



ESCUELA TÉCNICA SUPERIOR DE
INGENIERÍA

ESPECIALIDAD MECÁNICA

DESIGN OF AN ELECTRIC
MOTOR

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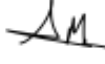
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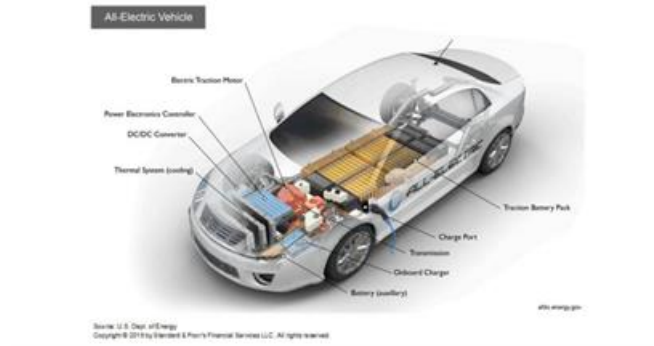
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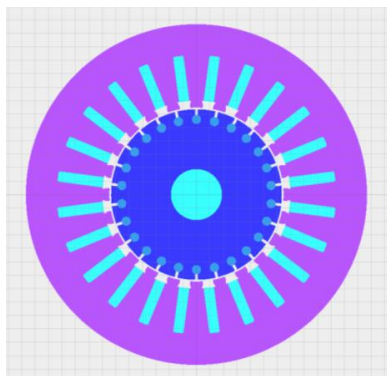
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Resumen en español

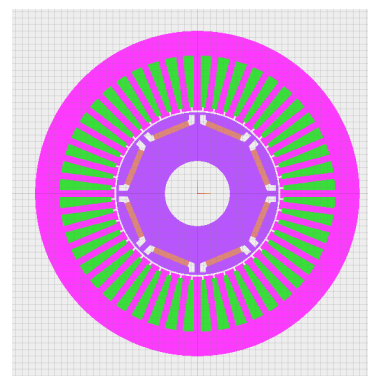
El objetivo principal de este trabajo fin de grado es el diseño de un motor eléctrico con el propósito de adaptar un coche propulsado por un motor de combustión a uno únicamente impulsado por energía eléctrica. Para esta labor he decidido usar un motor de inducción trifásico AC y un motor sin escobillas DC, de modo que diseñe ambos para que puedan ser usados para el cometido dicho y posteriormente hacer una comparativa entre ellos para concluir cuál de los es el más conveniente para el cometido.



Esquema Vehículo Eléctrico



Induction Motor Final Design



Brushless Motor Final Design

El motivo por el cual me embarco en este proyecto es por la evolución de la industria automovilística que, como ya reflejo en el análisis del estado del mercado, está tomando un rumbo a tecnologías más eficientes y que reduzcan el nivel de contaminación, como es el caso del motor eléctrico, cuya emisión es cero en su misión de propulsar al vehículo. La razón por la cual esta tecnología aun no ha triunfado es debido al almacenamiento de batería que, aun hoy en día, es limitado y, en muchos casos, insuficiente para el cometido que se les pide a los coches eléctricos y, sobre todo, si comparamos su autonomía con las de un coche que use tecnología de

Diesel o de Gasolina, por lo cual aún no han podido triunfar frente al coche con motor de combustión.

Evolution of the global electric car stock, 2010-16

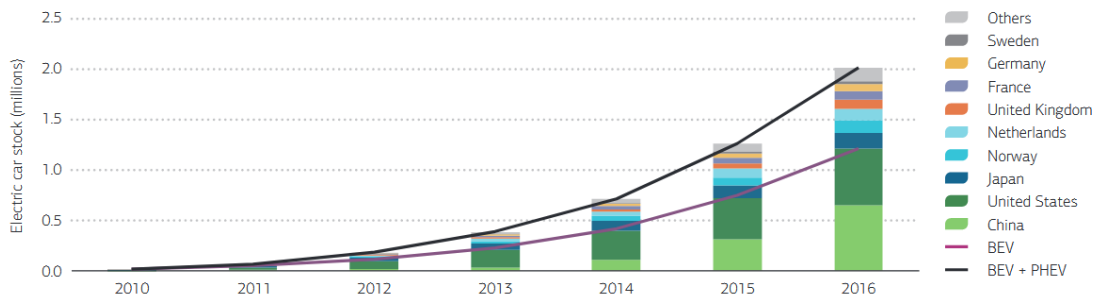
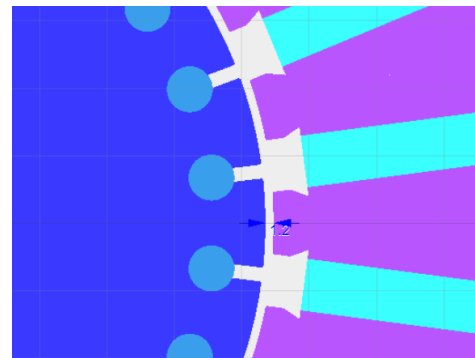


Gráfico evolutivo de ventas del coche eléctrico a nivel mundial

En el apartado de diseño usare un programa llamado JMAG, un programa dedicado al diseño de motores eléctricos de toda clase y que he tenido que aprender a dominar desde cero para poder hacer este proyecto; en el cual, tras introducir parámetros de diseño previamente calculados en hojas de Mathcad (Un programa de cálculo matemático que es útil para situaciones en las cuales tienes que variar valores base y cálculos iterativos) , puedo iterar todas las dimensiones y parámetros del motor para conseguir el resultado más eficiente de este, teniendo en cuenta de que ha de dar el par y tener la potencia dentro de los valores preestablecidos.



Ejemplo de parámetro de diseño del motor eléctrico

A raíz de este programa, he realizado un estudio de como influencia cada parámetro de diseño de ambos motores para los tres resultados primordiales: la potencia, el par y la eficiencia. Tras ejecutar este análisis, que no servirá únicamente para mi cometido, sino para futuros diseños ya sean míos o de gente que use mi trabajo, he podido modificar mi motor para obtener el resultado más beneficioso de cara a las especificaciones finales de este. El análisis se ha llevado a cabo de manera que solo vario un parámetro variándolo de diferentes formas para ver como afecta a las curvas de eficiencia – rpm, par – rpm y potencia – rpm, de manera que pueda hacerse una idea de como afectan en realidad al motor en sus especificaciones finales. Y no solo desde este punto de vista, sino desde el punto de vista de la estabilidad y la funcionalidad del motor al variar estos parámetros.

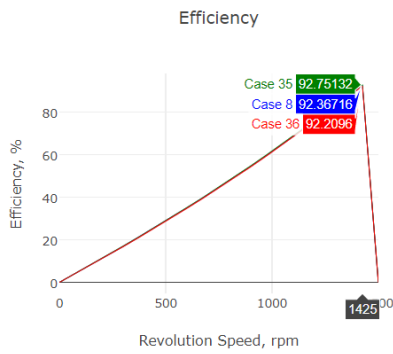


Gráfico comparativo de la eficiencia al variar el valor de un parámetro del motor

algo menor, es más ergonómico y indicado para el cometido, ya que su volumen y peso son mucho menores dando el mismo par y



Gráfico comparativo de la potencia al variar el valor de un parámetro del motor

potencia, lo cual es beneficioso para un coche, ya que el objetivo es minimizar al máximo el espacio y peso del motor con el objetivo de que el sobrante sea aprovechado, por ejemplo, por las baterías. Aparte de esto, he podido comprobar que esta clase de motores son más controlables por la electrónica de potencia, es decir, por el inversor y el controlador vectorial, ambos elementos usados en el coche para variar de la manera mas eficiente la velocidad y el par del motor.

Tras diseñar ambos motores, he hecho un análisis de sus resultados finales, dando prioridad a los valores referentes a las dimensiones y a las especificaciones finales, comparando las curvas antes nombradas de ambos tipos de motores. He podido comprobar que el motor de inducción, aun dando una eficiencia

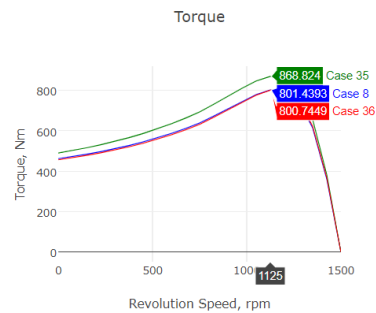
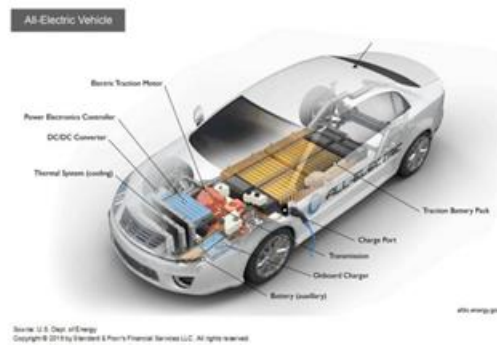


Gráfico comparativo del par al variar el valor de un parámetro del motor

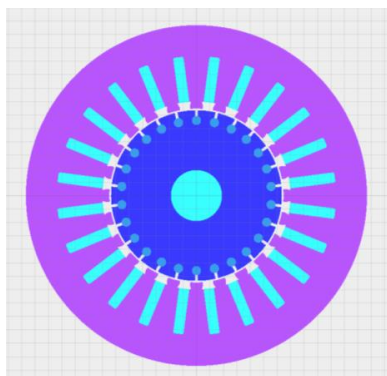
potencia, lo cual es beneficioso para un coche, ya que el objetivo es minimizar al máximo el espacio y peso del motor con el objetivo de que el sobrante sea aprovechado, por ejemplo, por las baterías. Aparte de esto, he podido comprobar que esta clase de motores son más controlables por la electrónica de

Summary in English

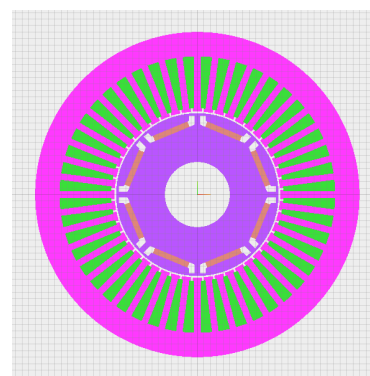
The main objective of this end-of-grade work is the design of an electric motor for the purpose of adapt a car powered by a combustion engine to one driven only by electric power. For this work I have decided to use a three-phase AC induction motor and a DC brushless motor, so that it designs both so that they can be used for the said task and then make a comparison between them to conclude which of them is most convenient for the task.



Electric Vehicle Scheme



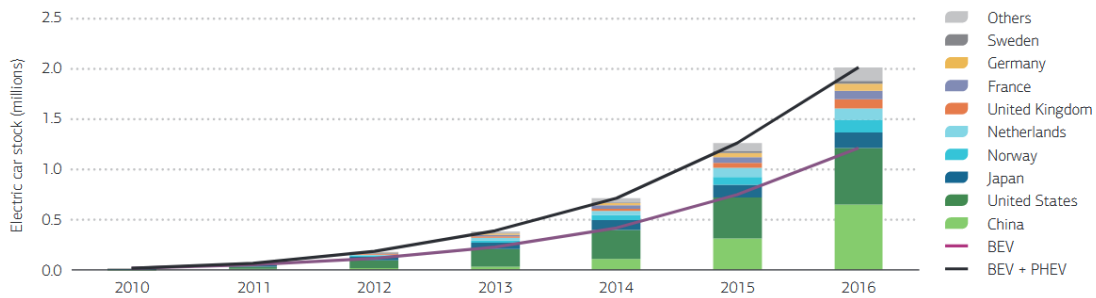
Induction Motor Final Design



Brushless Motor Final Design

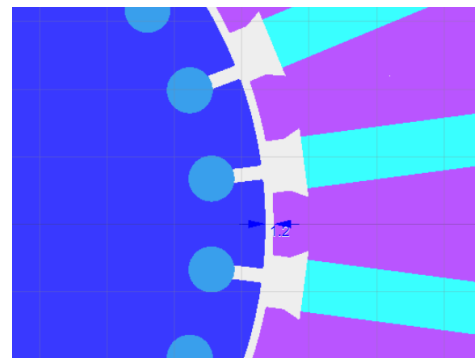
The reason I am embarking on this project is because of the evolution of the automotive industry which, as reflected in the analysis of the state of the market, is taking a course towards more efficient technologies and that reduce the level of pollution, such as the electric motor, which is zero emission in its mission to propel the vehicle. The reason this technology has not yet succeeded is due to battery storage, which, even today, is limited and, in many cases, insufficient for the task that is being asked to electric cars and, above if we compare their autonomy with those of a car that uses Diesel or Gasoline so they have not yet been able to succeed in front of the combustion engine car.

Evolution of the global electric car stock, 2010-16



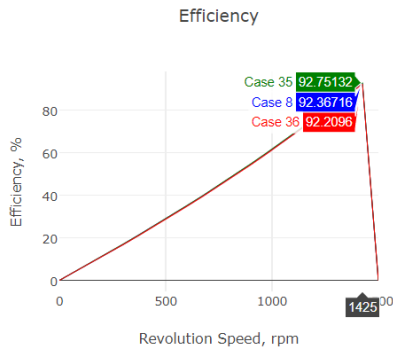
Global evolving electric car sales chart

In the design section I will use a program called JMAG, a program dedicated to the design of electric motors of all kinds and that I have had to learn to master from scratch to be able to do this project; where, after introducing pre-calculated design parameters in Mathcad sheets (A mathematical calculation program that is useful for situations in which you have to vary base values and iterative calculations) , I can iterate all the dimensions and parameters of the engine to get the most efficient result of this, considering that you have to give the torque and have the power within the preset values.



Example of electric engine design parameter

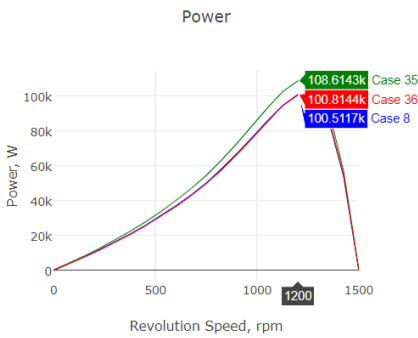
As a result of this program, I have conducted a study of how each design parameter of both engines has influenced the three main results: power, torque and efficiency. After running this analysis, which will not only serve my purpose, but for future designs whether mine or for people using my work, I have been able to modify my engine to obtain the most beneficial result for the final specifications of this. The analysis has been carried out in such a way that only one parameter vary it in different ways to see how it affects the efficiency curves – rpm, torque – rpm and power – rpm, so that you can get an idea of how they actually affect the engine in its specific final specifications. And not only from this point of view, but from the point of view of the stability and functionality of the engine by varying these parameters.



Comparative graph of efficiency by varying the value of an engine parameter

After designing both engines, I have made an analysis of their final results, giving priority to the values related to dimensions and final specifications, comparing the previously named curves of both types of engines. Hand it could be seen that the induction motor, while giving a somewhat lower efficiency, is

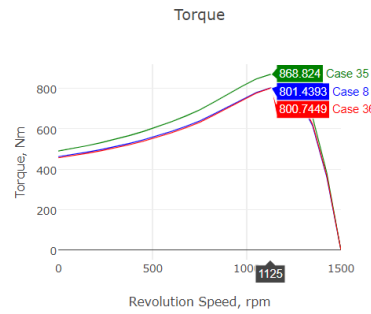
More ergonomic and suitable for the task, since its volume and weight are much smaller giving the same torque and power, which is



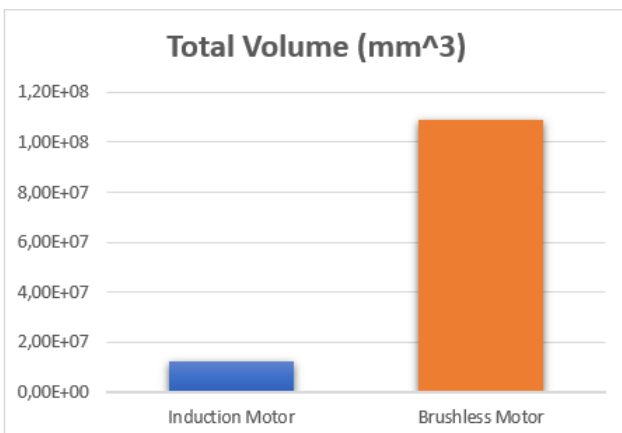
Comparative power chart by varying the value of an engine parameter

beneficial for a car, since the goal is to

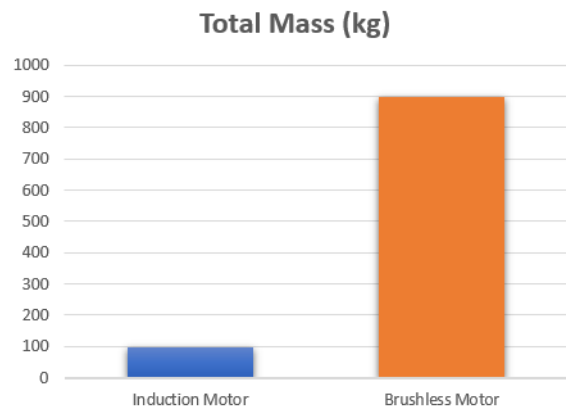
minimize the space and weight of the engine to the maximum in order for the excess to be exploited, for example, by the Batteries. Apart from this, I have been able to verify that this class of motors are more controllable by power electronics, that is, by the inverter and vector controller, both elements used in the car to vary in the most efficient way the speed and torque of the engine.



Torque comparison chart when varying the value of an engine parameter



Comparison of the total volume of both engines



Comparison of the total weight of both engines

Memory

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1. Objectives and Methodology

1.1. Objectives for the project

The main objective of the project is the design of an electric motor with the purpose of implementing it to a market car that currently works with a combustion engine.

That said, the main purposes will be to learn all the knowledge required for the design of the selected electric motors (which will be the three-phase induction electric motor and the brushless electric motor), learn to use the design programs for this field (Of which I have chosen JMAG for its quality after a study and comparison of the different programs, such as the design module of ANSYS), and design different variants of both engines and make a comparison to achieve the most optimal design.

1.2. Methodology

The steps to follow will be the following:

- Learn and review everything possible about these engines to carry out a coherent analysis of these. This will include a research work on its parts, its operation and its implementation to the motorsport sector. I will rely mainly on past projects that relate to this and the use of books provided by my exchange university on the subject, apart from the reports of engines of this style that are already being used today in cars for sale.
- Choose the design parameters of the reports of my colleagues in the project in order to support them from the beginning (such as torque, voltage or power). The use of these parameters at the beginning does not mean that I cannot modify them as I advance in the design, since they are not limited specifications, but are bases on which to settle and which I hope to improve as far as possible.
- Write all the equations for the previous mathematical analysis of the design parameters apart from stipulating tabulated parameters that will be needed so that the motor does not fail when analyzing it. These values, as well as the equations, I will be able to extract from previous works and books, as I have said before. For the convenience to change the parameters "input", I will introduce all the equations in a mathematical calculation program called Mathcad (specifically the most recent version, Mathcad Prime 5.0).
- Once obtained the values of the previous mathematical calculations, I will introduce these in JMAG Express. In this program are calculated through

mathematical analysis and iterations results from the engine, giving values such as par - rpm or efficiency - rpm graphs, being able to vary the values analyzing the modifications in the graphs to get an idea of how they alter these graphs modifying these values. The fact that results are achieved in this program does not mean that the engine is functional, that is, modifying certain values give magnificent results of torque and efficiency without the program not giving you any type of error does not mean that in the subsequent analysis (of finite elements) the engine will work, since the program only does an advanced mathematical analysis, not a finite element analysis.

- Once the two designs and their results have been obtained, we will carry out a comparison of both with the objective of concluding which of them is better to implement it for the application in question.

2. Introduction

In the current state of technology, every car company that aspires to be at the forefront invests a large part of its budget for innovation and design of electric vehicles. And it is because the market asks for it, not only because of the current environmental situation (whose deterioration is largely due to the use of combustion engines in vehicles), but because of the high energy efficiency they present.

The main purpose of studying engineering is to apply everything learned to problems and designs of the real world. That is why, when you leave the university, one must adapt to the conditions of the industry and adapt their knowledge for what they are asked to do. It is for this reason that an engineer who wants to be part of the design of engines for the automotive sector must adapt to the current situation and know in depth the application and design of this type of engines to participate in the advancement of the automotive sector.

The industry at this moment requires an advance in the electrical sector applied to the automobile, not only with motors, but also with batteries and energy recovery systems, such as "regenerative braking". But, to fully understand this type of vehicle you must start from the bases, which I consider to be the electric motor of the vehicle.

The first thing that an engineer has to know to design this type of motors is its operation, which is why I have to analyze thoroughly before starting with the design part of the operation and the parts of the two electric motors chosen: brushless electric motor and three-phase induction motor.

In this project I will compare the results of both engines to conclude which of the two is optimal for the required use. For this I will use the JMAG Designer design programs and the ANSYS theme design module.

The steps to follow will be generic: First, I will put a target torque and power that I will achieve by varying the characteristics of the engine until the best possible result of efficiency is achieved getting to the marked specs.

The reason why this work is done is to help the ECOCAR ERAU project, in which my exchange university, Embry Riddle Aeronautical University, participates in competition against other 12 US universities in the adaptation of a car powered by gasoil or gasoline to electric.

3. Motivations

As I have already highlighted in the introduction, the main reason why I chose industrial engineering was to dedicate myself to the automotive industry. It is true that the design of an electric motor is not an issue that covers well the specialty of mechanics, but if my goal is to enter this sector, and the future of it, as I see it, is in electric cars, I have to take advantage of this work to establish the base in this field.

The general objective of the project in which I participate, the ECOCAR, which is to transform a car with a combustion engine to a completely electric one, has the purpose of introducing engineers to the working world of the automobile industry. That is why the fact that I can contribute to a project that affects the industry by applying the knowledge learned in the race motivates me to do this work.

In addition to this, I believe that advancing this project can expand my borders and learn a lot in different fields, making me a more versatile engineer and a more organized and easier to instruct worker.

Once the project is finished, knowing how to use programs that I have not used before, I am sure that it will not cost me the same to redesign an electric motor or learn about other components, whether mechanical or electrical, of a vehicle and Start designing them.

It is true that, being a field in which I have been instructed in a few subjects, it will be more difficult for me to understand the procedures and calculations, but from my point of view it is about being an engineer, acquiring new and difficult knowledge. understand to be able to evolve in the field to which I will dedicate myself. With the passage of time, as it has already happened to me with the race, understanding complicated knowledge will make me more bearable, that is why I should not settle for a project of concepts that I have already learned, but embark on a job with some repercussion and help me face the world of work.

I would also like to focus on an aspect that I highlighted earlier, which is my hypothesis about the future of the automotive world. From my point of view this is not a bet, but a certainty, you just must look at the sales graphs (which grow exponentially over the years) and the sums of money that companies invest in the I + D of this field. With this I want to conclude that an engineer has to adapt to what the market demands in the sector that concerns him, that is why I must start as soon as possible to adapt to what is probably my work future.

In case I dedicate myself to another field, as I have emphasized before, overcoming obstacles of new knowledge will make me improve as a student, and at the same time, as a worker. That is why the results obtained from doing this project can only take advantage.

4. State of the Art

4.1. What is an electric motor?

A device capable of converting electrical energy into mechanical energy thanks to the action of the magnetic fields generated in its coils. Reducing it to the basics, they are rotating electrical machines composed of a stator and a rotor.

An electric motor can be reversible, that is, they can convert mechanical energy into electrical energy functioning as generators or dynamo.

Electric motors are divided into several groups, depending on the type of power they have:

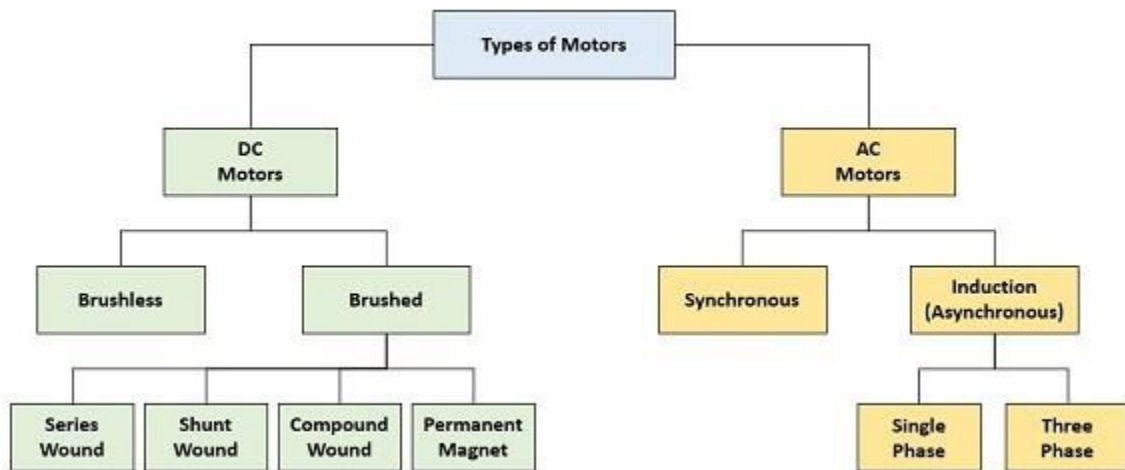


Figure 1. Types of electrical motors

- AC (Alternating current) motors: highly flexible in many functions, including speed control (variable speed drives) and have a much larger installed base compared to direct current motors. Among its main advantages are:

- Low energy demand at the beginning
- Controlled acceleration
- Adjustable operational speed
- Controlled starting current
- Adjustable torque limit
- Reduction of disturbances of the power line

In this type of motors, the induction or asynchronous motor is included, one of the ones that will be treated in this work.

- DC motors (direct current): The distinctive feature of this group is that its speed can be regulated by varying the supply voltage. Among its advantages are:

- Easy installation
- Speed control in a wide range
- Quick start, stop, inversion and acceleration
- High starting torque
- Speed linear torque curve

4.2. Comparison of electric motor classes

Motor Item	AC motor			Universal motor	Brush DC motors	Brushless DC motor	Stepping motor	Servo motor	
	Single-phase	Three-phase (Induction)	Three-phase (Sync)					AC servo	DC servo
Power type	AC			AC/DC	DC	DC (including driver)/Driver	Drivers	Drivers	Drivers
Efficiency	40-60%	60-70%	70-80%	50-60%	60-80%	80%-	60-70%	50-80%	60-80%
Size (same output)	Large	Intermediate or large		Large	Small	Small	Intermediate	Small or intermediate	Small
Noise	Small			Large	Large	Small	Intermediate	Small	Large
Speed range	Narrow	Wide		Intermediate	Wide	Wide	Wide	Intermediate	Narrow
Response	Slow			Slow	Intermediate	Intermediate	Intermediate	Fast	
Service life	Long			Short	Short	Long	Long		Short
Price	Low		Intermediate	Low	Low	Intermediate or high	Intermediate	High	
Applications	Washing machines Air blowers Vacuum cleaners Pumps	Cranes Conveyors Air conditioners Industrial machinery	Compressors Dishwashers Washing machines	Vacuum cleaners Electric tools Juicers	Electric toys Electric tools Automobile electric components Small home appliances	Air conditioners Dishwashers Washing machines Small home appliances	Robots Small home appliances Air-conditioning equipment	Conveyors Robots Machine tools	Printers Plotters Working machines
Judgment	Cost focused	Versatility focused		Cost focused	Cost focused	Efficiency focused Versatility focused	Versatility focused	Performance focused	

4.3. The three-phase induction motor

The asynchronous or induction machine is an electromechanical conversion device for rotary-type energy. The transformation of energy is produced by the interaction of two magnetic rotating fields developed by the inductor and the armature.

The squirrel cage induction motors (although it is also applicable to the rest of electric motors) are characterized by their simplicity, robustness, reliability and resistance; they are also economical and, thanks to their low

number of incidences (they occur mostly in the rolling elements), they are reasonably cheap to maintain. Together with this, the power factor at full load is considerably good and start-up occurs autonomously. Thanks to these properties, the electric motor has been implemented in all types of sectors (industrial, residential, etc.) in a wide range of sizes and powers.

That said, it also has a series of drawbacks to consider: its speed is practically constant from zero to full load, so it is impossible to vary this without losing performance. It should also be noted that its speed decreases with the increase in the driven load, in addition that the torque is lower than in DC motors.

Even with the disadvantages that it presents, thanks to the application of the control electronics when regulating the speed of rotation, leading to an improvement in its operation, the induction motor has managed to replace the DC motor in most of its usages.

4.3.1. Main parts of the induction motor

Stator

The stator is the stationary part of the electromagnetic circuit of the motor and is formed by thin metal sheets, called laminations. The laminations are used to reduce the energy losses that would occur if a solid core were used. The stator laminations are stacked together to form a hollow cylinder to reduce eddy currents and hysteresis losses.

Stator windings

Insulated wire coils are inserted into the grooves of the stator core. When the assembled motor is in operation, the stator windings are connected directly to the power supply. Each bundle of coils together with the surrounding steel core becomes an electromagnet when current is applied. Induction is the basic principle behind the operation of the engine.

Rotor

The rotor is the rotating part of the electromagnetic circuit of the motor. The most common type of rotor used in a three-phase induction motor is a squirrel-cage rotor. The rotor of the squirrel cage is so called because its construction is reminiscent of the rotating exercise wheel found in some pet cages. The rotor core of a squirrel cage is made by stacking thin steel laminations to form a cylinder. Instead of using cable coils as conductors, the conductor bars are inserted into the uniformly spaced slots around the cylinder. Most squirrel cage rotors are made of cast aluminum to form the

conductive bars. After die casting, the rotor conductor bars are mechanically and electrically connected to the end rings. Then the rotor is pressed on a steel shaft to form a rotor assembly.

In addition to the squirrel-cage rotor, the wound rotor is also frequently used, which has windings that are connected through slip rings to external resistors.

Case

The enclosure consists of a frame and two end bells (or bearing housings) in which the stator is mounted inside the frame. The rotor fits inside the stator with a slight air space that separates it from the stator. There is no physical connection between the rotor and the stator. The housing protects the internal parts of the motor from water and other environmental elements. The degree of protection depends on the type of enclosure.

Bearings and Fans

The bearings mounted on the shaft hold the rotor and allow it to rotate. Some engines use a fan mounted also on the rotor shaft to cool the motor when the shaft is spinning.

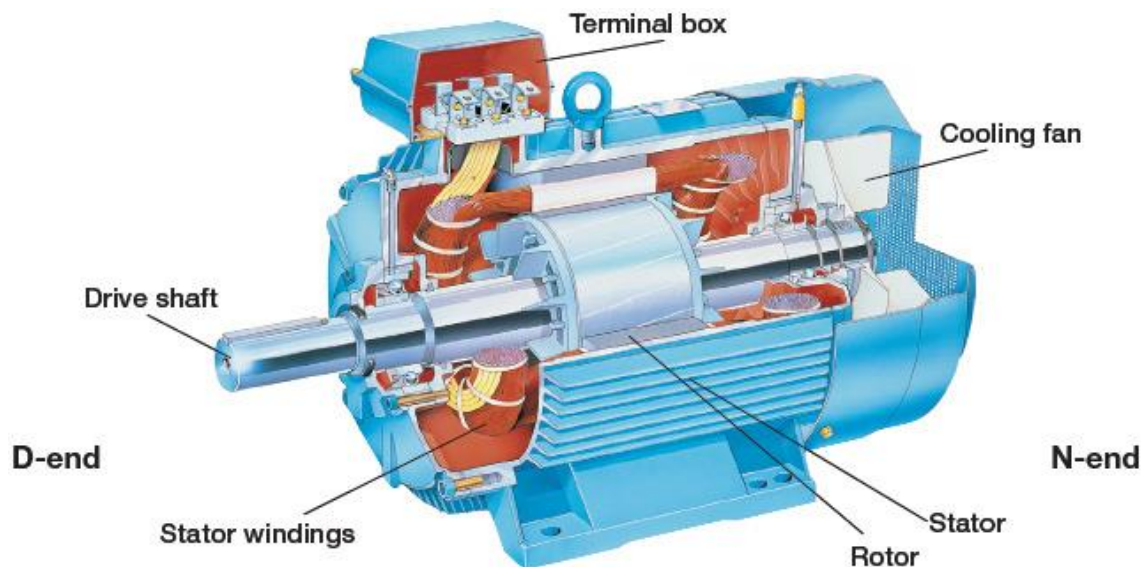


Figure 2. The parts of an electrical motor

4.4. The brushless electric motor

It often helps to explain how a DC motor with brushes works first, since they were used for a while before the brushless DC motors were available. A brushed DC motor has permanent magnets on the outside of its structure, with a rotating armature inside. The permanent magnets, which are stationary on the outside, are called stator. The armature, which rotates and contains an electromagnet, is called a rotor.

In a DC motor with brushes, the rotor rotates 180 degrees when an electric current is directed to the armature. To go further, the poles of the electromagnet must turn. The brushes, when rotating the rotor, make contact with the stator, change the magnetic field and allow the rotor to rotate 360 degrees.

The so-called "brushless DC motors" ("Brushless DC Motors" or BLDC) are electric machines with permanent magnet in the rotor and coils in the stator (usually 3 phases), fed with a set of alternating polyphase voltages (sinusoidal or trapezoidal), generated by means of an inverter circuit controlled so that the operating characteristics of the electric machine emulate those of a conventional DC motor ("DC motor with brushes") in relation to the torque / current and angular / voltage ratio.

In a field DC motor generated by a permanent magnet, the structure of the machine automatically produces the desired optimum ratio between the field of the stator magnet and that generated by the armature current in the energized coil of the rotor. The desired alignment between the two fields is defined by the position of the brushes that feed the rotor circuits (armature circuits) in relation to the contacts of the commutator and remains fixed at the moment when the machine is assembled.

A brushless DC motor is essentially turned upside down, eliminating the need for the brushes to reverse the electromagnetic field. In brushless DC motors, the permanent magnets are in the rotor and the electromagnets in the stator. Then, a switch charges the electromagnets in the stator to rotate the rotor 360 degrees.

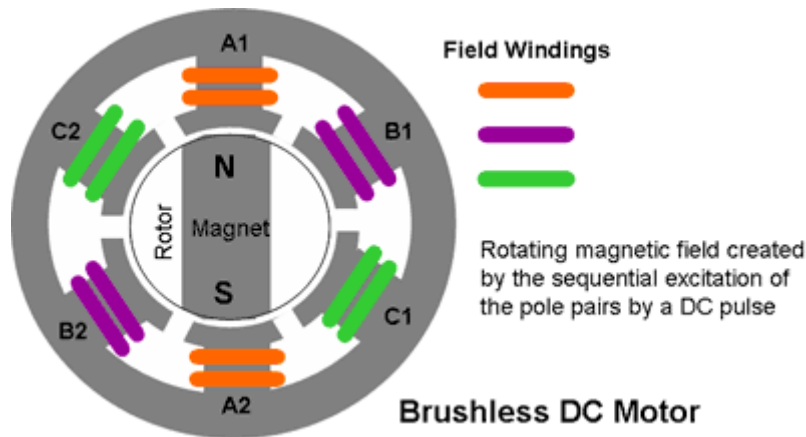


Figure 3. The working of a Brushless motor

A motor with brushes would have the following disadvantages, which we saved with the BLDC:

- The friction between the brushes and the delgas of the commutator produces wear; those parts (especially the brushes) should be inspected regularly and replaced periodically.
- The electrical contact between the brushes and the delgas of the commutator is not ideal and sparking may occur.
- The speed of rotation of the rotor is limited by the need to maintain an adequate contact between the brushes and the delgas of the commutator
- Electrical losses occur in the armature circuit, which is placed in the rotor, the innermost part and, therefore, the least ventilated part of the machine, which makes it difficult to dissipate the heat generated during the operation of the machine

Brushless DC motors generally have a performance of 85-90%, while brush motors generally have a performance of 75-80%. The brushes eventually wear out, sometimes causing dangerous sparks, limiting the service life of a brushed motor. The brushless DC motors are silent, lighter and have a much longer lifespan. Because the terminals control the electric current, achieving much more precise motion control.

Due to all these advantages, brushless DC motors are often used in modern devices where low noise and low heat are required, especially in continuously operating devices. This can include washing machines, air conditioners and other consumer electronic products. They can even be the main source of energy for service robots, which will require very careful

control of the force for safety reasons. Nowadays they even apply to the automotive industry, which is what we are dealing with.

4.4.1. Components

This electric machine is structurally almost the dual DC permanent magnet motor: The brushless engines are composed of a moving part, the rotor, where the permanent magnets are located, and a fixed part, called stator or housing, on which are arranged the wire windings. The image reflects a section of one of these motors where the arrangement of the windings and the permanent magnets can be seen.

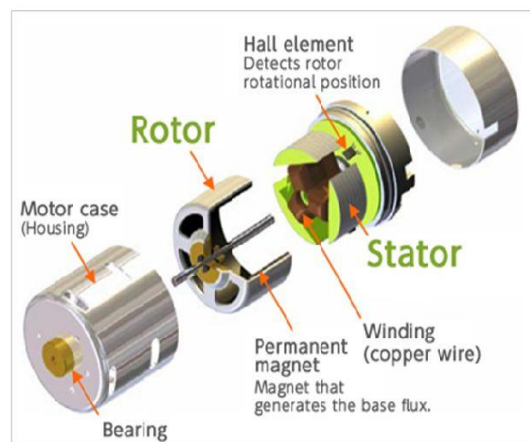


Figure 4. The parts of a Brushless Motor

BLDC with integrated position sensor

This electric machine adds a sensor system of the position of the rotor to an electric machine of similar structure to the permanent magnet synchronous. The sensor system can be optical (encoded disk), or magnetic, usually of the "Hall effect" type. The sensors inform the controller of the position of the rotor in relation to the coils, which allows to activate a set of electronic switches that energize each of the coils in the optimum position. The electronic sensor-controller-switch assembly replaces the conventional DC motor electromechanical switch.

The need to use this system implies a fundamental difference between the conventional DC machine and the BLDC machine with position sensors. A conventional DC motor can operate "in open loop", that is, without the need to control it, connected to any DC source that is capable of delivering

the necessary current. The BLDC machine with position sensors cannot operate on its own. To turn, even in "open loop", it is necessary to connect the external system that interprets the position signals and controls the inverter that feeds it.

BLDC without integrated position sensor

In this type of motors, as we have said we do not have sensors, therefore, the variator is less complicated and must use another method to determine the position of the rotor. To do this, the drives associated with these motors perform a monitoring of the impulses or signals they send to the motor; but this has the disadvantage that when the motor rotates at lower speeds in which the intensity generated by the magnetic field has a lower value, it can be difficult to analyze this accurately.

4.5. What is the electric car?

An electric car is a vehicle driven by one or more electric motors that uses electrical energy stored in rechargeable batteries and transforms it into kinetic energy. Unlike internal combustion vehicles, which operate by burning fuel, an electric car obtains traction from electric motors. This energy is stored in rechargeable systems, batteries, which then consume the energy stored during its displacement. The motor of an electric car can be either alternating current or direct current.

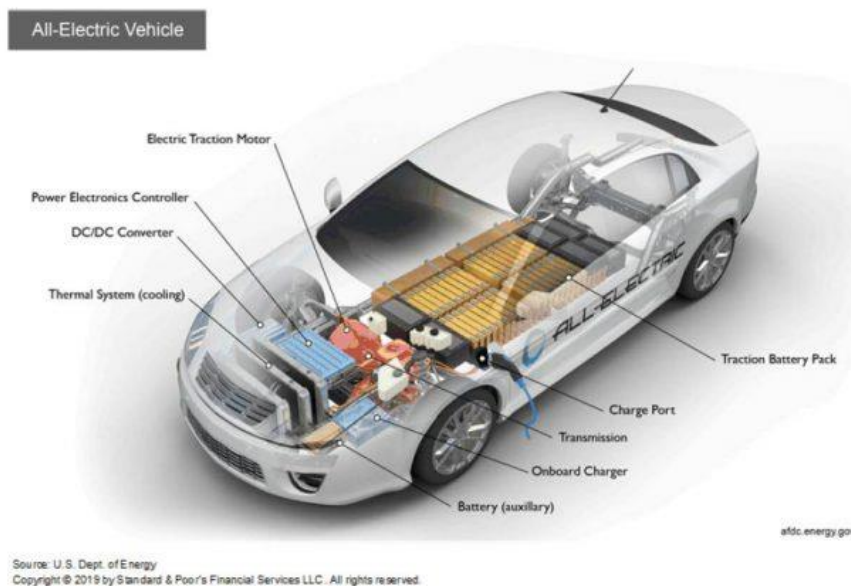


Figure 5. The electrical car

Other variants of electric car would be:

- Hybrid Vehicle:

A car whose engine uses two engines of different technology to obtain propulsion. It usually refers to the use of an internal combustion engine (diesel or gasoline) next to an electric motor. One of the two is used as the main source and the other is used as support; There is also the case in which each of the energy sources works independently depending on the situation.

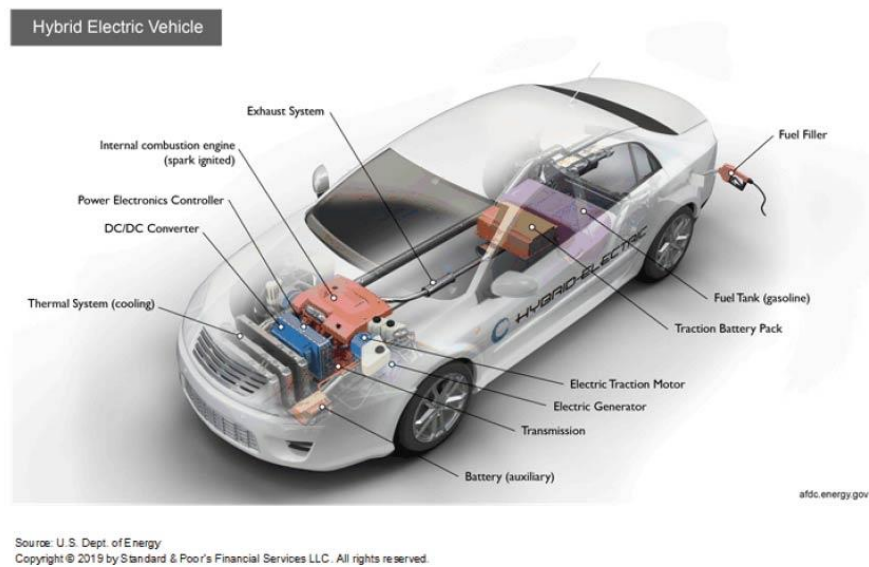


Figure 6. The Hybrid Car

- Plug-in Hybrid Electric Vehicle

A car that shares the characteristics of the hybrid car, with the exception that the batteries can be recharged through a power source external to the vehicle (hence the plug-in term) in addition to the internal recharging systems of the same.

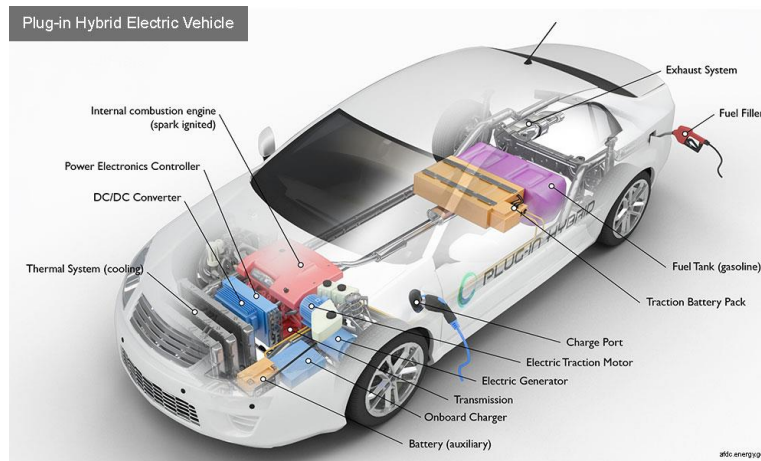


Figure 7. The Plug-in Hybrid Car

- Extended range electric vehicle

Cars whose battery can be recharged by using a dynamo driven by a combustion engine to generate power and extend the vehicle's autonomy, the main propulsion system being the electric motor

4.6. State of the market

In the current state of automotive technology, the electric car is the model in which most companies invest, not only for the ecological issue, in which the electric motor is the best option since it does not emit any gas for its operation ; but also because of its high efficiency compared to the combustion engine, in addition to the great monetary savings involved in the use of electric power in comparison to gasoline or diesel.

Evolution of the global electric car stock, 2010-16

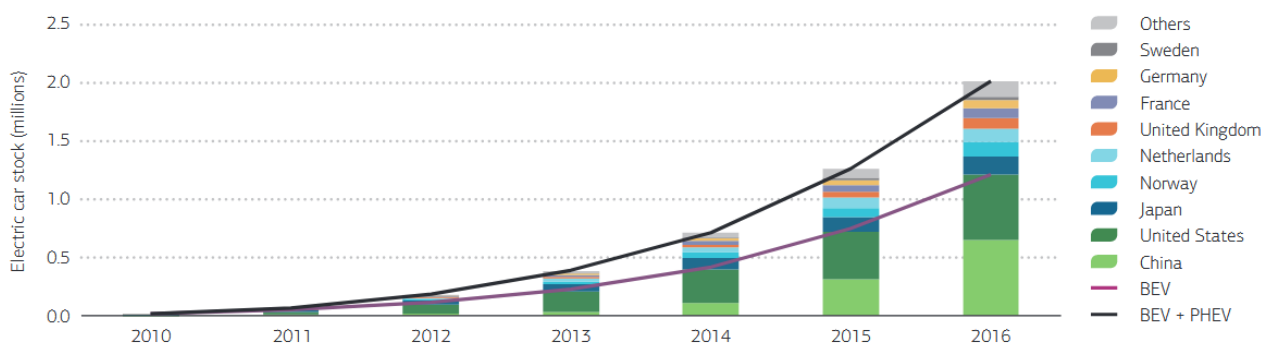


Figure 8. Electric Car Sails Graphic

As we can see in the graph, which shows the aforementioned, the production of the electric car is in exponential growth. That is why I focus the design of this engine for an electric car instead of a different machine.

4.7. History of the electric car

The first electric cars

Electric cars are not a recent innovation. Its evolution is parallel to internal combustion engines. They were produced for the first time in 1880, gaining popularity for their ease of use, in addition to the fact that they did not emit any kind of smoke, making them much less "sweet" than the rest.

The characteristics of the first models were quite mediocre in comparison to the current ones, their maximum speed was only 32 km / h and they had a limited range.

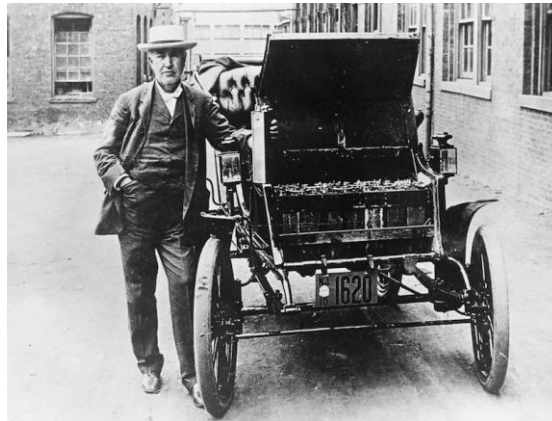


Figure 9. The Tomas Edison's first electric car

4.8. The hybrid car

The progress of this type of cars progressed in a reduced way, until the world faced the problem of high pollution due to the emission of gases from combustion engines (among other reasons). As an alternative came the so-called "Hybrid Car", in which the combustion engine and the electric motor were combined (using this for reduced speeds), thus reducing the emission of harmful gases for the ozone layer.

The most remarkable and famous model of hybrid technology is, clearly, the Toyota Prius, which combines (currently) a motor of a 4-cylinder engine with a permanent magnet AC synchronous motor 71kW, thus increasing the efficiency of the automobile thanks to this combination.

But the first hybrid car is older than you think. The first model dates from the early twentieth century. In 1899 an employee of Jacob Lohner & Co makes his first design of a hybrid car, with electric motor and gasoline. His name was Ferdinand Porsche. Its design consisted of a gasoline engine that rotated at constant speed, feeding a dynamo, to charge some electric batteries. In addition, the start of the gasoline engine was done by that same dynamo.

Electric power was used to move electric motors in the front axle inserted in the wheels, the excess was stored. It is considered the first hybrid production car in the World.

This data is remarkable because the electric motor used in the car not only advanced its progress by one line, but by two: The electric car and the hybrid.



Figure 10. Lohner-Porsche, the first hybrid car in history

4.9. The main problem: Autonomy

The main problem facing this type of vehicle is not the efficiency or longevity of the engine, but the reduced range of energy storage of the batteries. At present, the car with the most autonomy without recharging is the Hyundai Nexo, with a range of 600km, which is considerably high in absolute terms, but scarce compared to the average autonomy of a car with a combustion engine, joining it with the data that is a hybrid car extended autonomy. The entirely electric car with greater autonomy is the Tesla Model S, with almost 400km.

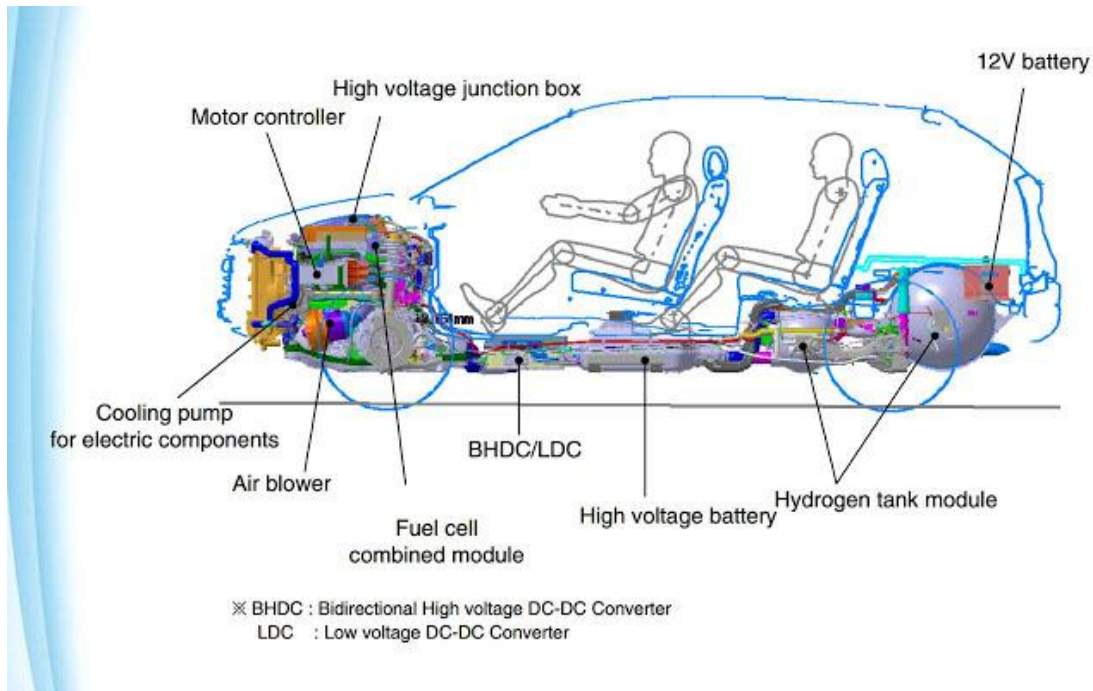


Figure 11. The Working of an electric car

These figures are not achievable only with the integrated capacity of the battery, but with a system that takes advantage of the energy left over or generated when braking or descending slopes, the KERS system (Kinetic Energy Recovery System), in which the motor does not it is only capable of consuming energy to generate movement, but it can also reverse its polarity to function as a generator when driving situations allow it, recharging the engine as the car is used and increasing the autonomy of the car.

4.10. The electric car today

Focusing now on the topic that concerns us, electric motors, the development of these engines covers more than a century, implanted in all types of machinery nowadays, used in all sizes and power range, having increased its performance over the years to figures as high as 96%.

Specifying the automotive sector, after comparing models and selecting among them, I have not been able to look at two in particular: The Nissan Leaf and the Tesla Model S. I have selected them because, due to their technical data, their electric motors are at the forefront of the automotive market in this issue.

The most remarkable feature of the Nissan Leaf engine, which stands out for its simplicity, is its power consumption, which is 18.7 kWh at 100 km / s, placing it among the best in the market in this section. Analyzing this

model thoroughly I have been able to verify that this data is due to the meticulous analysis that has been carried out when analyzing the torque required for each speed of rotation of the engine.

The Tesla Model S is surely the goal model that all companies have when it comes to designing an electric car. The characteristic of this car that I most want to highlight in this project is the autonomy, which covers almost 400km without having an exaggeratedly large battery, so this attribute is thanks to the efficiency of its engines. Its design is based on 2 motors (one in each axis) three-phase induction electric with copper rotor and 4 poles that can rotate up to 15,000 rpm. Obviously, I would not be able to match the performance of their engines but putting me on target their performance specifications would ensure that I achieved the highest possible performance with my capabilities.

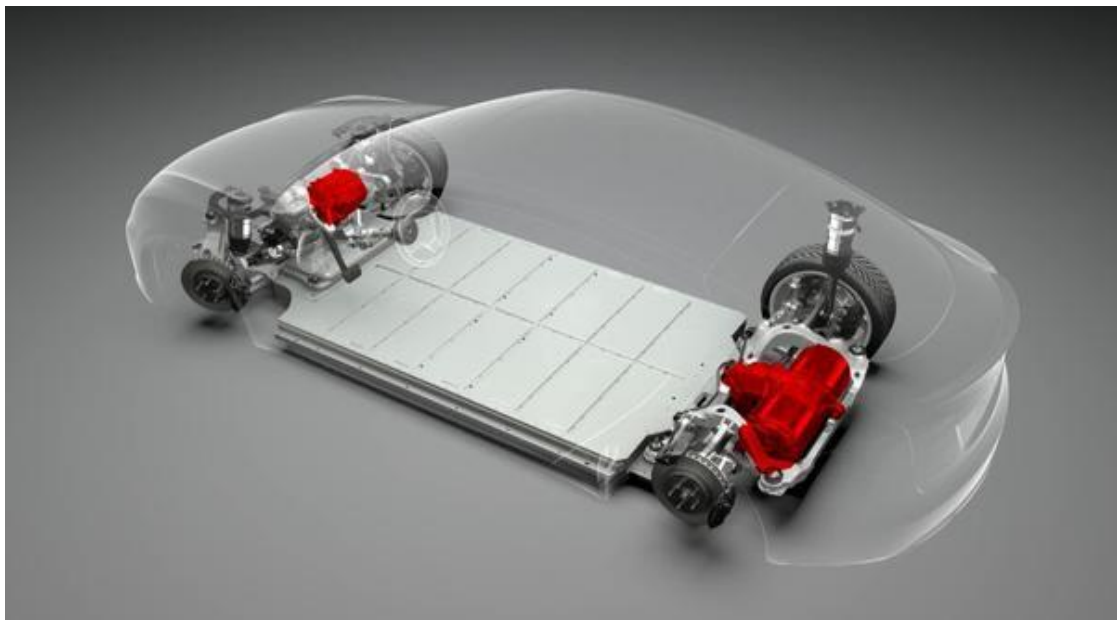


Figure 12. Tesla Model S Schematic

5. Design

The procedure for the designing will be the same for both kinds of motors: In first place I will realize a calculation through each of the motor's formulation with the design parameters established (with the tabulated parameters for this kind of motors), after it, with the resultant theoretical design, I will introduce the results in JMAG Express to evaluate the specs results (Overall efficiency, Torque and Power mainly) and I will iterate the design values till reach the goal results, and have a final motor design.

Before performing the iterations in JMAG, I will study all of the design parameters in order to know how they impact in the motor's resultant specs, and I will include all the analysis and the conclusions in this project.

5.1. Induction Motor Designing

5.1.1. Mathematical Calculations

For this part I will study and include all the mathematical formulation with the calculations for this specific motor we want to design. For this duty I will use a software specialized on this field called "MATHCAD PRIME", in which you can write the formulation and the parameters and the program automatically calculates every parameter through the introduced formulas and change them if you apply any change on any of the parameters or formulas.

For some parameters, I have introduced values advice by previous research and tables that provides guide in this kind of aspects.

All the MATHCAD sheets are included in the Annex 1

5.1.2. Analysis of the Design Parameters

Before designing the induction motor, I will analyze the impact of every change done on each of the design parameters of the motor. For this duty, I will study the change in three graphics that describes the behavior of the motor: Torque – rpm, Efficiency – rpm and Power – rpm.

I will establish base parameters in order to compare the torque, efficiency and power results when I vary only the value of the parameter that I am analyzing on each point, leaving the rest of them in its base value (The optimized value that I have reached after iterating with all the sizes and rest of the design parameters).

5.1.2.1. Dimensions

Height

Base value = 227.4 mm

The axial length of the motor. A variation makes a great impact in the motor specs. By increasing its value, we decrease the torque and the power, but we increase the efficiency. If we decrease it, we have the complete opposite result.

This value is one of the most important of the motor and the one that's makes more variation in the motor specs by varying it.

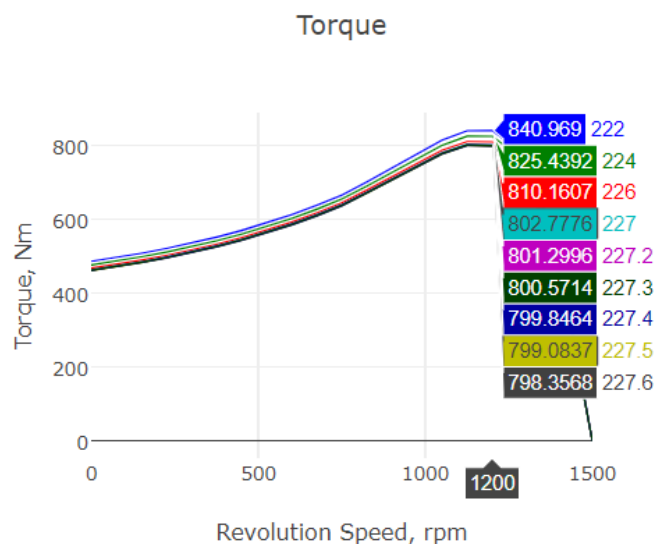


Figure 13. Height Torque Graphic

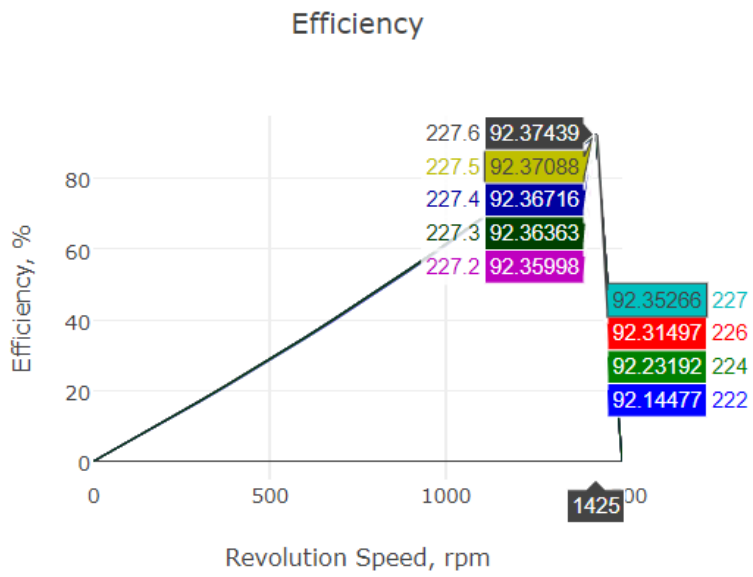


Figure 14. Height Efficiency Graphic

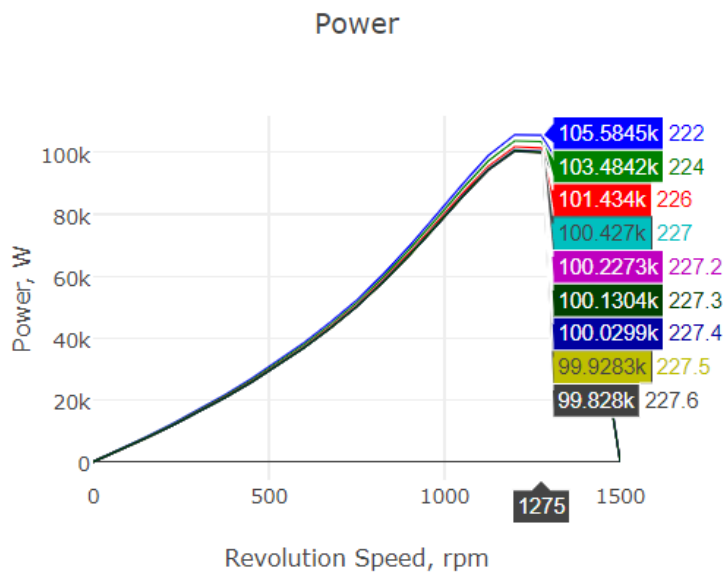


Figure 15. Height Power Graphic

OUTD

Base value: 253.7 mm

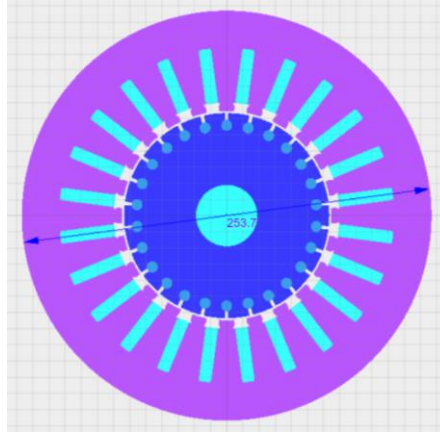


Figure 16. OUTD

The outside diameter of the stator, what is the complete diameter of the motor itself. An increment in this value makes a great variation in power and torque, decreasing both of them, as well as in efficiency, increasing it.

Table 1. OUTD Cases

Case	Value
Case 8	Base Value
Case 10	252 mm
Case 11	254 mm

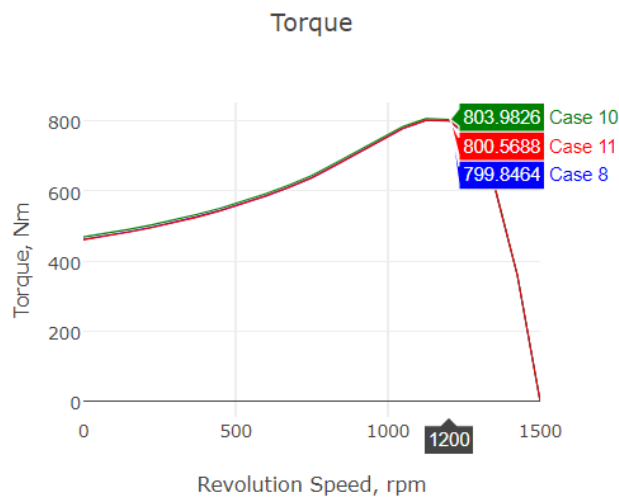


Figure 17. OUTD Torque Graphic

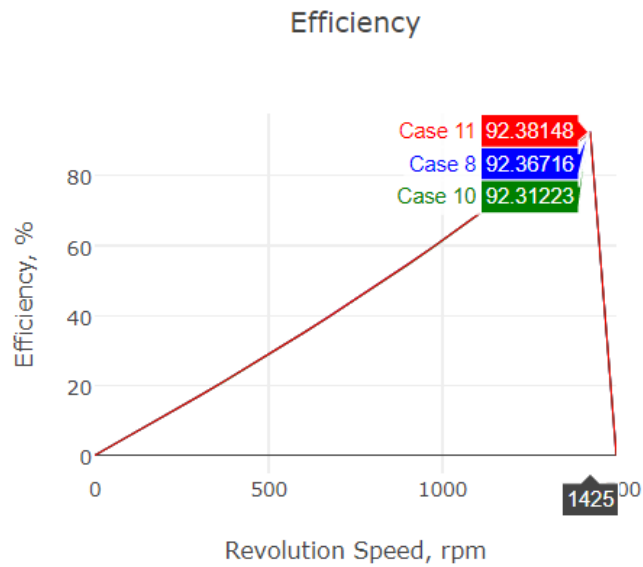


Figure 18. OUTD Efficiency Graphic

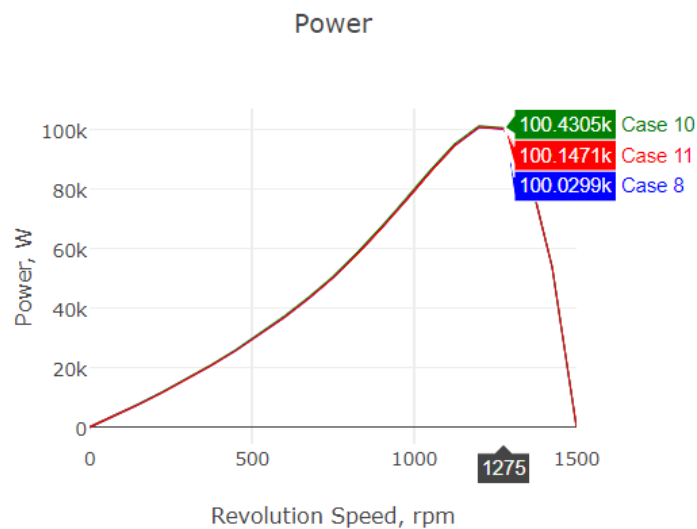


Figure 19. OUTD Power Graphic

Gap Type

The design for the air gap. There are two possibilities: fixed or free

Comparing both of them we can see that the free gives a much better performance, increasing the efficiency with an almost negligible decrement of the Torque and Power.

Table 2. Gap Type Cases

Case	Value
Case 8	Free
Case 12	Fix

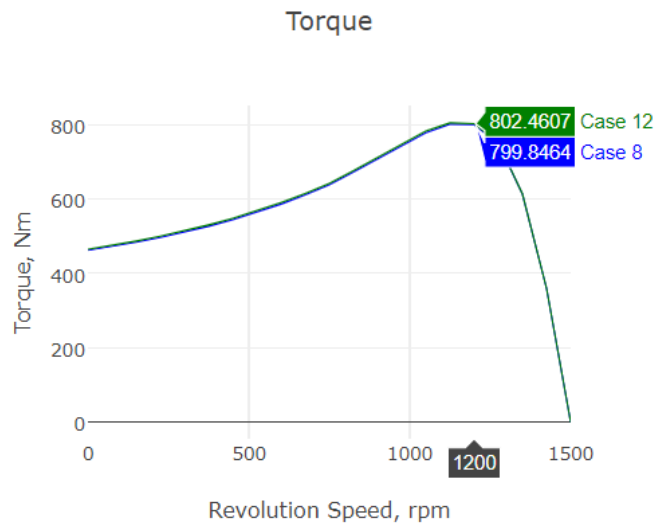


Figure 20. Gap Type Torque Graphic

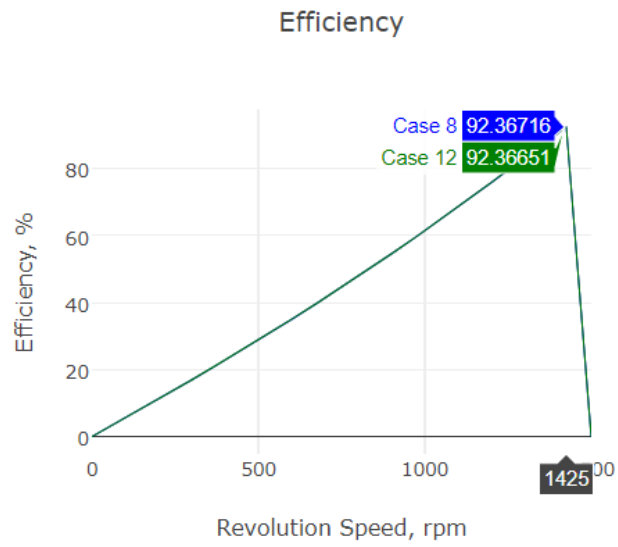


Figure 21. Gap Type Efficiency Graphic

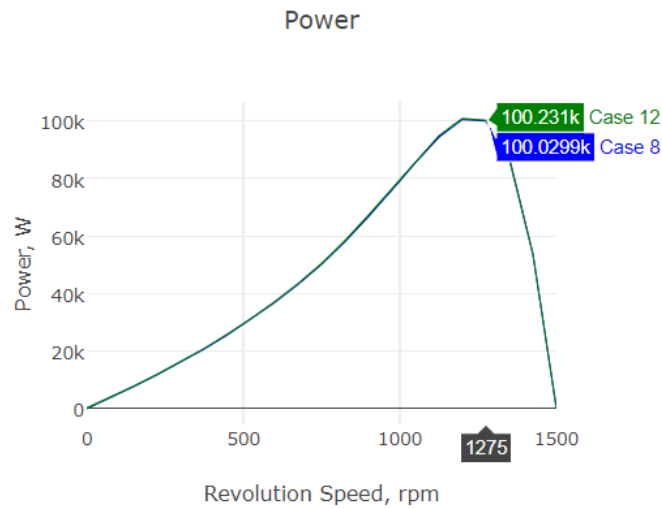


Figure 22. Gap Type Power Graphic

Poles

The number of poles of the induction motor. This will make a variation in the rotation speed of the motor. For my design I have tried with 4 poles and with 8 poles. The results showed that the 8 poles machine gave an increment in the Torque and Power, but a decrement in efficiency. These results are not accurate for a correct comparison, cause changing the number of poles changes completely the motor, that's why the number of poles is usually an input data to design the motor. For this motor I have decided to use 4 cause is the most common value.

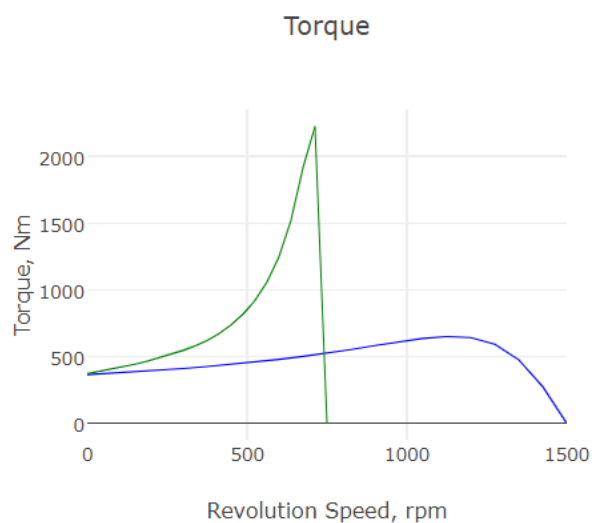


Figure 23. POLES Torque Graphic

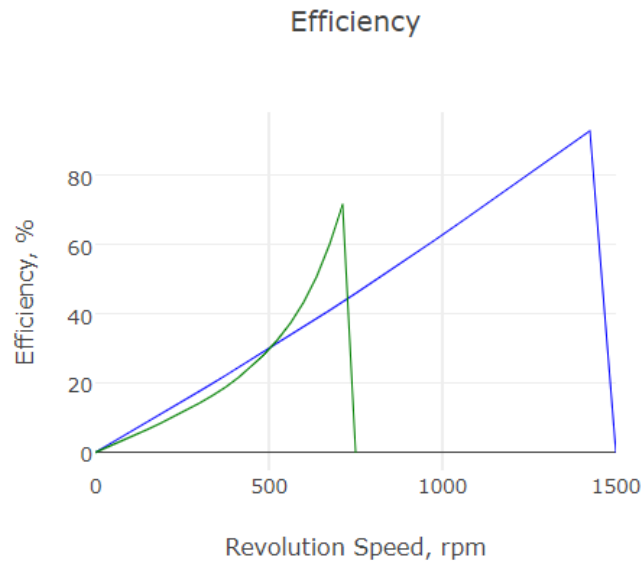


Figure 24. POLES Efficiency Graphic

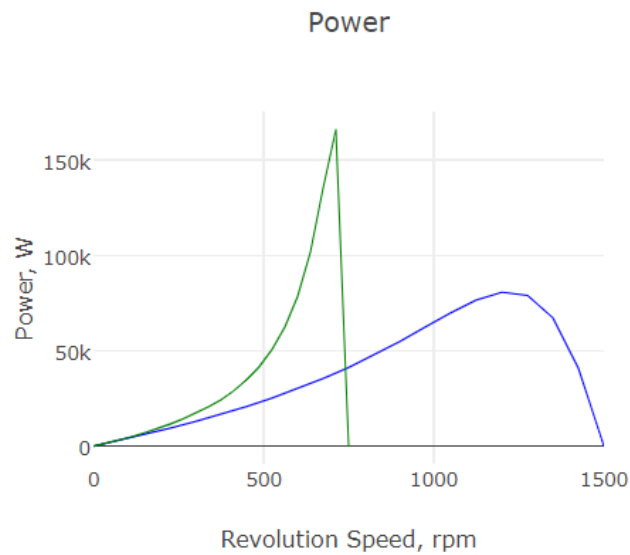


Figure 25. POLES Power Graphic

GAP

Base Value: 1.2 mm

The space you live between the rotor and the stator, commonly known as “Air Gap”.

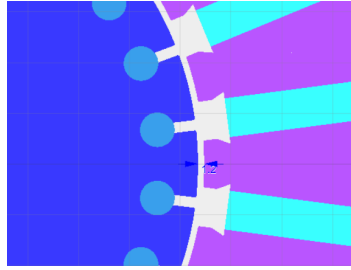


Figure 26. GAP

For the analysis of this parameter, the diameter of the stator and the rotor are of great importance. That's why for the comparison I've only been able to decrease its value, because an increment would make an error in the design.

As the graphics show, by decreasing the air gap distance, we can make an improvement in the Torque, Power and Efficiency, but by decreasing it a lot we can make the motor unstable, that's why we cannot bring it down to almost 0, what would be mathematically optimum.

Table 3. GAP Cases

Case	Value
Case 8	Base Value
Case 13	0.7 mm

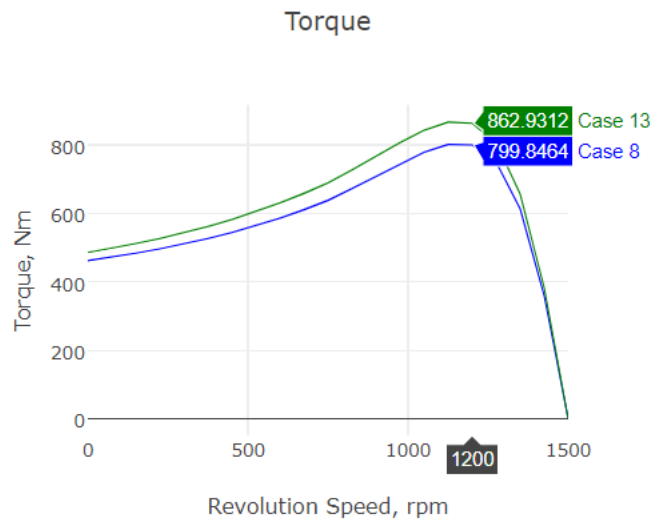


Figure 27. GAP Torque Graphic

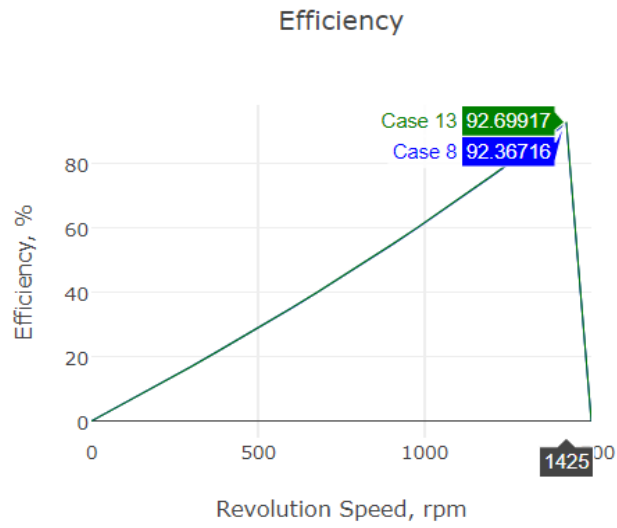


Figure 28. GAP Efficiency Graphic

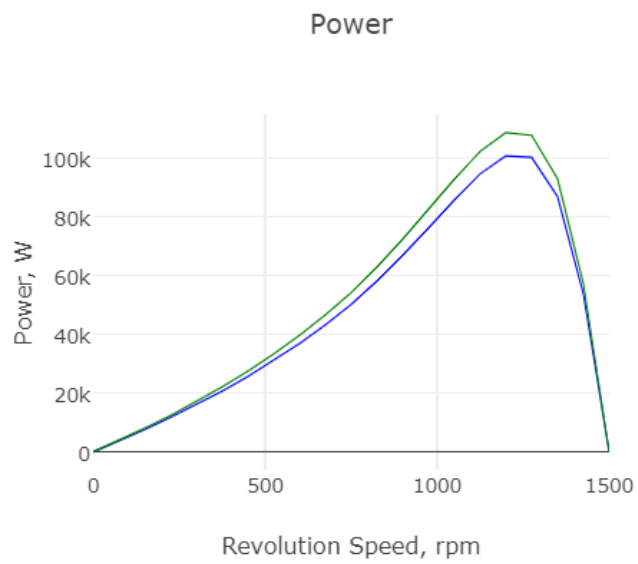


Figure 29. GAP PowerGraphic

SLOTS

Base Value: 24

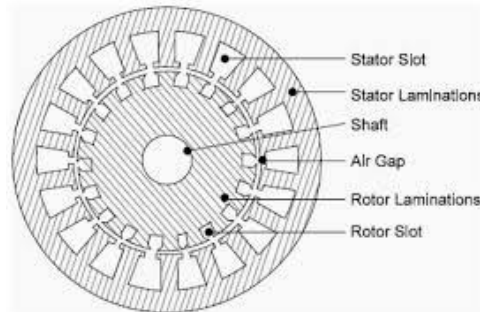


Figure 30. SLOTS

The slots are an important part of the motor for the winding part of the design. A variation in the number of slots could make a great variation in the motor values but could make it much more complex for the construction of the motor, due to its importance in the windings.

Decreasing the number of slots, we can achieve a great increment in the Torque and the Power, but we dangerously decrease the efficiency of the motor. In the opposite site, if we increase the number of slots, we lose torque and power (not in the same scale), but we increase the efficiency.

Table 4. SLOTS Cases

Case	Value
Case 8	Base Value
Case 16	36
Case 17	12

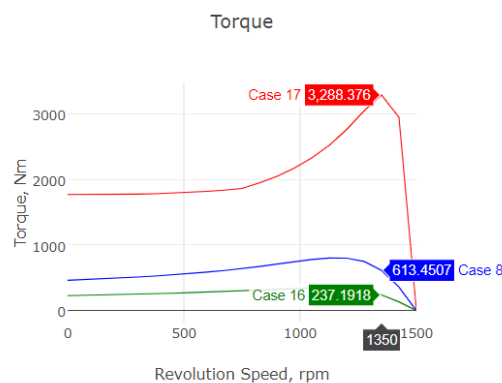


Figure 31. SLOTS Torque Graphic

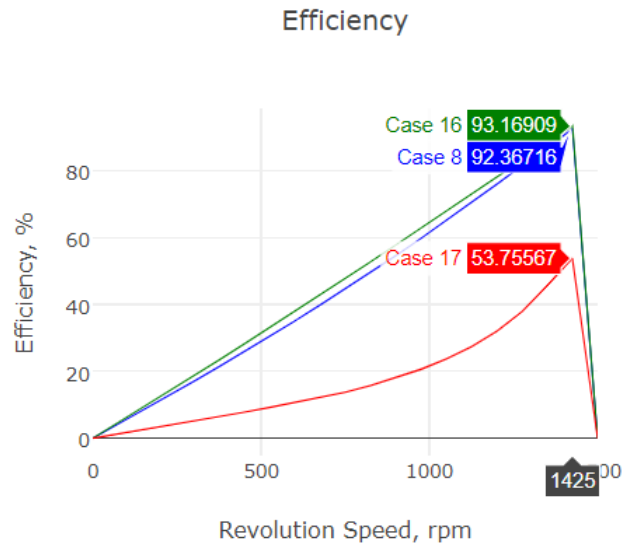


Figure 32. SLOTS Efficiency Graphic

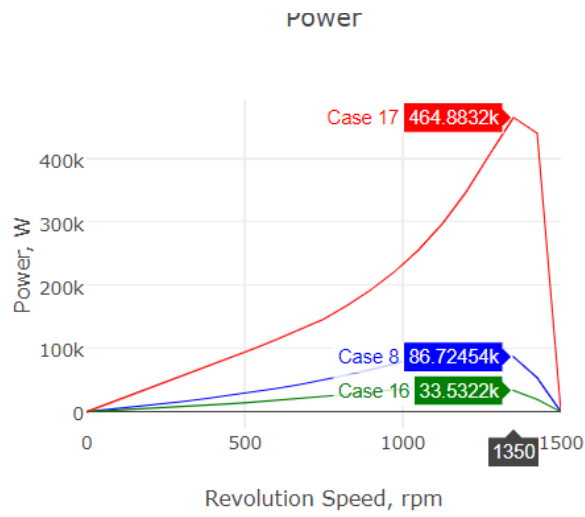


Figure 33. SLOTS Power Graphic

SD4

Base Value: 129.4 mm

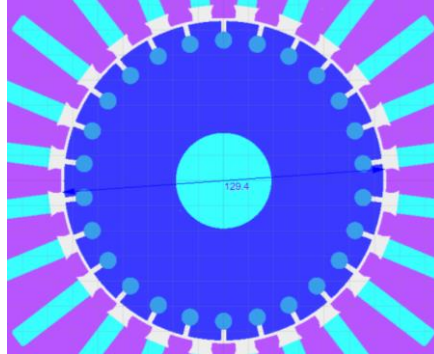


Figure 34. SD4

The inside diameter of the stator, which is strongly influenced by the Rotor's outside radius and the air gap dimension.

The results of decreasing it are equivalent to the ones achieved by decreasing the air gap dimension, we can increment the efficiency, power and torque, but we can make the motor unstable if we reduce it too much, being hard to find an optimum dimension for this parameter.

Table 5. SD4 Cases

Case	Value
Case 8	Base Value
Case 35	128 mm
Case 36	130 mm

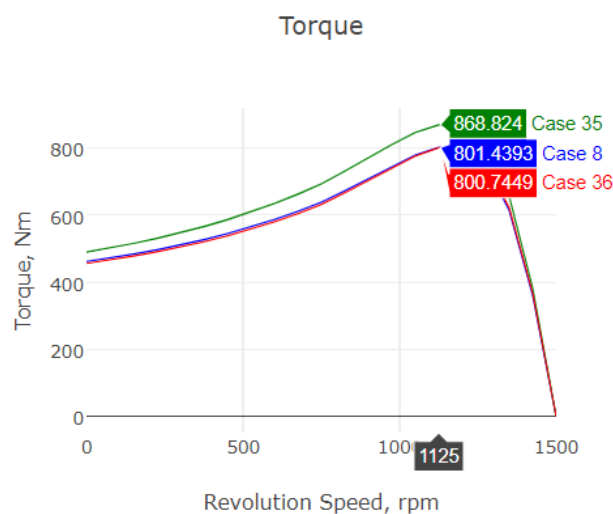


Figure 35. SD4 Torque Graphic

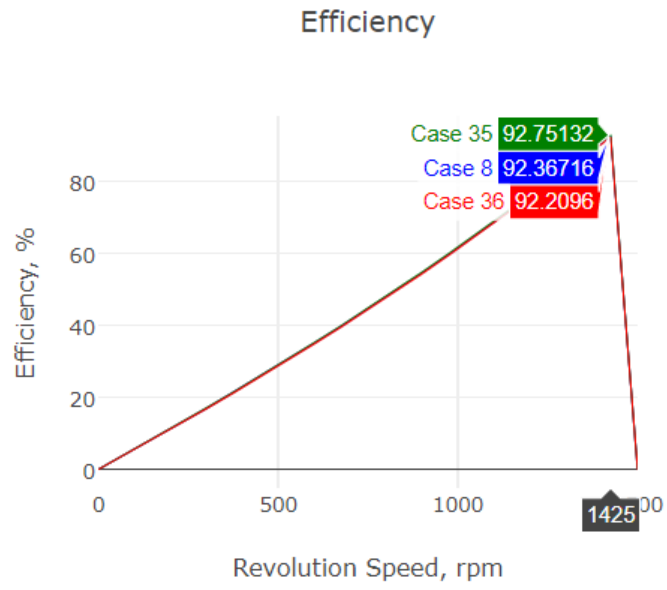


Figure 36. SD4 Efficiency Graphic



Figure 37. SD4 Power Graphic

SW3

Base Value: 7.726 mm

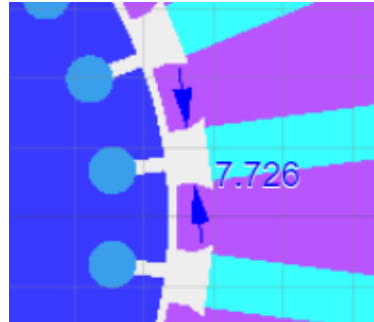


Figure 38. SW3

This number refers to the slot's width. Making a variation in its value we can see that it doesn't give a great impact in the reference results of the motor, it's more important for the stability of the motor.

By incrementing it we can gain Torque and Increase the efficiency, but we lose efficiency. In the other hand, by decreasing it, the three results decrease.

Table 6. SW3 Cases

Case	Value
Case 8	Base Value
Case 39	7.3 mm
Case 40	7.2 mm

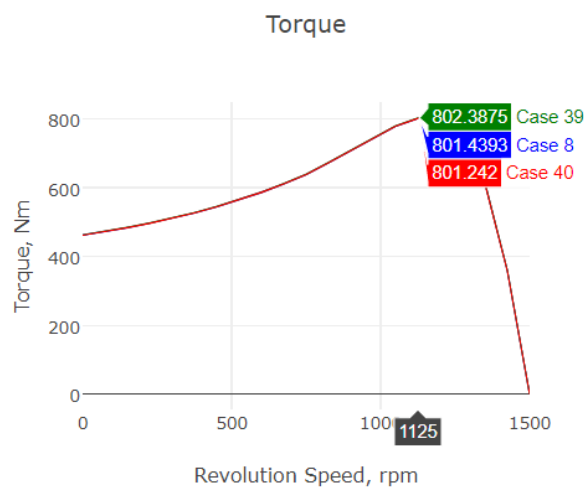


Figure 39. SW3 Torque Graphic

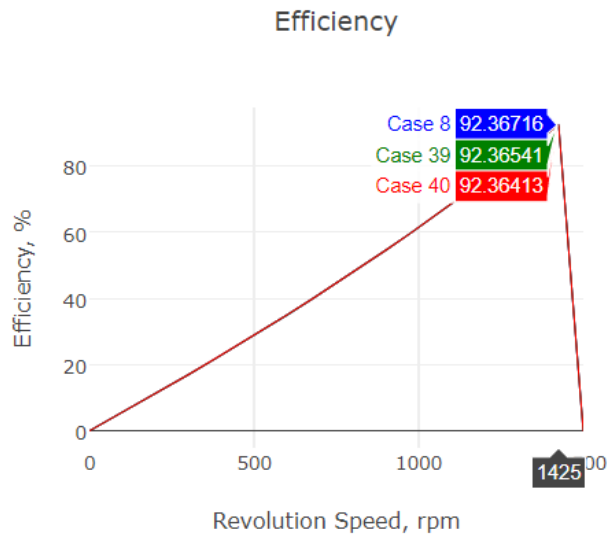


Figure 40. SW3 Efficiency Graphic

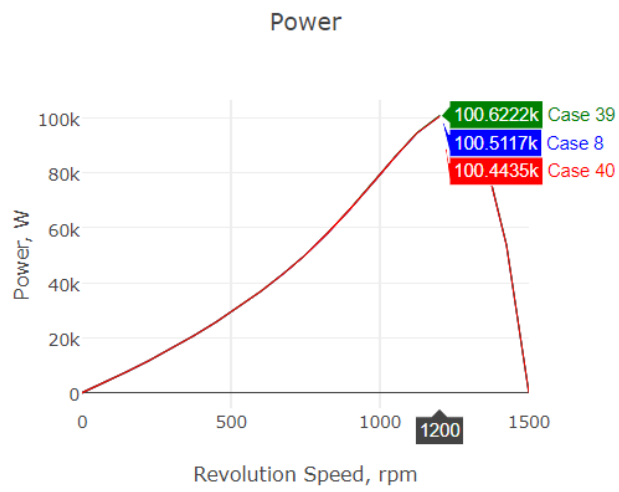


Figure 41. SW3 Power Graphic

SW4

Base Value: 23.07 mm

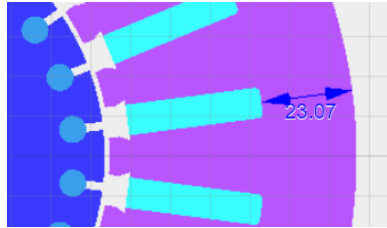


Figure 42. SW4

This value refers to the core back width. Its change doesn't cause a great variation in the main results of the motor, but these changes are not negligible. The value is more important for magnetic properties of the stator and stability.

Rising the width, we can see a decrement in the maximum torque and in the maximum power, but a rise in the efficiency, doing exactly the opposite variation in the case of a reduction of this width.

Table 7. SW4 Cases

Case	Value
Case 8	Base Value
Case 42	22 mm
Case 43	23 mm

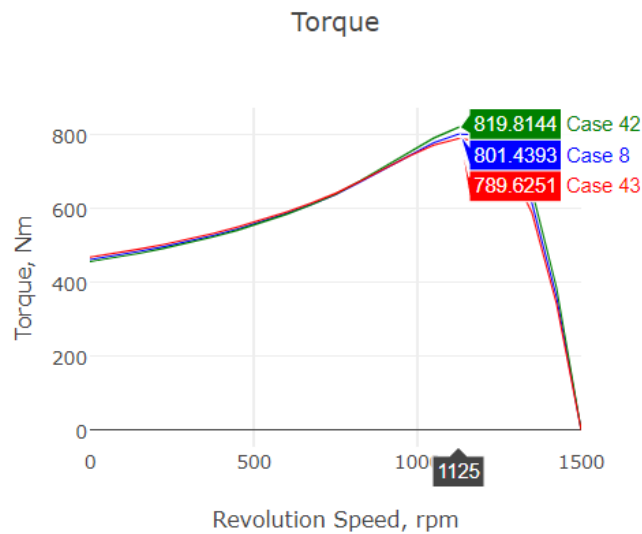


Figure 43. SW4 Torque Graphic

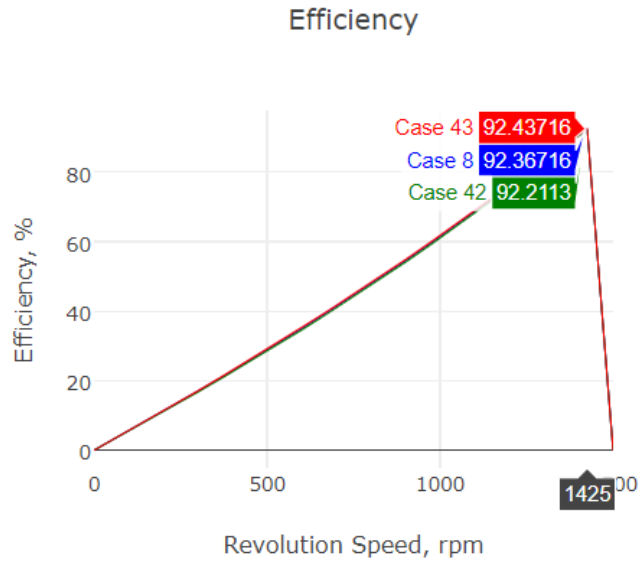


Figure 44. SW4 Efficiency Graphic



Figure 45. SW4 Power Graphic

ST

Base Value: 5.126

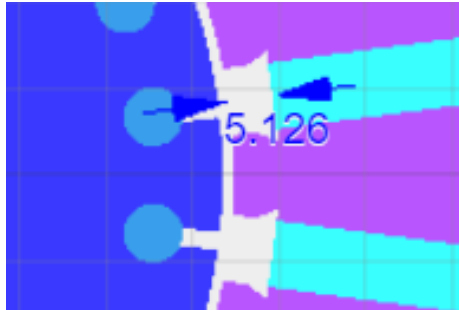


Figure 46. ST

This dimension refers to the tooth tang depth. The variation of this dimension makes a similar impact in the results to the Air Gap, making it as well important for the stability and the correct working of the motor.

A decrease on its value produces a rise in the maximum torque and power, but a fall in the efficiency, making the complete reverse result in the opposite case, in the case of an increase of the depth.

Table 8. ST Cases

Case	Value
Case 8	Base Value
Case 47	4.5 mm
Case 48	5.5 mm

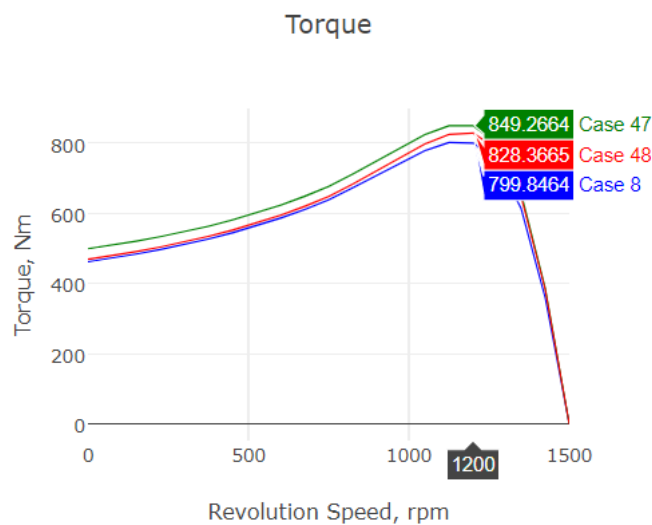


Figure 47. ST Torque Graphic

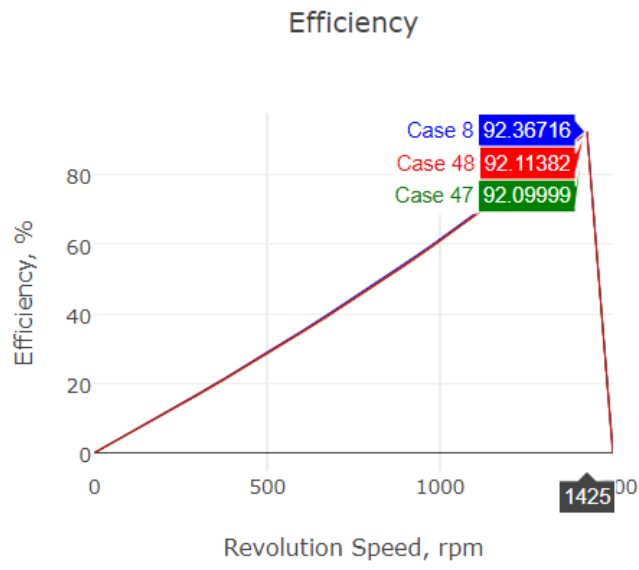


Figure 48. ST Efficiency Graphic

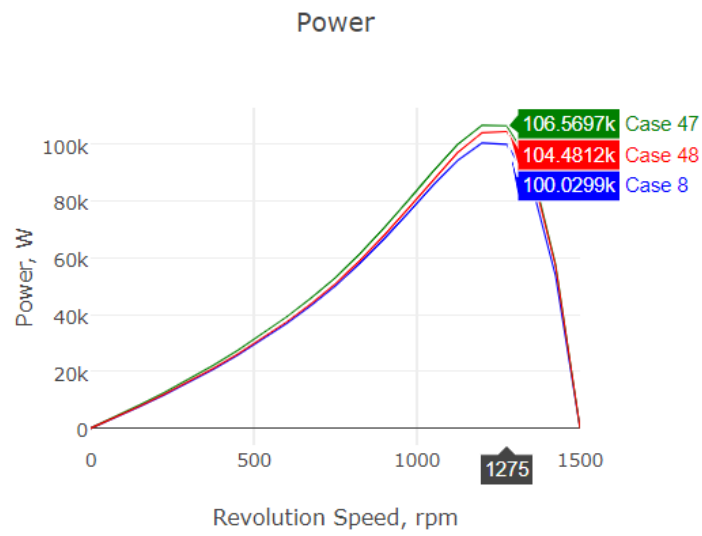


Figure 49. ST Power Graphic

SW5

Base Value: 2.55 mm

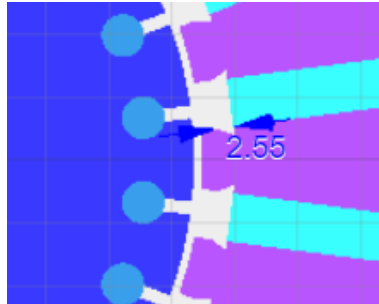


Figure 50. SW5

It makes reference to the wedge length, a dimension that varies the results less than the tooth tang depth but has the same repercussions in stability.

An increment of this dimension produces a higher maximum torque and efficiency than in the case of the base value, but with a lower efficiency. The decrement of the length produces the exact opposite result.

Table 9. SW5 Cases

Case	Value
Case 8	Base Value
Case 55	2.1 mm
Case 56	2.9 mm

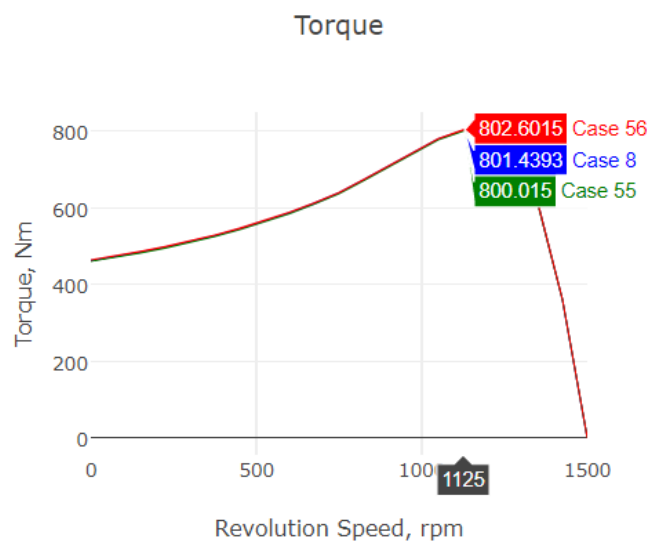


Figure 51. SW5 Torque Graphic

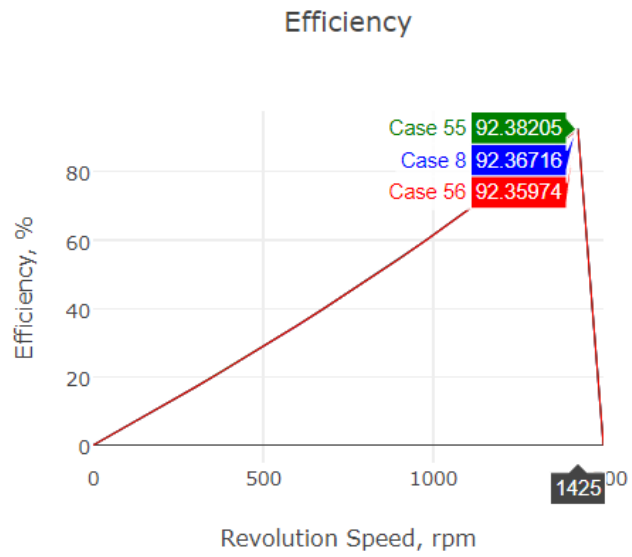


Figure 52. SW5 Efficiency Graphic

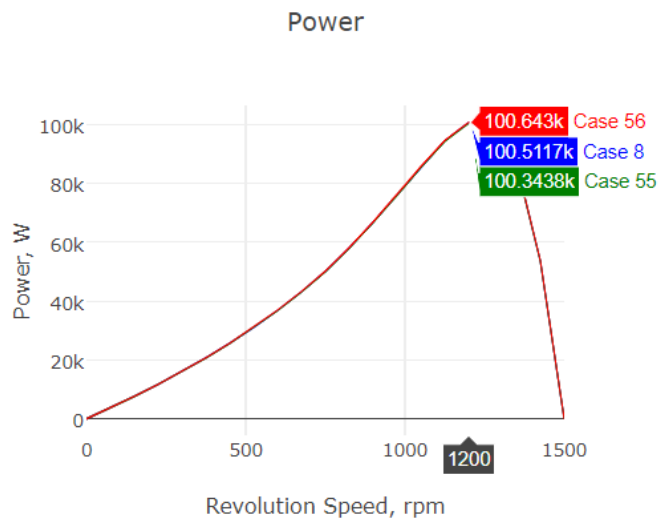


Figure 53. SW5 Power Graphic

STD2

Base Value: 1.307 mm

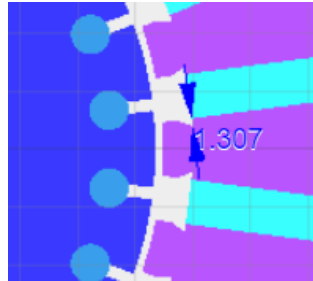


Figure 54. STD2

This dimension refers to the Wedge Depth, a value that cannot vary in great quantities without compromising the stability and producing a malfunction.

Its variation produces small changes in the results but could be useful for a more accurate optimization of the motor. A decrement of it produces a rise on the three main results (Maximum Torque, Power and Efficiency), making the inverse result in the opposite.

In parameters such as this or the air gap we can also optimized the amount of material used in the motor and the weight without reducing in a great way the motor final specs.

Table 10. STD2 Cases

Case	Value
Case 8	Base Value
Case 57	1 mm
Case 58	1.6 mm

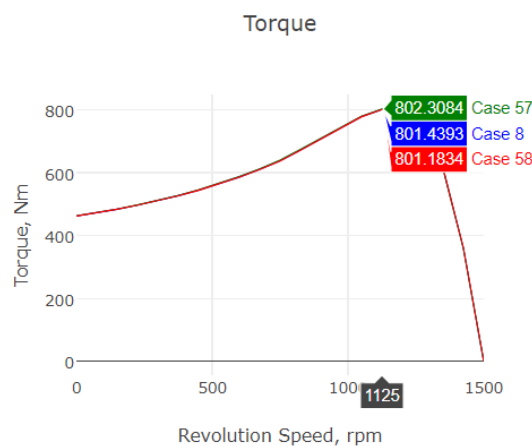


Figure 55. STD2 Torque Graphic

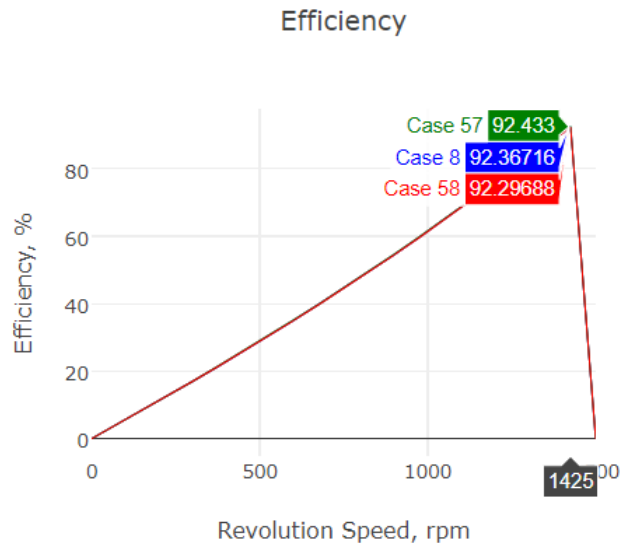


Figure 56. STD2 Efficiency Graphic

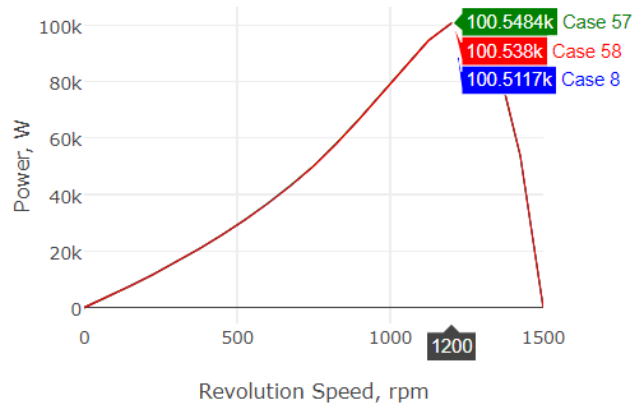


Figure 57. STD2 Power Graphic

SF1 and SF2

They make reference to the teeth top R and the slot bottom R dimensions. They are almost negligible for the results we are highlighting in this project, but there are important for other results, such as the Cooper losses.

BARS

Base Value: 26

It refers to the number of secondary conductors. The variation of this parameter makes a great difference in the results, not all of the number of bars are possible, cause it could make the model mathematically impossible

for the motor if it is not even, and it matters as well the relation with the number of slots.

If we increment the number of bars, we gain a great quantity of maximum torque and power, but we have a considerable loss of efficiency. A decrement would produce the opposite result. This parameter is one of the most important in which to impact on result refers.

Table 11. BARS Cases

Case	Value
Case 8	Base Value
Case 57	24
Case 58	12
Case 59	20
Case 60	28
Case 61	36

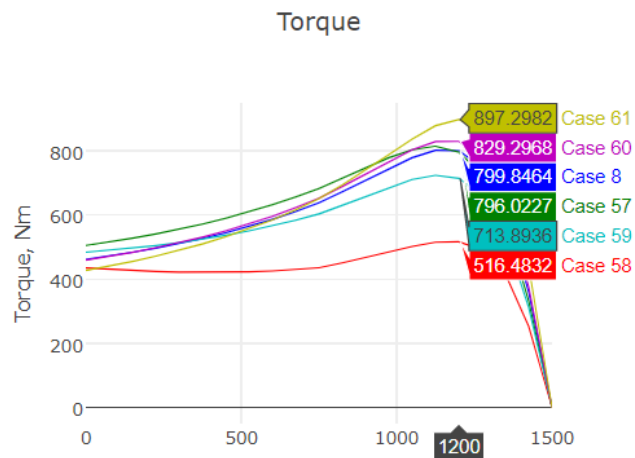


Figure 58. BARS Torque Graphic

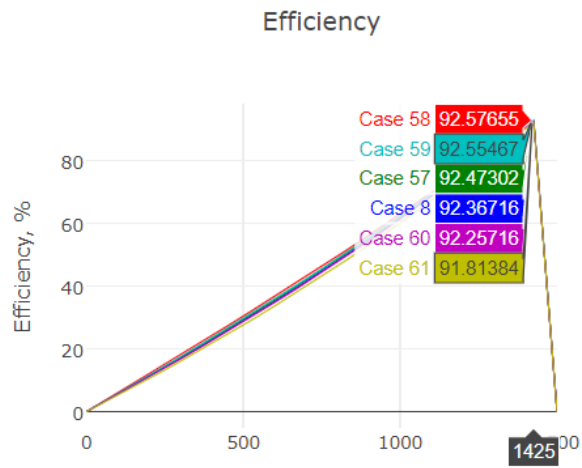


Figure 59. BARS Efficiency Graphic

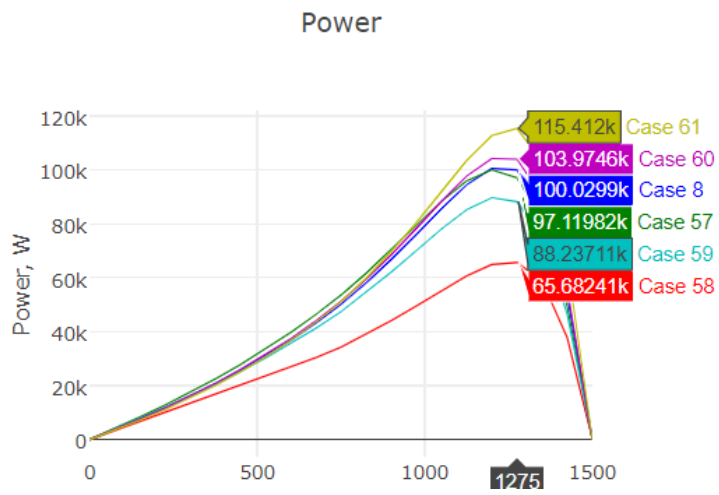


Figure 60. BARS Power Graphic

RD1

Base Value: 127 mm

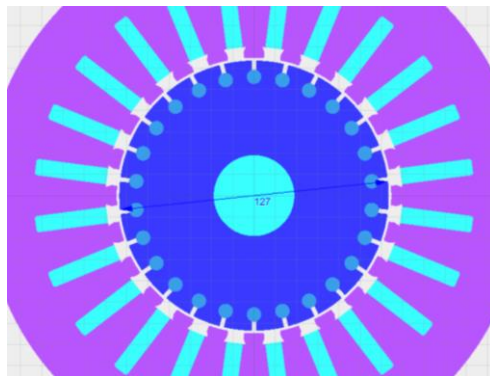


Figure 61. RD1

It refers to the outside diameter of the rotor. This value is directly related to the air gap width and the stator outside diameter.

An increment of its value produces a great ascension in the resultant maximum torque, efficiency and power, but increments the volume and the weight of the motor as well, that's why we should look for an optimum point of the 5 named parameters.

Table 12. RD1 Cases

Case	Value
Case 64	Base Value
Case 65	128 mm
Case 66	126 mm

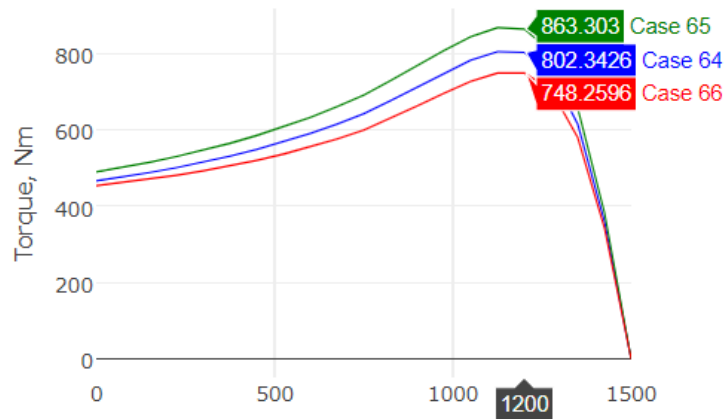


Figure 62. RD1 Torque Graphic

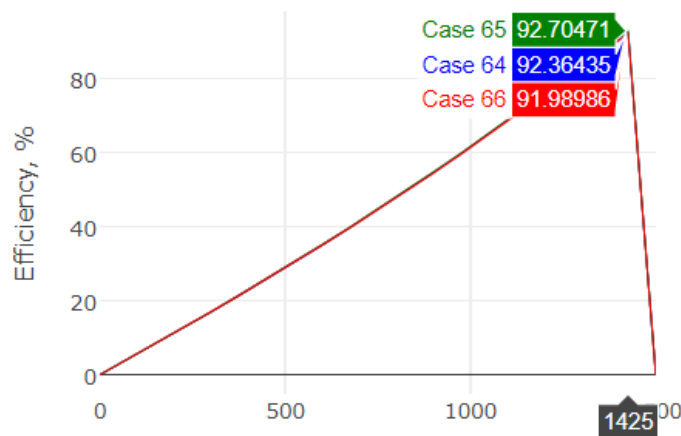


Figure 63. RD1 Power Graphic

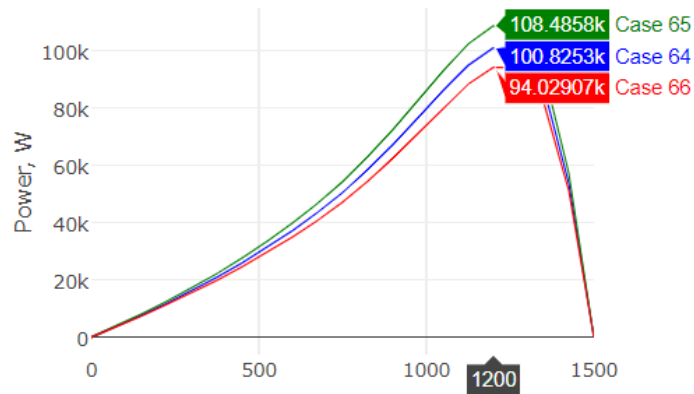


Figure 64. RD1 Power Graphic

RL1

Base Value: 38 mm

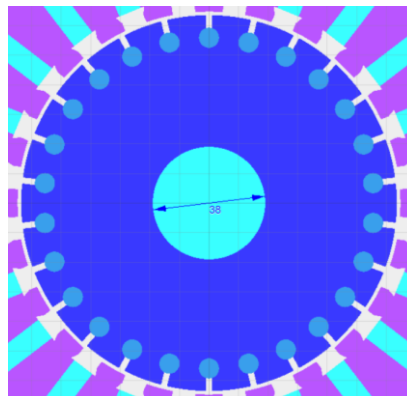


Figure 65. RL1

This parameter refers to the shaft diameter. Its variation doesn't make a great change in the results, but it matters for topics such as the resistant torque or the structural analysis of the shaft.

An increment of the shaft diameter makes a little decrease in torque, power and efficiency, making the opposite result in the opposite case of a decrement on its value.

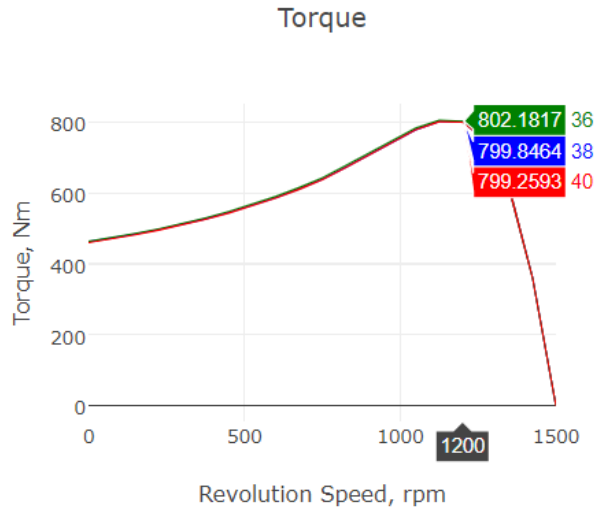


Figure 66. RL1 Torque Graphic



Figure 67. RL1 Efficiency Graphic

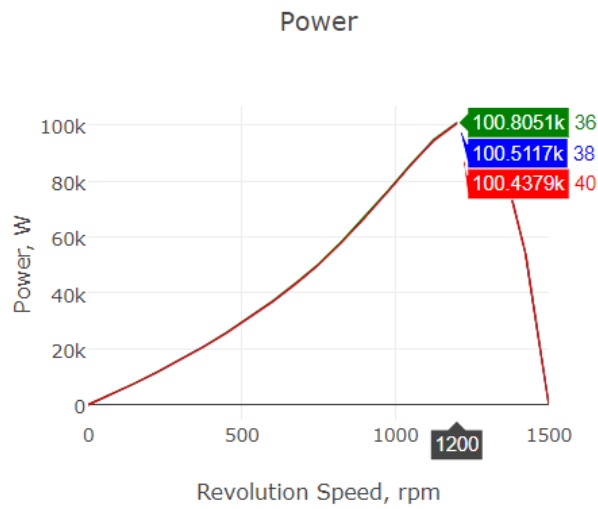


Figure 68. RL1 Power Graphic

RB1

Base Value: 6.81 mm

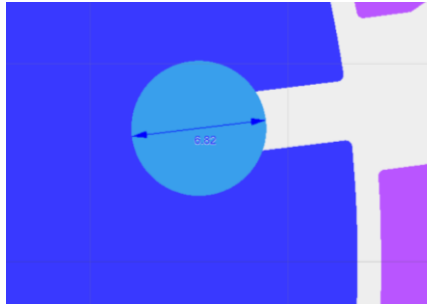


Figure 69. RB1

This parameter adjusts the rotor's bars diameter. This point is important for things like the magnetic fields generated, the stability of the complexity of construction of the motor, as well as making a great change in the analysed results.

A decrement on this diameter makes an ascension in the torque, efficiency and power specs, but it puts in risk the stability of the motor and the complexity of its construction, as I've said before.

Table 13. RB1 Cases

Case	Value
Case 64	Base Value
Case 72	6 mm
Case 73	9 mm

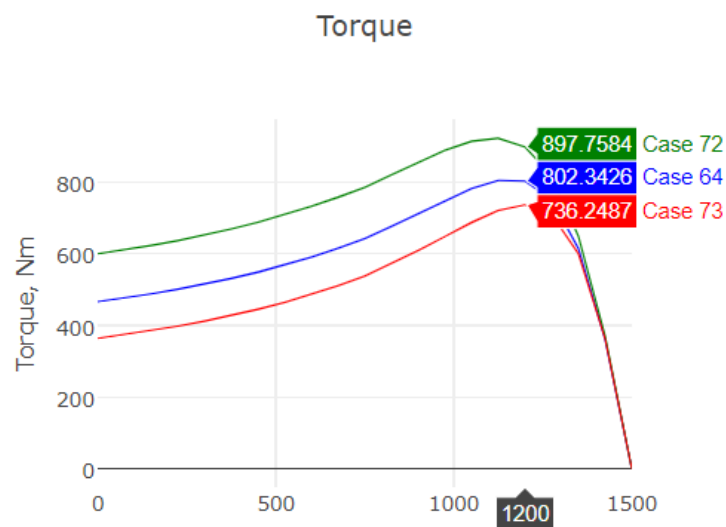


Figure 70. RB1 Torque Graphic

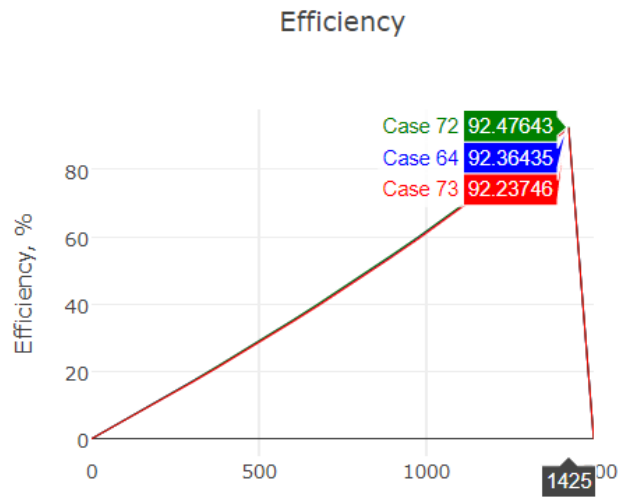


Figure 71. RB1 Efficiency Graphic

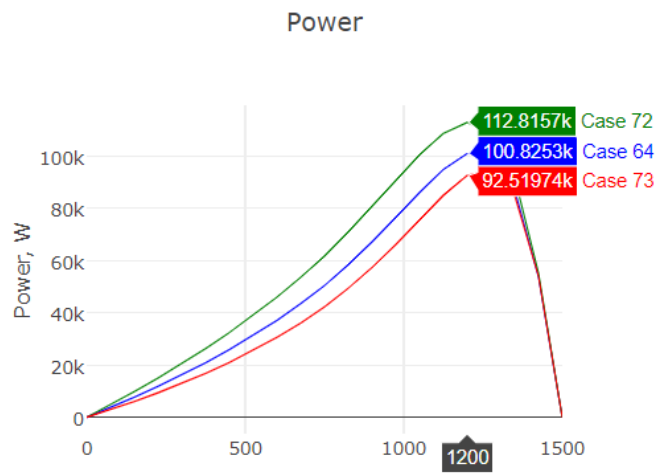


Figure 72. RB1 Power Graphic

RC1

Base Value: 7.61

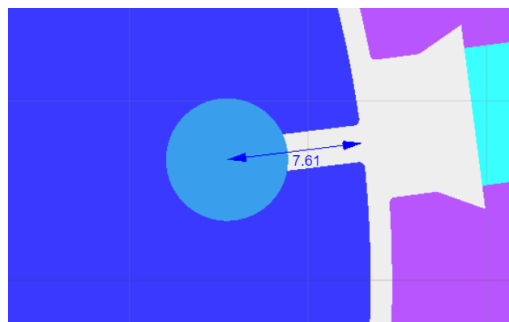


Figure 73. RC1

This value modulates the distance for the center of the bar to the outside diameter of the rotor.

Analyzing the variation of this value, I have reached the conclusion that, for very little decrement, we can have a great increase in the maximum torque, efficiency and power, but having in count that we risk the functionality of the motor if we reduce it too much.

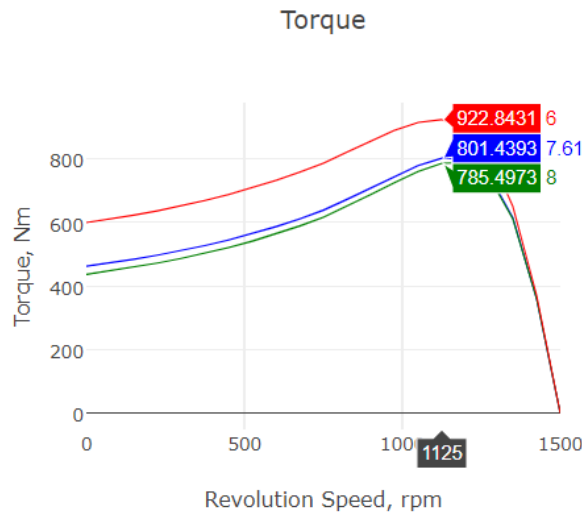


Figure 74. RC1 Torque Graphic

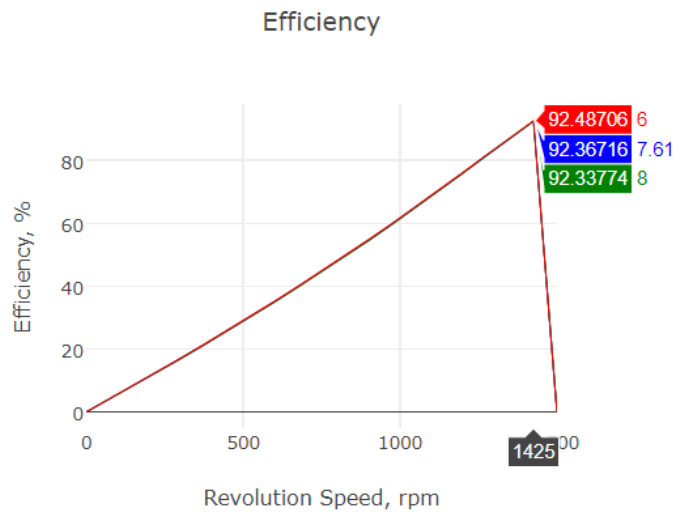


Figure 75. RC1 Efficiency Graphic

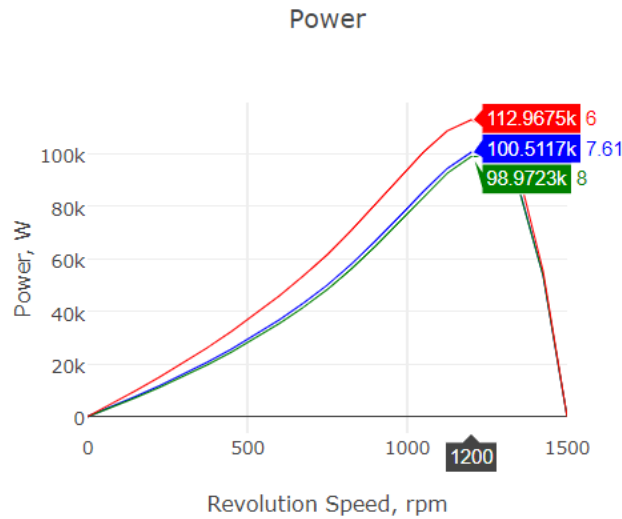


Figure 76. RC1 Power Graphic

RW1

Base Value 2.05

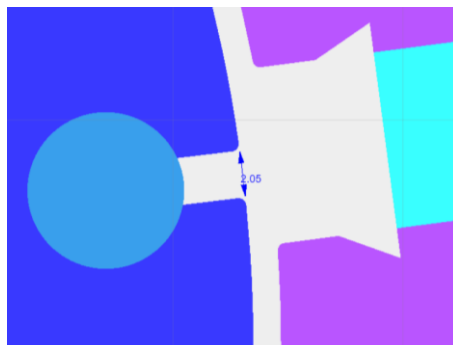


Figure 77. RW1

This value varies the slot opening width. This parameter is directly related with the air gap that we named before, making its variation have similar effects than the air gap's.

A reduction of this width produces a rise of the motor efficiency, as well as favoring the stability of the system, but producing a lower maximum torque and power.

Table 14. RW1 Cases

Case	Value
Case 64	Base Value
Case 74	1 mm
Case 75	3 mm

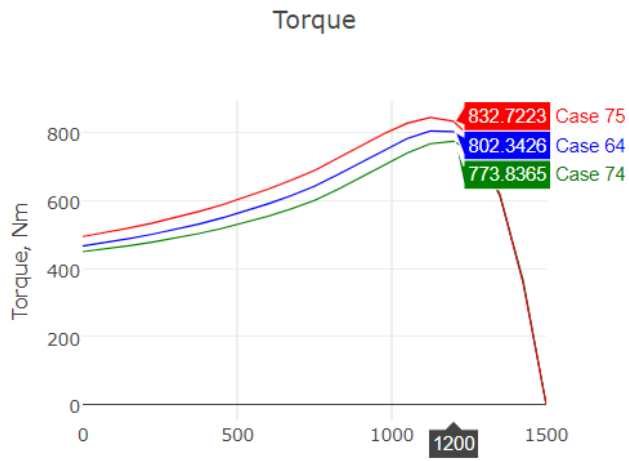


Figure 78. RW1 Torque Graphic

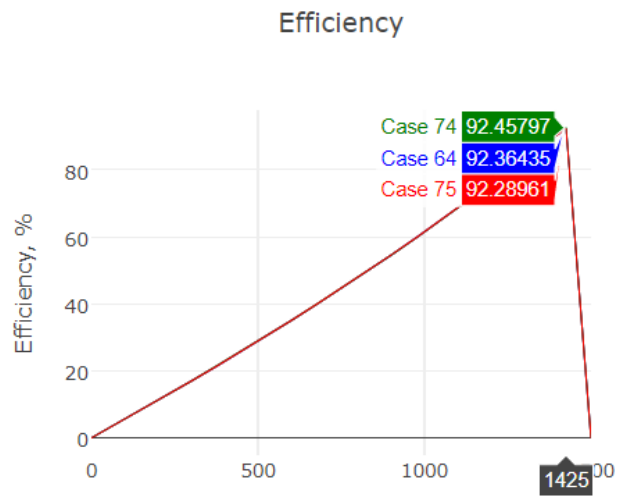


Figure 79. RW1 Efficiency Graphic



Figure 80. RW1 Power Graphic

End Ring

There are two main possibilities for this parameter: the first is making the same figure for both parts of the end ring, and the second is making them different. Trying all the possible combinations of the second case I've reached the conclusion that the same for both parts is much more optimal for our design,

Inside the figures, we have three possible cases: Trapezoid, Rectangular or introducing the section's area. As the next graphics reflects, the more efficient for our motor is the Section Area, but, thanks to the research done in this topic, the more stable that gives less trouble for the post analysis is the trapezoid, that's why I have chosen that one for my design.

Table 15. End Ring Cases

Case	Value
Case 64	Trapezoid
Case 77	Rectangular
Case 78	Section Area

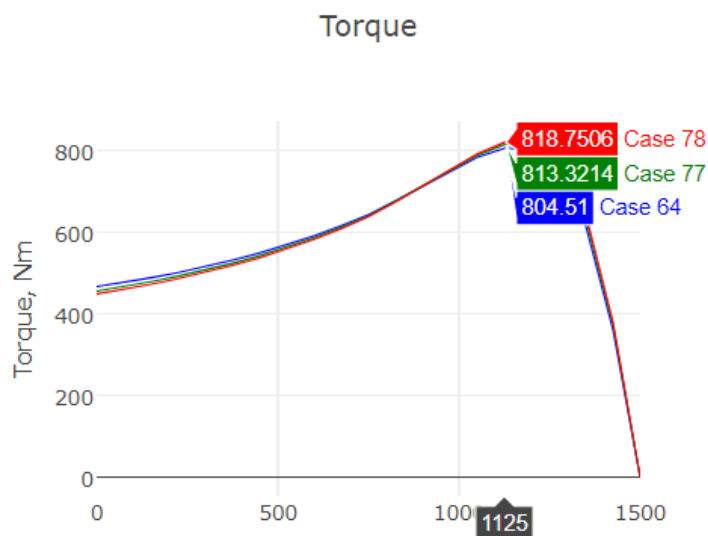


Figure 81. END RING Torque Graphic

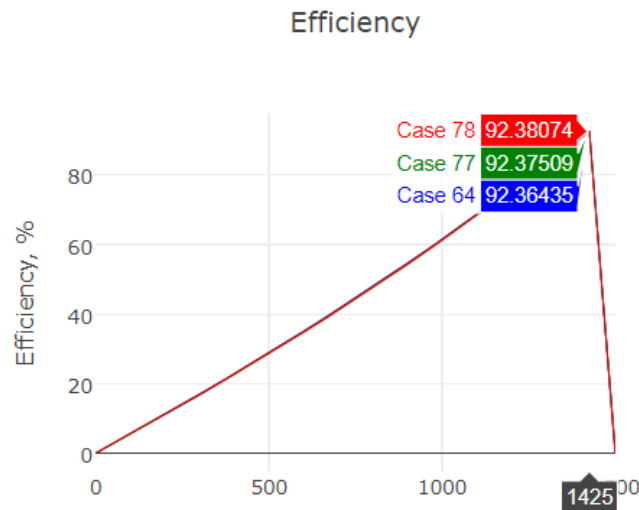


Figure 82. END RING Efficiency Graphic

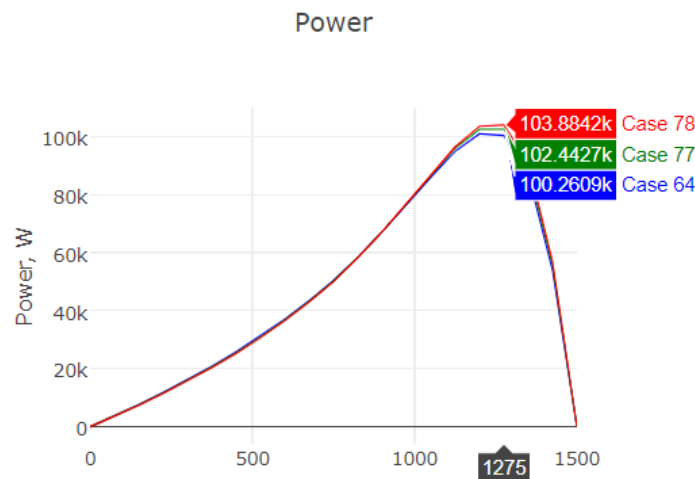


Figure 83. END RING Power Graphic

5.1.2.2. Materials

In this part I will analyze the different materials that we can use in the motor components. For this choice I have not only had in count the results of the efficiency, torque and power, although I have analyzed the cost of the chosen material.

Stator Core

Analyzing all the possible materials, I've decided to use the 50A100 (A Cold Rolled Silicon Steel Coil) due to its reduced price and its results that fits perfectly with our goals. In addition to this, I would like to include the analysis of the other possible materials.

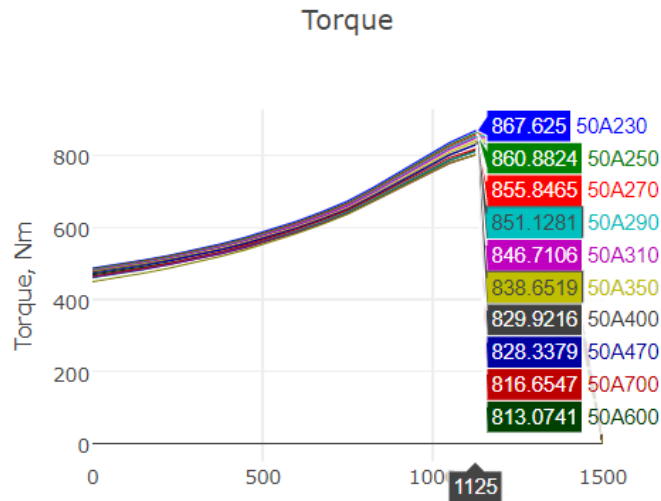


Figure 84. Stator Core Torque Graphic

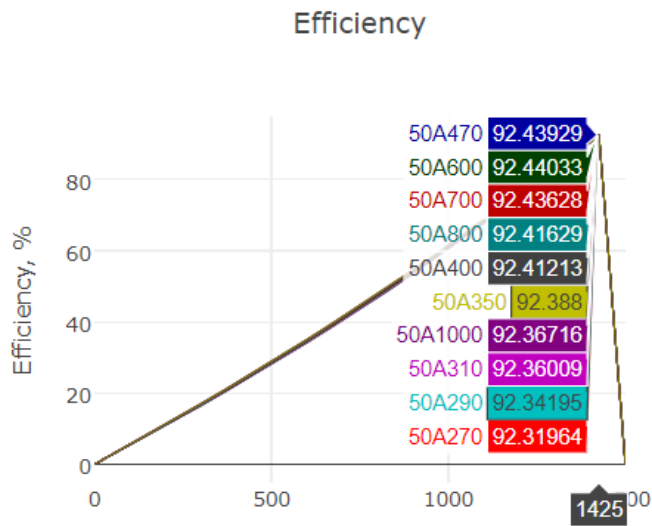


Figure 85. Stator Core Efficiency Graphic

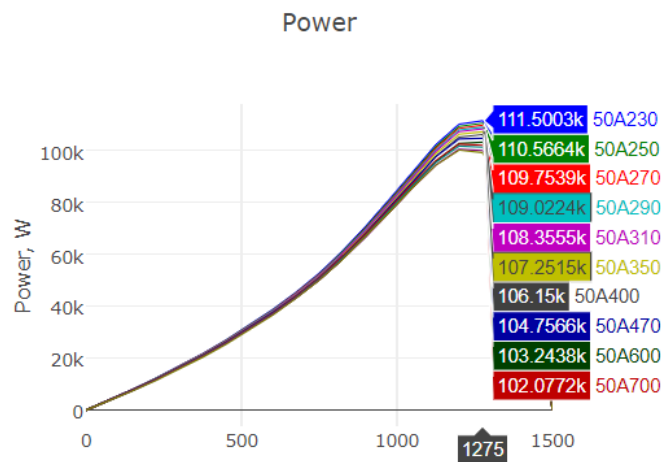


Figure 86. Stator Core Power Graphic

Rotor Core

Analyzing all the possible materials, I've decided to use the 50A100 (A Cold Rolled Silicon Steel Coil) for the same reasons I have said before for the stator's material, due to its reduced price and its results that fits perfectly with our goals. In addition to this, I would like to include the analysis of the other possible materials.

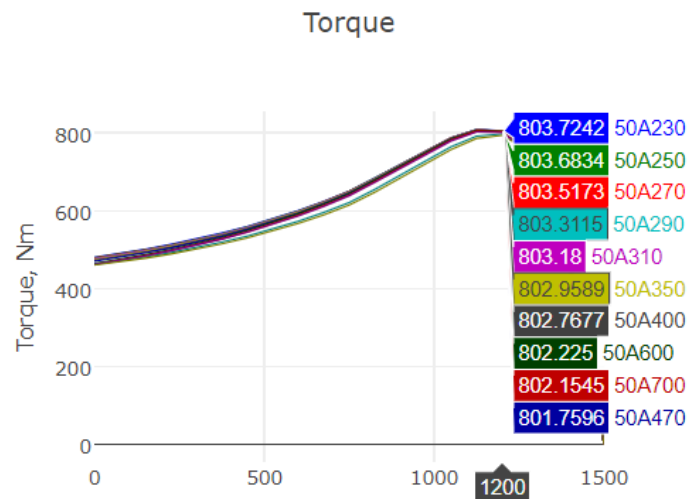


Figure 87. Rotor Core Torque Graphic

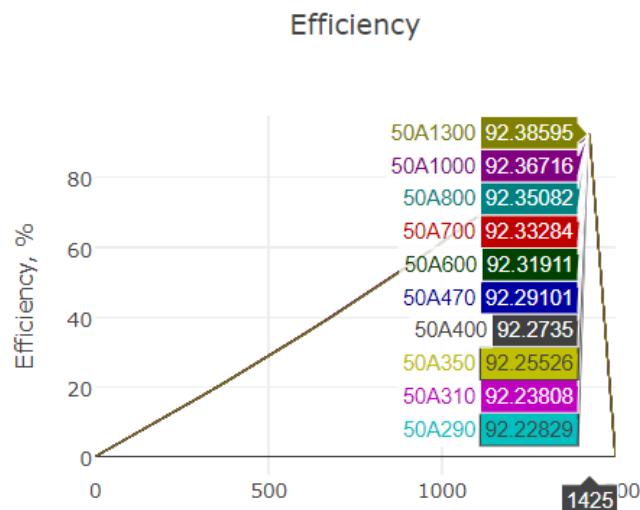


Figure 88. Rotor Core Efficiency Graphic

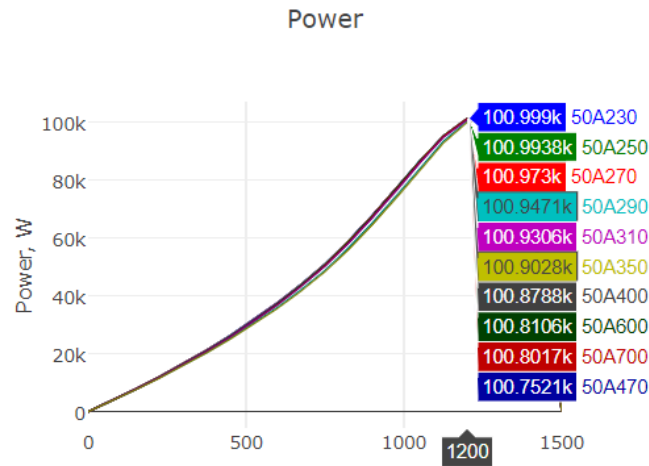


Figure 89. . Rotor Core Power Graphic

Coil

For this part of the motor we can choose between the two most common materials used: Cooper and Aluminum. In the analysis I could saw that the results where the same for the two material, it just changed in the post analysis of the design, changing some parameters that matters on the stability analysis, but not creating a huge difference.

Cage

With this component we have the two same options as for the Coil: Aluminum and Cooper. But, in this case, they make a great variation in the results. Analyzing both, I have chosen the Cooper due to its better performance. Having in count that the Aluminum produces an increment in the efficiency but is not make up for the loss of Torque and Power.

Table 16. Cage Cases

Case	Value
Case 14	Cooper
Case 15	Aluminum

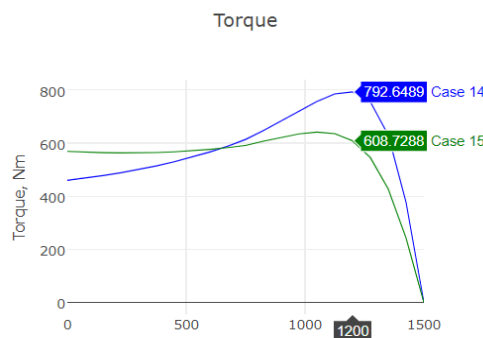


Figure 90. Cage Torque Graphic

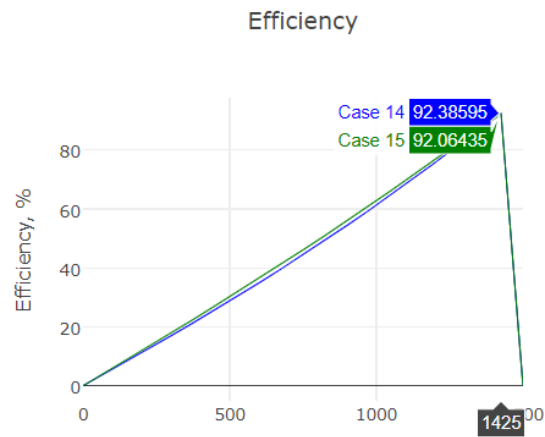


Figure 91. Cage Efficiency Graphic

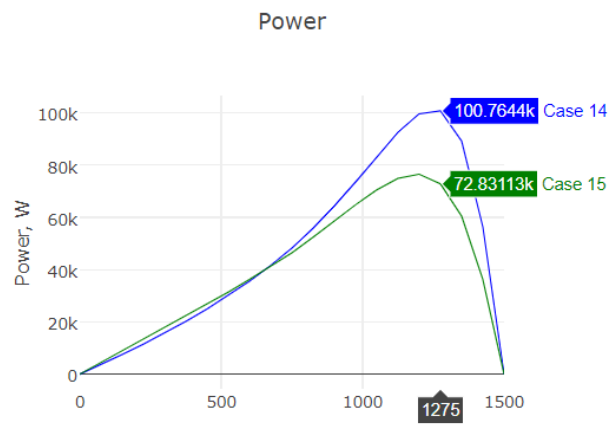


Figure 92. Cage Power Graphic

5.1.2.3. Winding

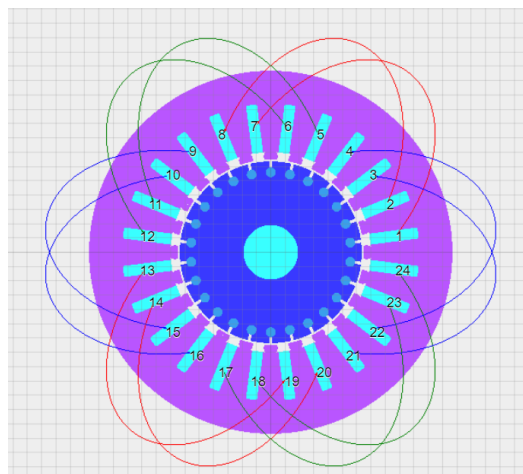


Figure 93. Induction Motor Winding

Connections

For this aspect we can chose between two possible connections: the star connection and the delta connection. For both we can also decide the number of parallel that they will have, 1, 2 or 4.

After analyzing all the different possibilities, the star connection with one parallel is the simplest and more optimal for my design. Although, there is not much difference between both types of connection on which to the results refers, but it affects the electrical analysis of the machine and its complexity.

Star Connection:

- Case 4: 1 Parallel
- Case 5: 2 Parallels
- Case 6: 4 Parallels

Delta Connection:

- Case 7: 1 Parallel
- Case 8: 2 Parallels
- Case 9: 4 Parallels

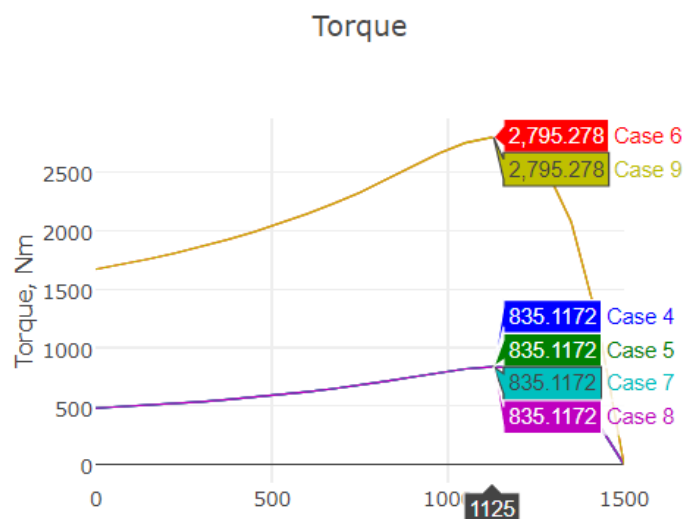


Figure 94. Connections Torque Graphic

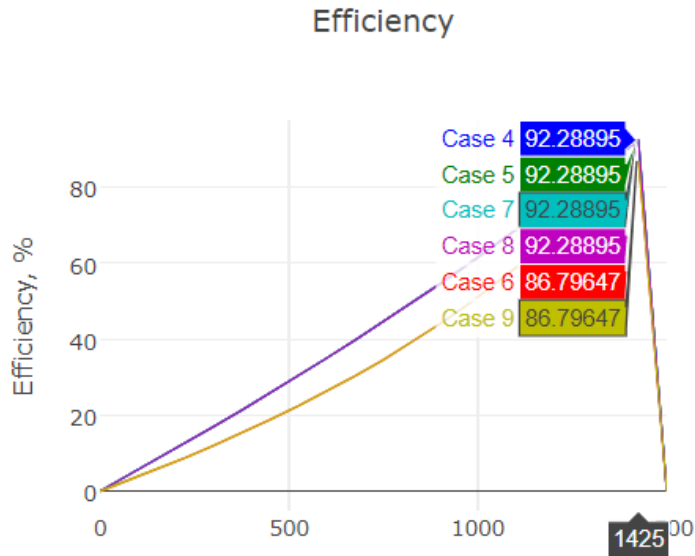


Figure 95. Connections Efficiency Graphic

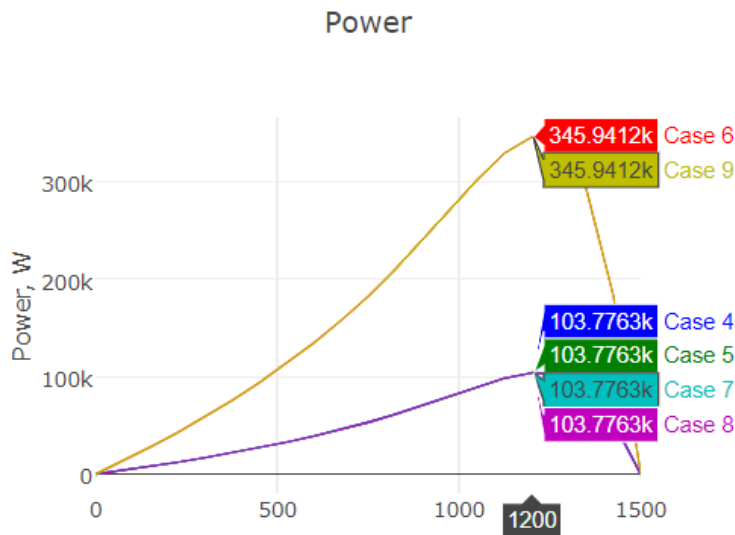


Figure 96. Connections Power Graphic

Number of Layers

This aspect of the winding affects directly to the resultant specs and to the difficulty of construction of the motor. We only have two options for this variable: one or two layers, but it changes completely the electrical and electrical schemes of the motor, as well as the results. The founded optimal point is with one layer only, in which we gain power and torque with few losses of efficiency.

Table 17. Number of Layers Cases

Case	Value
Case 26	1 layer
Case 27	2 layers

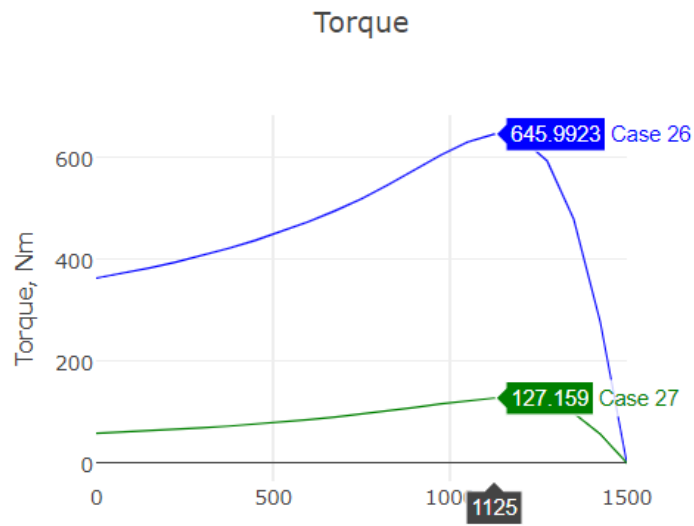


Figure 97. Number of Layers Torque Graphic

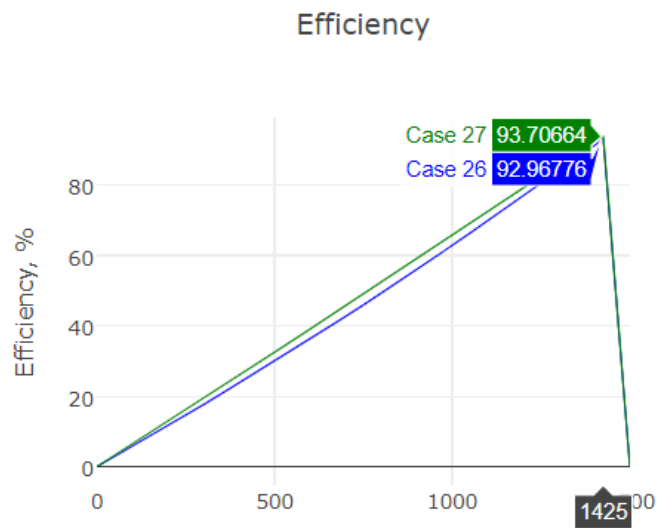


Figure 98. Number of Layers Efficiency Graphic

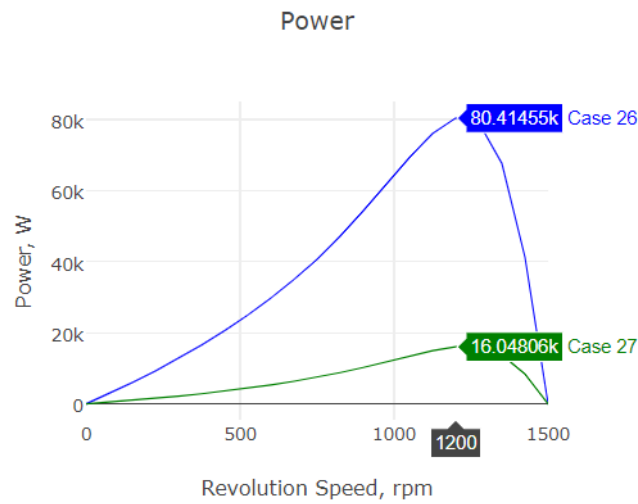


Figure 99. Number of Layers Power Graphic

Number of turns

This value changes as well the construction complexity and the resultant specs of the motor, but with this variable we have more freeness. Increasing the number of turns increases the complexity of the motor but improves the specs as well of it.

The optimal point I have founded in 20 turns, making the motor contractable and efficient at the same time.

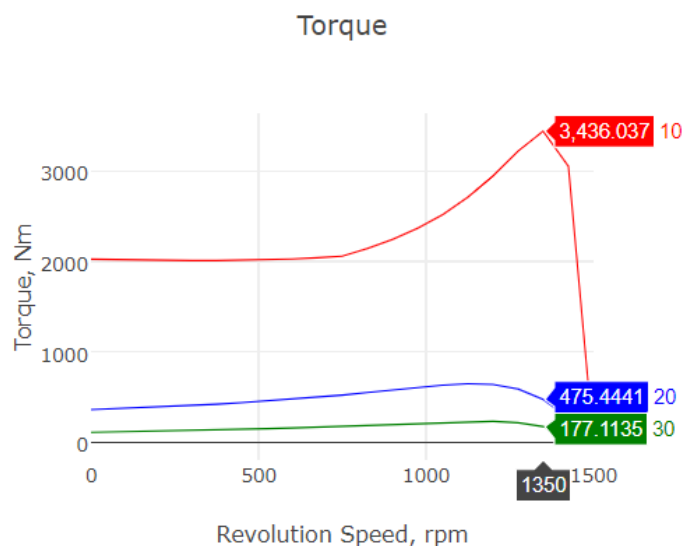


Figure 100. Number of turns Torque Graphic

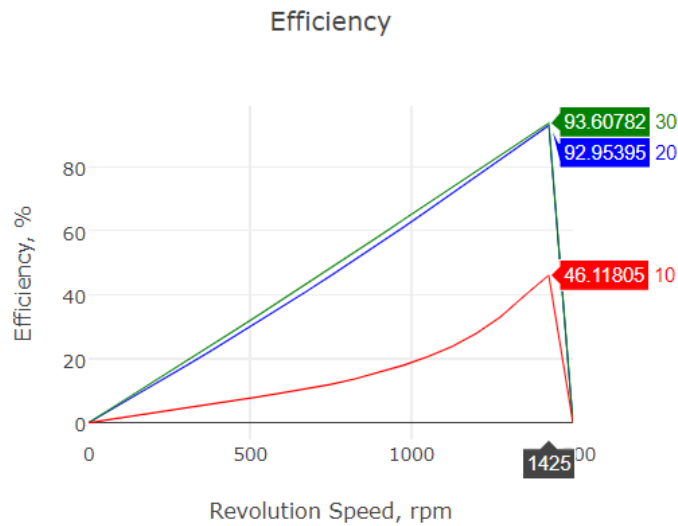


Figure 101. Number of turns Efficiency Graphic

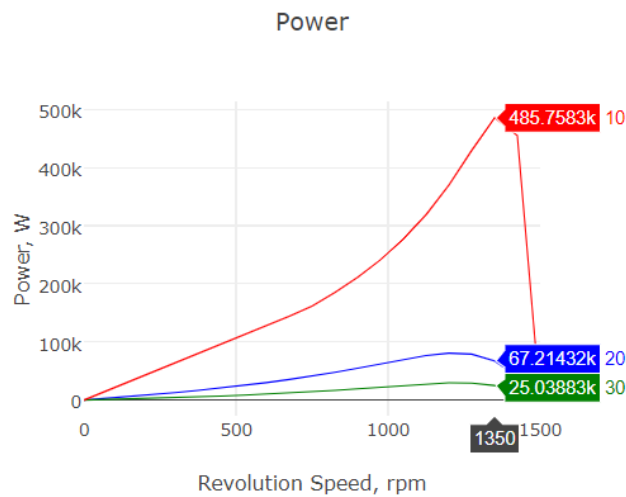


Figure 102. Number of turns Power Graphic

Pitch

The variation of this parameter makes the results completely different, making even the model unstable in some cases. Increasing the number of pitches produces a lower torque and power but makes a great increment in efficiency and gives stability to the model.

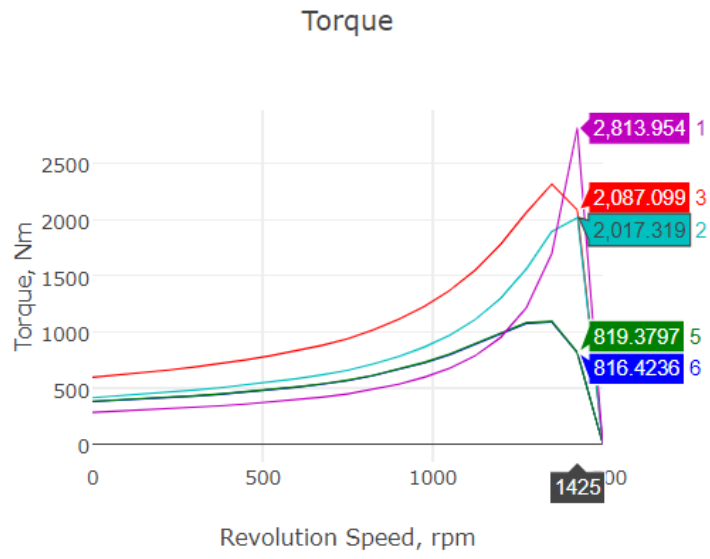


Figure 103. Pitch Torque Graphic



Figure 104. Pitch Efficiency Graphic

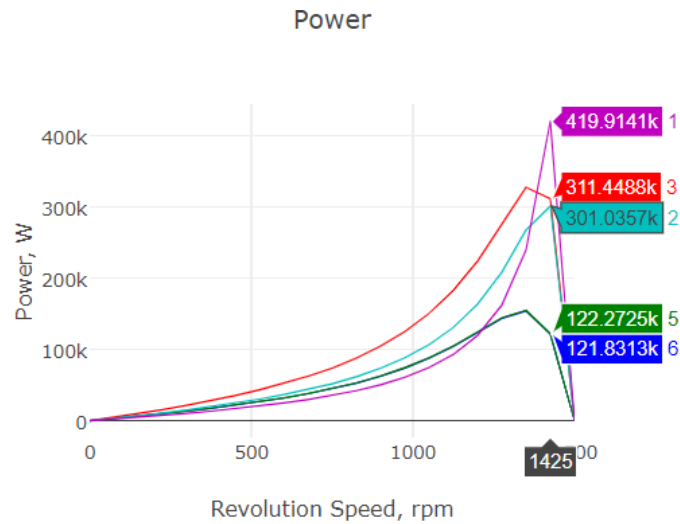


Figure 105. Pitch Power Graphic

5.1.3. Final Design

After doing several iterations, with the torque and power goal and the duty of optimizing to the maximum the efficiency, I have reached a final design that has outstand above the rest.

5.1.3.1. Parameters Value

The first step for the design is to choose the combination of Stator – Rotor. Depending of the duty and the final desire specs of the motor, the optimum combinations could vary. After a research on different sources, I’ve reached the conclusion that the next combination is the optimum for our kind of induction motor.

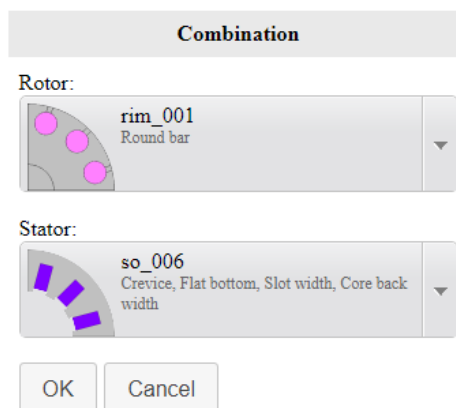


Figure 106. Stator – Rotor Combination

5.1.3.1.1. Dimensions

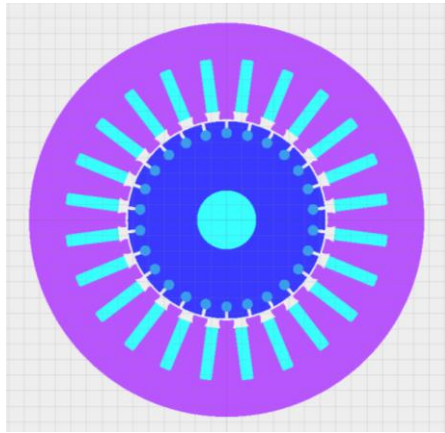


Figure 107. Final Design of the Induction Motor

General Parameters

Table 18. Induction Motor General Parameters

PARAMETERS	VALUE
OUTD	253.7 mm
GAP	1.2 mm
GAP TYPE	Free
HEIGHT	227.4 mm
POLES	4

Stator

Table 19. Induction Motor Stator

PARAMETERS	VALUE
SLOTS	24
SD1	253.7 mm
SD4	129.4 mm
SW3	7.726 mm
SW4	23.07 mm
ST	5.126 mm
SW5	2.9 mm
STD2	1.307 mm
SF1	0.3204 mm
SF2	1.281 mm

Rotor

Table 20. Induction Motor Rotor

PARAMETERS	VALUE
BARS	26
RD1	127 mm
RD2	37.9 mm
RL1	6.81 mm
RC1	7.2 mm
RW1	2.05 mm
RF1	0.34 mm

End Ring

Table 21. Induction Motor End ring

PARAMETERS	VALUE
SECTION SETTING	Same
SECTION TYPE	Trapezoid
CEH	6.516 mm
CEU	19.55 mm
CEL	19.55 mm
CEP	0
CES	100

5.1.3.1.2. Materials

Table 22. Induction Motor Materials

PARAMETERS	VALUE
STATOR CORE	Steel Sheets 50A1000
COIL	Cooper
ROTOR CORE	Steel Sheets 50A1000
CAGE	Cooper

5.1.3.1.3. Winding

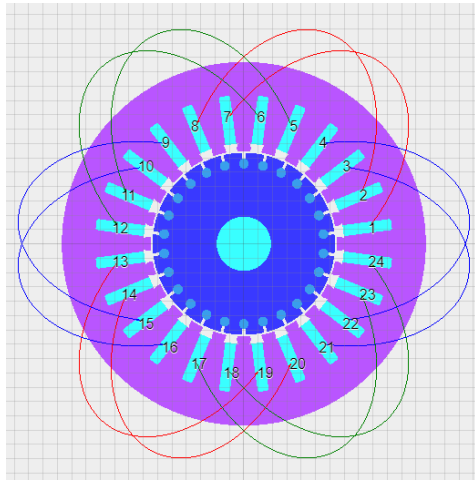


Figure 108. Winding Diagram of the Induction Motor,

Table 23. Induction Motor Winding

PARAMETERS	VALUE
CONNECTION SYSTEM	Star Connection
NUMBER OF PARALLEL	1
INPUT ITEM	Phase Resistance
NUMBER OF TURNS	20
SLOT-FILL FACTOR	71%
PHASE RESISTANCE	0.04044 Ω
LAYERS	1
COIL PITCH	6

5.1.4. Final Results

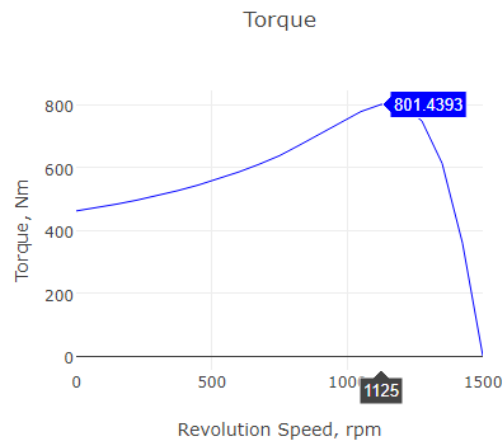


Figure 109. Induction Motor Final Results Torque Graphic

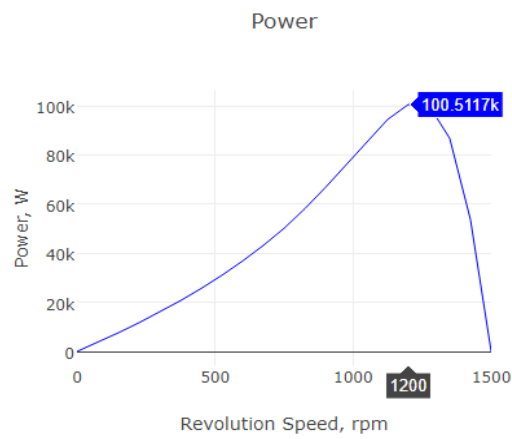


Figure 110. Induction Motor Final Results Power Graphic

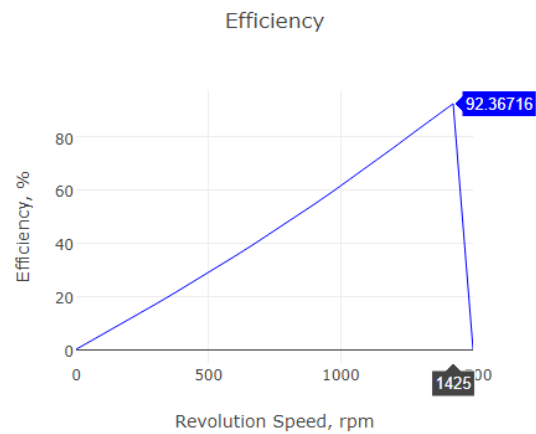


Figure 111. Induction Motor Final Results Efficiency Graphic

Table 24. Induction Motor Results

RESULT	MAXIMUM VALUE	RPM
TORQUE	801.41 Nm	1125
POWER	100.52 kW	1200
EFFICIENCY	92.37%	1425

5.2. Brushless Motor Designing

5.2.1. Mathematical Calculations

For this part I will study and include all the mathematical formulation with the calculations for this specific motor we want to design. For this duty I will use a software specialized on this field called “MATHCAD PRIME”, in which you can write the formulation and the parameters and the program automatically calculates every parameter through the introduced formulas and change them if you apply any change on any of the parameters or formulas.

For some parameters, I have introduced values advice by previous research and tables that provides guide in this kind of aspects.

All the MATHCAD sheets are included in the Annex 2

5.2.2. Analysis of the Design Parameters

Before designing the brushless motor, I will analyze the impact of every change done on each of the design parameters of the motor. For this duty, I will study the change in three graphics that describes the behavior of the motor: Torque – rpm, Efficiency – rpm and Power – rpm.

I will stablish base parameters in order to compare the torque, efficiency and power results when I vary only the value of the parameter that I am analyzing on each point, leaving the rest of them in its base value (The optimized value that I have reach after iterating with all the sizes and rest of the design parameters).

There are a great number of parameters that its variation is very similar to the induction motor one (The difference of variation is almost negligible). That’s why in this section I will inly analyze the parameters that changes from one motor to another.

The first step is to decide which kind of brushless motor we want to design. There are two different types:

- SPM: Surface mounted Permanent Magnet motors have the magnets affixed to the exterior of the rotor surface. Because of this mechanical mounting, their mechanical strength is weaker than that of IPM motors. The weakened mechanical strength limits the motor's maximum safe mechanical speed.
- IPM: Interior Permanent Magnet motors have the permanent magnet imbedded into the rotor itself. Unlike their SPM counterparts, the location of the permanent magnets makes IPM motors very mechanically sound, and suitable for operating at very high speeds.

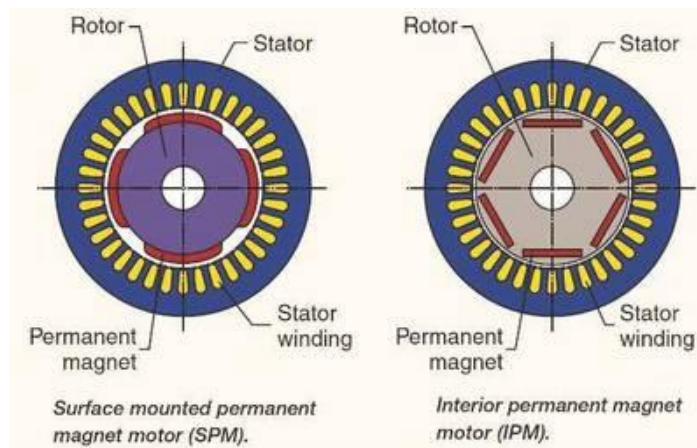


Figure 112. Brushless Motor SPM VS IPM

For our design is logically better the IPM, because we want the motor to work at very high speeds (very high rpm).

5.2.2.1. Dimensions

Poles

Base Value: 8 magnets

Refers to the number of magnets it the rotor. For our design the two more suitable would be 8 magnets, due to the fact that using 4 or 16 magnets only makes a great decrement at the torque and the power without a great gain in the maximum efficiency, displacing as well the efficiency curve.

Table 25. Poles Cases

Case	Value
Case 13	Base Value
Case 14	4 magnets
Case 15	16 magnets

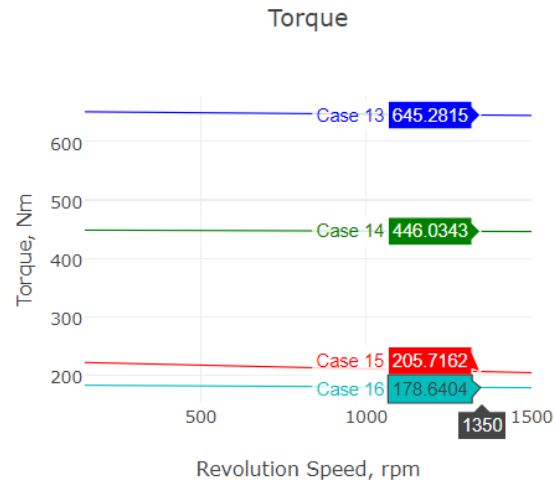


Figure 113. POLES Torque Graphic

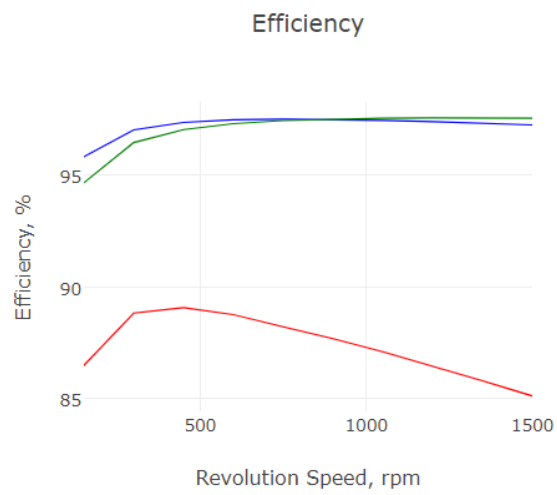


Figure 114. POLES Efficiency Graphic

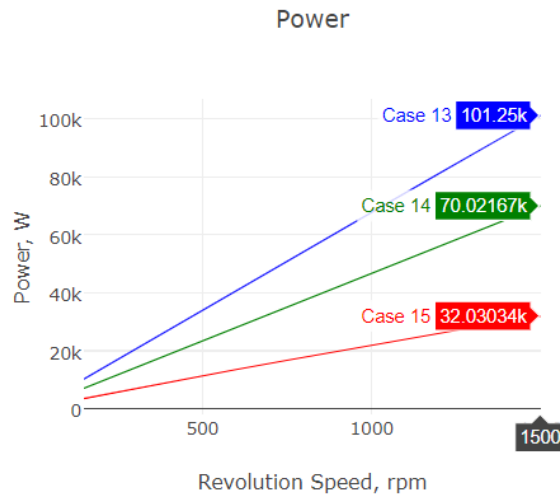


Figure 115. POLES Power Graph

DMAG

Base Value: 51.1 mm

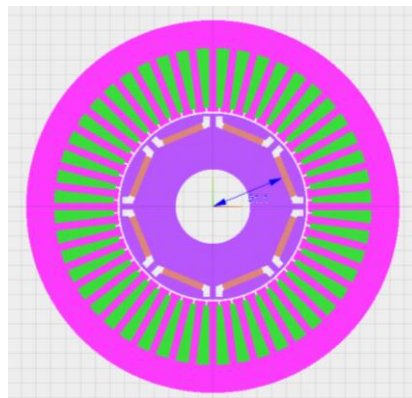


Figure 116. DMAG

This parameter makes reference to the position of the magnets from the center of the motor measured radially. A decrement of this value produces a loss in the three analyzed results: in torque, efficiency and power.

Table 26. DMAG Cases

Case	Value
Case 20	Base Value
Case 21	40 mm
Case 22	42 mm

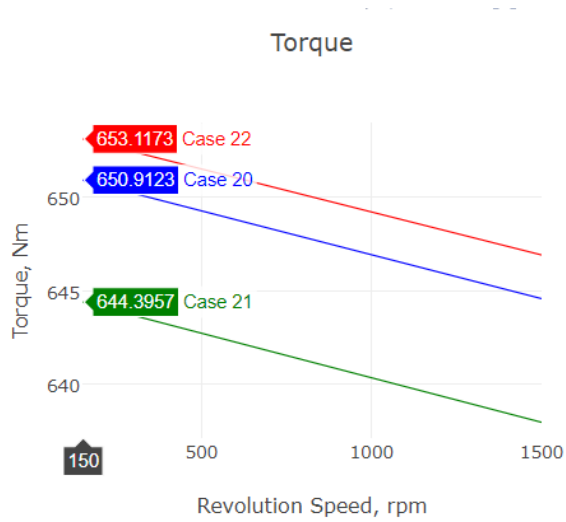


Figure 117. DMAG Torque Graphic

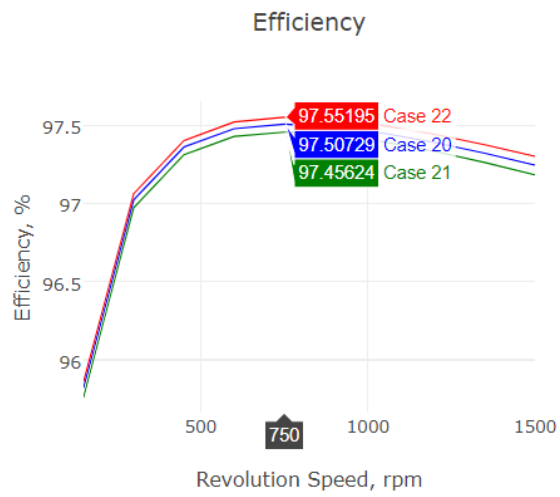


Figure 118. DMAG Efficiency Graphic

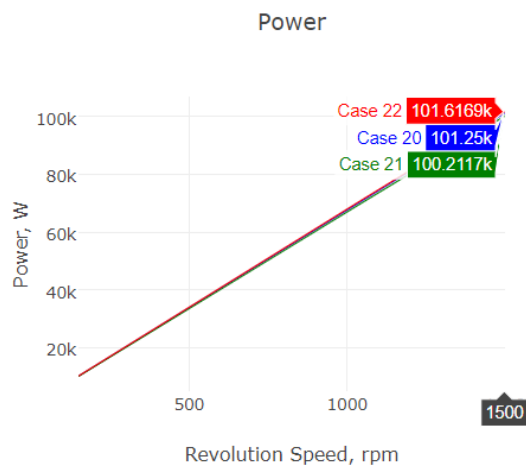


Figure 119. DMAG Power Graphic

TMAG

Base Value: 4.44 mm

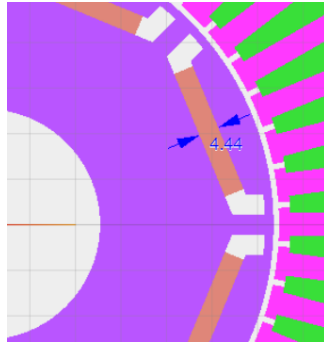


Figure 120. TMAG

This value refers to the magnet thickness, what directly affect to the magnetic fields and to the resultant specs. An increase in this parameter makes a great improvement in the three analyzed results (torque, efficiency and power).

Table 27. TMAG Cases

Case	Value
Case 23	Base Value
Case 24	5 mm
Case 25	4 mm

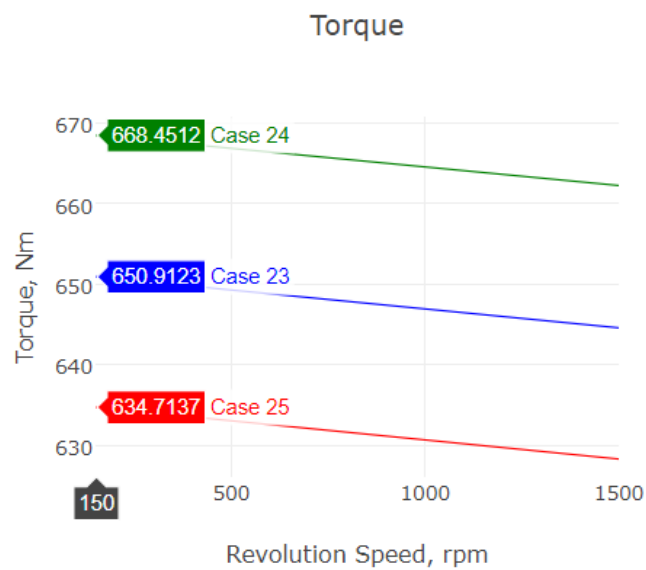


Figure 121. TMAG Torque Graphic

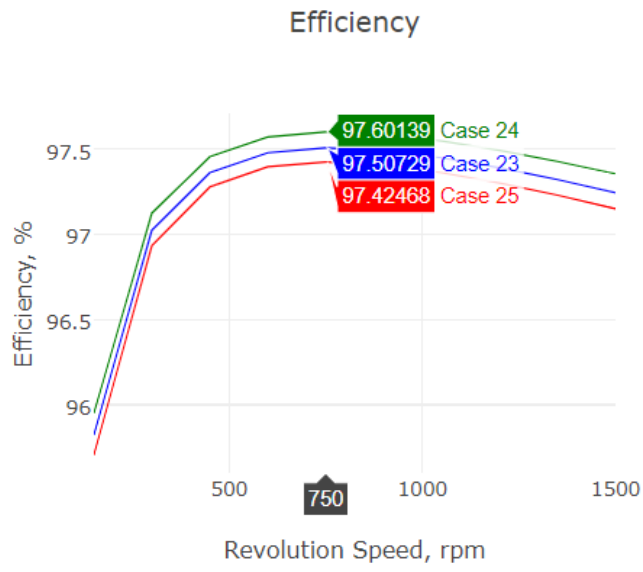


Figure 122. TMAG Efficiency Graphic

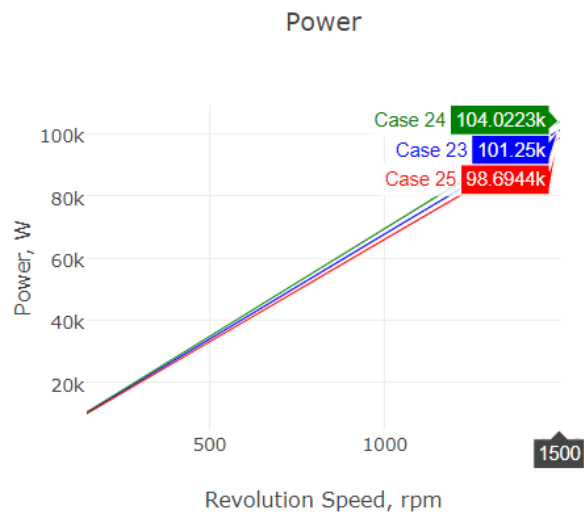


Figure 123. TMAG Power Graphic

WMAG

Base Value: 29.2 mm

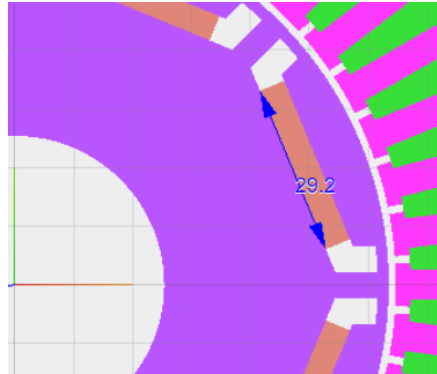


Figure 124. WMAG

This parameter refers to the magnet width, which variation makes similar results than the previous analyzed parameter. The TMAG, DMAG and WMAG are all related, which means that the increase of one of them could make impossible to increment the other two.

If we increase this width, we can gain torque, power and efficiency, but it could compromise the stability of the motor.

Table 28. WMAG Cases

Case	Value
Case 26	Base Value
Case 27	30 mm
Case 28	29 mm

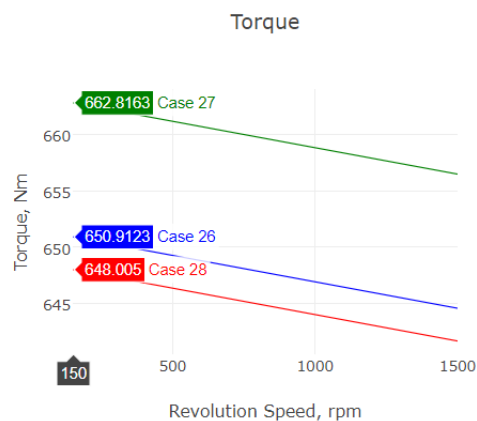


Figure 125. WMAG Torque Graphic

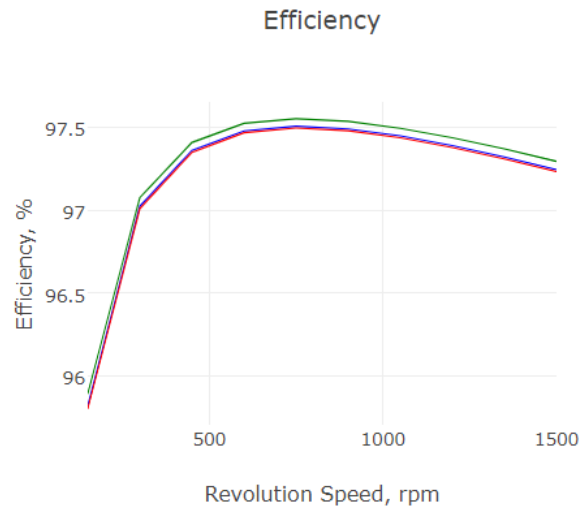


Figure 126. WMAG Efficiency Graphic

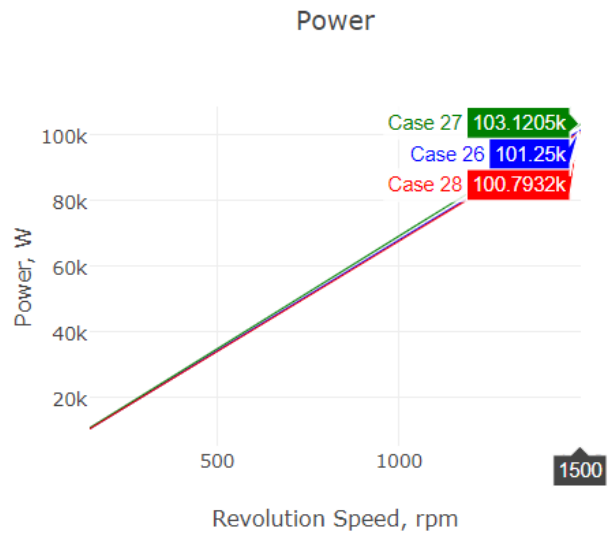


Figure 127. WMAG Power Graphic

SLIT

Base Value: 4.44 mm

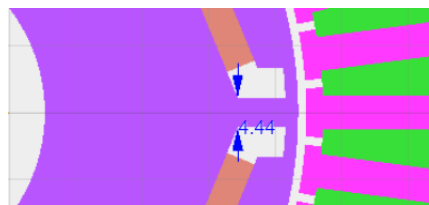


Figure 128. SLIT

This value makes reference to the clearance between slits, which makes a similar impact in the results as the main dimensional values of the magnets, as well as being influenced by this. A decrement on it produces a decrease of the efficiency, torque and power.

Table 29. SLIT Cases

Case	Value
Case 26	Base Value
Case 29	4 mm
Case 30	5 mm

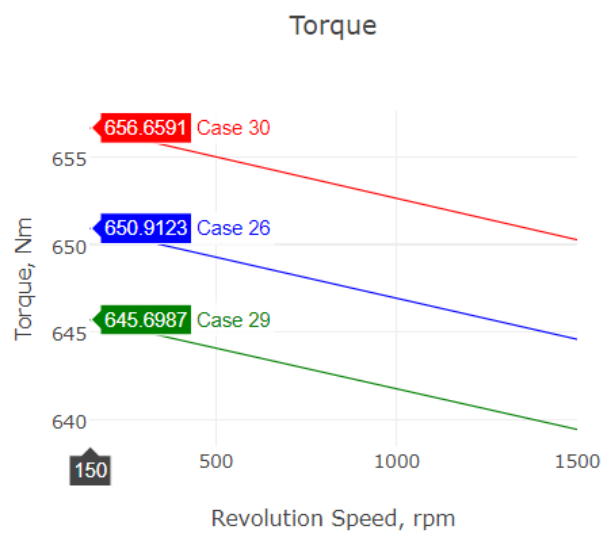


Figure 129. SLIT Torque Graphic

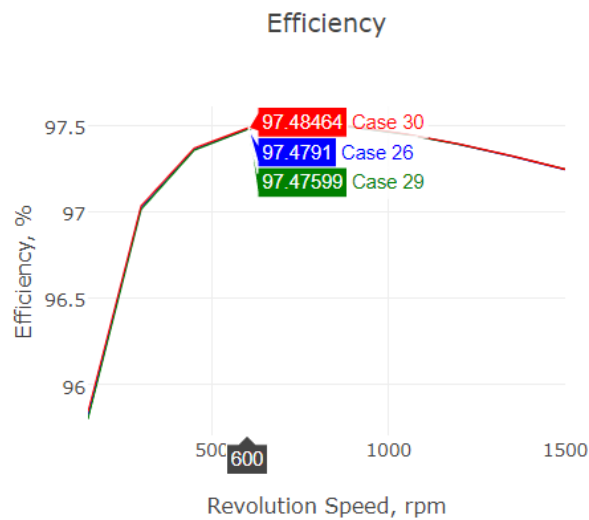


Figure 130. SLIT Efficiency Graphic

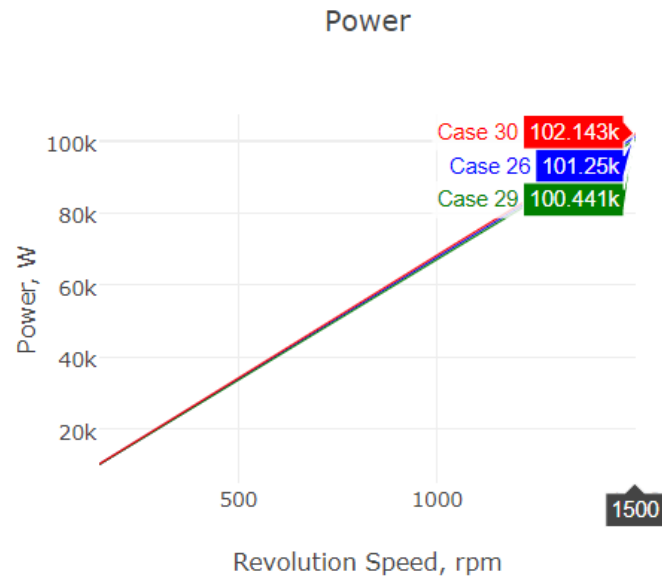


Figure 131. SLIT Power Graphic

SW

Base Value: 4.44 mm

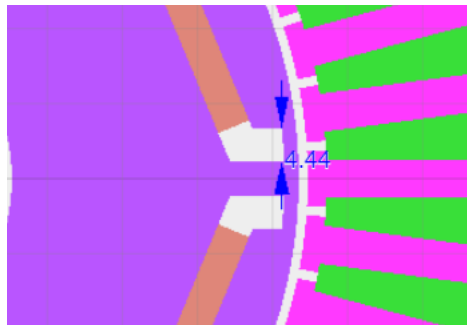


Figure 132. SW

This parameter establishes the slit's main width. The issue of changing this parameter are present in the stability of the motor context. Its variation doesn't change in great quantities the studied results.

If we increase its value, we will rise the three of the main results but in a reduced manner in comparison with the previous parameters.

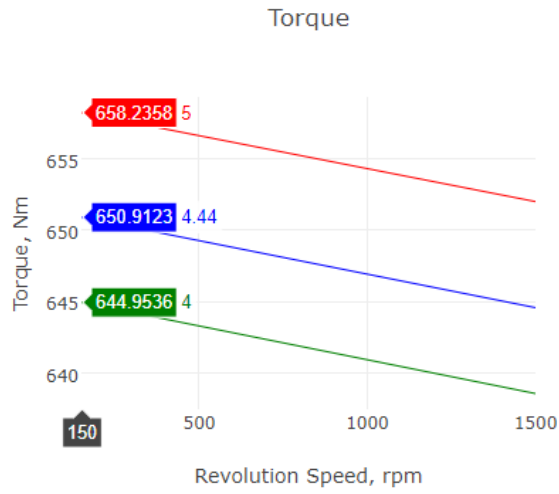


Figure 133. SW Torque Graphic

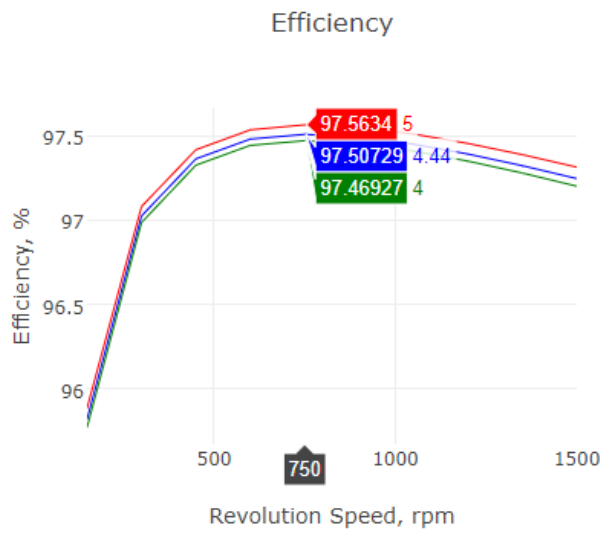


Figure 134. SW Efficiency Graphic

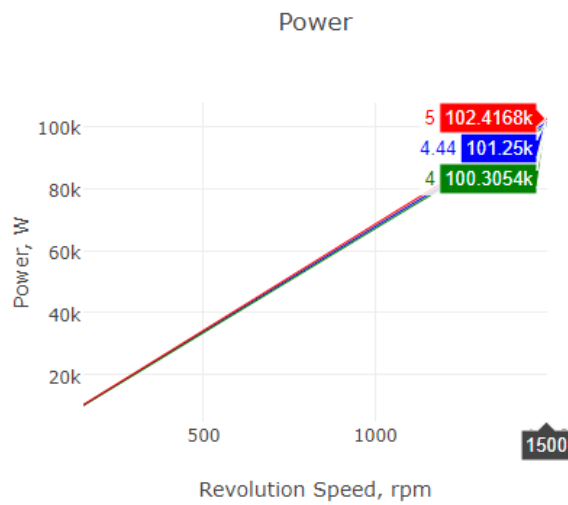


Figure 135. SW Power Graphic

DSLIT

Base Value: 1.9 mm

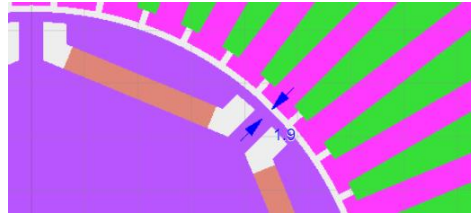


Figure 136. DSLIT

The importance of this value is very similar to the lit width, its main repercussions are in the stability and not in the main results (not meaning that doesn't makes an impact on them). Its decrease produces and increase in the torque, efficiency and power.

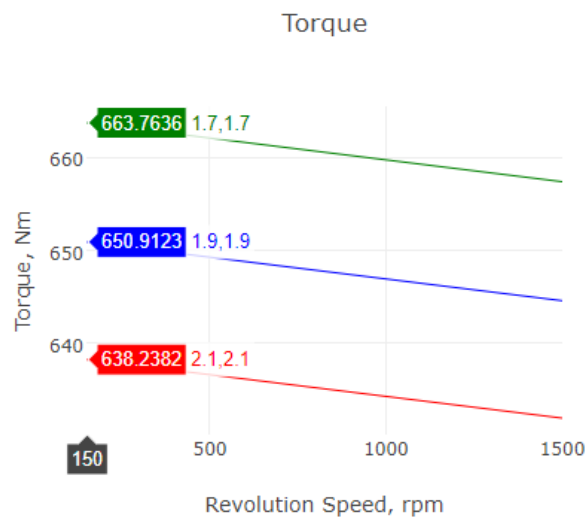


Figure 137. DSLIT Torque Graphic

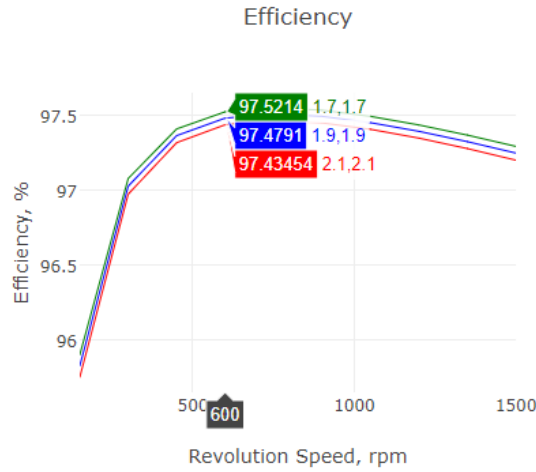


Figure 138. DSLIT Efficiency Graphic

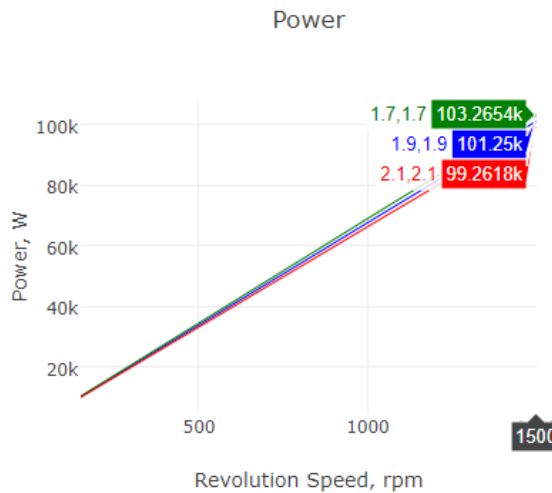


Figure 139. DSLIT Power Graphic

5.2.2.2. Materials

Rotor Magnet

Category

In this parameter we found to typical options usually used in the industry: The Iron Magnet and the NdFeB Magnet. The amount of magnetic flux density is different for each of them, the Iron Magnet support only till 0.4T, when the NdFeB can support till 1.4T. Comparing both options, the optimal one as the results show is the second one, with which we found a great improvement in all the parameters.

Table 30. Rotor Magnet Category Cases

Case	Value
Case 1	NdFeB Magnet
Case 6	Iron Magnet

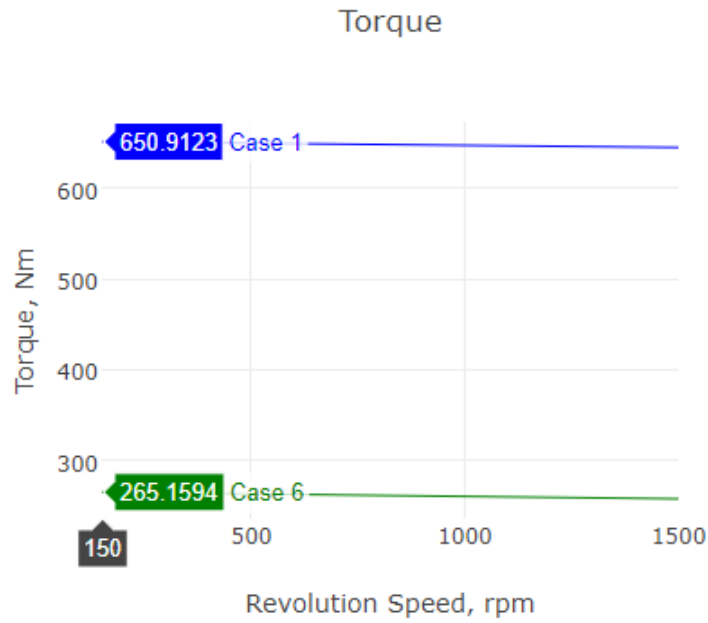


Figure 140. Rotor Magnet Category Torque Graphic

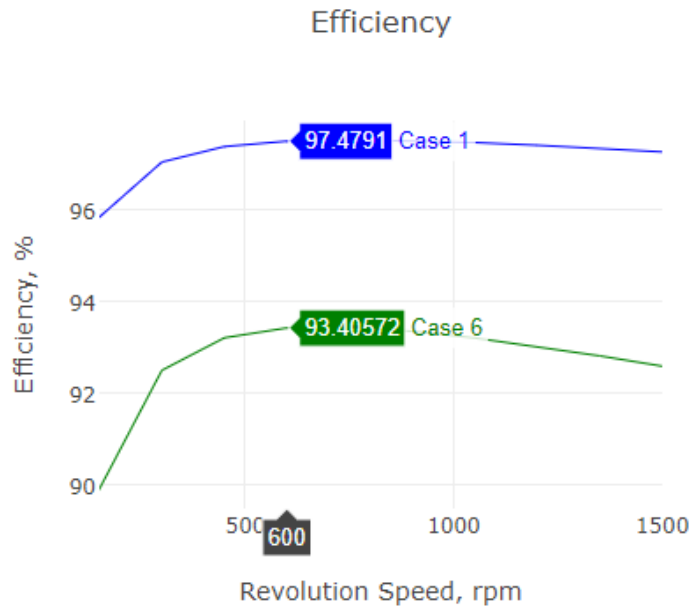


Figure 141. Rotor Magnet Category Efficiency Graphic

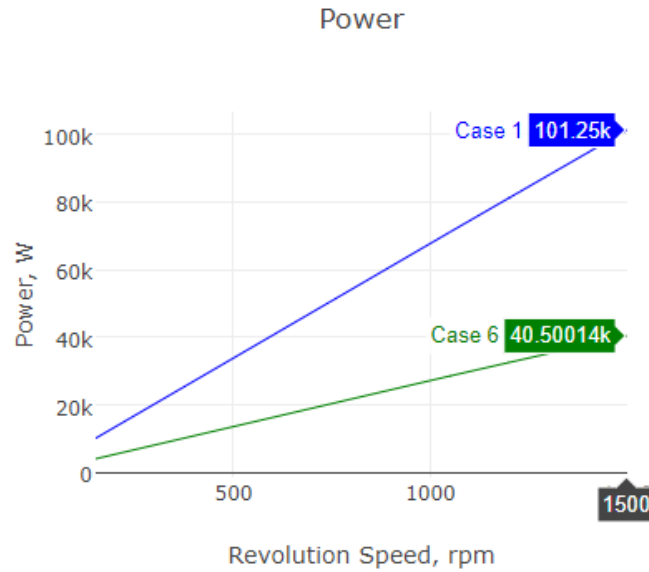


Figure 142. Rotor Magnet Category Power Graphic

Product

This part of our selection refers to the amount of magnetic flux density that the material can manage. Depending on our choice we can put in risk the correct functionality of the motor, cause depending on the size of the motor (in addition to other factors) it could not deal with it and produce a malfunction.

For our case, even doe increasing the material T could produce better resultant specs, to assure the correct working of the motor the optimal one would be the 1T option for the magnets.

Table 31. Rotor Magnet Product Cases

Case	Value
Case 1	NdFeB 1T Magnet
Case 9	NdFeB 1.2T Magnet
Case 10	NdFeB 1.4T Magnet

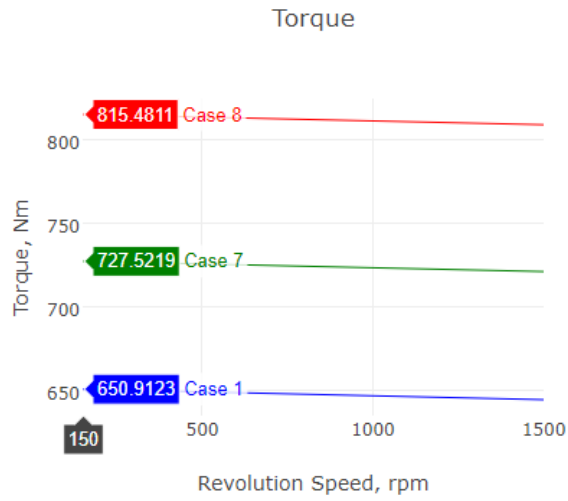


Figure 143. Rotor Magnet Product Torque Graphic

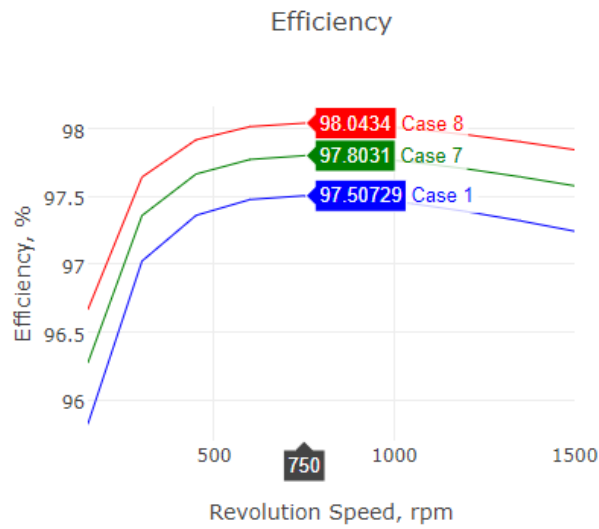


Figure 144. Rotor Magnet Product Efficiency Graphic

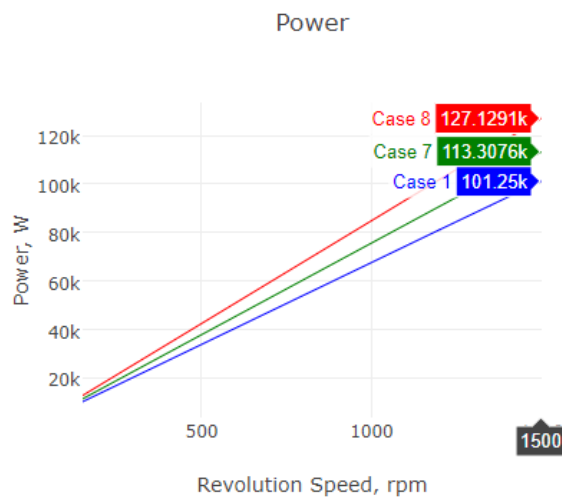


Figure 145. Rotor Magnet Product Power Graphic

5.2.3. Final Design

After doing several iterations, with the torque and power goal and the duty of optimizing to the maximum the efficiency, I have reached a final design that has outstand above the rest.

5.2.3.1. Parameters Value

The first step for the design is to choose the combination of Stator – Rotor. Depending of the duty and the final desire specs of the motor, the optimum combinations could vary. After a research on different sources, I've reached the conclusion that the next combination is the optimum for our kind of induction motor.

5.2.3.1.1. Dimensions

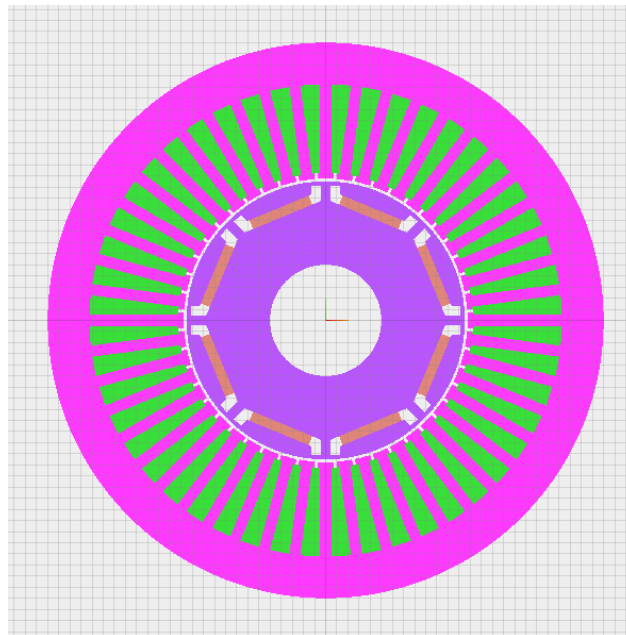


Figure 146. Brushless Motor Final Design

General Dimensions

Table 32. Brushless Motor General Dimensions

PARAMETER	VALUE
OUTD	500 mm
GAP	2.35 mm
GAP TYPE	Free
HEIGHT	505

Stator

Table 33. Brushless Motor Stator

PARAMETER	VALUE
SLOTS	48
SD1	500 mm
SD2	255 mm
SW1	10 mm
SW2	2.501 mm
SW4	37.5 mm
ST	5 mm

Rotor

Table 34. Brushless Motor Rotor

PARAMETER	VALUE
POLES	8
RD1	250.3 mm
RD4	100.1 mm
DMAG	100.9 mm
TMAG	8.76 mm
WMAG	57.57 mm
SLIT	8.76 mm
SW	8.76 mm
DSLIT	3.754 mm

5.2.3.1.2. Materials

Table 35. Brushless Motor Materials

PARAMETER	MATERIAL
COIL	Cooper
STATOR CORE	Steel Sheets 50A1000
ROTOR MAGNET	NdFeB 1T Parallel
ROTOR CORE	Steel Sheets 50A1000

5.2.3.1.3. Winding

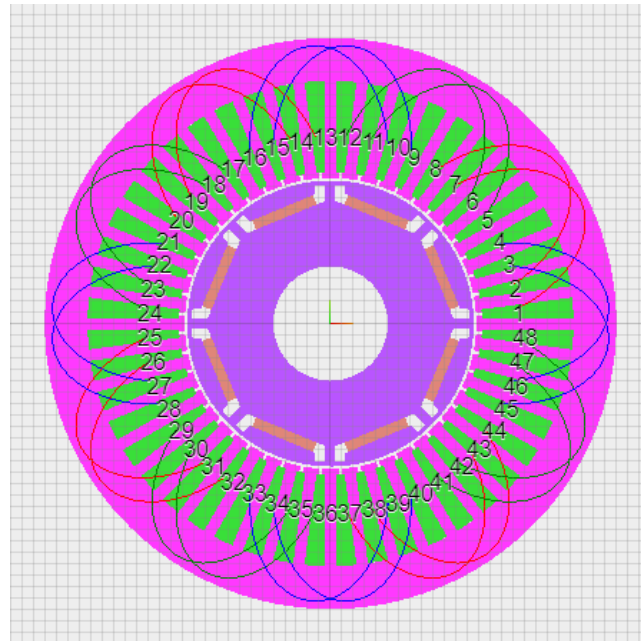


Figure 147. Winding Diagram of the Brushless Motor

Table 36. Brushless Motor Winding

PARAMETER	VALUES
CONNECTION SYSTEM	Star Connection
NUMBER OF PARALLEL INPUT ITEM	1
NUMBER OF TURNS	Phase Resistance
SLOT-FILL FACTOR	2
PHASE RESISTANCE	71%
NUMBER OF LAYERS	0.00096 Ω
PITCH	1
	6

5.2.4. Final Results

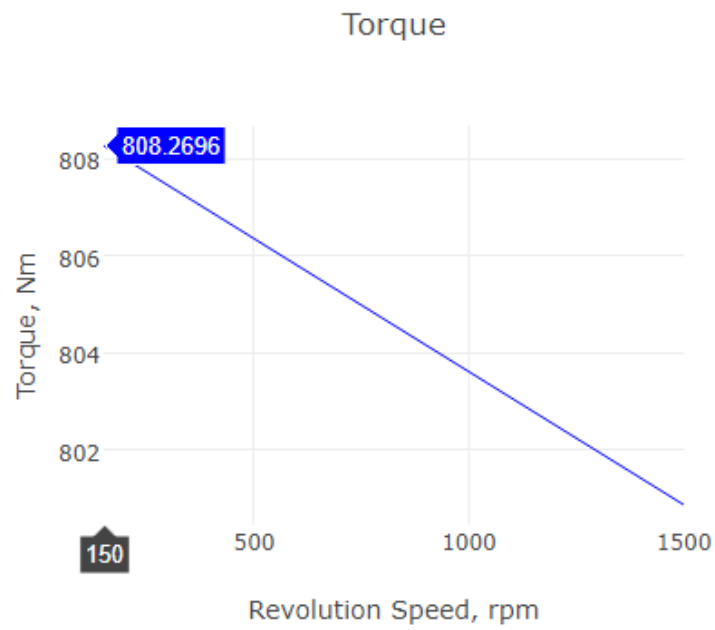


Figure 148. Brushless Motor Final Results Torque Graphic

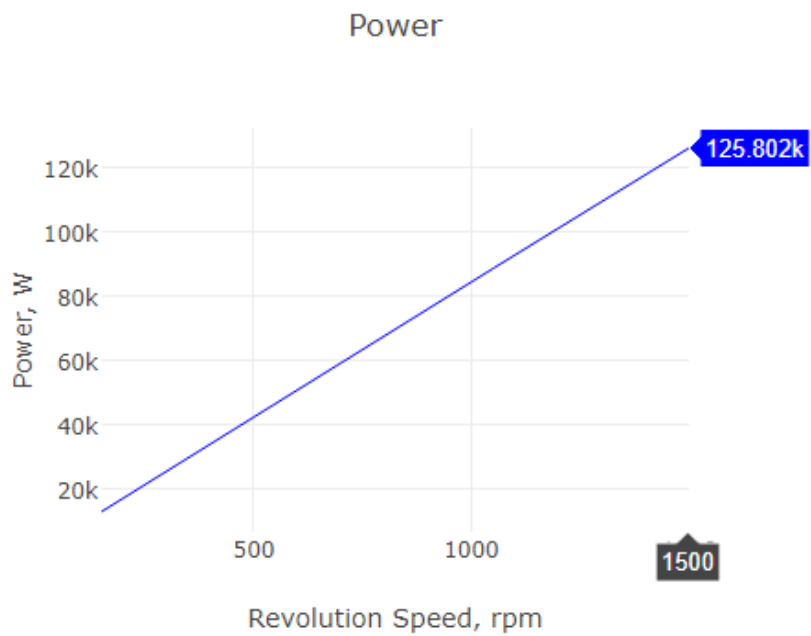


Figure 149. Brushless Motor Final Results Efficiency Graphic

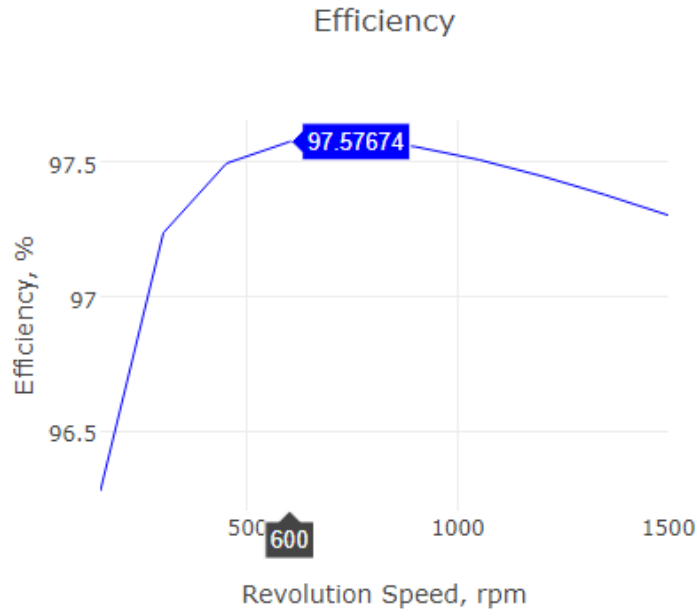


Figure 150. Brushless Motor Final Results Power Graphic

Table 37. Brushless Motor Final Results

RESULT	VALUE	RPM
TORQUE	808.27 Nm	150
POWER	125.8 KW	1500
EFFICIENCY	97.58%	600

6. Results Analysis

Having the results of torque, power and efficiency for both motor, as well as other important specs, such as the motor's total volume or weight, in this section we will compare both motors by their final specs and extrapolate the differences between both designs.

6.1. General Dimensions

Table 38. General Dimensions Comparison

MOTOR	HEIGHT (MM)	OUTER DIAMETER (MM)	TOTAL VOLUME (MM ³)	TOTAL MASS (KG)
INDUCTION MOTOR	227.4	253	1.22E+07	98.8
BRUSHLESS MOTOR	505	500	1.09E+08	897.5

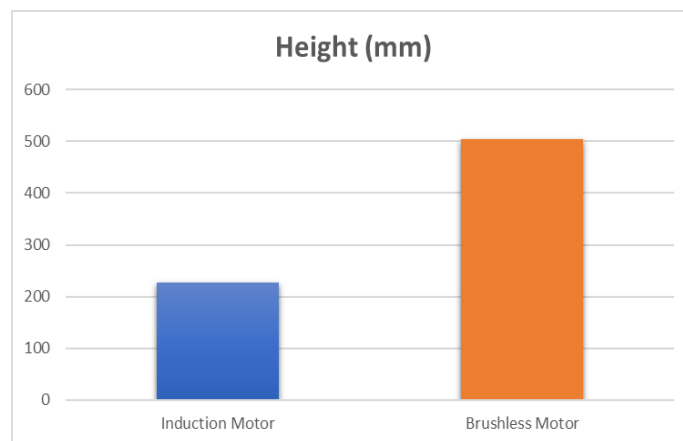


Figure 151. Height Graphical Comparison

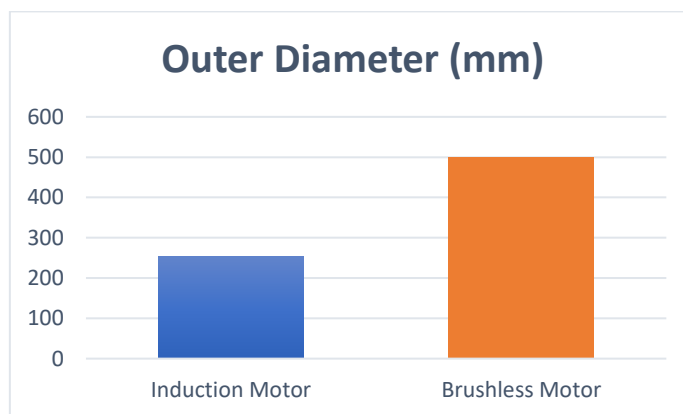


Figure 152. Outer Diameter Graphical Comparison

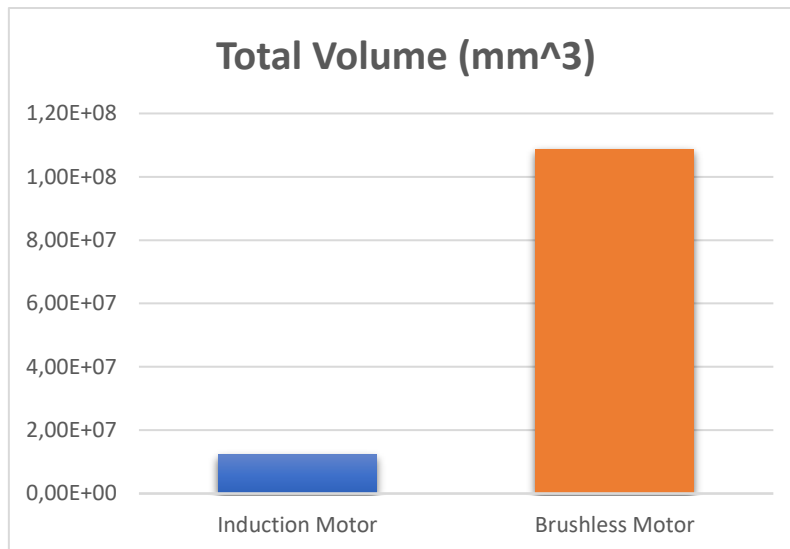


Figure 153. Total Volume Graphical Comparison

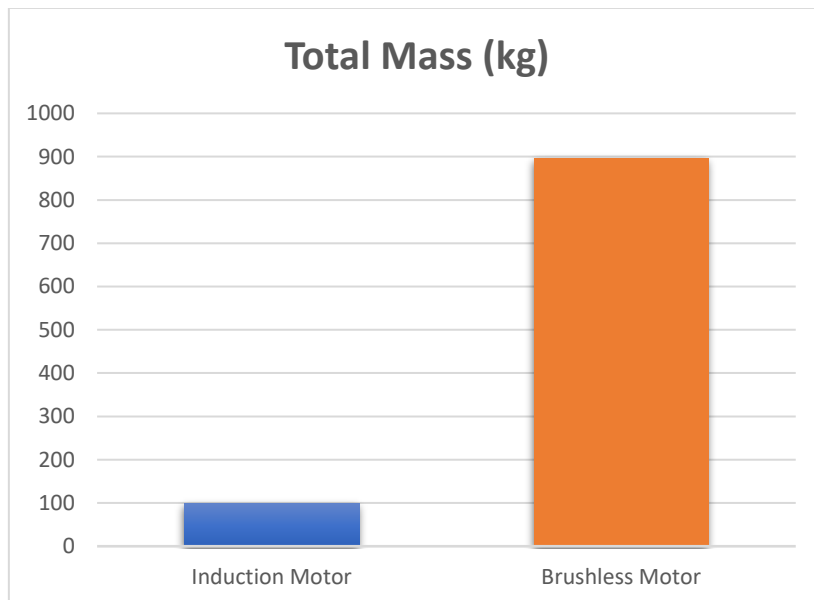


Figure 154. Total Mass Graphical Comparison

As we can see in the graphical comparison and in the table, the results show that the Induction motor (having in count that both fulfill the requirements of power and torque) is much smaller in every comparison, not only in size, although in weight, making it more optimal for the car, due to the fact that we need a motor as small as possible in order to increment the minimum the total weight and size of the car.

6.2. Torque

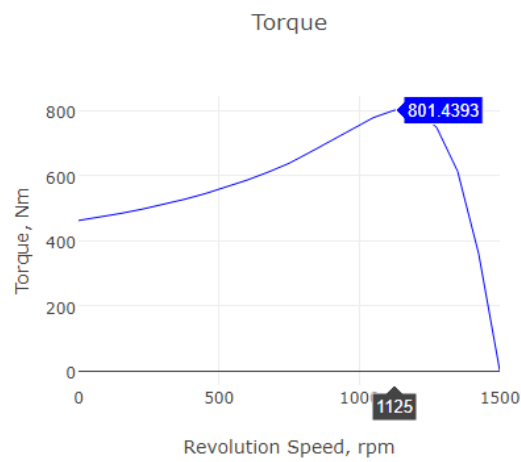


Figure 155. Induction Motor Torque Graphic

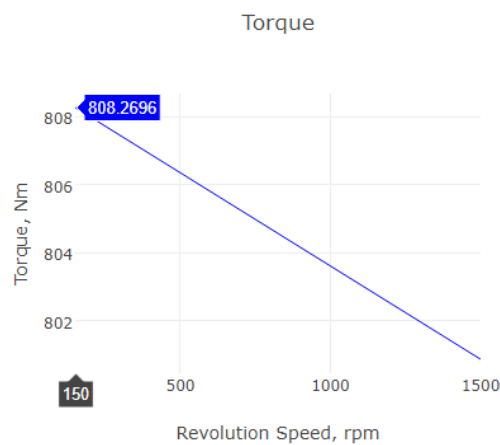


Figure 156. Brushless Motor Torque Graphic

As the graphics shows, the maximum torques are, more or less, the same (the goal torque that we marked for the design), the greatest difference we can see it in the evolution of the torque through the different speeds of the motor. In the induction motor, the torque varies a lot along the graphic, what makes it perfect for the vector controller and the inverter in order to modulate this parameter for the different speeds required by the car. In the other case, the brushless motor presents a graphic much more equal for every along the rpm axis, doing this kind of motor more proper for a machine that is not going to vary the maximum speed.

6.3. Power

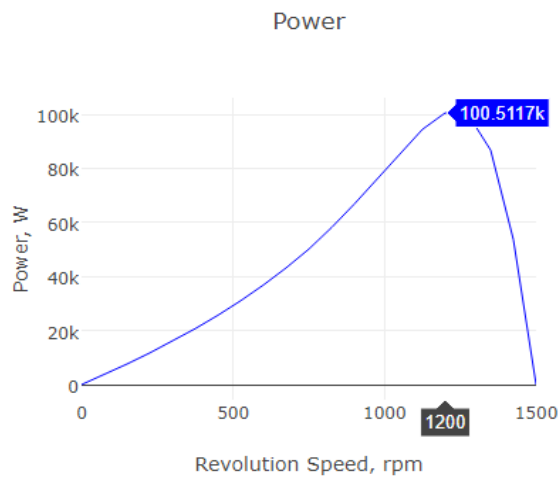


Figure 157. Induction Motor Power Graphic

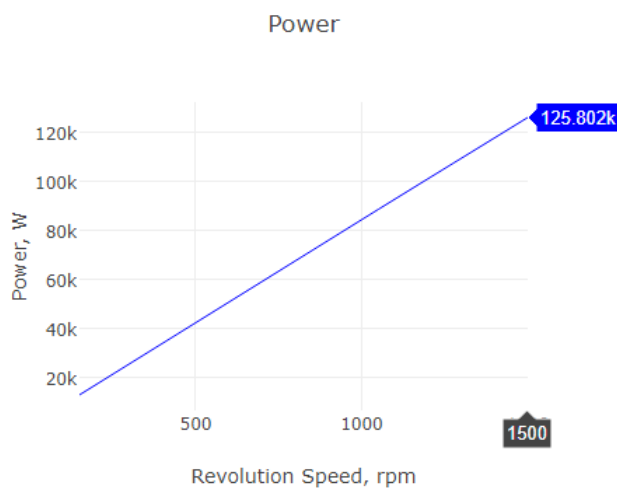


Figure 158. Brushless Motor Power Graphic

In the case of the power, to reach the desired torque at the same speed limit without risking the stability, the maximum power of the brushless motor is 25 kW higher than the induction's motor, making the consumption of energy, at the same time, higher, what makes the induction motor a better candidate in this parameter as well, due to the fact that the batteries will last more with it in the car.

Another point to have in count is that the graphic of the induction motor is more parabolic (making it easier to be controlled by the power electronics systems), in the other hand, the brushless graphic is perfectly linear, making it perfect for other applications that we are not going to need.

6.4. Efficiency

This point is the other part where we can see the difference between the performances of both motors.

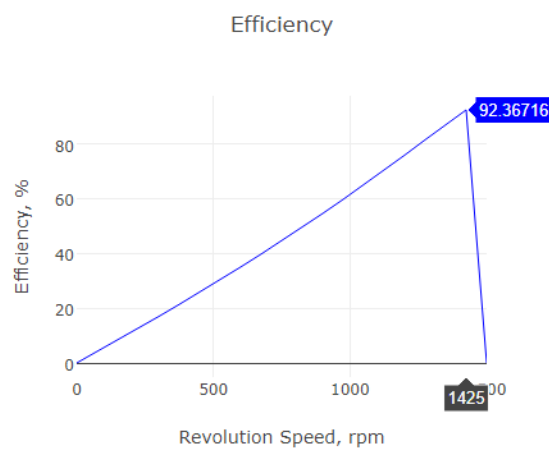


Figure 159. Induction Motor Efficiency Graphic

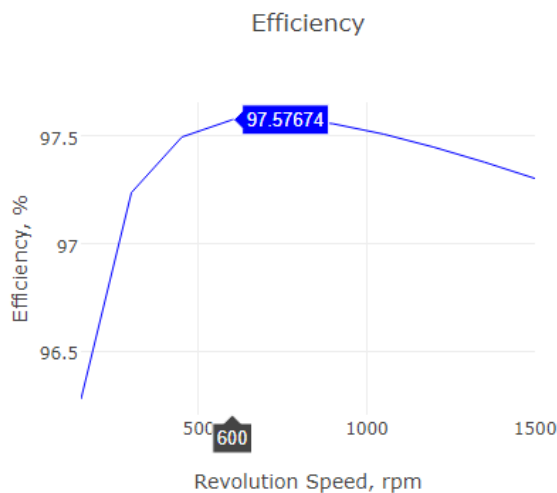


Figure 160. Brushless Motor Efficiency Graphic

First, analyzing the maximum efficiencies of each motor, we can see that the brushless motor's is much higher than the induction motor, as well as more stable during the different speeds of the motor. Is true that, when we apply it to the car, the vector controller and the inverter are going to make the maximum efficiency as stable for all the different motor's speeds as possible, that's why a brushless motor is more indicated for a machine in which we are not going to use this kind of systems.

Also, is true that, in the previous research, I have noticed that the maximum efficiency for an induction motor is not normally higher than 94%, so the fact that the difference of volume could be the cause of this difference is not true.

These results make me think that, applying another view to the design of the brushless motor, we could have optimized the volume without decrementing in a great amount the efficiency. If I've got more experience designing this kind of motor, maybe the differences would have not been this high. But also, I have to say that, having analyzed the repercussion of a variation in all the parameters, it is not possible to decrement in a great amount the eventual volume of this design for this torque at this speed.

7. Conclusions

7.1. Motor Decision

Having in count all the results and the comparisons, and even though that the brushless motor has given better efficiency results, I would conclude that the induction motor is the most appropriate for the car we want to transform into electrical.

It is not only for the fact that is less heavy and has a lower volume (properties that are very important for an electric car motor), also for the tendency of it's graphics, that's make it easier to be control by the electric power part, the invertor and the vector controller.

7.2. Final Conclusions of the project

After having finished this project, I have seen how difficult is to handle an individual designing project. Even with the invaluable help of my director, Dr. S.Daniel it has been tough for me in some points, but that's the key of working as an engineer, to know how to surpass the difficulties that appears along every project.

As I have demonstrated, the electrical motor specs are much better than a combustion engine, not only from the ecological point of view, also in their performance, few can see it in the efficiency, in which an induction motor reaches a 94%, much higher than the 60% of a combustion motor.

The key why this motor hasn't been introduced in a mayor manner in the market is due to the batteries. The day will come when a more efficient way to stock electric power appears, and that's the day when the electric car will dominate completely the market. It's only a matter of time.

7.3. Conclusions of methodology

Putting myself in the case of repeating the project from the beginning, I would have changed several things in the methology. The first one would have been to do a better schema and timetable of how I am going to do the project, in order to do everything more organized. The second and very important is to contact from the beginning with the companies that has given me the license of the programs that I am going to use in order to make sure that I don't have any problem with it and develop the project with any problem from the beginning.

Referring now to the design of the motor, in first place I tried to design it without doing the analysis of each of the parameters, what made me waste a lot of time. I would have done that analysis in first place and then start doing the final design of the motor with a good idea of what to change in order to optimize it. And at finally, I would have written the hole project from the beginning in English. I say this due to the fact that I tried to write it in Spanish and then adapt it to English, but this made me waste a lot of time and made some parts unclear due to the translation.

7.4. Conclusions for future projects

As I said at the beginning, this project will help others to design an electric motor thanks to all the analysis that I have developed on it. I would suggest other engineers that have to do this project to have a very clear idea of what they are designing and stablish goals for their project from the beginning, that is helpful to make the best design possible.

From a personal point of view, this project has made me work on a design by myself from the beginning, what will help me in the future to develop more design in my future work area. Also has made me grown as an engineer, making me apply all the acquired knowledge and seek for more ideas from a lot of sources, what will be useful for the future, cause an engineering continues learning though all his professional career.

Special Thanks

First of all, I would like to thank both of the universities in which I've been able to study, ICAI and Embry Riddle Aeronautical School for giving me the opportunity of doing a project on my own and for giving me the knowledge that I needed for it. But, specially, to Dr. S.Daniel, the director of my project, for his eternal patience with me and for dedicating me his time that has being crucial for this project. Thanks to him, I have started to like the world that he has shown me of the electric motors.

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Annex 1

Induction Motor Design

1. Assigned Characteristic

1.1. Synchronous speed and slip

$$f := 50 \cdot \text{Hz} \quad \omega_e := 2 \cdot \pi \cdot f = 314.159 \frac{1}{s} \quad f = \text{Applied frequency}$$

$$p := 4$$

p = Number of poles

$$S_m := \frac{2}{p} \cdot \omega_e = (1.5 \cdot 10^3) \frac{\text{rev}}{\text{min}} \quad S_m = \text{Synchronous Mech Speed}$$

$$S_N := 1490 \cdot \frac{\text{rev}}{\text{min}}$$

S_N = Desired full load speed

$$\text{slip} := \frac{S_m - S_N}{S_m} = 6.667 \cdot 10^{-3} \quad \text{slip} = \text{Calculated slip}$$

1.2. Nominal Torque

$$P_N := 100 \cdot \text{kW}$$

P_N = Nominal Power

$$\Omega_N := S_N = (1.49 \cdot 10^3) \text{ rpm}$$

Ω_N = Radian speed

$$T_m := \frac{P_N}{\Omega_N} = 640.892 \text{ N} \cdot \text{m}$$

T_m = Torque based on input values

1.3. Absorbed Power

$$\eta_N := 0.93$$

η_N = Desired efficiency

$$P_{IN} := \frac{P_N}{\eta_N} = 108.696 \text{ kW}$$

P_{IN} = Power at motor electrical terminal

1.4. Assigned Phase Intensity

$$V_{ph} := 440 \cdot \text{volt}$$

V_{ph} = Phase voltage

$$\phi := 0.7$$

ϕ = Desired power factor

$$I_{ph} := \frac{P_{IN}}{3 \cdot V_{ph} \cdot \phi} = 117.636 \text{ A}$$

I_{IN} = phase current

2. Estimated value of the Initial Dimension

2.1. Principal Dimension

$$J := 60480 \cdot \frac{\text{amp}}{\text{m}}$$

J = Linear current density

$$B_M := 0.9 \cdot \text{T}$$

B_M = Maximum magnetic induction in the air gap

$$\sigma_{Ftan} := \frac{J \cdot B_M \cdot \phi}{\sqrt{2}} = (26.942 \cdot 10^3) \frac{\text{N}}{\text{m}^2}$$

σ_{Ftan} = Tangential stress

$$V_r := \frac{2 \cdot T_m}{\pi \cdot \sigma_{Ftan}} = (15.144 \cdot 10^{-3}) \text{ m}^3$$

V_r = Rotor volume

$$\lambda := 1.5$$

λ = Ratio between axial length of the air gap and polar pitch of the stator

$$l := \frac{\pi \cdot \lambda}{p} = 1.178$$

l = Ratio between axial length and inner diameter of the stator

$$D_s := \sqrt[3]{\frac{V_r}{l}} = (234.251 \cdot 10^{-3}) \text{ m}$$

D_s = Stator diameter

$$g := l \cdot D_s = (275.971 \cdot 10^{-3}) \text{ m}$$

g = Axial Length of the Air Gap

2.1.2. Air Gap Geometric Thickness

$$\delta_g := 0.2 \text{ mm} + 2 \cdot \sqrt{D_s \cdot g} \cdot 10^{-3} = (708.514 \cdot 10^{-6}) \text{ m} \quad \delta_g = \text{Air Gap Geometric Thickness}$$

2.1.3. Rotor Outside Diameter

$$D_r := D_s - 2 \cdot \delta_g = (232.834 \cdot 10^{-3}) \text{ m} \quad D_r = \text{Rotor Outside Diameter}$$

2.2. Dimensions of the Stator's Rollings

2.2.1. Characterization of the Wind Outs

$$N_{spp} := 2$$

N_{spp} = Number of slots per pole per phase

$$N_{ph} := 3$$

N_{ph} = Number of stator phases

$$N_{ss} := N_{spp} \cdot p \cdot N_{ph} = 24$$

N_{ss} = Total number of stators slots

$$p s_{si} := \pi \cdot \frac{D_s}{p} = (183.981 \cdot 10^{-3}) \text{ m}$$

$p s_{si}$ = Polar step measured in circumference length stator interior

$$y_{pl} := \frac{N_{ss}}{p} = 6$$

y_{pl} = Polar step measured in circumference length stator interior

$$a := 1$$

a (slots/pole) = Shortening

$$y_l := y_{pl} - a = 5$$

y_l (slots/pole) = Stepped stator winding in "a" slots

$$s p_s := \frac{\pi \cdot D_s}{N_{ss}} = (30.663 \cdot 10^{-3}) \text{ m}$$

$s p_s$ = Stator slot pitch

$$N_{cpph} := 2 \cdot N_{spp} = 4$$

N_{cpph} = Number of coils per pair of poles per phase of the stator

Winding factor: Distribution factor, shortening factor

$$\gamma_l := \frac{360 \cdot \text{deg}}{N_{ss}} = 15 \text{ deg}$$

γ_l = Geometric degrees

$$k_{ds} := \frac{\sin\left(\frac{N_{spp} \cdot p \cdot \gamma_l}{4}\right)}{N_{spp} \cdot \sin\left(\frac{p \cdot \gamma_l}{4}\right)} = 965.926 \cdot 10^{-3} \quad k_{ds} = \text{Stator's Distribution Factor}$$

$$v_s := 1$$

$$k_{vds} := \frac{\sin\left(v_s \cdot \frac{N_{spp} \cdot p \cdot \gamma_l}{4}\right)}{N_{spp} \cdot \sin\left(v_s \cdot \frac{p \cdot \gamma_l}{4}\right)} = 965.926 \cdot 10^{-3}$$

$$e_{deg_s} := \left(1 - \frac{y_1}{y_{p1}}\right) \cdot 180 \cdot deg \cdot v_s = 30 \text{ deg} \quad e_{deg_s} = \text{Stator's Electrical degrees}$$

$$k_{ss} := \cos\left(\frac{e_{deg_s}}{2}\right) = 965.926 \cdot 10^{-3} \quad k_{ss} = \text{Stator's Shortening Factor}$$

$$k_{vss} := \cos\left(v_s \cdot \frac{e_{deg_s}}{2}\right) = 965.926 \cdot 10^{-3}$$

$$k_{sw} := k_{ds} \cdot k_{ss} = 933.013 \cdot 10^{-3} \quad k_{sw} = \text{Stator's Winding Factor}$$

$$k_{vsw} := k_{vds} \cdot k_{vss} = 933.013 \cdot 10^{-3}$$

2.2.2. Number of Turnzs and Flow per pole

$$\Phi_p := g \cdot \frac{D_s \cdot B_M}{\frac{p}{2}} = (29.091 \cdot 10^{-3}) \text{ Wb} \quad \Phi_p = \text{Flux per Pole}$$

$$K_E := 0.98 - 0.005 \cdot \frac{p}{2} = 970 \cdot 10^{-3} \quad K_E = \text{Relation } E_{sph} / V_{ph}$$

$$E_{sph} := K_E \cdot V_{ph} = 426.8 \text{ V} \quad E_{sph} = \text{f.e.m. in one phase of the Stator}$$

$$N_{sph} := \frac{E_{sph}}{4.44 \cdot k_{vsw} \cdot f \cdot \Phi_p} = 71 \quad N_{sph} = \text{Number of efective turns in serie per phase}$$

$$N_{sbph} := 1 \quad N_{sbph} = \text{Number of branches in parallel in a phase}$$

$$N_{tsph} := N_{sbph} \cdot N_{sph} = 71 \quad N_{tsph} = \text{Total number of efective turns in serie per phase}$$

$$n_{sc} := \frac{N_{tsph}}{\frac{p}{2} \cdot N_{cph}} = 9$$

n_{sc} = Number of turns in one simple coil of the stator

$$n_{ss} := 2 n_{sc} = 18$$

n_{ss} = Number of turns in one simple coil of the stator

2.2.3. Conductors Dimension

$$J_s := 3.6 \frac{A}{mm^2}$$

J_s = Current Density in one conductor of the stator

$$I_{sr} := \frac{I_{ph}}{N_{sbph}} = 117.636 A$$

I_{sr} = Rated current of a parallel branch of a stator phase

S_{sc} = Transversal section in a one of the stator's conductor

$$S_{sc} := \frac{I_{sr}}{J_s} = (32.677 \cdot 10^{-6}) m^2$$

$$id := 0.15 \text{ mm}$$

$$icw := 1 \text{ mm}$$

$$N_c := 8$$

$$N_l := 2$$

$$itc := 1.5 \text{ mm}$$

$$dhcw := 14 \text{ mm}$$

$$tg_{sth} := id \cdot N_l + N_l \cdot icw = (2.3 \cdot 10^{-3}) \text{ m}$$

$$r_{sth} := N_l \cdot id \cdot N_c + N_l \cdot icw + itc + dhcw = (19.9 \cdot 10^{-3}) \text{ m}$$

id = Isolation of driver

icw = Isolation of coil wall

N_c = Number of coils

N_l = Number of layers

itc = Isolation between 2 coils

$dhcw$ = Dedicated height to closing wedge

tg_{sth} = Total tangencial thickness

r_{sth} = Total radial thickness

$$G_I := 0.42$$

G_I = interval between 0.36 and 0.5

$$w_{sg} := sp_s \cdot (G_I) = (12.879 \cdot 10^{-3}) \text{ m}$$

w_{sg} = Stator gap width

$$w_{sc} := w_{sg} - tg_{sth} = (10.579 \cdot 10^{-3}) \text{ m}$$

w_{sc} = Stator conductor width

$$h_{sc} := \frac{S_{sc}}{w_{sc}} = (3.089 \cdot 10^{-3}) \text{ m}$$

h_{sc} = Height of an stator's conductor

2.3. Dimensions of the Stator's Core

$$K_{sFe} := 0.97$$

K_{sFe} = Stator Stacked Factor

$$l_{sFe} := K_{sFe} \cdot g = (267.692 \cdot 10^{-3}) \text{ m}$$

l_{sFe} = Useful axial length of stator iron

$$\Phi_{maxsy} := \frac{\Phi_p}{2} = (14.545 \cdot 10^{-3}) \text{ Wb}$$

Φ_{maxsy} = Maximum flow in the stator yoke

$$B_{maxsy} := 1.45 \text{ T}$$

B_{maxsy} = Maximum magnetic induction in the stator yoke

$$h_{sy} := \frac{\Phi_{maxsy}}{l_{sFe} \cdot B_{maxsy}} = (37.474 \cdot 10^{-3}) \text{ m}$$

h_{sy} (m) = Height of the stator yoke

$$B_{maxst} := 1.65 \text{ T}$$

$$j := \frac{B_M}{B_{maxst} \cdot K_{sFe}} = 562.324 \cdot 10^{-3}$$

$$r := 1 - j = 437.676 \cdot 10^{-3}$$

$$w_{minst} := j \cdot sp_s = (17.243 \cdot 10^{-3}) \text{ m}$$

$$w_{maxss} := r \cdot sp_s = (13.421 \cdot 10^{-3}) \text{ m}$$

B_{maxst} = Maximum magnetic induction in stator teeth

w = Minimum Relationship between tooth width and groove pitch of the stator

r = Minimum Relationship between the slot width and the slot pitch of the stator

w_{minst} = Minimum Stator tooth width

w_{maxss} = Maximum Stator slot width

$$w_{minss} := w_{sc} + tg_{sth} = (12.879 \cdot 10^{-3}) \text{ m}$$

$$h_{minss} := n_{ss} \cdot h_{sc} + r_{sth} = (74.598 \cdot 10^{-3}) \text{ m}$$

$$S_{clins} := (w_{sc} + 2 \cdot id) \cdot (h_{sc} + 2 \cdot id) = (36.867 \cdot 10^{-6}) \text{ m}^2$$

$$th_{su} := 0.5 \text{ mm}$$

$$K_{sCu} := 0.75$$

$$h_{ssu} := \frac{S_{clins} \cdot n_{ss} + 2 \cdot th_{su} \cdot (K_{sCu} \cdot (w_{sg} - 4 \cdot th_{su}))}{K_{sCu} \cdot (w_{sg} - 4 \cdot th_{su})} = (81.014 \cdot 10^{-3}) \text{ m}$$

$$h_{sm} := 14 \text{ mm}$$

$$h_{ss} := h_{ssu} + h_{sm} = (95.014 \cdot 10^{-3}) \text{ m}$$

w_{minss} = Minimum width of stator slot

h_{minss} = Minimum stator slot height

S_{clins} = Thickness of the stator U-piece

K_{sCu} = Stator slot filling factor

h_{ssu} = Useful height of the stator slot

h_{sm} = Depth of stator slot mouth

h_{ss} = Height of the stator's slot

$$h_{tl} := h_{ss} = (95.014 \cdot 10^{-3}) \text{ m}$$

$$d_{0.33} := D_s + \frac{2 \cdot h_{tl}}{3} = (297.594 \cdot 10^{-3}) \text{ m}$$

$$SP_{0.33hsr} := \pi \cdot \frac{d_{0.33}}{N_{ss}} = (38.955 \cdot 10^{-3}) \text{ m}$$

$$w_{0.33hst} := SP_{0.33hsr} - w_{sg} = (26.076 \cdot 10^{-3}) \text{ m}$$

$$B_{0.33hst} := \frac{\Phi_p}{l_{sFe} \cdot SP_{0.33hsr} \cdot y_{p1}} = (464.953 \cdot 10^{-3}) \text{ T}$$

$d_{0.33}$ = Diameter corresponding to $\frac{1}{3}$ of the tooth height of the stator

$sp_{0.33hst}$ = Slot pass measured as arc length of circumference of $d_{0.33}$

$w_{0.33hst}$ = Tooth width $\frac{1}{3}$ of the height of the stator tooth

$B_{0.33hst}$ = Magnetic induction a $\frac{1}{3}$ of the height of the stator tooth

$$D_{es} := D_s + 2 \cdot (h_{sy} + h_{ss}) = (499.227 \cdot 10^{-3}) \text{ m}$$

2.4. Dimensioning the Rotor Cage

2.4.1. Characterization of the Wind Out

$$N_{rs} := 26$$

$$N_{rph} := \frac{N_{rs}}{p} = 6.5$$

$$a_r := \frac{p}{2} = 2$$

$$y_{pr} := \frac{N_{rs}}{p} = 6.5$$

$$y_r := 6$$

$$gp_r := \pi \cdot \frac{D_r}{N_{rs}} = (28.133 \cdot 10^{-3}) \text{ m}$$

$$N_{rph} := 1$$

$$N_{spp} := \frac{N_{rs}}{p \cdot N_{rph}} = 1$$

$$v_2 := 1$$

$$k_{rw} := \frac{\sin\left(\frac{v_2 \cdot \pi}{2 \cdot N_{spp} \cdot N_{rph}}\right)}{\frac{v_2 \cdot \pi}{2 \cdot N_{spp} \cdot N_{rph}}} = 990.295 \cdot 10^{-3}$$

N_{rs} = Total number of rotor slots

N_{rph} = Number of rotor phases

a_r = Number of parallel branches of a rotor phase

y_{pr} = Polar rotor pitch measured in grooves

y_r = Passage of rotor coil measured in number of slots

gp_r = Rotor groove pitch

N_{rph} = Number of effective turns per phase of the rotor

v_2 = Number of slots per pole and rotor phase

k_{rw} = Rotor winding factor

$$I_{rph} := I_{ph} \cdot \phi = 82.345 \text{ A}$$

$$m_i := \frac{N_{sph} \cdot k_{sw} \cdot N_{ss}}{N_{rph} \cdot k_{rw} \cdot N_{rs}} = 9.477$$

$$I_{2N} := m_i \cdot I_{rph} = 780.39 \text{ A}$$

$$I_{bN} := \frac{I_{2N}}{a_r} = 390.195 \text{ A}$$

$$J_r := 5 \frac{A}{mm^2}$$

$$S_{rc} := \frac{I_{bN}}{J_r} = (78.039 \cdot 10^{-6}) m^2$$

I_{rph} = Rated intensity in the rotor referred to the stator

m_i = Current Transformation relationship

I_{2N} = Intensity per phase of the rotor

I_{bN} = Intensity assigned to a bar in the cage

J_r = Current density in the bar

S_{rc} = Section of a rotor cage bar

$$d_{rc} := \sqrt{\frac{2 \cdot S_{rc}}{\pi}} = (7.048 \cdot 10^{-3}) m$$

d_{rc} = Diameter of one of the rotor cage bars

$$K_{rFe} := K_{sFe} = 970 \cdot 10^{-3}$$

$$I_{rFe} := I_{sFe} = (267.692 \cdot 10^{-3}) m$$

$$B_{l2M} := 1.65 T$$

$$d_{mn} := \frac{B_M}{B_{l2M} \cdot K_{rFe}} = 562.324 \cdot 10^{-3}$$

$$g_{max} := 1 - d_{mn} = 437.676 \cdot 10^{-3}$$

d_{min} = Minimum Relationship between tooth width and groove pitch of the rotor

g_{max} = Maximum Relationship between the slot width and the slot pitch of the rotor

$$N_{rcpph} := 39 \text{ mm}$$

$$h_{rb} := 4 \text{ mm}$$

$$d := D_r - 2 \cdot \left(h_{rb} + \frac{N_{rcpph}}{2} \right) = (185.834 \cdot 10^{-3}) \text{ m}$$

$$sp_r := \frac{\pi \cdot d}{N_{rs}} = (22.454 \cdot 10^{-3}) \text{ m}$$

N_{rcpph} = Maximum rotor slot width

h_{rb} = Depth of rotor slot mouth

d = Diameter of the circumference in which find the centers of the bars

sp_r = Rotor slot pitch measured as length of circumference arch of d

$$\begin{aligned}
OUTD &:= D_s = (234.251 \cdot 10^{-3}) \text{ m} \\
GAP &:= \delta_g = (708.514 \cdot 10^{-6}) \text{ m} \\
HEIGHT &:= g = (275.971 \cdot 10^{-3}) \text{ m} \\
POLES &:= p = 4 \\
SLOTS &:= N_{ss} = 24 \\
SD1 &:= OUTD = (234.251 \cdot 10^{-3}) \text{ m} \\
SD4 &:= D_s = (234.251 \cdot 10^{-3}) \text{ m} \\
SW3 &< w_{maxss} \quad w_{maxss} = (13.421 \cdot 10^{-3}) \text{ m} \\
SW4 &:= h_{sy} = (37.474 \cdot 10^{-3}) \text{ m} \\
ST &:= h_{sm} = (14 \cdot 10^{-3}) \text{ m} \\
BARS &:= N_{rs} = 26 \\
RDI &:= D_r = (232.834 \cdot 10^{-3}) \text{ m} \\
RL1 &< edrt \quad edrt := g_{max} \cdot sp_r = (9.828 \cdot 10^{-3}) \text{ m} \\
RC1 &:= \frac{RDI - d}{2} = (23.5 \cdot 10^{-3}) \text{ m} \\
RW1 &:= 5.4 \text{ mm}
\end{aligned}$$

Annex 2

MathCad code property of Dr. Daniel S.Daniel

Radial Brushless DC motor design

$$mils := .001 \cdot in$$

Input Variables

$$P_{hp} := 100 \text{ kW} \text{ Rated power}$$

$$S_r := 1500 \cdot \frac{rev}{min} \text{ Rated speed in rpm}$$

$$E_{max} := 440 \cdot volt \text{ line-line}$$

$$J_{max} := 5.0 \cdot 10^6 \cdot \frac{amp}{m^2} \text{ max slot current density}$$

$$N_{ph} := 3 \text{ Number of phases}$$

$$N_m := 4 \text{ Number of magnet poles}$$

$$N_{sp} := 4 \text{ Number of slots per phase}$$

$$g := 25.4 \cdot mils \text{ Air gap distance}$$

$$R_{ro} := 0.033 \cdot m \text{ Rotor outside radius}$$

$$R_{so} := 0.0762 \cdot m \text{ Stator outside radius}$$

$$l_m := 0.00254 \cdot m \text{ Magnet thickness}$$

$$L := 0.602 \cdot m \text{ axial length of motor}$$

$$k_{st} := 0.96 \text{ Lamination stacking factor}$$

$$\rho_{st} := 16.8 \cdot 10^3 \cdot \frac{kg}{m^3} \text{ Steel Mass Density}$$

$$\rho_{cu} := 1.7241 \cdot 10^{-8} \cdot ohm \cdot m \text{ Conductor resistivity}$$

$$\beta_t := 0.0043$$

Temp Coefficient

$$k_{cp} := 0.6 \text{ Conductor packing factor}$$

$$\alpha_m := 0.96$$

Magnet fraction

$$B_r := 1.1 \cdot T \text{ Magnet remanence}$$

$$T_c := 30.0$$

Core loss multiplier

$$\mu_r := 1.01 \text{ Magnetic recoil permeability}$$

$$B_{max} := 1.0 \cdot T \text{ Max steel flux density}$$

$$w_s := 0.00254 \cdot m \text{ Slot width opening}$$

$$\alpha_{sd} := 0.4585 \text{ Shoe depth Fraction}$$

Mechanical and Electrical Speeds

$$\omega_m := S_r \cdot \frac{\text{rad}}{\text{s}} = 157.08 \frac{1}{\text{s}^2} \quad \text{mech radian speed}$$

$$\omega_e := \left(\frac{N_m}{2} \right) \cdot \omega_m = 314.159 \frac{1}{\text{s}^2} \quad \text{Electrical radian speed}$$

Slot parameters

$$N_s := N_{sp} \cdot N_{ph} = 12 \quad \text{Number of slots} \quad N_{spp} := \frac{N_{sp}}{N_m} = 1 \quad \text{\#slots/pole, error if <1}$$

$$N_{sm} := N_{spp} \cdot N_{ph} = 3 \quad \text{Number of slots per pole} \quad \alpha_{cp} := \frac{\text{ceil}(N_{spp})}{N_{spp}} = 1 \quad \text{Coil-pole Fraction}$$

Pitches

$$\theta_p := \frac{2 \cdot \pi}{N_m} = 1.571 \text{ rad} \quad \text{Angular pole pitch} \quad \theta_s := \frac{2 \cdot \pi}{N_s} = (523.599 \cdot 10^{-3}) \text{ rad} \quad \text{Angular slot pitch}$$

$$\theta_{se} := \frac{\pi}{N_{sm}} = 1.047 \quad \text{Slot pitch, electrical} \quad R_{si} := R_{ro} + g = (33.645 \cdot 10^{-3}) \text{ m} \quad \text{Stator inside radius}$$

$$\tau_p := R_{si} \cdot \theta_p = (52.85 \cdot 10^{-3}) \text{ m} \quad \text{Pole pitch} \quad \tau_c := \alpha_{cp} \cdot \tau_p = (52.85 \cdot 10^{-3}) \text{ m} \quad \text{Coil pitch}$$

$$\tau_s := R_{si} \cdot \theta_s = (17.617 \cdot 10^{-3}) \text{ m} \quad \text{Slot pitch at air gap}$$

Flux Adjustment Factors

$$k_d := \frac{\sin\left(N_{spp} \cdot \frac{\theta_{se}}{2}\right)}{N_{spp} \cdot \sin\left(\frac{\theta_{se}}{2}\right)} = 1 \quad \text{Distribution factor} \quad k_p := \alpha_{cp} = 1 \quad \text{Pitch Factor}$$

$$k_s := 1 - \frac{\theta_{se}}{2\pi} = 833.333 \cdot 10^{-3} \quad \text{Skew factor} \quad C_\phi := \frac{2 \cdot \alpha_m}{1 + \alpha_m} \quad \text{Flux Conc. Factor}$$

$$P_c := \frac{l_m}{(g \cdot C_\phi)} = 4.019 \quad \text{Permeance Coefficient} \quad g_e := g + \frac{l_m}{\mu_r} = (3.16 \cdot 10^{-3}) \text{ m eff. air gap}$$

$$k_{ml} := 1 + \left(\frac{4 l_m}{\pi \cdot \mu_r \cdot \alpha_m \cdot \tau_p} \right) \cdot \ln \left(1 + \frac{\pi \cdot g}{(1 - \alpha_m) \cdot \tau_p} \right) = 1.042 \quad \text{Magnet Leakage Factor}$$

$$k_c := \left(1 - \frac{1}{\frac{\tau_s}{w_s} \cdot \left(5 \cdot \frac{g_c}{w_s} + 1 \right)} \right)^{-1} = 1.02 \quad \text{Carter Coefficient}$$

Flux Calculations

$$A_g := \frac{\tau_p \cdot L \cdot (1 + \alpha_m)}{2} = (31.179 \cdot 10^{-3}) \text{ m}^2 \quad \text{Air Gap Area}$$

$$B_g := \frac{C_\phi \cdot B_r}{1 + \frac{\mu_r \cdot k_c \cdot k_{ml}}{P_c}} = (850.27 \cdot 10^{-3}) \text{ T} \quad \text{Air gap flux density}$$

$$\phi_g := A_g \cdot B_g = (26.511 \cdot 10^{-3}) \text{ Wb} \quad \text{Air gap flux}$$

Mechanical Dimensions

$$w_t := \tau_s - w_s = (593.566 \cdot 10^{-3}) \text{ in} \quad \text{Tooth width at air gap}$$

$$w_{bi} := \frac{\phi_g}{2 \cdot B_{max} \cdot k_{st} \cdot L} = (903.005 \cdot 10^{-3}) \text{ in} \quad \text{Back iron width}$$

$$w_{tb} := \frac{2 \cdot w_{bi}}{N_{sm}} = (602.003 \cdot 10^{-3}) \text{ in} \quad \text{Tooth width}$$

$$R_{sb} := R_{so} - w_{bi} = 2.097 \text{ in} \quad \text{Stator back iron radius}$$

$$R_{ri} := R_{ro} - l_m - w_{bi} = (296.207 \cdot 10^{-3}) \text{ in} \quad \text{Rotor inside radius}$$

$$w_{sb} := R_{sb} \cdot \theta_s - w_{tb} = (495.981 \cdot 10^{-3}) \text{ in} \quad \text{Slot bottom width}$$

$$w_{si} := (R_{si} + \alpha_{sd} \cdot w_{tb}) \cdot \theta_s - w_{tb} = (236.085 \cdot 10^{-3}) \text{ in} \quad \text{Slot width inside shoes}$$

$$\alpha_s := \frac{w_{si}}{w_{si} + w_{tb}} = 281.695 \cdot 10^{-3} \quad \text{Slot fraction inside shoes}$$

$$d_s := R_{sb} - R_{ro} - g = (772.382 \cdot 10^{-3}) \text{ in} \quad \text{Total slot depth}$$