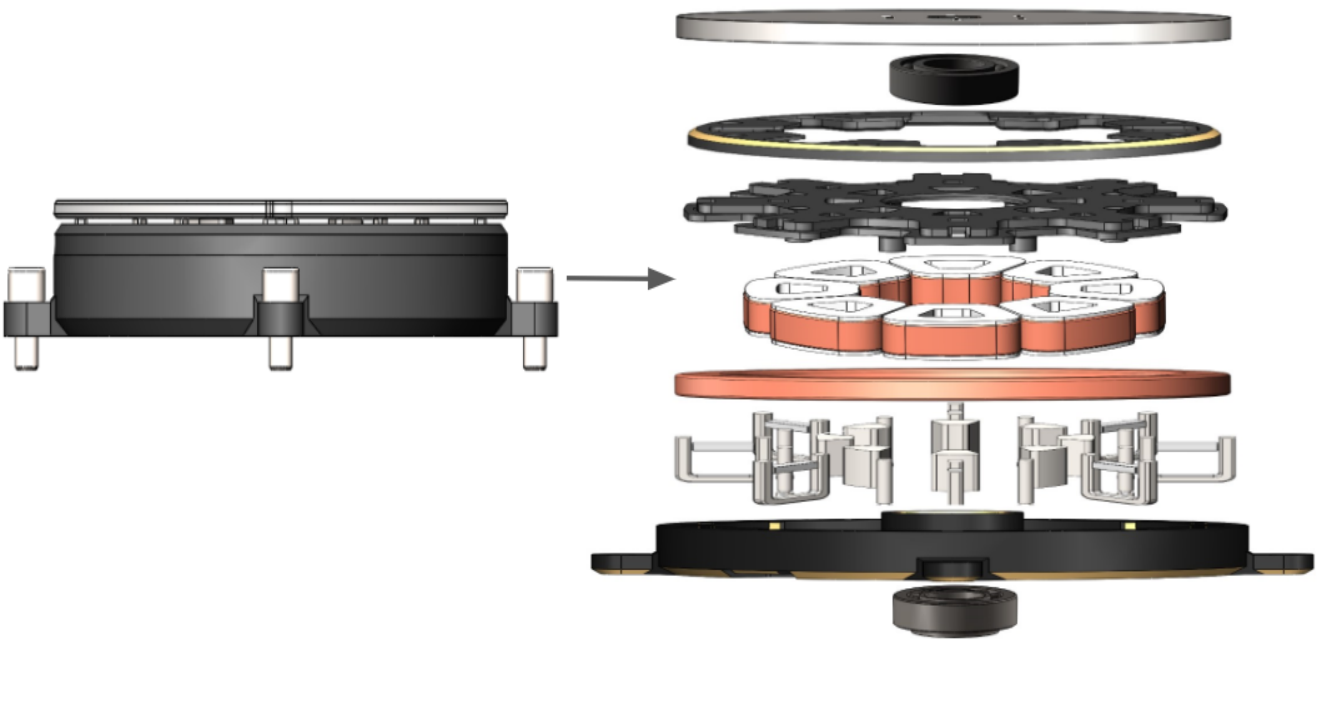




a.Side view



b.Top view



c.Inside view

Fig25:Compact Eddy current braking model

2.In detail description of the braking model

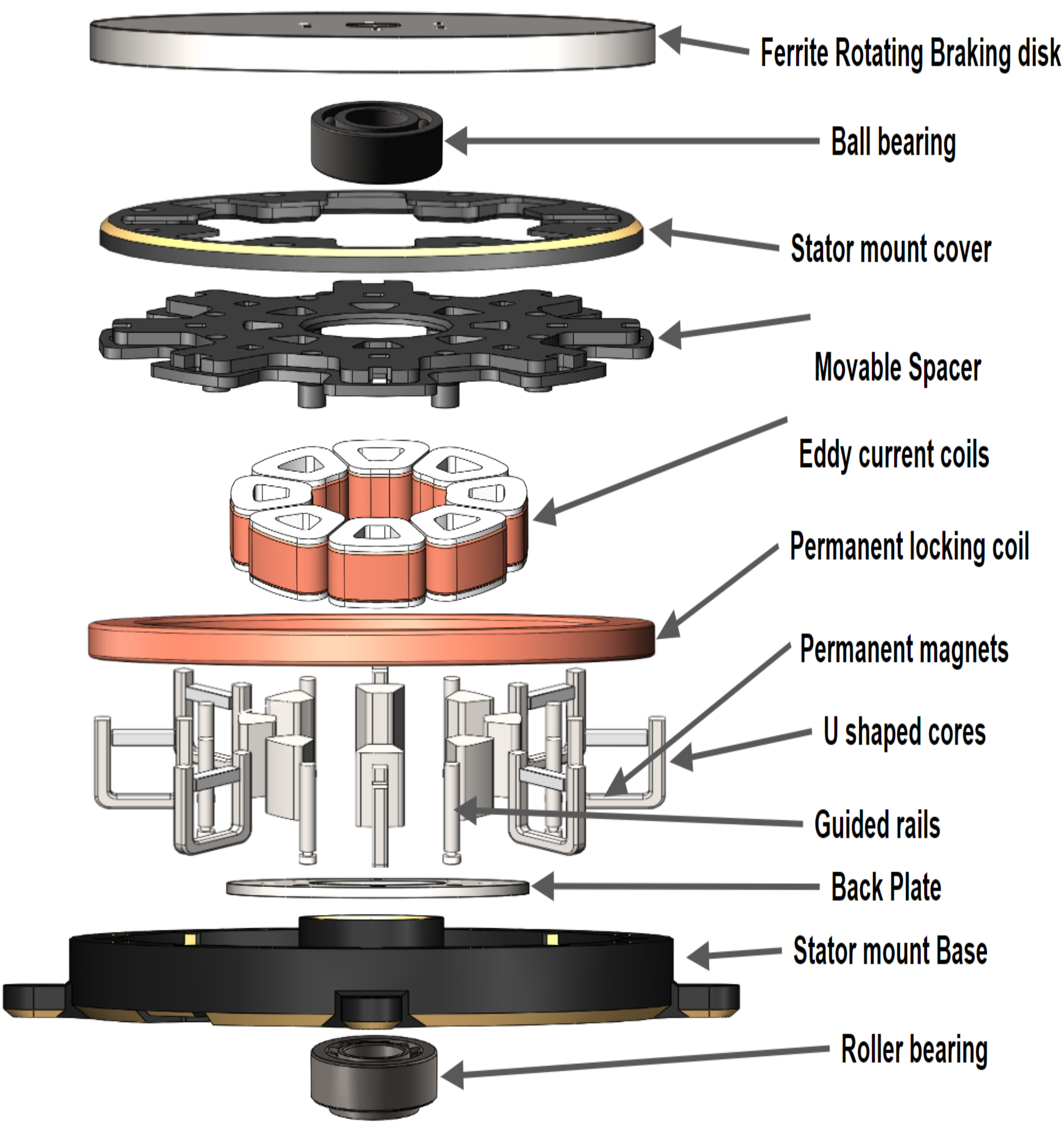
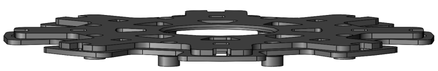
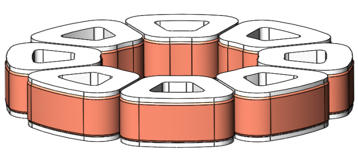
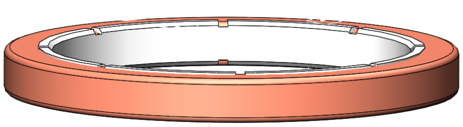
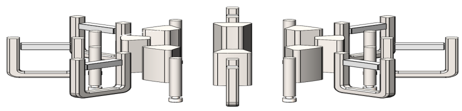
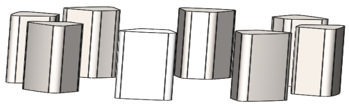
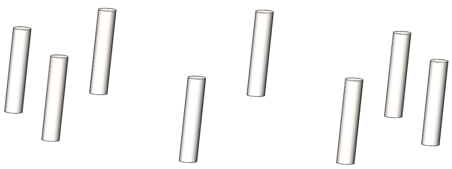
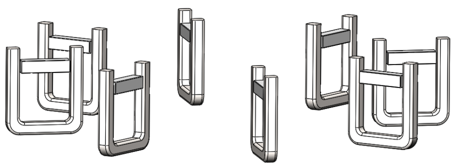
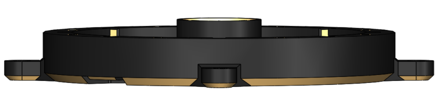


Fig26:Components of the braking model

Table4:Breaking Model Components and their functions

Components	Name	Type of material	Function
Rotor Part			
	Rotating Brake Disk	Ferrite	It is a freely rotating braking disk which will be connected to the shaft.
Stator Parts			
	Stator Mount Cover	Plastic	It protects the stator component and keeps the spacer plate in place.
	Spacer Plate	Plastic	When the locking mechanism for the shaft is engaged, it moves up and down to lock the rotating disc with the help of 8 permanent magnets.
	Eddy current coils	Plastic, Copper	It is an octal arrangement of the eddy current coils in which the copper coils are winded around the plastic bobbin. These coils are utilized as eddy current brakes to control the speed of the turbine.
	Shaft locking coil/permanent locking coil	Plastic, Copper	It is a single circular coil in which the copper coils are winded around the circular plastic bobbin. This coil is used as an electromagnetic coil for the shaft locking mechanism.

	Octal(8) Arrangement		
	Eddy poles,	Ferrite	These poles are fixed to the mount base upon which eddy current coils are placed.
	Guided rails	Steel	These rails help keep the spacer plate in place as the shaft locking mechanism raises and lowers it.
	U-shaped metal core with permanent magnet	Ferrite	This U-shaped metal core is mounted on the stator mount base, which also serves to ensure that the spacer plate with permanent magnets is in the correct position. Additionally, the shaft locking coil is mounted on this base.
	Back plate	Steel	The eddy poles are secured to the base by means of this back plate, which also contributes to the process of controlling the speed of the turbine and ensuring that the correct eddy current loop is maintained.
	Stator Mount base	Plastic	This serves as the primary foundation of the braking model, upon which the various components of the stator are positioned.

	Ball bearing	Steel	This helps in maintaining the stability of the shaft.It is placed above the mount base.
	Roller bearing	Steel	This helps in maintaining the steadiness and the stability of the shaft.It is placed below the mount base.

3.Inside Mechanism of the Stator

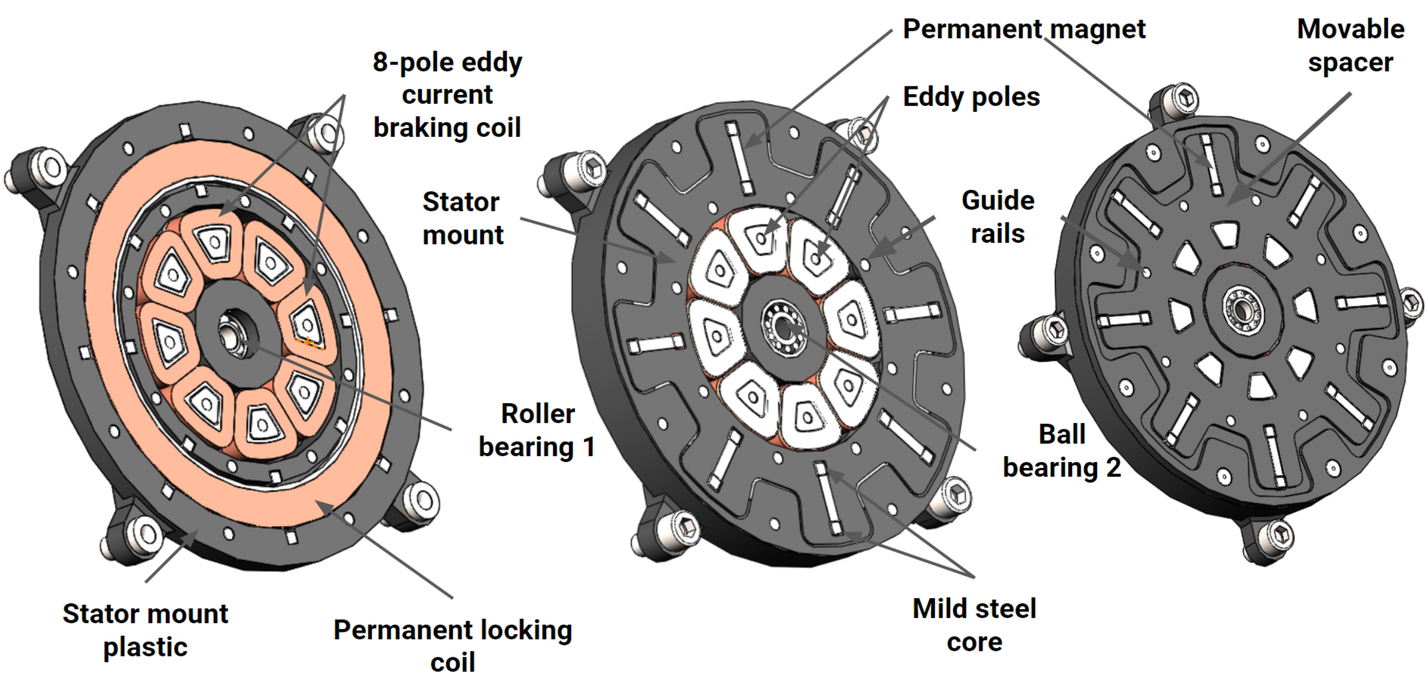
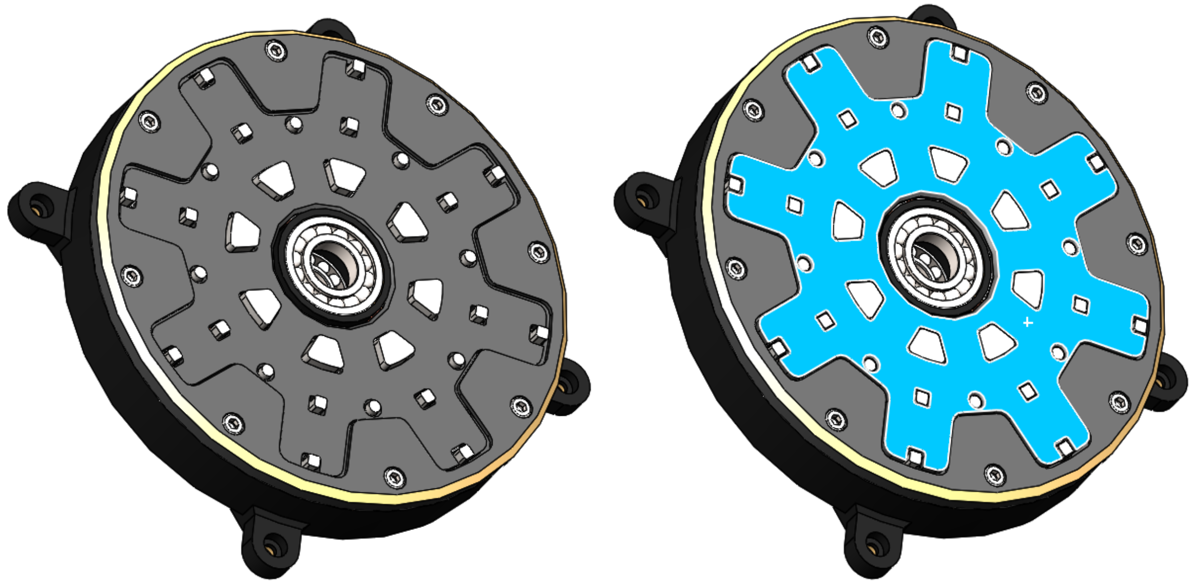


Fig27: Inside mechanism of the stator

The eddy current braking and shaft locking mechanism can both be achieved with this compact brake model. When the 8 eddy current coils are activated, they begin to exert a magnetic force on the rotating brake disc through eddy poles, just like an electromagnet. As shown in the figure 26 a braking disk will be placed upon the stator part with the help of the shaft. The eddy currents produced by the braking disk's altering magnetic field bring the spinning disc to a halt position. The larger outer coil, often referred to as a shaft locking coil, performs the role of an electromagnet. In addition, the U-shaped metal core and the guided rails are used to accurately position the spacer plate, which features permanent magnets at each of the plate's eight corners.



a.Unlocking position b.Locking position

Fig28:Shaft locking process in an compact brake model

When the electromagnet is activated, a magnetic force is applied to the permanent magnet, causing the spacer plate to move upward and downward as the braking disc is locked and unlocked during the shaft locking process as shown in the figure above.

4.Control unit

The activation of the electromagnets for both the eddy current braking process and the shaft locking process is the primary topic of discussion at this phase. Circuitry path plays a significant function in ensuring that these electromagnets are activated in accordance with our requirements in order for us to accomplish the goal of our project. The figure below shows the schematic representation of the circuit diagram.

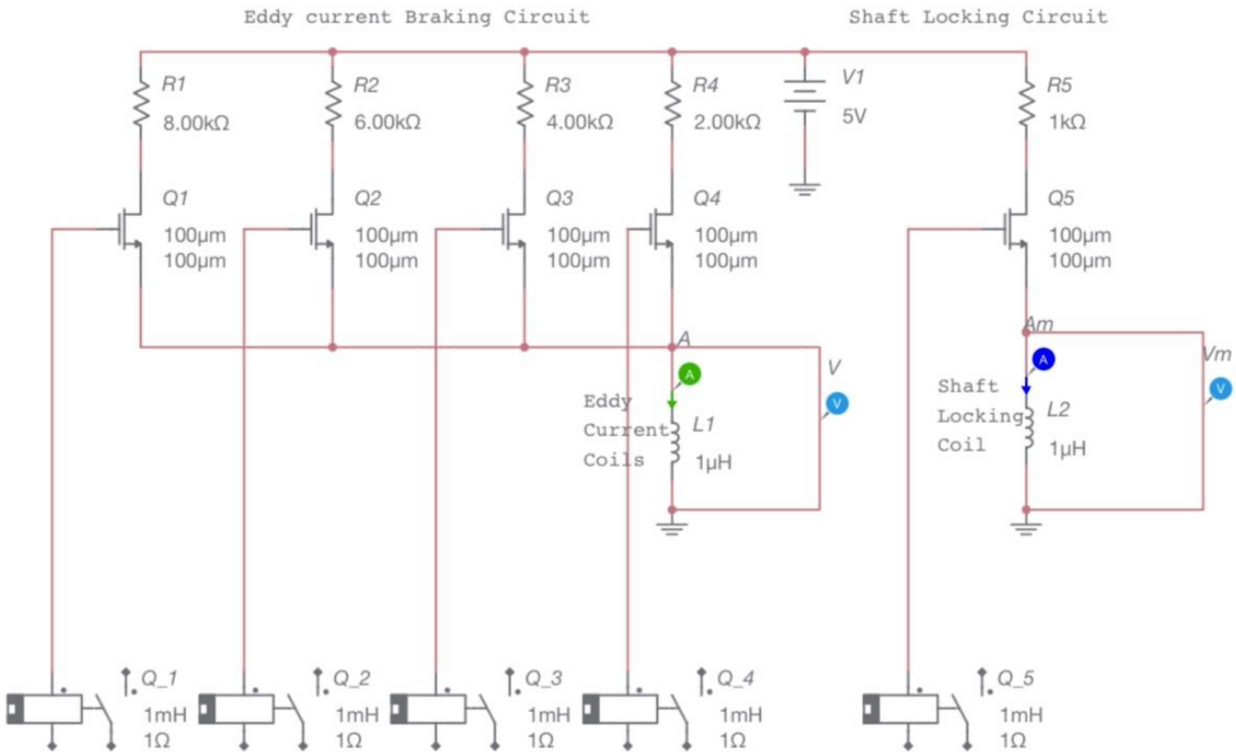


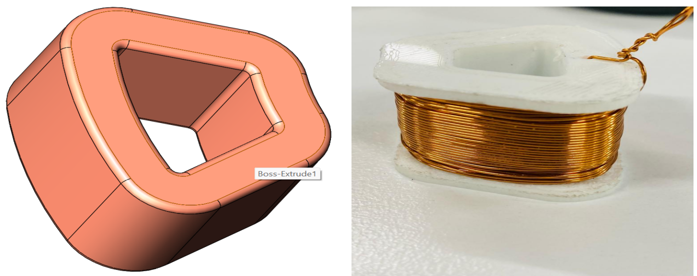
Fig29:Schematic representation of the circuit diagram

From the above circuit diagram we can see that the circuitry path is divided into two parts one for activating the eddy current brake and another for the shaft locking process. In the above figure L1 and L2 represent the electromagnets which are controlled with the DC voltage of 5V. Q1, Q2, Q3, Q4, Q5 are the MOSFETS connected to the relays Q_1, Q_2, Q_3, Q_4, Q_5. These relays are controlled through the arduino nano.

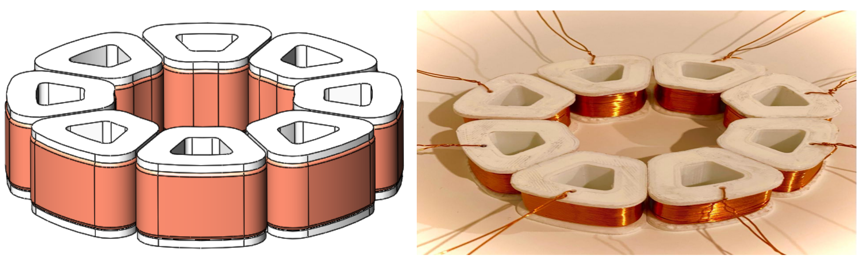
In order to control the speed of the turbine these relays are utilized.The level of braking is controlled through each MOSFETS which is connected to the 5V battery source through the resistance R1, R2, R3, R4. Sending an electrical pulse via the Arduino nano allows you to control the level of braking power required by simply operating the relays. This may be done based on the information regarding the wind speed. For example, in order to achieve a lower braking performance, we use a path that has a high resistance value. On the other hand, in order to achieve a higher braking performance, we use a path that has a lower resistance value. Both of these paths are used to activate the electromagnets. Similarly, for the shaft locking process we send an electrical pulse to the relay Q_5 which directly activates the electromagnets for stopping the wind turbine completely.

5.Manufacturing and Building the Braking Model

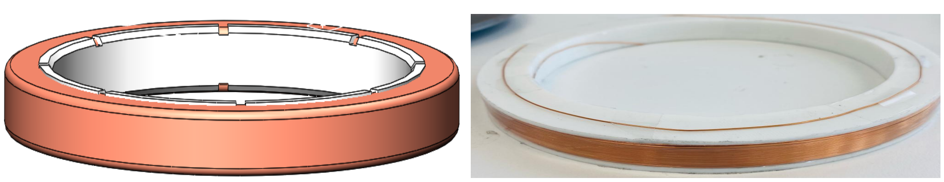
A braking model components which consist of plastic are manufactured through the 3D printing process and the parts which are supposed to be ferrite and steel were ordered with the help of Flinders Engineering Service.



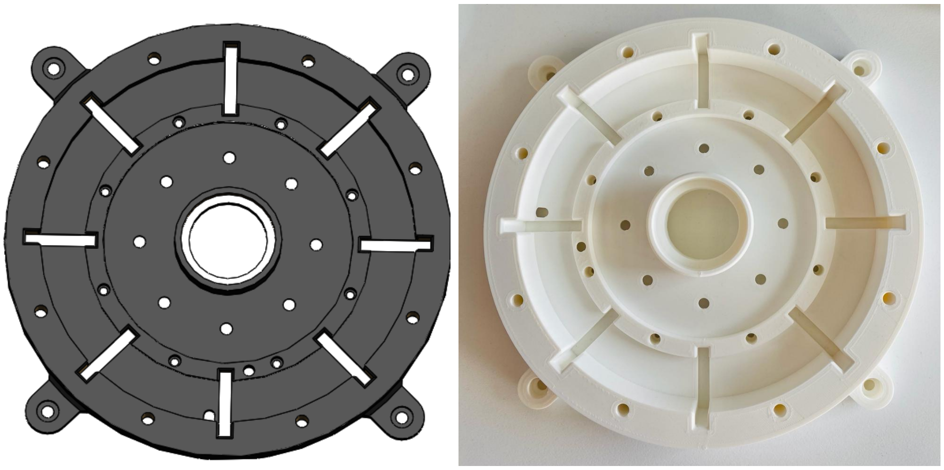
a.Eddy current braking single coil



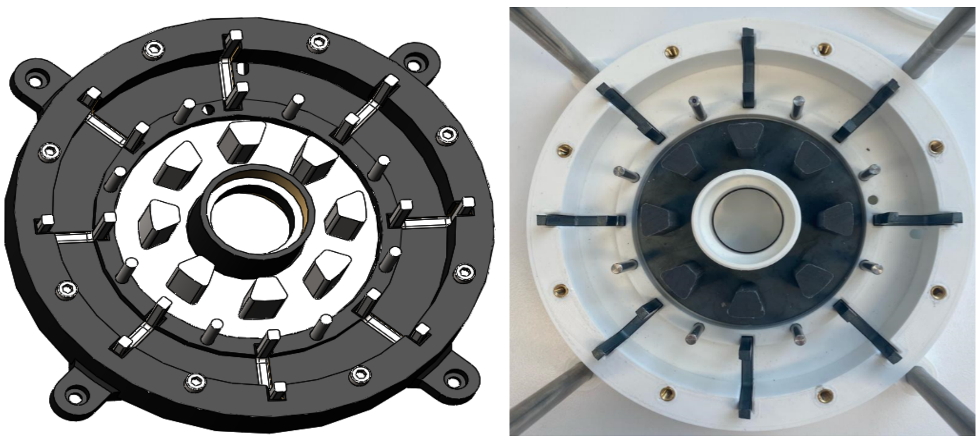
b.Eddy current coils



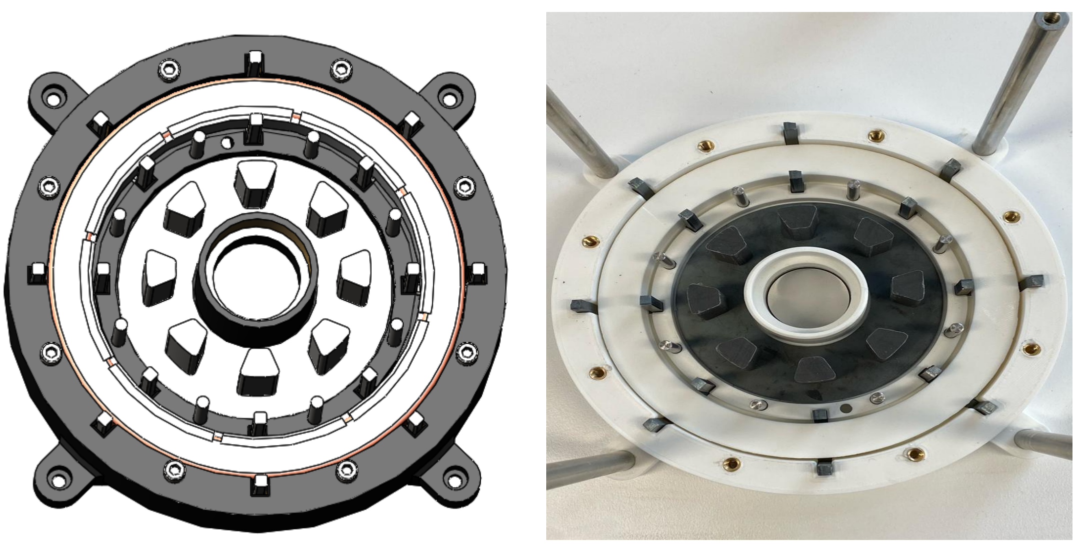
c.Shaft locking coil



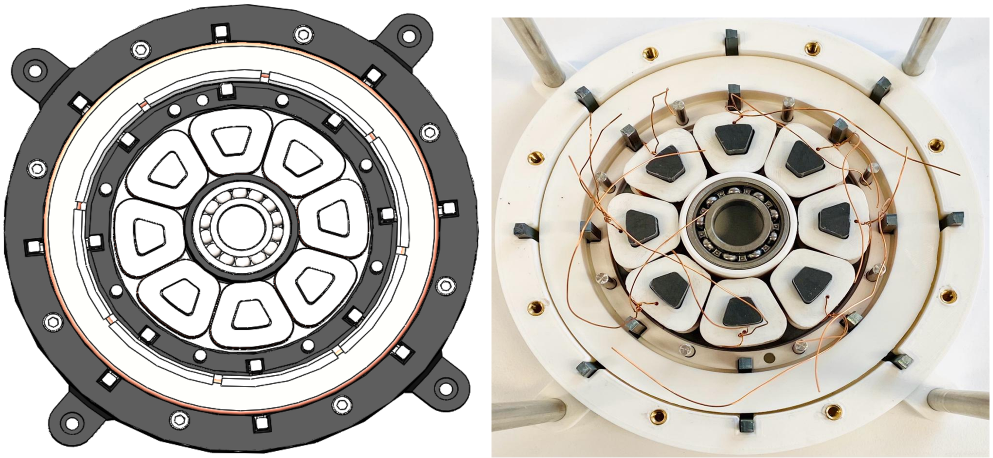
c:3D printed Stator mount base



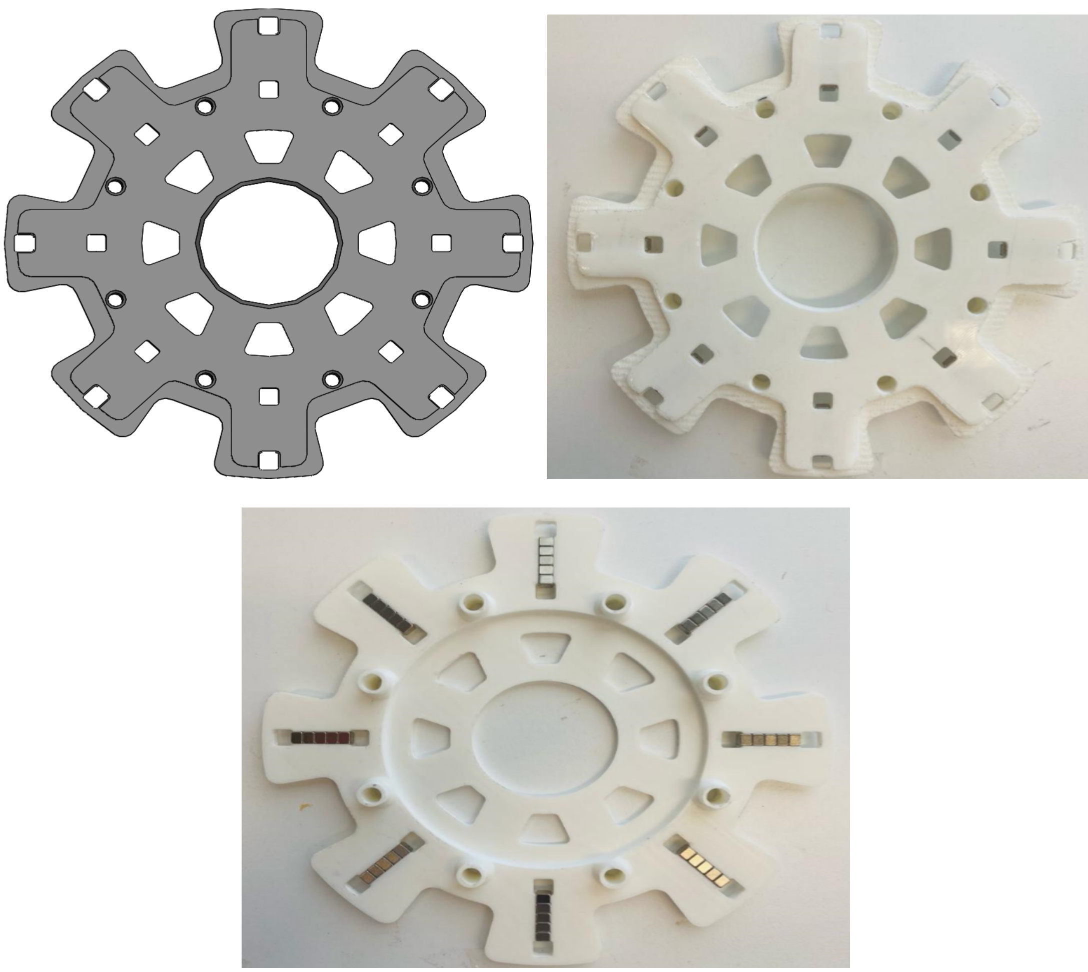
d.Mount base fitted with back plate, eddy poles, guided rails and U-shaped metal core



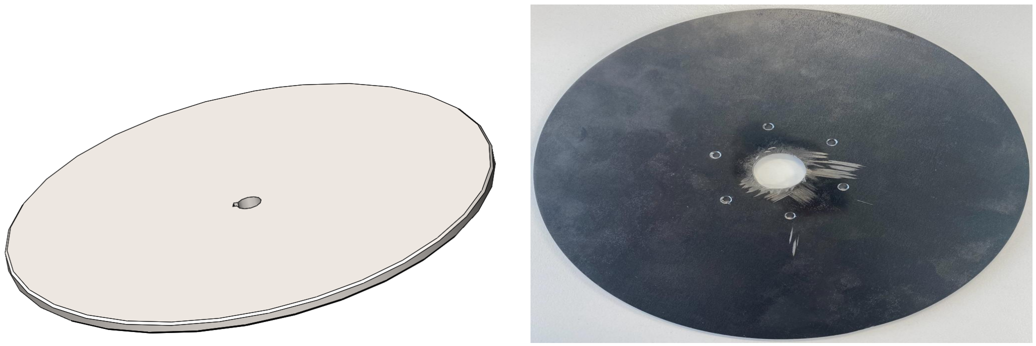
e.Mounted with shaft locking coil



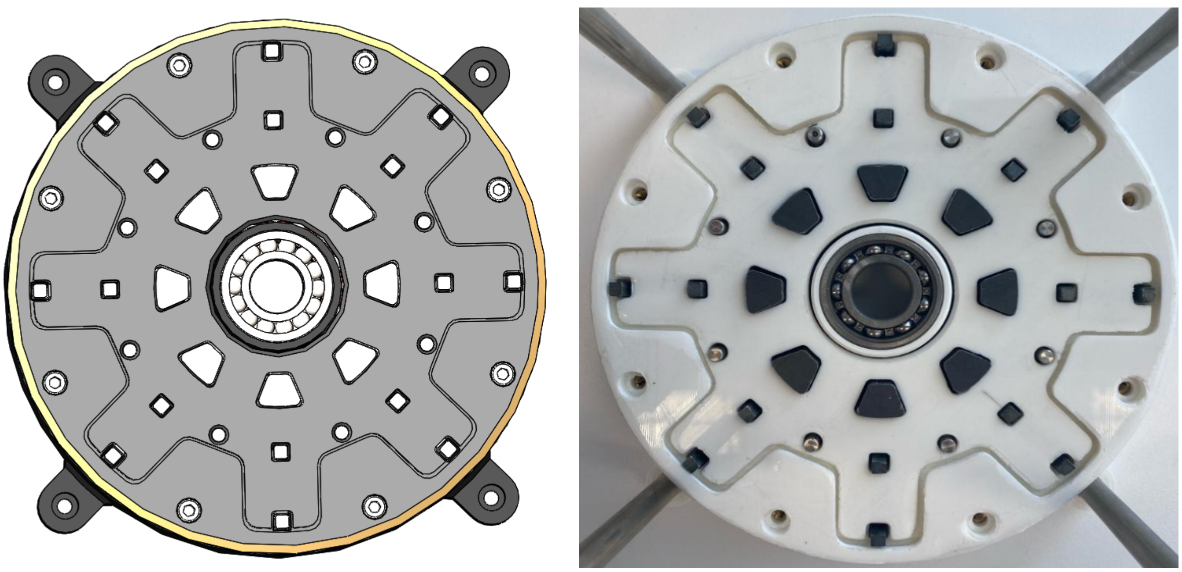
f:Mounted with eddy current coils



g.Spacer plate with magnets in position



h.Brake disk



g.Complete assembly of braking model

Fig30:Manufacturing and assembling the compact braking model

6.Testing

This braking model is designed to be compact in size and has the capability to perform both eddy current braking and shaft locking. With this model, there is no need for an external emergency brake. Therefore, this model successfully meets our fifth objective of implementing a fail-safe braking system in VAWTs. The braking performance of this model was evaluated by connecting the braking disc to the DC motor via the shaft. This braking model is associated with the generator model, as indicated in the image below. The complete generator model with braking model is currently in the build and assembly phase, and unfortunately, we have encountered some manufacturing limitations that have caused delays. Due to these constraints, there has been a sense of urgency in completing the final stages of the project as the submission date approaches. Therefore, the efficiency tests for this complete model is still pending.

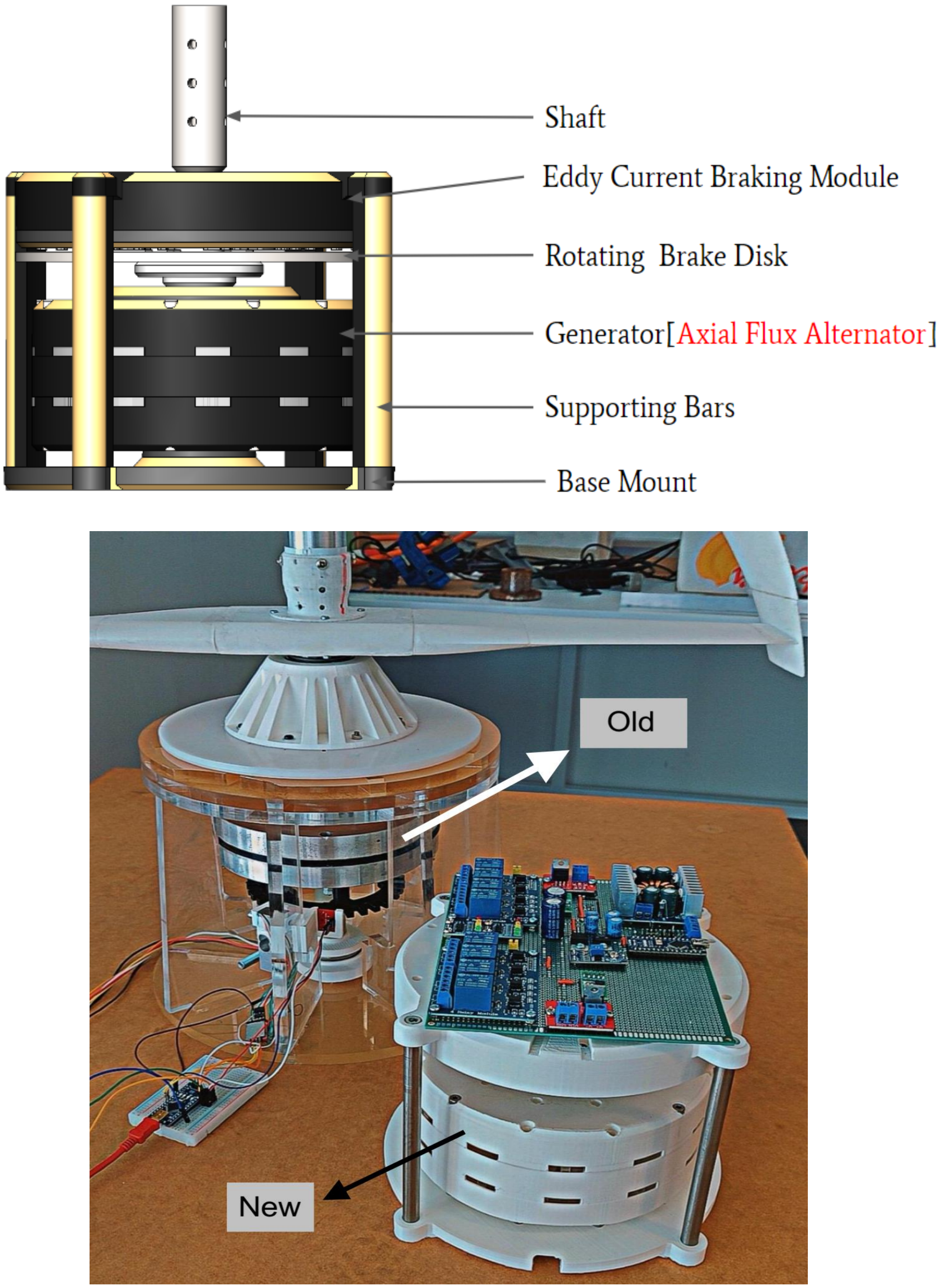


Fig31:Braking model connected to generator through the single shaft

Limitations and Suggestion on Future Work

Limitations	Suggestion on future Work
Heat Generation	The heat generated by the eddy coils on the braking disc in eddy current braking was excessively high. Designing the appropriate pathway for air flow can be highly beneficial.
Winding Automation	Winding the stator components by hand requires a high level of expertise and a lot of time and effort because they include the eddy current coil and the electromagnetic coil. The potential for automation in this process could increase industrial efficiency. This sort of mechanism could shorten manufacturing cycles and cut down on the amount of time needed for winding.
Energy Storage	A considerable amount of energy is lost whenever eddy current coils are activated. Therefore research to develop efficient methods of storing and manipulating the energy produced by eddy current systems for use in a wide range of applications will be much useful.
Brake plate engraving	Our brake disc has a consistent surface to reduce production costs. As per my observation, engraving the brake plate to match the spacer plate pattern improves the effectiveness in the shaft locking process.

Conclusion

The primary aim of my project is towards the development of a braking system for a VAWT X-6/5 using an electrical approach and the creation of a compact braking model that combines eddy current braking and shaft locking processes have successfully allowed me to accomplish my research goals and create a reliable braking system. The electrical method of constructing an eddy current brake for a VAWT offers numerous benefits compared to conventional mechanical methods. First, it is highly efficient, as it operates without the need for any moving components. Second, it is more reliable, as it is less susceptible to wear and tear. Additionally, its compact design is crucial for VAWTs with limited space. The compact braking model I have designed incorporates the benefits of eddy current braking and shaft locking to produce a fail-safe braking system. The eddy current braking mechanism offers quick and efficient braking, while the shaft locking mechanism ensures secure locking to prevent any unwanted rotation of the rotor.

Overall, with the outcomes of my research project. I have designed an advanced eddy current braking system for VAWTs that offers enhanced efficiency, reliability, compactness, and fail-safe features compared to current braking systems. I am confident that this innovative braking system has the ability to make substantial advancements in the wind energy sector.

Bibliography

Mechanical Braking Systems for Wind Turbines: A Literature Review by E.A. Sirotkin, A.S. Martyanov, E.V. Solomin, and S.V. Kozlov (2018).

Design and Analysis of a Mechanical Brake System for a Vertical Axis Wind Turbine by E.A. Sirotkin, E.V. Solomin, and S.V. Gandzha (2017).

The Design and Analysis of Automotive Hydraulic Brake Systems by Rudolf Limpert (1992)

Analysis and design of hydraulic brake systems by T.J. Viersma (1980).

High Efficiency Braking Mechanism for Electric Vehicles by Y. He, Z. Zhang, X. Zhang, G. Lu, and X. Wang (2022)

Design and Analysis of a High Efficiency Eddy Current Brake for Wind Turbines by E.A. Sirotkin, E.V. Solomin, and S.V. Gandzha (2017)

High Efficiency Mechanical Brake System for Vertical Axis Wind Turbines by K.M. Parammasivam, S. Balaji, and M.A. Muzaffar (2020)

Eddy current braking experiment using brake disc from aluminum series of A16061 and A17075 M Z Baharom, M Z Nuawi, G Priyandoko and S M Harris.

On eddy currents in a rotating disk, in Electrical Engineering, vol. 61, no. 9, pp. 681-684, September 1942 by W. R. Smythe.

Modeling and control of eddy current brake, in IFAC Proceedings Volumes, vol. 28, no. 8, pp. 109-114, July 1995 by E. Simeu and D. Georges.

Optimal robust control of a contactless brake system using an eddy current, in Mechatronics 9, pp. 615-631, 1999 by K. Lee and K. Park.

Parameter Analysis on Torque Stabilization for the Eddy Current Brake: A Developed Model, Simulation, and Sensitive Analysis, in Mathematical Problems in Engineering, 2015 by Q. Zhou, X. Guo, G. Tan, X. Shen, Y. Ye and Z. Wang.

Design Study in Single Disk Axial Eddy Current Brake. 2018 5th International Conference on Electric Vehicular Technology (ICEVT).

A comparative study of different braking systems for vertical axis wind turbines by V. Murugan et al. (2018).

Optimizing eddy current braking system for vertical axis wind turbine by S. Arunachalam et al. (2019).

Optimization of eddy current braking for vertical axis wind turbines using response surface methodology by K. Anbalagan et al. (2020).

Magnetic locking for vertical axis wind turbines An overview by S. Kalaiselvan et al. (2020).

Development of a magnetic locking system for a vertical axis wind turbine by N. L. Othman et al. (2020).

Magnetic bearing design for vertical axis wind turbines by S. B. Sharma et al. (2021)

Seok-Myeong Jang, Sang-Sub Jeong, and Sang-DoCha. The Application of Linear Halbach Array to Eddy Current Rail Brake System[J]. IEEE Trans. Magn., vol. 37, no. 4, pp. 2627–2629, 2001.

Sharkh S M, Qazalbash A A, Irenji N T, et al. Effect of Slot Configuration and Airgap and Magnet Thicknesses on Rotor Electromagnetic Loss in Surface PM Synchronous Machines [C]. IEEE International Conference on Electrical Machines and Systems

Seok-MyeongJ ang, and Sung-Ho Lee. Comparison of Three Types of Permanent Magnet Linear Eddy-Current Brakes According to Magnetization Pattern[J]. IEEE Trans. Magn., vol. 39, no. 5, pp. 3004–3006, 2003.

G. Aiello, S. Alfonzetti, E. Dilettoso, and N. Salerno. Transient Thermal Analysis of an Eddy-Current Heated Conductor Applying FEM-DBCI[J]. IEEE Trans. Magn., vol. 49, no. 5, pp. 1861–1864, 2013.

R. Yazdanpanah and M. Mirsalim, “Axial-flux wound-excitation eddy current brakes: Analytical study and parametric modeling,” IEEE Trans. Magn., vol. 50, no. 6, pp. 1–10, Jun. 2014.

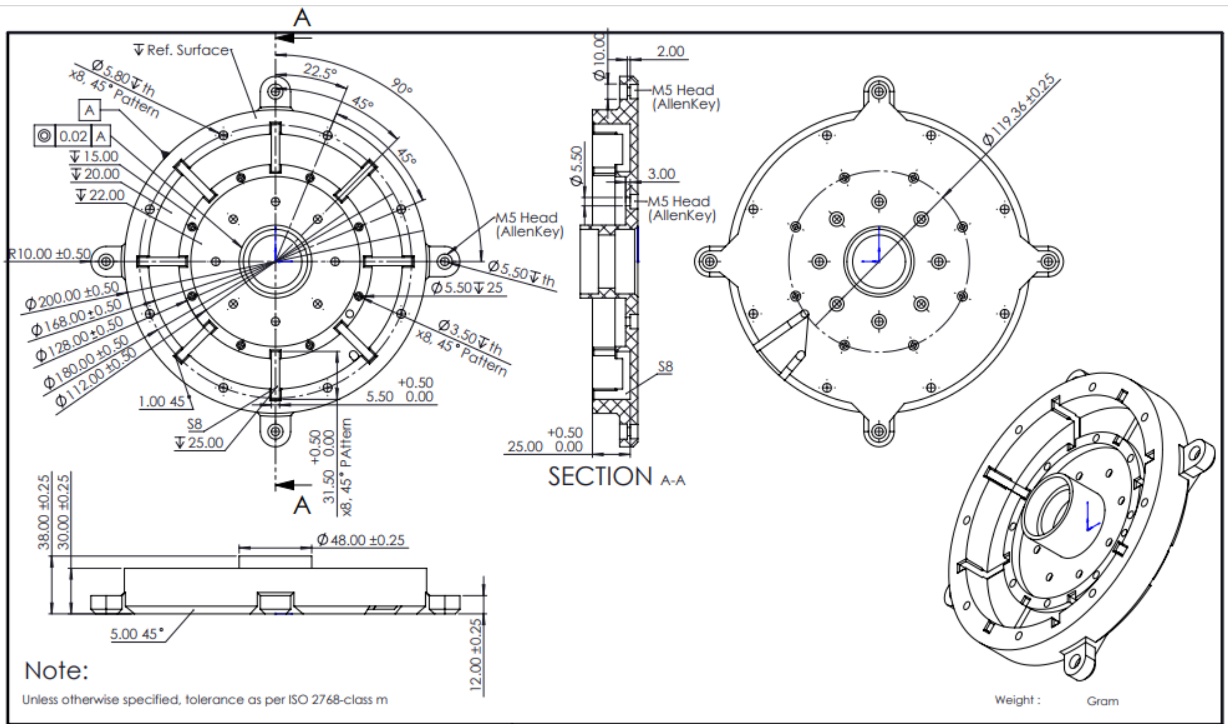
A. Zamani, "Design of a controller for rail eddy current brake system," IET Electrical Systems in Transportation, vol. 4, pp. 38-44, 2013.

S. Cho, H.C. Liu, J. Lee, C. M. Lee, S. C. Go, S. H. Ham, J. H. Woo, and H. W. Lee., "Design and Analysis of the Eddy Current Brake with the Winding Change." J. Magn., vol. 22, no. 1, pp. 22-28, Mar. 2017.

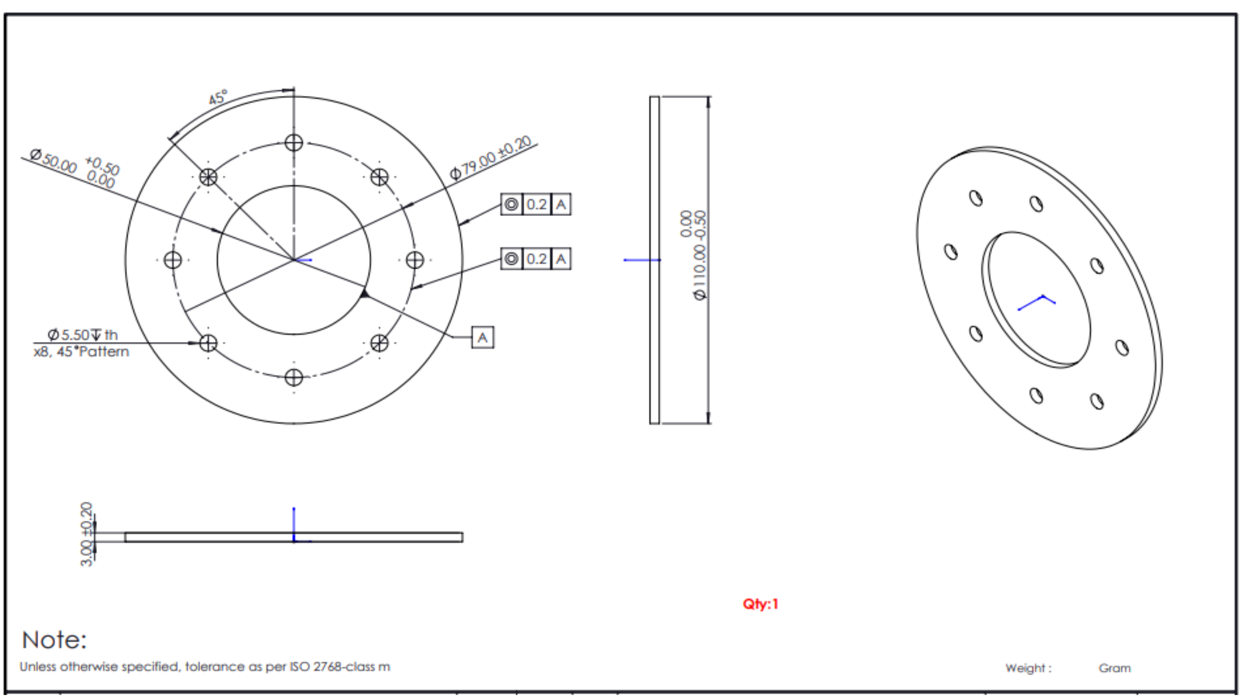
S. E. Gay and M. Ehsani, “Parametric analysis of eddy-current brake performance by 3-D finite-element analysis,” IEEE Trans. Magn., vol.42, no. 2, pp. 319–328, Feb. 2006.

Appendices

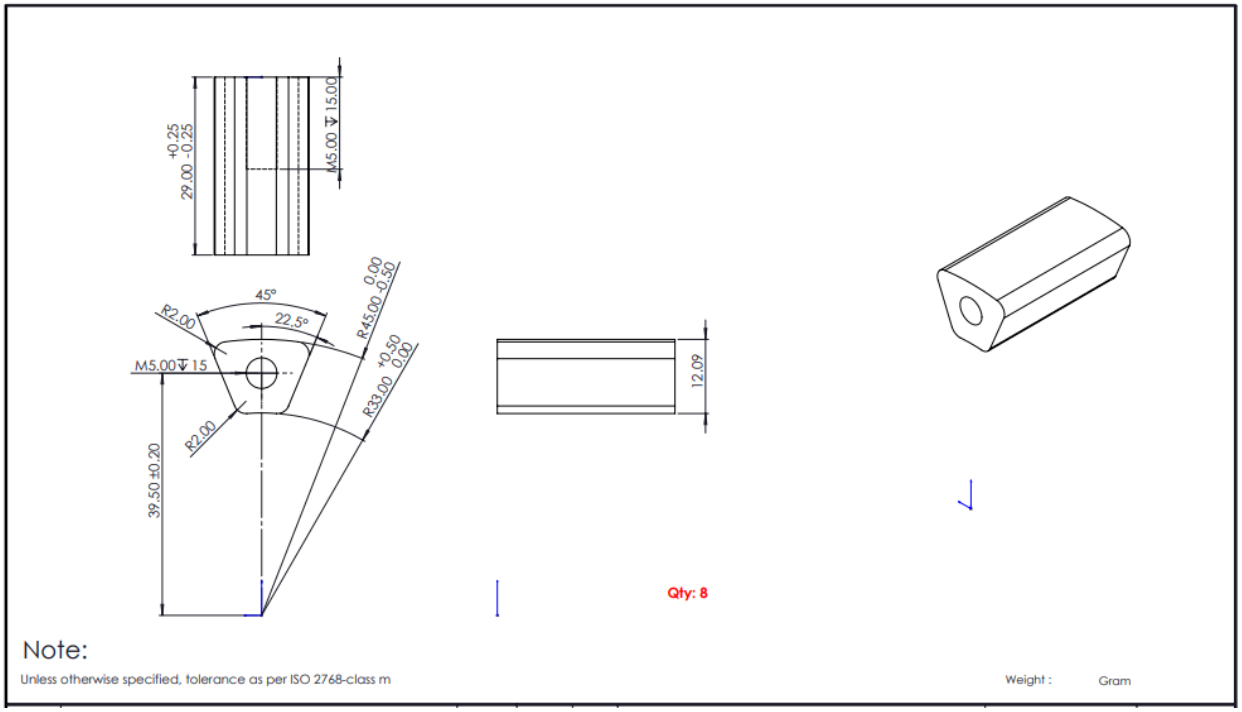
1.Stator mount base:



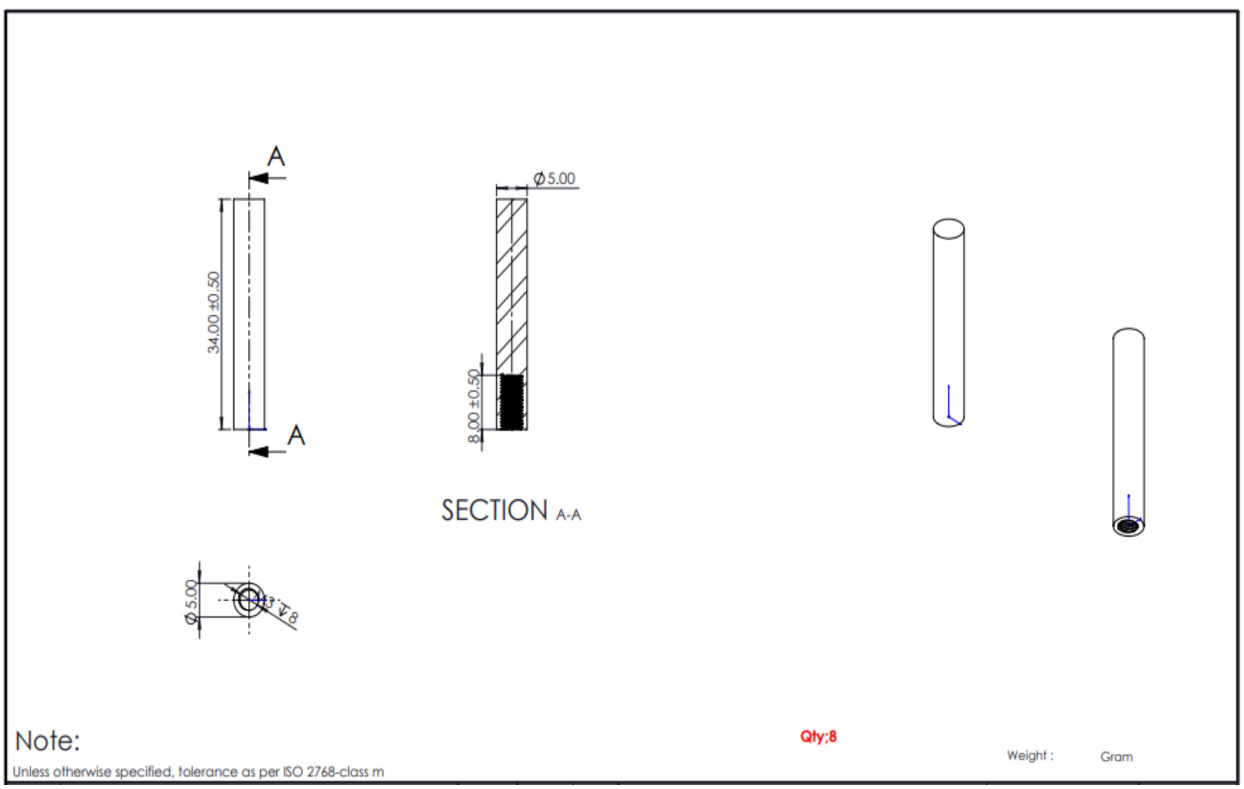
2.Back Plate:



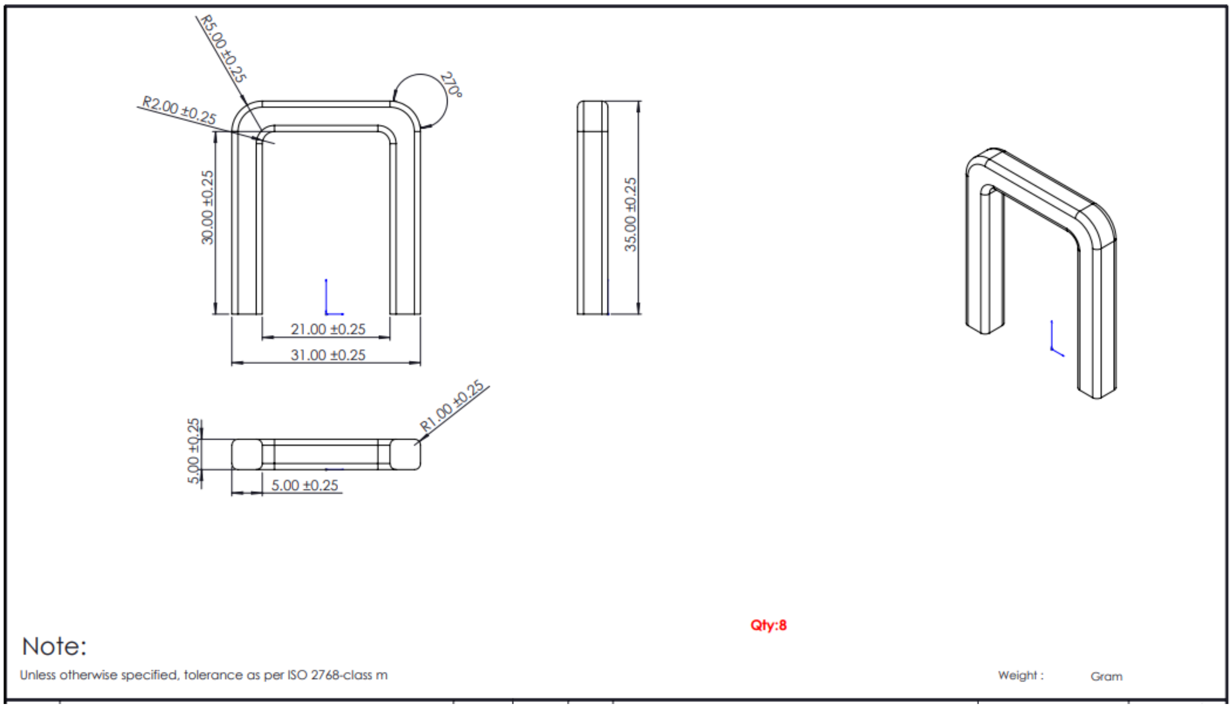
3.Eddy Poles:



4.Guided Rails:



5.U-shaped metal core:



6.Permanent Magnets:

Dimensions:5*5*4mm

5 magnets in one slot of spacer plate