POLITENICO DI TORINO

Master of Science in Automotive Engineering

E-Motor technology study and design: Patent landscape of the today EESM technology, Trend mapping analysis of the actual state of the e-Motors & Bridgeless design for an IPM motor

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For A. and M.T.,

you have shown me how to find the strength and the reasons to believe in myself, especially in the darkest and difficult days, and reach my goals.

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Abstract

This thesis work has the objective to summarise six months of internship in Toyota Motor Europe. The work focus on Electric Motors for Automotive Traction and develop a landscaping analysis, a trend mapping analysis, and a bridgeless design project.

In the first work a EESM patent landscaping analysis is performed, where different patents are analysed focusing on the pros and cons that the studied technology present and on the actual development of this type of motor

In the trend mapping analysis rotor and stator geometries values and power and torque values are combined to perform a trending in the years about the gravimetric and volumetric power and torque density of the electric vehicles.

In the last work a bridgeless design is develop considering different solutions and configurations to retain the rotor elements and to achieve better electromagnetic performance, considering the torque and the torque ripple.

Introduction

In the automotive field, nowadays, a revolution on its technologies is developed, pushed by the climate crisis that is affecting the automotive legislations. In Europe the legislations are becoming more and more severe about the CO2 released by the vehicles and for this the trend is to have a more and more electrification of the cars.

The internship work that is described in this document fits this scenario, as three different works are developed considering the electric vehicles and motors.

The first work is related to an EESM patent landscape, an analysis about the externally excited synchronous motor. This motor typology is becoming more attractive since the magnets are not required, substituting by copper windings, that is a positive effect from a supply chain robustness , cost and environmental point of view. In this analysis different companies and topics are analysed, to see which is the trend and the company effort of the study on this technology. The studies on this topic are more and more increased in the last years.

A trend mapping analysis is the second developed work. In this project different electric vehicles are analysed, focusing on the geometry of the rotor and of the stator in relationship with the power and torque that they can provide. A first analysis is performed on the power density, to study the compactness of the motor related to their power. Then some analyses regarding the power and torque density in the years are performed, to observe which will be the future trend of this technology. So some difficulties are encountered, such as the lack of enough data points, of a standardize method and the presence of physical differences in the design.

The last works relates to design a rotor that is bridgeless, so without the bridges characteristic of the internal permanent magnet motors that have the drawback to reduce the electromagnetic performances. The previous designs removed the central bridges and replaced them by an anchor element made by a magnetically inert material as the stainless steel, but it was not possible to remove the outer bridges.
A first design that comprehend three anchors is developed with very good results from the torque and torque ripple point of view, but it is not capable to retain the rotor elements, that due to the centrifugal forces tend to fly away.
A second design with four anchors is evolved, re-adding the central anchor. Thanks to this it is possible both to retain the rotor element and to have beneficial effect for the torque and the torque ripple.

1 EESM Patent landscape

1.1 Introduction

An electric motor is an electric machine that converts the electrical energy in mechanical energy by means of the interaction between the stator and the rotor magnetic flux.
One of the most used classification of this motor is based on the rotor configuration: passive and active.
The passive devices utilize power or energy into a circuit and do not require any external source to operate in the circuit. The induction motors, the permanent magnets motors and the synchronous reluctance motor are part of this category. The active components transform and injects power or energy into a circuit and require an external and conditional source to operate in the circuit.

In this patent landscape this last rotor type is considered, as the target of this analysis is to understand the state of art of the externally excited synchronous motor (EESM).
The externally excited synchronous motor peculiarity is the rotor, that, instead of having permanent magnets that produce the magnetic field, is wound by copper wires, as it is done for the stator. Their terminal ends are connected to 2 slip rings on the output shaft. These slip rings are attached to brushes with which an electronic controller can change the speed of the motor by varying the resistance through the rotor coils. These slip rings allow for speed and torque control and are the defining feature of wound rotor motors.

Different aspects are creating attraction on this type of motor. The former one is that there is not the presence of magnets. This is of major importance from an environmental and economical-political point of view as magnets are formed by rare earths, in particular neodymium. This magnet material is more and more difficult to obtain due to its higher and higher cost and dependent on imports from outside the EU.
Another important aspect is that there is no drag torque
The latter positive characteristic of the EESM motor is the possibility to control the magnetic field in the rotor by the current control, developing in this way higher power density.

1.2 Work done

To perform this EESM patent landscape the initial step is the research of the patents through different patent websites like Espacenet©, Google patents© and Deutsches Patent-und Markenamt© until twenty-five patents are obtained considering four different languages, English, French, Italian and German, and ten years of development, focusing on the last five years.

The patents are then divided in seven categories, considering their application field:

- High rpm & high volume production,
- Cooling,
- Cleaning,
- NVH,
- Electrical,
- Control,
- Conceptual.

Then a pro and cons analysis is performed to identify what are the valuable characteristic of the invention and what could require an improvement or affect the performance.

1.3 High rpm & high volume production

This first category focuses on finding proper solutions to realise an easier and cost-effective production and to overcome the issues that this type of motor encounters at high rpm, when the centrifugal force arises.

1.3.1 Collector design for crimping and insulation-FR3101209A1

At high rpm the wires are affected by the centrifugal forces that can produce high mechanical solicitations that could damage the wire. To connect it to the collector we need to use a crimping tool, that requires some space to fix it in a secure way, so the target of this patent is to ensure the accessibility of the crimping tool and the axial compactness of the rotor while maintaining sufficient isolation distances. This is achieved by adding a small additional space J and a spur, as shown in figure 1.1, that ensures that the wire always remains below the negative hook at a sufficient isolation distance from the opposite hook and prevent that the wire from rising too high from the collector displacement step from the intermediate position to the final position.

This solution allows to have a better retention of the wire in the collector, to avoid a possible detachment of the wire that will produce an interruption on the current flow. It is a simple change in the geometry of the collector, so it is also cost-effective.

The cons of it are the fact that giving an additional space for the accessibility of the crimping tool increase the axial length of the collector, so it is obtained a bigger collector.

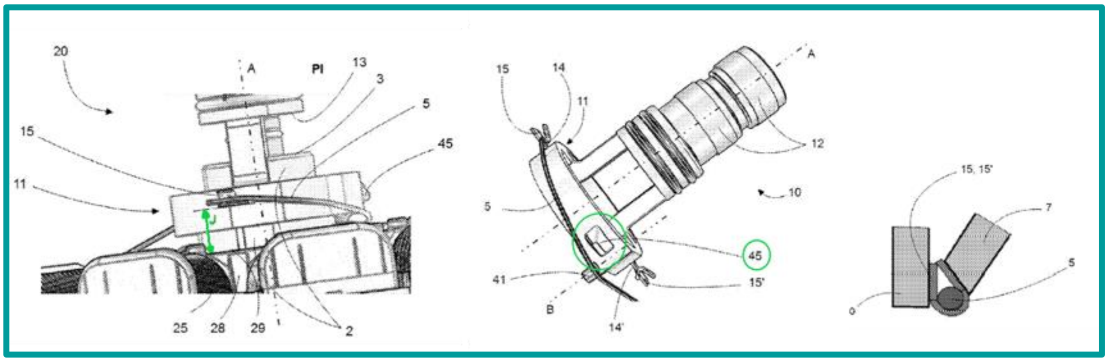

Figure 1.1-Collector design

1.3.2 Method for winding a rotor with more robust wire connection to the collector-[WO2021139925A1](WO2021139925A1)

From the collector the wires have to be set on the rotor teeth and when centrifugal force arises, they can move outside to their position or break. To avoid this, a new method for winding a rotor with a more robust wire connection to the collector. The poles are numbered in series and the wire connection on the collector is on the opposite direction with respect to the pole 1. The wire starts from the connection 26 and then 1,2,4,3. With this configuration an angle alfa is created, more than 45 degrees, and through it the contact is maximise. The same thinking at the end of the winding between the pole 3 and the connection 27 with the angle beta. The general rule for n wound poles distributed radially around the main axis, the n poles being wound with the wire in series in turn according to their numbers in ascending order, the last pole not being wound last, as shown in figure 1.2.

Thanks to this improve method for winding, it is possible to achieve a mechanical robustness of the wire connection with the collector, the residual stresses in the connections are reduced or even eliminated and it is cost-effective as it does not introduce any new element for example.

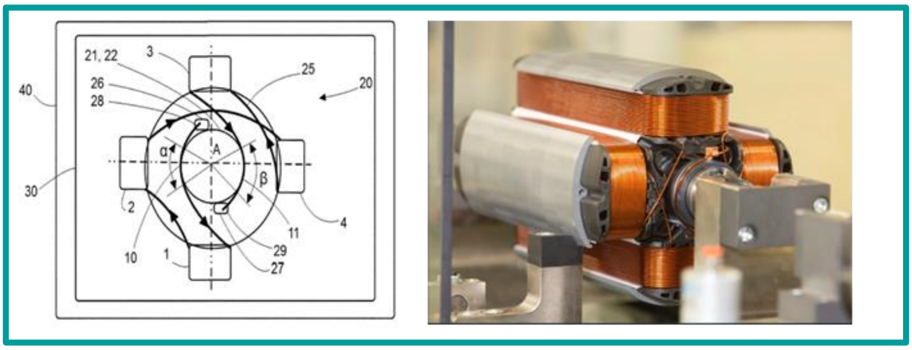

Figure 1.2-Winding method

1.3.3 Retention guide wire device-WO2019197266A1

At very high rpm one of the main issue is related to keep the wires in their position, as this force is trying to separate and push them away from the teeth of the rotor. In this patent a possible solution is developed by using a guiding head support and a guide head inserted between the lamination assembly. It is composed by an internal radial face of the support that abuts against an external radial face. It is possible to add balance masses on this guide, where a material (plastic) could be injected inside the contact face 33, shown in figure 1.3. This device is also useful to guide the wire by means of its teeth.

Thanks to this device it is possible to have a better wire and lamination stack retention, a faster assembly and the possibility to use balancing masses inside the cavities to balance the rotor shaft.
The possible cons are that in this way it is added an additional weight to the rotor, the cost rise due to the presence of a new element and a balancing design is needed.

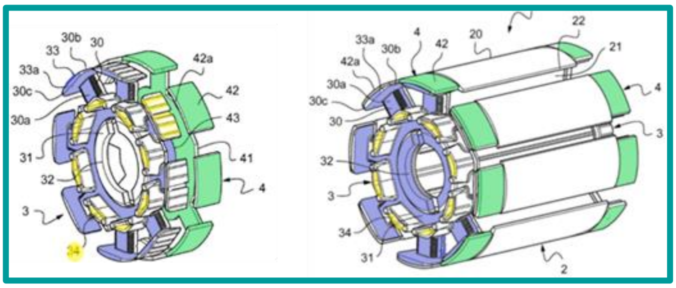

Figure 1.3-Retention guide wire device

1.3.4 Wire retention device for high rpm rotor-WO2020020551A1

In this patent the focus is on developing the guide head, that has the target to hold the winding against the centrifugal forces. It is composed by a metal sheet co-moulded with a plastic structure, that allows to avoid the use of screws, bolts, retaining rings used in the prior state of art. Through this structure it is possible to balance the rotor, there are 3 possible configurations: the first one, already seen in the first patent, has these slots to add balanced mass and a disc that could be drilled for balancing, the second one has additional parts on the metal sheet and the last one presents a balancing crown, as shown in figure 1.4.

This device is capable to simplify and lighten the rotor assembly as it avoids the use of crowns, retaining rings, through bolts and it is made by one rigid piece. Another pro of this solution is the greater stiffening and resistance to the risk of breaking and cracking. Then it takes up the axial load.

The possible cons of this device focus on the assembly method as the interference to fit the head guide and the set of laminations must be well calibrated. Then the removal material for balancing could damage the guide head and the rotor. As it is an additional component it means that the cost is high.

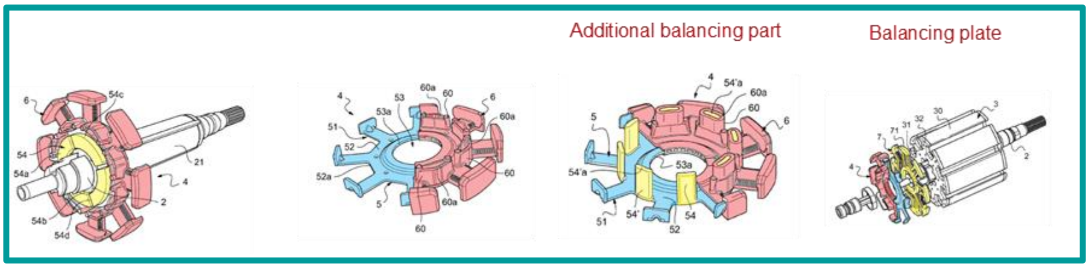

Figure 1.4-Wire retention device for high rpm motor

*1.3.5 Bayonette teeth-*DE102018128521A1

This patent presents a disc support device with the aim to provide a more stable rotor for high rpm preventing damage to the star disc by centrifugal force. As it is possible to see in figure 1.5, the main difference with the previous patents is the type of connection that has the purpose to eliminate screws and welding. It is used a bayonetted connection device composed by a star disk and a support ring that is arranged on the laminated core of the rotor between an end side of the laminated core and end windings.

This device has the pros to eliminate the crews and the welding to obtain an high retention of the laminations at high rpm with an easy assembly. As the previous patent, as this solution adds an element the cost and the weight arise.

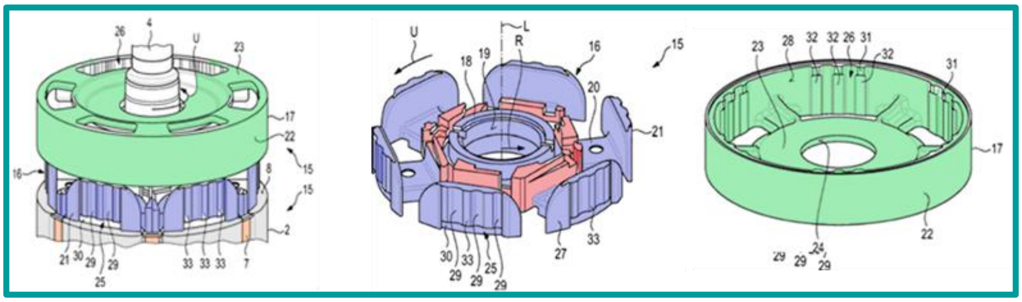

Figure 1.5-Bayonette teeth

1.1.4 Co-moulded rotor for high rpm- IT201800020491A1

In this patent another possible solution to retain the wires at high rpm is developed. The wires are pre-assembled and the rotor teeth are co-molded with an electrically isolated material with undercuts. In this way it is prevented the direct contact of the wire in the winding zone that could lead to damage or the breakage of the wire due to high stresses.

This solution gives an optimal balancing and fixing, as it maximises the constraint of the guide to the main body and reduces the exposed area. In addition to this the moulding is very easy to be obtained. The cons is related to the additional cost and the additional weight of this device.

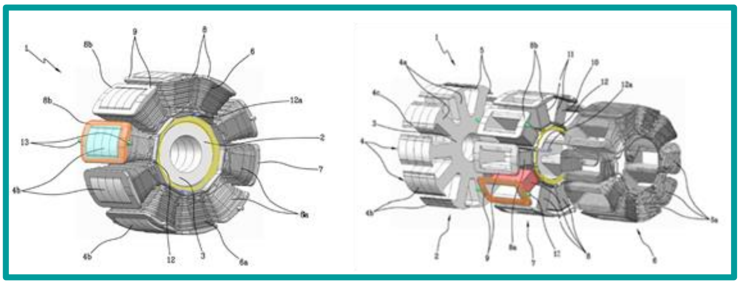

Figure 1.6-Co-moulded rotor for high rpm

1.3.7 Bandaged rotor with easy tooth assembly-[DE102020107830A1]

In this patent a different approach to contrast the effect of the centrifugal force on the rotor and the winding. As shown in figure 1.7, the rotor presents rectangular grooves in each pole and inside them are located the rotor teeth by means of a rectangular connection. The windings are pre-assembled and inserted in the teeth externally and individually. To keep the teeth in position a retained CFRP bandage is used.

The target of this invention is to provide a rotor with rotor teeth which are simpler and with an improved winding quality. Thanks to the sleeve a higher protection is achieved. The problems related to this technology affect most the teeth, as they need a very good retention otherwise, they will fly away or can oscillate, and it is easy to have possible damage between the groove and the small teeth.

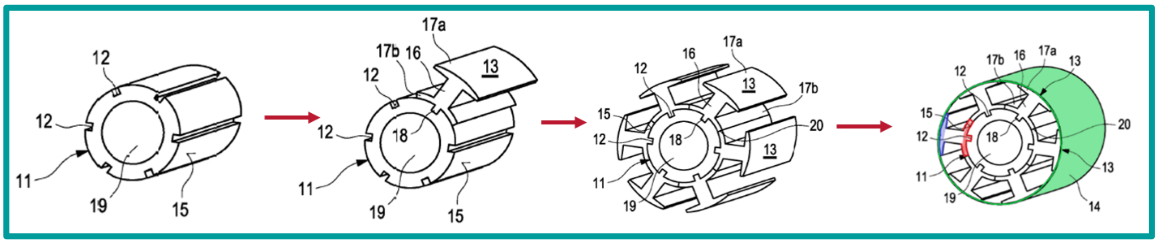

Figure 1.7-Bandaged rotor

1.3.8 Puzzle teeth-[DE102018213567B3]

A similar approach, a rotor formed and assembled by multiple parts, with respect to the previous one is the one presented in this patent. The windings here are pre-assembled and then inserted in the rotor pole. Then, by means of dovetail connection in the upper part of the pole, the pole shoes are assembled in the left and right end, like a puzzle. A first solution is a mechanical constrain between the pole shoe element that is capable to help in the retention of the rotor teeth and close completely the groove. This last solution is developed in a radial mechanical reinforcement that has a T cross-section between two rotor winding.

This solution allows a simpler winding method, the rigidity is increase due to reinforcing element and higher rotational speed is achievable but adding all these elements increase both weight and cost.

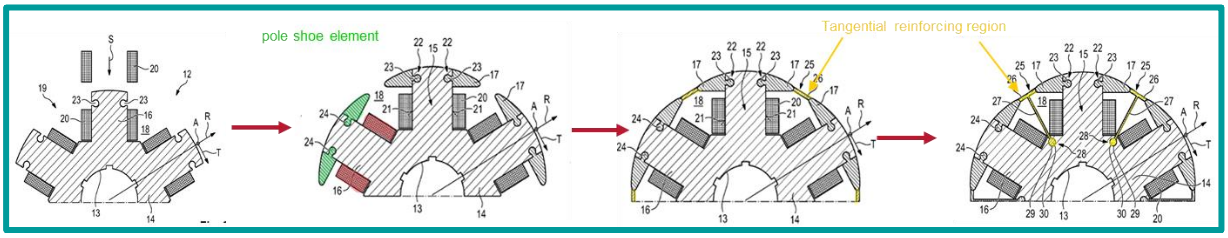

Figure 1.8-Puzzle teeth

1.3.9 Bandage with separated pole shoes+slot closure-DE102019218628A1

This patent considers again a puzzle approach to assembly the rotor pole shoes and to retain the lamination and the field winding at high centrifugal forces. A unique pole shoe is connected to the rotor teeth by means of a dovetail connection and then between two pole shoes add a non-magnetic slot closure to create a sort of new bandage type made by the summation of these rotor shoes and the nonmagnetic slot closure, as shown in figure 1.9.

This solution ensures the optimal mechanical strength of the rotor and the possibility to have different pre-assembled shapes of the rotor windings.
The difficulties are in the fact that the assembly process is long, and it is difficult to recycle as different parts are welded or glued.

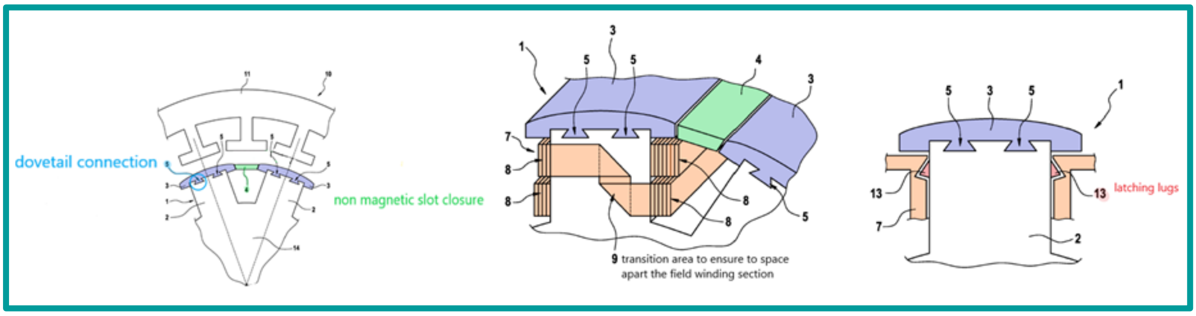

Figure 1.9-Bandage with separated pole shoes

1.3.10 Single piece shoes string with local magnetic disconnection-DE102019218628A1

Considering the previous concept of having a unique pole shoe, in this patent a single piece shoes string is developed, It has, instead of having a slot closure, a demagnetization connecting area made by reheated region, in order to decrease the magnetic properties and avoid short circuit. In this way the target of obtaining a mechanical winding retention at high rpm while still having magnetic separation of the poles is achieved.

This solution has the following pros: single piece shoes string, no need for separate slot closure and good mechanical retention of winding at high rpm, but it requires local demagnetization to avoid short circuit and this produce higher cost as it is required an additional energy and process cost.

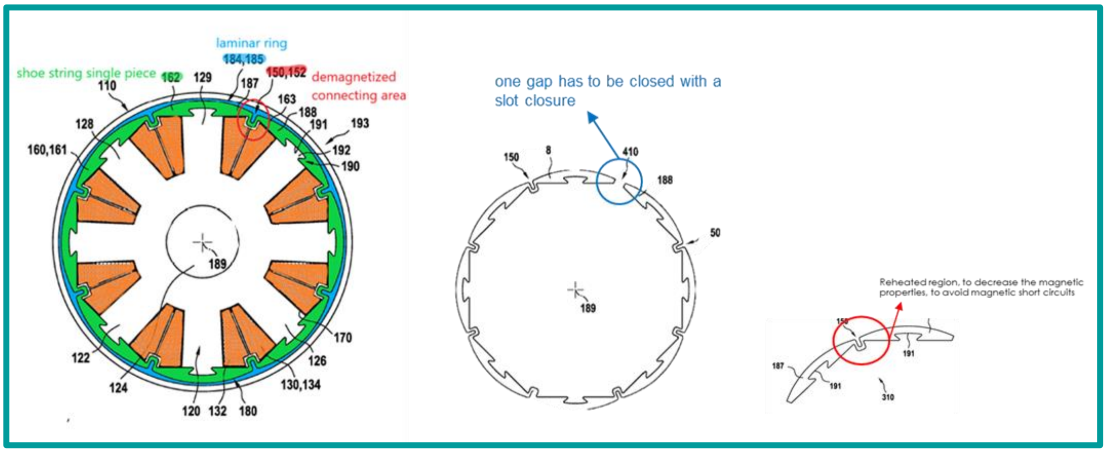

Figure 1.10-Single piece shoe string

1.3.11 Bar cage for high rpm motor-[EP3797468A1]

To protect the inner part of the motor a cage body mounted around the inner part of the rotor is developed in this patent. It is composed by two solidarized parts with stems that are interlocked and located between the teeth. This interlocking allows a rapid and simple assembly with the rotor. The stems on the tongue shape ensure that the coil is kept at the right distance to avoid their degradation due to excessive heating and mechanical destruction. To thermally and electrically insulate the stems an operation of hard anodization is required.
The presented invention presents also some problems, for example the tongue shape could be damage in the assembly of the cage and an additional cost should be taken into account due to the hard anodization.

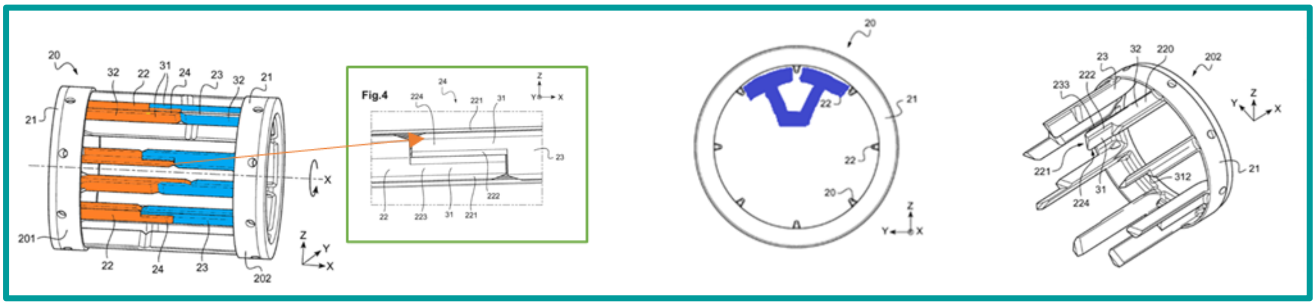

Figure 1.11-Bar cage for high rpm motor

1.4 Cooling

The externally excited synchronous motor EESM could generate high temperature due, for instance, to ohmic losses, so a cooling study is required to keep the temperature in the right range.

1.4.1 Crown cooling device-[WO2018095842A1]

In this solution the target is to avoid that the cooling liquid enters in the air gap creating friction inside the stator and the rotor, i.e. generating a decrease in the motor efficiency. It is developed a crown cooling device with evacuation holes of the cooling liquid inside the crown in order to push out the cooling medium through a specific direction to avoid that the cooling liquid enters in the air gap creating friction inside the stator and the rotor resulting in a decrease in the motor efficiency. A second configuration, as shown in figure 1.12, is possible with a constant reduction of the crown external diameter to have an easier way out of the oil.

With this solution is possible to achieve a better cooling, especially for inner side of the stator windings and higher motor efficiency, but it requires higher cost for the additional cooling parts and it could be weakened by the holes mechanically.

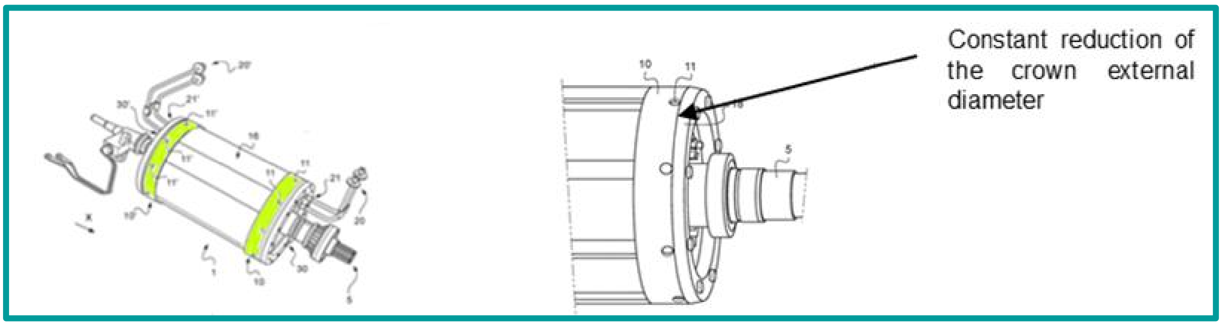

Figure 1.12-Crown cooling device

1.4.2 Air cooled rotor-10 2012 205 756.0

This patent is quite old, so it presents an easier solution to manage the temperature and the cooling. The device is an impeller that is arranged concentrically around the rotor shaft on the end winding cover, and it could be present holes to balance the rotor. It uses only the air to cool the rotor. Adding an impeller means an additional weight and cost.

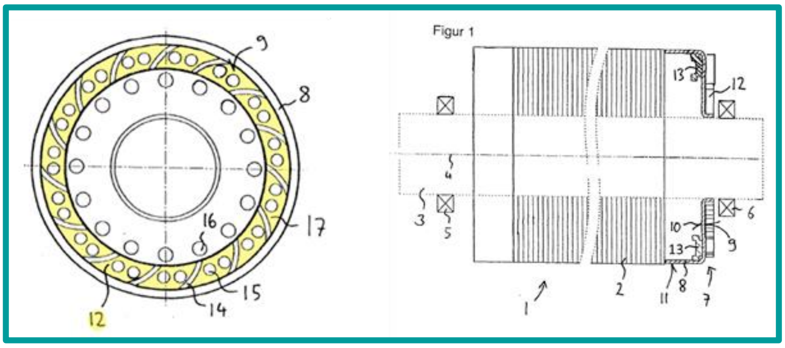

Figure 1.13-Air cooled rotor

1.5 Cleaning

Another issue related to this motor type is related to the brushes, as, going in contact to the slip ring and being made by graphite, are consumed by the friction. This material consumption is detrimental for this motor, as the small particles affect the performance of the rotor.

1.5.1 Dust collecting device-[EP3799269A1]

To solve this issue without the use of a fan or a pump, as they could bring additional dust, moisture or other fluid from the external environment, in this patent it is created a housing where the air is diverted thanks to a pressure difference generated by the rotation of the slip ring. Two sections are inclined in the housing to delimit the flow section and to generate an impact wall where the dust is separated from the air, then the dust flow into a closed configuration chamber where it is retained.

This patent by means of a simplified design can decrease the amount of dust that could deposit inside the rotor in a more energy efficient manner and giving the possibility to be used also in humid and/or wet environments.
What is not capable to solve is that the dust is rejected in the external environment and it requires a precise design of the inclined section to have the right impact of air on the wall that retain the dust.

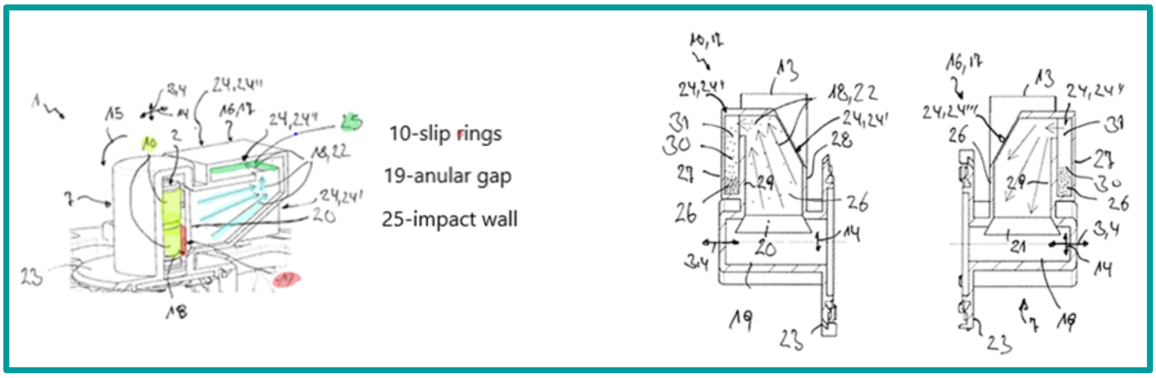

Figure 1.14-Dust collecting device

1.6 NVH

The e-motor could suffer about noise and vibrations due to the presence of torque ripple and the harmonic components of the voltage, in addition to this the externally excited synchronous motor can have more issues due to the presence also of the brushes that, going in contact with the slip rings, could have a sort of bounce and re-bounce that could generate vibrations and noise.

1.6.1 Vibrations limiting device for the brush at high rpm-DE102020114457A1

In this patent the target is to decrease the vibrations produced by the movement of the brush in the housing. The invention is related to two separate spring elements that are needed to clamp axially the brush and the roller that goes in contact against the side surface of the brush. In the prior state of art, it is used an hairspring element, with this patent this is avoided as it is difficult to optimize it. The presence of these two spring elements affects the cost and the space to host the two spring elements is required, increasing them.

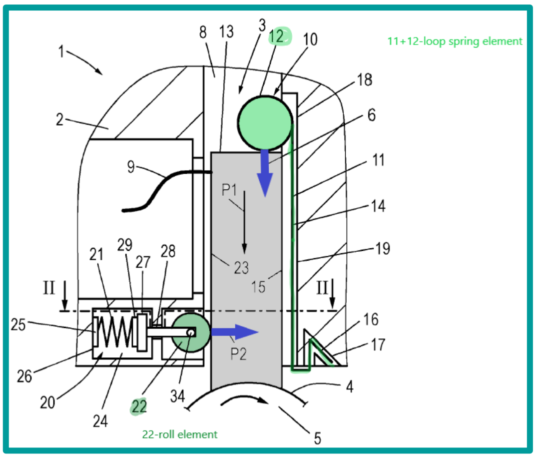

Figure 1.15-Vibrations limiting device for the brush

1.6.2 Flux optimized teeth arrangement for less vibration-FR3066333A1

In this patent is presented a wound rotor with twisted poles, with the arm that are aligned on a central radial axis and that have a convex top surface with four different possible geometrical design, in order to decrease the harmonic components of the voltage and the electromagnetic torque that causes high vibrations. Different thickness of the teeth head, varying on the opposite direction and this thickness variation has a maximum value and a minimum one. Two realization methods are presented: in the former the first and second lateral borders of the pole head of two adjacent metal sheet subpack are respectively in different parallel planes. In the latter method they are in the same plane along the stacking. In particular this design permits to vary the flow of the magnetic flux in the transition phases, in order to avoid the abrupt transition of the electromagnetic flux.
Analysing this patent, the cons of this solution are mainly two: that the thinner part of the rotor teeth could be damage easily and considering the mass production the cost will be high.

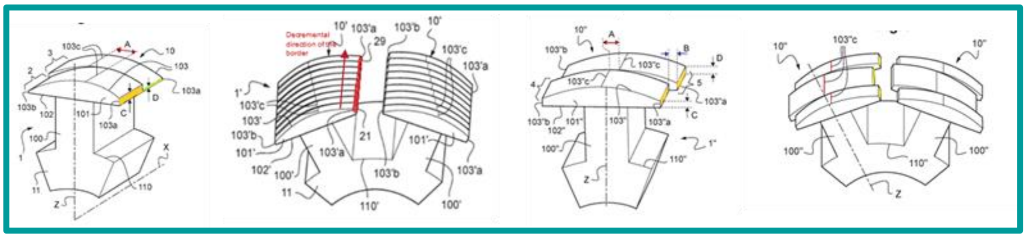

Figure 1.16-Flux optimized teeth

1.6.3 Asymmetric tooth shape and flux barrier-DE102020212636A1

The invention of this patent is an asymmetric pole shoe design with the presence of an opening filled with different kind of alloy that creates a non-constant airgap thickness. This rotor tooth presents a non-constant airgap thickness, that increases in the left radial direction with respect of the central axis of the tooth. This asymmetric shape, as shown in figure 1.17, can reduce the torque ripple, that affects the performance of the motor increasing vibrations and noise. In the right end of the tooth in the pole shoes the opening is present. The target is to prove a rotor for an electrical machine with which the power density of the electrical machine is increased and the installation space and cost is reduced. Thanks to this solution it is possible to achieve an higher torque value, the minimization of the torque ripple and noise and a good design flexibility due to the presence of the opening and the curvature. The difficult task is to ensure the retention of the material inside the flux barrier.

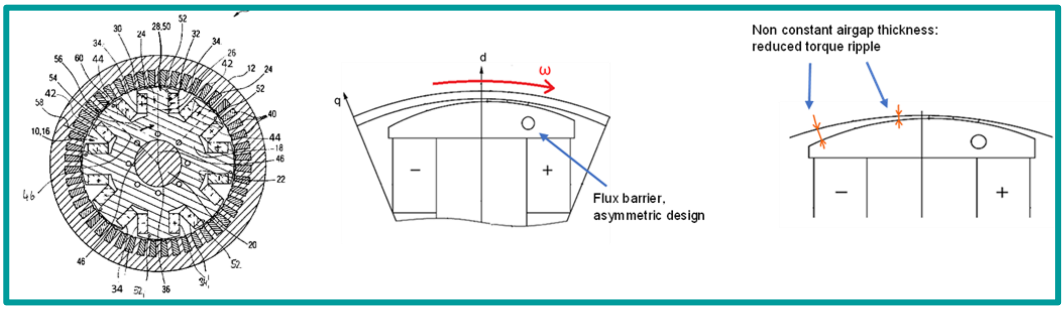

Figure 1.17-Asymmetric tooth shape and flux barrier

1.7 Electrical

1.7.1 Wire brush guide-WO2020128888A1

The brush is a very important component in the EESM motor without it is not possible to pass the current into the windings, so it is extremely important to assure their right functionality. In this patent the aim is to not have risk that the brushes, translating inside the duct damage the connections or interrupt the connection. To achieve this a conductive element 7 is designed with a deformable section 8 configured to deform along a preferential direction to follow the movement of the brush imparted by the presser members. It is possible to define these conductive elements by two pre-assembled conductive cartridges that are constrained to the connecting member by welding to facilitate the mounting method

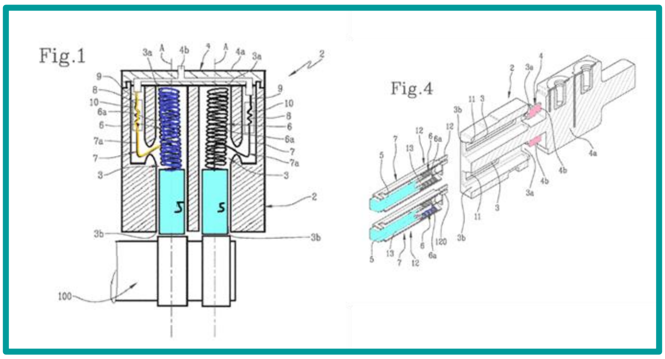

Figure 1.18-Wire brush guide

1.7.2 Shielding plate-DE102020210692A1

In this patent it is presented a shielding plate that is integrated with a minimum amount of installation space into the brush holder. The target of this device is to eliminate two disadvantages of the positioning of the electronic housing arranged radially outside the pole housing:

1 electromagnetic interference radiation, which can be disruptive for other electronic functions, emitted by the electronic circuit board

2 interference radiation which emits to the surroundings through the transmission

To achieve this result the shielding plate is attached to the rotor bearing by means of a large electric ground contact over the full surface area. The brush holder component can be connected to the bearing plate through the central opening in the shielding plate that is fastened axially between these two components. A bearing plate with a conducting region is fastened on the other side of the shielding plate.

To eliminate the electromagnetic interference radiation which is produced to the outside the shielding plate with the stator housing forms a Faraday cage.
The pros of this device are related in particular on the optimal shielding effect and on its compactness, while, considering the cons, the connecting elements have to be engaged to not interrupt the conductor layer conduction and there is the need of centring elements to centre the brush holder with the commutator

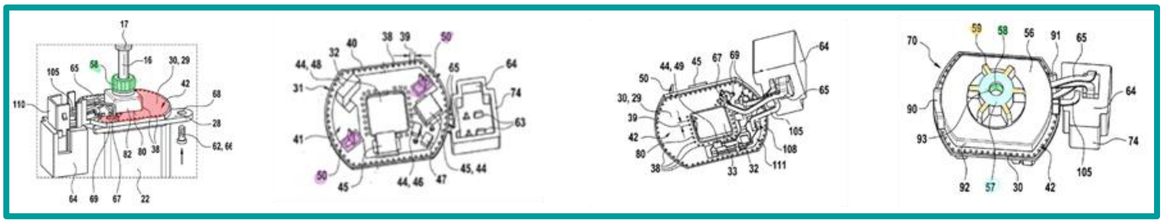

Figure 1.19-Shielding plate

1.7.3 Ferrite wireless feeding system-DE102019212406A1

As the brushes could have important drawbacks, some companies try to develop a wireless system to substitute them. This is the case of this patent, where it is created a wireless feeding system where two ferrite cores shaped as circular ring are the feeding system. The first ferrite core has a primary-side winding circuit for generating an alternating magnetic field that is transmitted to the secondary ferrite core for converting it in alternating voltage. The benefits that this device could have are a lower manufacturing cost, as less surfaces need to be ground the radial deviations are not critical and the less copper use, but it requires more axial length, that creates a second drawback as it is required more current at the primary and electromagnetic noise.

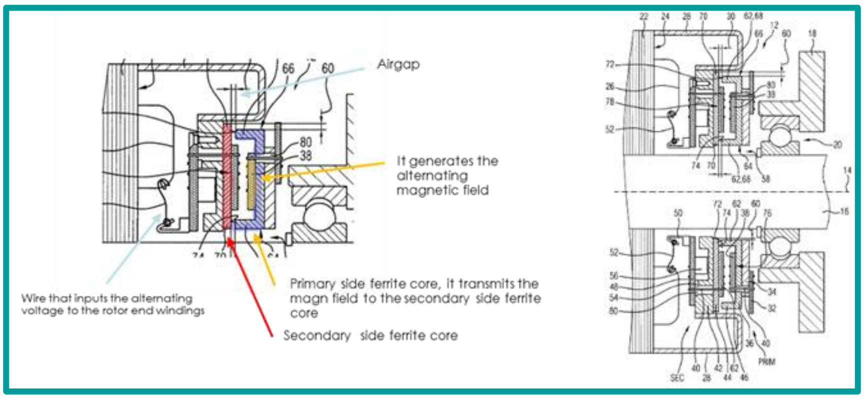

Figure 1.20-Ferrite wireless feeding system

1.8 Control

1.8.1 Method for limiting the sensors number-WO2016207510A1

This patent presents a sensor less-control device capable to estimate the motor parameters limiting the use of mechanical sensors by means of the combination of an estimator and an observer, to optimize the reliability and the robustness of the command of a wound rotor machine, limiting the sensors number. Starting from the 3 phases of the stator, we want to know the position and the speed of the rotor. It is need to pass from the fixed reference system of the stator (a,b,c) to the rotor one, that is fixed with respect to the rotor and is in motion form the stator point of view. By means of the Clark transformation the three-phase currents are converted to a stationary two-axis system. Then by means of Park transformation the stationary two-axis coordinate system is rotated to align with the rotor flux using a transformation angle calculated at the last iteration of the control loop. In this way it is possible to achieve a

Limitation of the complexity and size of the device with respect to similar control device, a cost reduction and a rapid and robust estimation, but the control design is complex.

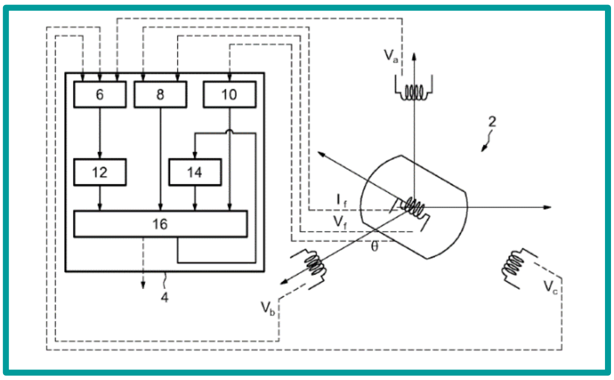

Figure 1.21-Method for limiting sensors number

1.8.2 Virtual speed and position sensor-[FR3101209A1](FR3101209A1)

To make the estimator independent from the machine parameters and to estimate the position, speed and acceleration of a rotor limiting the mechanical sensors, in this patent an estimator of a sensor less-control device that is not dependent on the machine parameters is developed. The invention uses an estimator σ that is independent from the machine parameters, and it is calculated by the error of the angle θ. From the estimator we can calculate the sign of the rotor position in 2 different time instant. From the sign we can calculate the rotor position and the speed of the rotor. A better way is to consider the dynamic speed in order to correct the error during the acceleration. Thanks to this solution a rapid and robust estimation with a cost reduction is achievable, but the control design is complex.

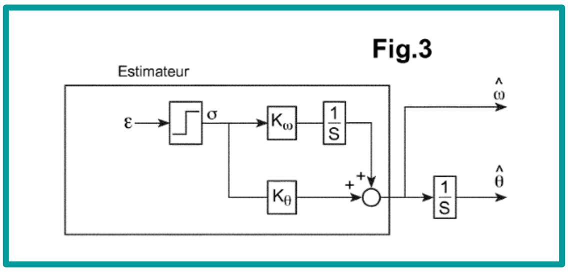

Figure 1.22-Virtual speed and position sensor

1.8.3 Limp home mode for electric motor-[EP2385622A2]

This control system is intended for a brushless synchronous machine. In the event of a failure of the exciter supplier device 4, it is immediately switched off by means of a switching device 10 and an emergency supply device is activated to maintain emergency operation.
The emergency supply device 5 it is not controlled, so during emergency it provides electrical energy in an uncontrolled manner.

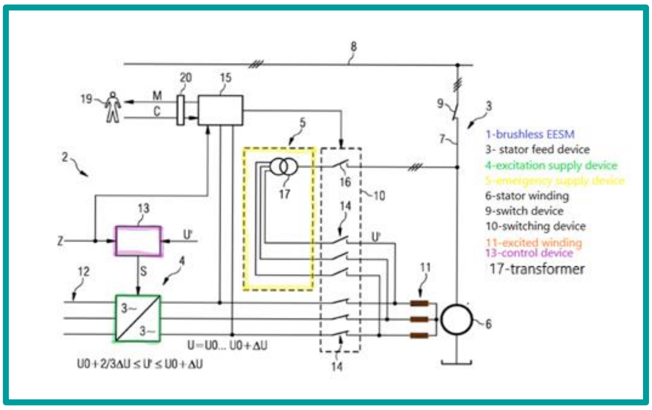

Figure 1.23-Limp home mode for electric motor

1.9 Conceptual

This paragraph is about patents that are interesting from a theoretical point of view, as they try unusual solutions, for example, to increase the power density or avoid the use of the brushes, but it could be difficult and very expensive to realise them.

1.9.1 Rotor with windings+PM+bandage-[DE102020105588A1]

In this patent it is presented a solution that combine the external excited synchronous motor with the permanent magnet synchronous motor, as shown in figure 1.24. To achieve a better mechanical retention the rotor is kept by a CFRP bandage. The rotor has coils around his rotor teeth and between the teeth a magnet is placed in two possible configurations. In the former the magnet is directly in contact with the bandage, while in the latter it is positioned in a slot that then goes in contact with the bandage.
Thanks to this solution is possible to achieve higher power density with a robust and compact structure, so considering that this more is suitable for high-speed operation. The use of both magnets and coils makes this type of motor expensive.

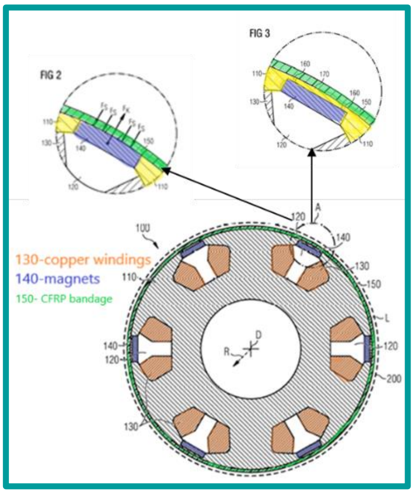

Figure 1.24-Rotor windings+PM+bandage

1.9.2 EESM wireless rotor feeding-[DE102013226785A1]

In this patent two rotor elements are combined. The first rotor element forms a South magnetic pole and the second rotor is the North pole. The excitation field is not directly generated by the rotating rotor, but by generated or reinforced by the electrical conductor fixed opposite to the stator. Two magnetic fluxes are present. The first one flows from the stator into the second ring elements then into the first ring and form a first magnetic excitation field. The second magnetic excitation field is formed between the second ring element, the first and the second rotor element and the stator. This solution with two rotors require more space with respect to the traditional one with the brushes.

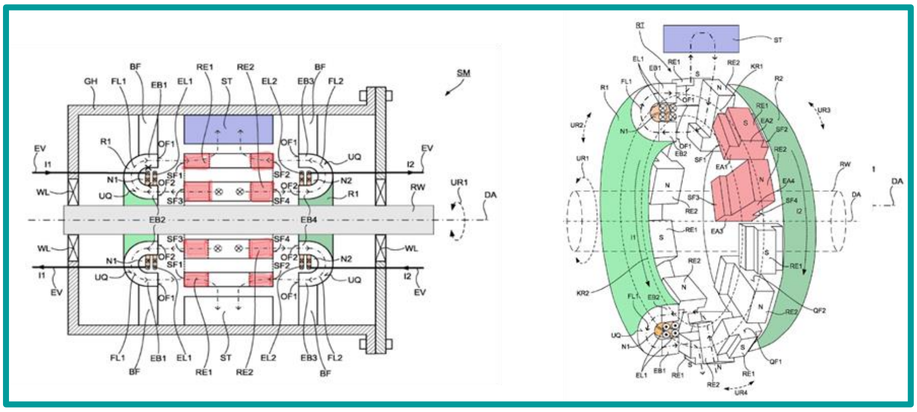

Figure 1.25-EESM wireless feeding system

1.10 Conclusions

Thanks to this EESM landscape it is possible to have a better understanding on the develop process that this type of motor is having thanks to its attractive performance and to the fact that it is possible to avoid the use of the rare earth, present in the magnets.

This develop is considering different aspects of this technology, such as the high rpm and high-volume production, cooling, cleaning, NVH, electrical and control applications, having consideration also for unusual solutions.

What is possible to analysed by this landscape in table 1 is that Renault has the most patents application and is leading the way in filing applications in this technology area, followed by Audi and Bosch. Considering the first filing date, when the company submit the patent to the authorities, the number of published patents from 2018 significantly increases.

The topics that have the highest interest by the companies, as shown in table 2, are the high volume production, as the target is to have a production as fast and cheap as possible and high rpm application, due to the great difficulties in the retention of the rotor and the wires at high centrifugal forces, as shown, for instance, in the analysed patent in Figure 1.3. EESM is not a major trend in the current market of electrify ed automotive powertrains, at this moment, but patent applications are increasing, that means that companies are finding it more and more interesting to be studied.

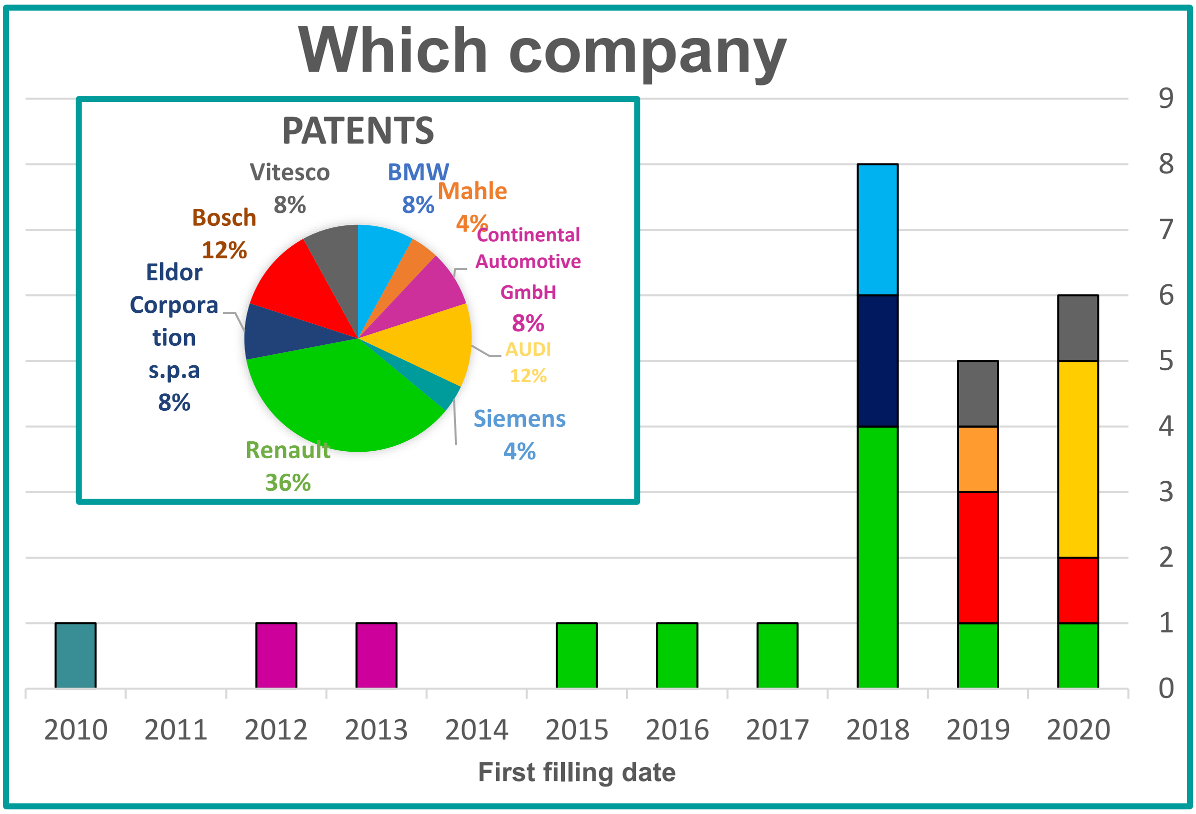

Table 1-Which company

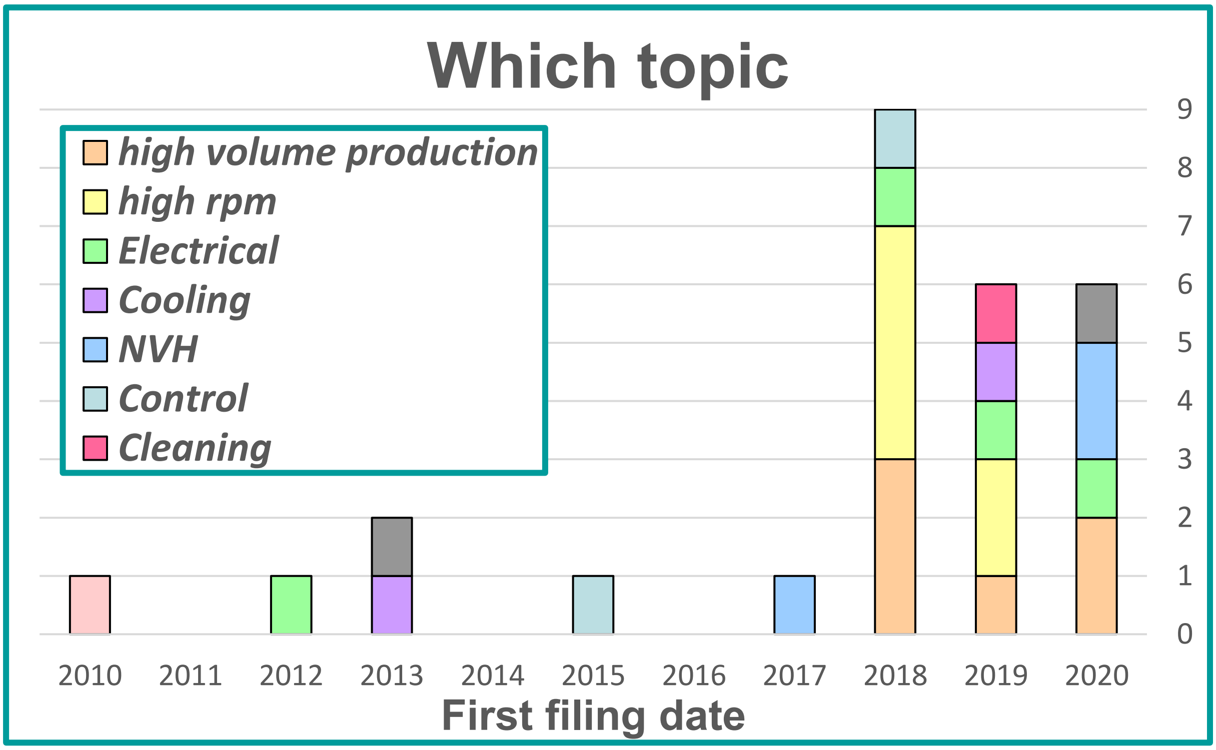

Table 2-Which topic

2 Benchmark analysis of EVs

2.1 Introduction

The benchmark analysis is the process of comparing one company's information or performance against other and to see trends in time.
To perform this analysis, first, it is required to collect the data of interest by different sources, then, to understand which relationships between these data could be the most interesting and at the end plot and analyse the graphs to see which is the position and the performance reach by the company.
In this analysis only the European market is considered, as the goal is to understand in this market how the present and future trends are.
After the geographical area of interest is decided, the focus is on decide which data could be needed for the benchmark analysis considering different parameters of the vehicle. The chosen parameters are related to the geometrical properties of the different electrical motor types that are presents in the analysed vehicle model, considering the rotor and stator dimensions, such as diameter, pure stack length, volume and weight and the torque and power values.
Once these data are collected the relationships that are considered are related to a comparison between geometrical parameters and torque or power and time.

2.2 Data collection

The data are collected by means of A2Mac1©, a benchmarking website where vehicles are analysed and disassembled in order to obtain information on all domains of the vehicle, such as the battery, the electric powertrain.
In the case of this analysis thanks to this website, it is possible to download the geometrical data of the rotor and the stator of interest. For some data, such as the pure stack length of the rotor and stator or the inner and outer diameter of the stator to have a higher precision it is possible to use a measurement tool in A2Mac1, that by means of the pixel of the picture is able to calculate approximately the requested dimensions. This is done especially for some vehicles, as sometimes the devices are not entirely disassembled, as, for instance, the shaft or the case are still attached to the motor.
The torque and power data are not present in A2Mac1, so to collect them a research vehicle by vehicle is done by means of the company press folders or specialized web site.

2.3 Graphs & analysis

2.3.1 Volumetric power density

The first graph in figure 2.1 is regarding the volumetric power density of the EVs. It is calculated considering the peak power of the vehicles and the total volume of the motor, that is the summation of the stator and rotor volume. It is of interest the fact that the mass production volume density nowadays is above 10 kW/L for most of the points and this value is increasing up to a pre-development stage of 50 kW/L. The power range of already available E-Motors varies from 12 kW to 285 kW. This analysis shows the potential for reduction in cost and space. The best area for the power density is the one in the top left area that now is only regarding a pre-development phase.

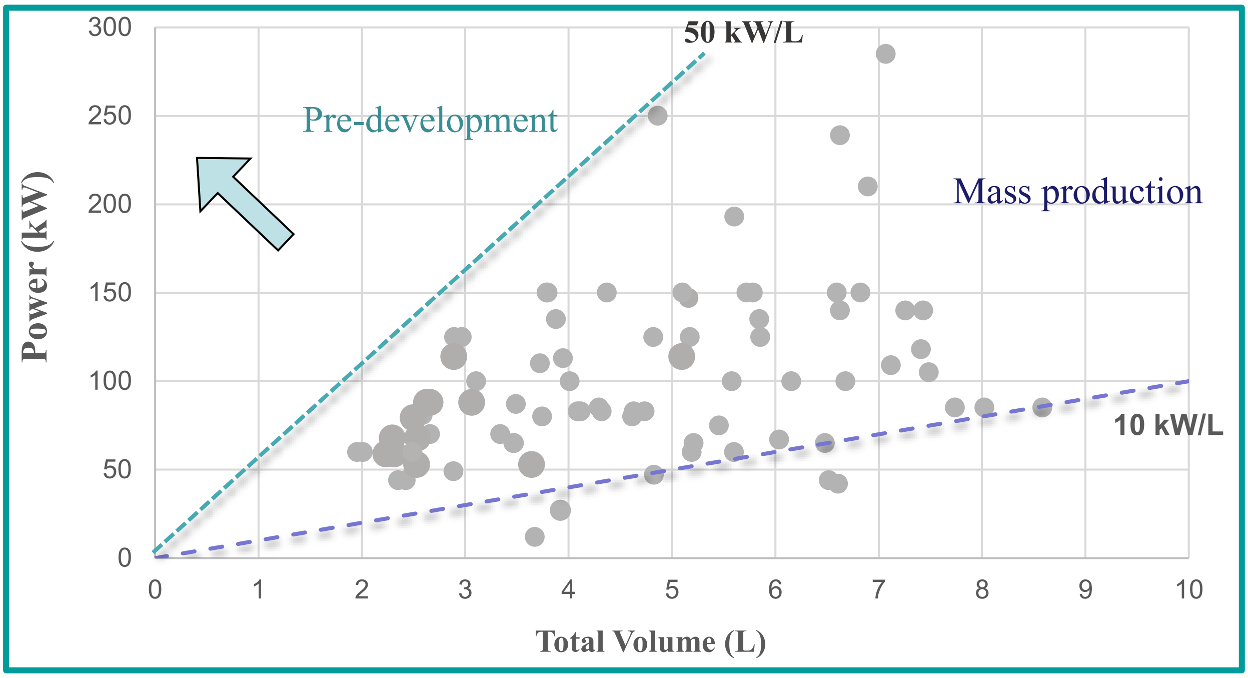

Figure 2.1-Volumetric power density

2.3.2 Gravimetric power density vs years

Considering the time, a gravimetric power density vs years graph is originated, shown in figure 2.2. Here the focus is more on the last five years where the number of points is higher and it is possible to notice that there is an increment of approximately 75% for the gravimetric power density. The E-Motor gravimetric power density is varying between 0.9 kW/kg to 5 kW/kg

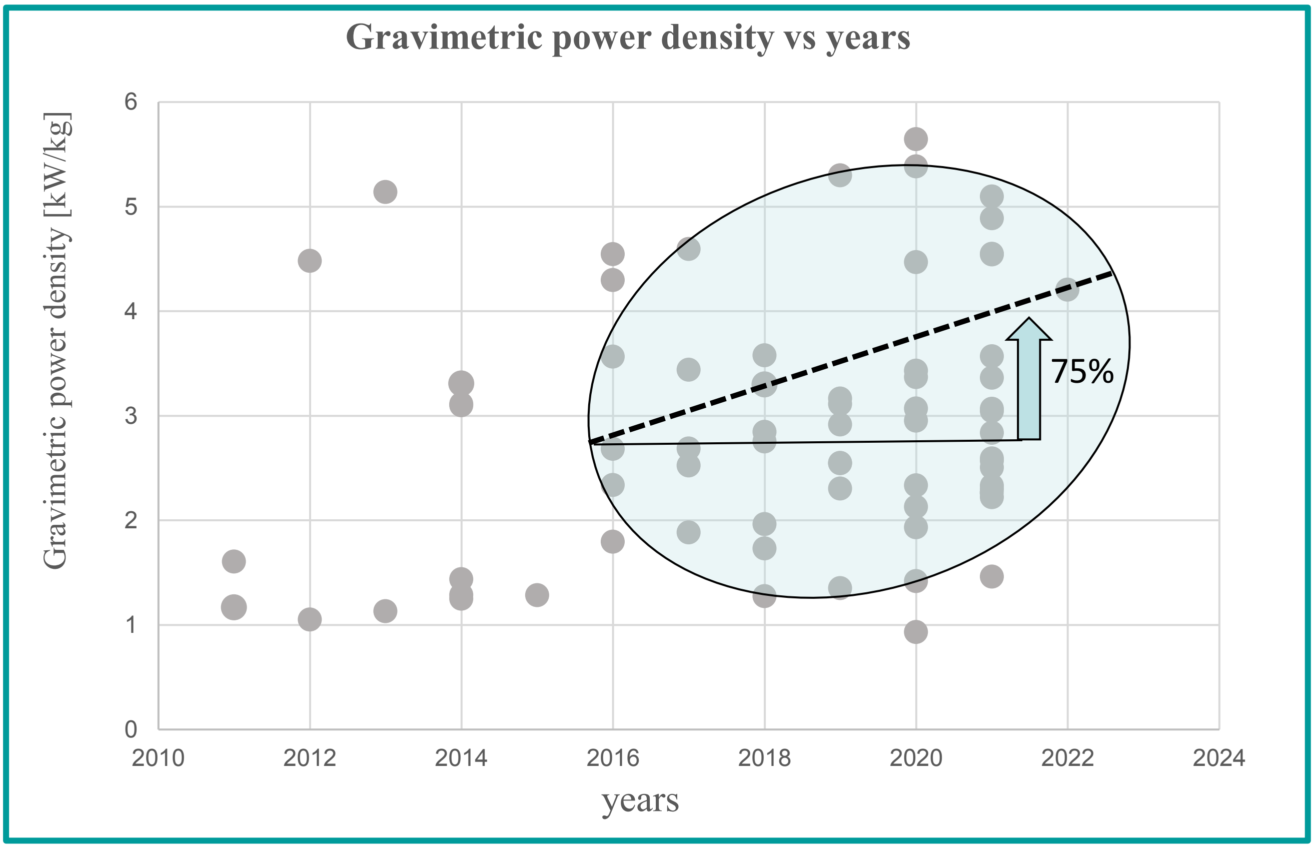

Figure 2.2-Gravimetric power density vs years

2.3.3 Volumetric power density vs years

Another interesting relationship is the one between the volumetric power density and the time shown in figure 2.3, where it is possible to see an increasing of approximately 81% every five years.
The E-Motor volumetric power density is varying between 3 Kw/L to 51 Kw/L

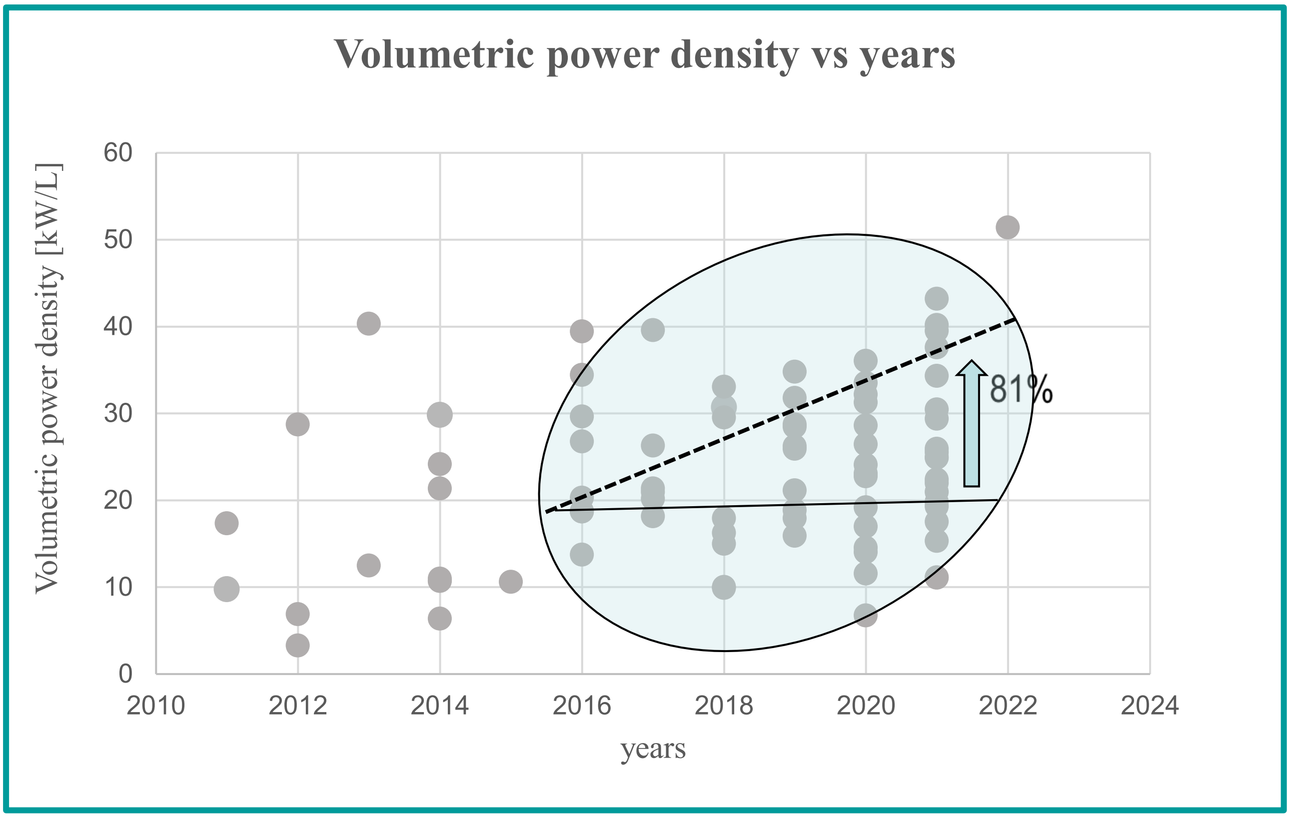

Figure 2.3-Volumetric power density vs years

2.1.2 Gravimetric torque density vs years

Considering the gravimetric torque and time graph shown in figure 2.4, it is possible to see that the gravimetric torque density is increasing of approximately 75% every five years.
The E-Motor gravimetric torque density is varying between 2Nm/kg to 17 Nm/kg

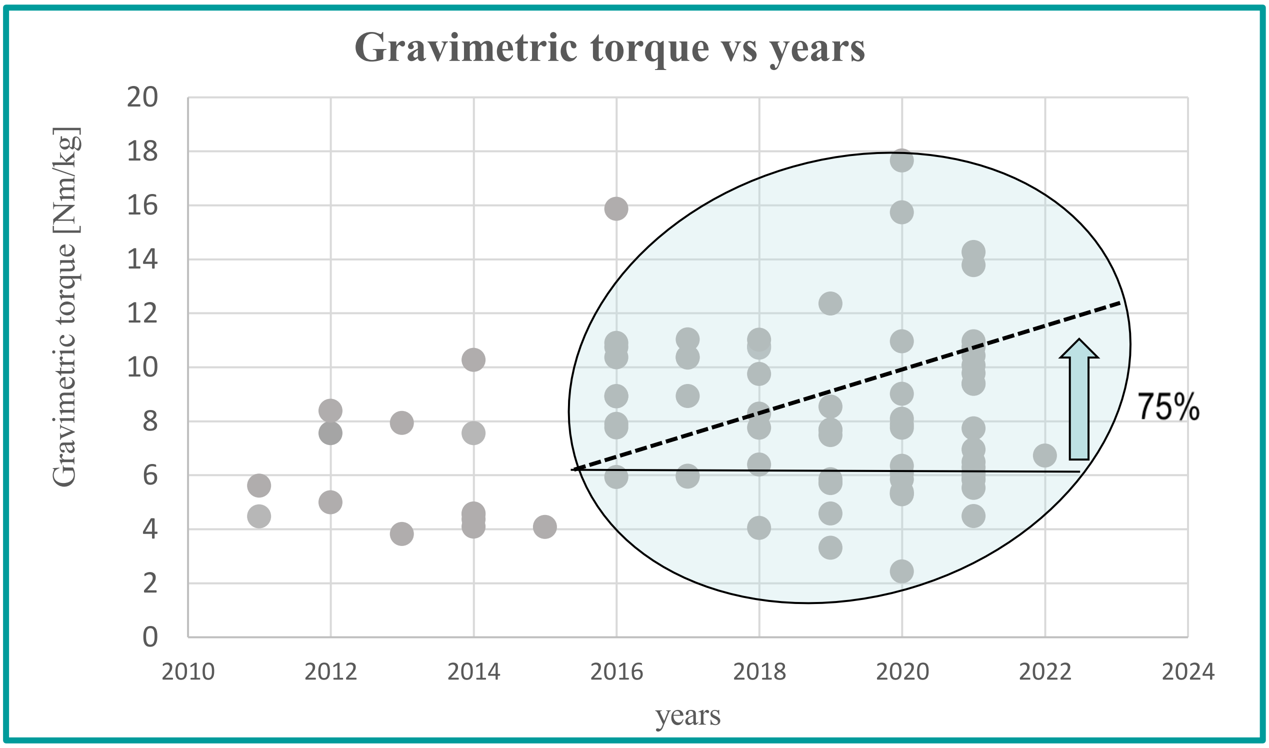

Figure 2.4-Gravimetric torque density vs years

2.1.3 Volumetric torque density vs years

Considering the gravimetric torque and time graph shown in figure 2.5, it is possible to see that the gravimetric torque density is increasing of approximately 75% every five years.
The E-Motor gravimetric torque density is varying between 15 Nm/L to 123 Nm/L

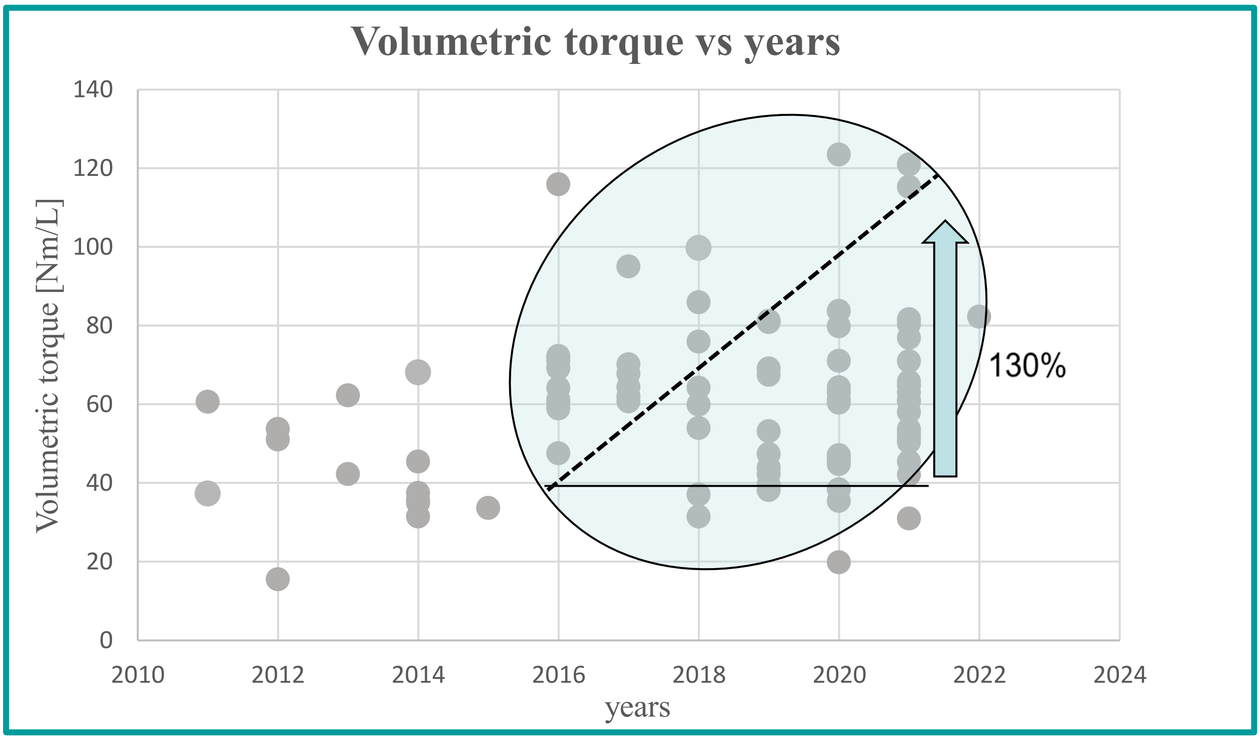

Figure 2.5-Volumetric torque vs years

2.2 Conclusion

This analysis is performed and some difficulties are encountered. The first issue is related to the need of more data points to have a more precise analysis and in particular future trend in the graph that consider the time. In addition, the mass and volumetric definition are not standardized (ISO/DIN) at this moment and they are hard to standardize due to physical differences in the design, for instance A2Mac1 sometimes cannot remove shaft or case from the motor, so this affected the mass value, as it is shown in figure 2.6

Some interesting trends are visualized in the graph, as, for example, the continue increase in the last and future years in the performance of power and torque density, so that achieving the maximum torque and power with the smaller volume and weight of the motor.

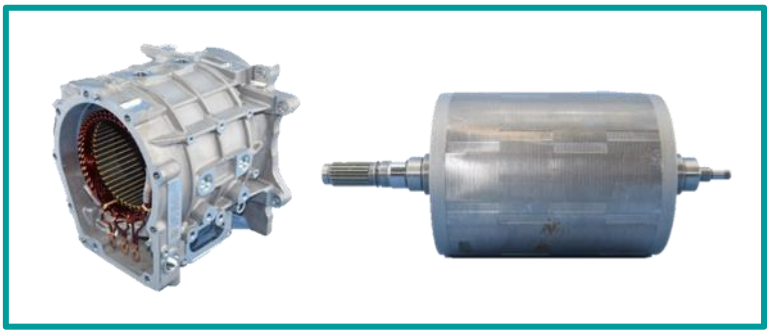

Figure 2.6-A2Mac1 issue

3 Internship bridgeless design project

The internship main project is related to the development of a retention system for the Toyota motor generator MG2. This type of motor is an internal permanent magnet motor IPMM, characterised by the presence of two flux barrier closed by thin upper bridges and constrained by two central bridges. The task of this project is to develop a system capable to keep the rotor elements without the presence of these bridges that are responsible of the performance decreasing considering torque and torque ripple. The analysis, in particular structural and magnetic analysis, are performed by means of the software JMAG©, a simulation software used for the development and design of electrical devices.

3.1 Base motor design

The starting point of the internship project is the original design of the motor-generator MG2 developed by Toyota. The MG2 is an internal permanent magnet motor IPMM.

3.1.1 MG2 layout

The Toyota hybrid system is composed by two e-motors, the motor generator MG1 and the motor generator MG2. The MG1 is driven by the internal combustion engine and its main functions are to start the combustion engine, recharge the battery and supply electric current to the MG2. The motor generator MG2 could act in two different modes: as a motor as it is directly connected to the wheel or as a generator during braking.
The first component of the MG2 is the stator, that is the stationary part of the motor. The stator provides a magnetic field, travelling around it, that drives the rotor. In the MG2 the stator magnetic field is generated by a three-phase current source. The stator is composed by 48 slots that host the winding in form of hairpin conductors insulated by each other, to avoid short circuit.

The second component is the rotor that is the moving component of the motor. It is composed by a series of e-steel sheets. As the MG2 is an internal permanent magnets motor, the rotor has two flux barriers, the former with a U-shaped and the latter with a V-shaped design, where six magnets, 2 for the V-shaped and 4 for the U-shaped flux barrier, are hosted for 8 magnetic poles and produce the stationary magnetic field.

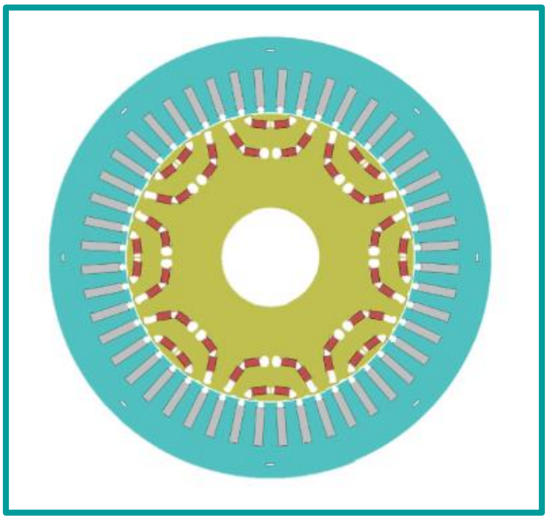

Figure 3.1-MG2 layout

3.1.2 Model assumptions

Some assumptions are considered to move from the CAD model to the FEM simulations, as the motor geometry is quite complex and to have a time-saving approach in the simulations some simplification is required.
The first simplification regards the coil configuration, indeed the slot filling factor is considered as 100%, but in the reality is formed by the winding and air regions, but in the simulation the stator slots are considered as entirely filled by the hairpins. The number of turns has been modelled inside the FEM software.
During the simulation only one sector of 45°of the eight presented in the motor is considered, having six slots in the stator region and one magnetic pole.
The rotational periodic boundary has been modelled as antiperiodic, in order to model for a rotor having the total magnetic flux passing through the rotor external surface equal to zero.

3.1.3 Background technology

The design of the PMSM is not an easy task and there occur issues during the design phase that must be addressed and handled carefully. The stator of the PMSM has a three-phase winding where the coils are excited with a sinusoidally time varying current, which produces a rotating magnetic field with constant magnitude. On the other hand, the permanent magnets in the PMSM rotor, produce a stationary magnetic field, which rotates along with the rotor revolution. The interaction of the two magnetic fields in the air gap result in the electromagnetic torque production.

The IPMSM is a type of motor that has permanent magnets embedded inside the rotor core laminations. A major consideration during the design stage of an IPMSM is the geometry of the rotor's pole. The arrangement of the magnets in the rotor and the design of their respective flux barriers is crucial if one wants to achieve a high torque output with low torque ripple. Flux barrier design is a topic of great importance. For that matter, the objective is to design the flux barriers in order to obtain a uniform distribution of the flux density in the air gap. However, there are some other aspects that need to be considered in the design of the pole geometry of the rotor. Another major consideration is the mechanical stability and strength of the rotor. MSM's have a wide speed range and at high rotational speeds the centrifugal forces are becoming very big. During this operation conditions, a lot of mechanical stress is developed in the rotor. Therefore, the rotor should have a high enough mechanical strength to be able to withstand the centrifugal forces. For that matter, during the design of the pole's flux barriers, the mechanical aspect should be considered.

The rotor magnetic pole comprises 4 permanent magnets in a U-shaped formation and 2 permanent magnets in a V-shaped configuration, arranged symmetrically to the center of the rotor. The V-shaped configuration is located close to the outer rotor diameter while the U-shaped configuration embraces the other magnet formation. The design of the V-shaped flux barriers improves the torque ripple because of the distribution of the flux density in the air gap becomes more uniform. The design of the U-shaped flux barrier improves the average torque output by reducing the leakage flux from the magnets close to the web, while retaining the mechanical strength of the rotor.

The U-shaped flux barrier with magnet receiving pockets has flux barriers that are placed inwards in the radial direction. Considering the original electric motor, in both the U-shaped and V- shaped configuration a central bridge is present, and it separates the magnets symmetrically. In the upper part of the rotor, close to the stator, there are upper bridges that close the rotor. The bridges are shown in the figure 3.2

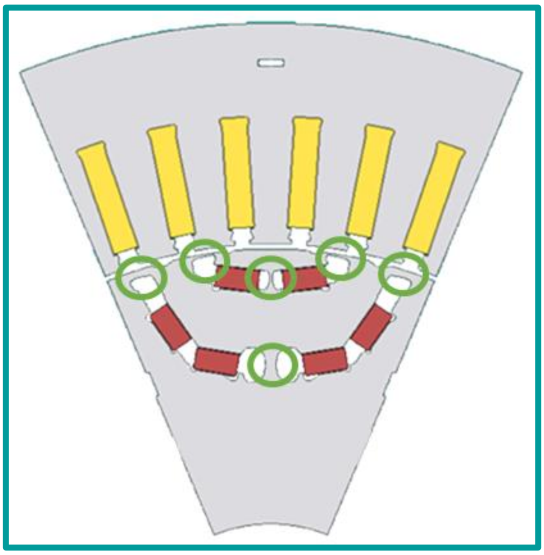

Figure 3.2-Bridges

3.2 Bridgeless rotor design

These considerations about the bridges are the starting point for the bridgeless design that is developed in this study. The bridgeless design target is to remove the e-steel bridges present in the outer and central part of the V-shaped and U-shaped flux barrier in order to increase the average torque and decrease the torque ripple responsible for the noise and vibrations in the motor. The drawback of removing them is that the mechanical integrity of the rotor is lost, so in this way three rotor elements are detached and under the centrifugal force they fly away as shown in figure 3.3.

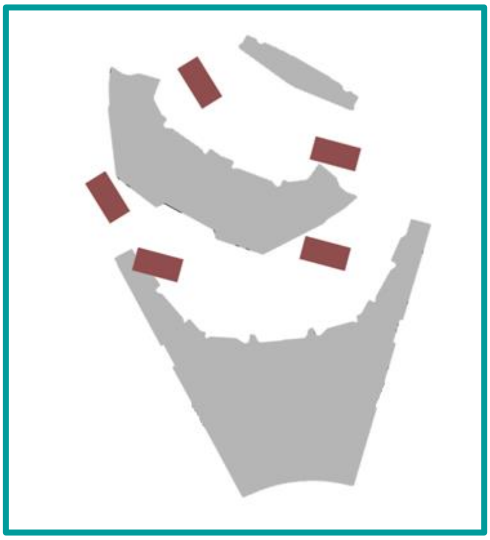

Figure 3.3-Bridgeless rotor design

So the concept design is capable both to retain the rotor and to be seen by the magnets as magnetically inert.

3.2.1 Previous concept

A first concept was developed where the central bridges in the U-shape and V-shape pockets for the magnets are removed completely and substituted by two anchors made by a non-magnetic material, such as stainless steel, as shown in figure 3.4 The choice of the material is done considering the fact that it is required a material that is seen by the magnets as air, so magnetically inert. In this way a composite rotor layout is created, and the rotor elements are held by these two anchor elements. The external bridges are made thinner with respect to the original layout, as in this way they can immediately saturate and are quite close to be inert by a magnetic point of view. With this solution higher torque is achieved and the torque ripple is reduced.

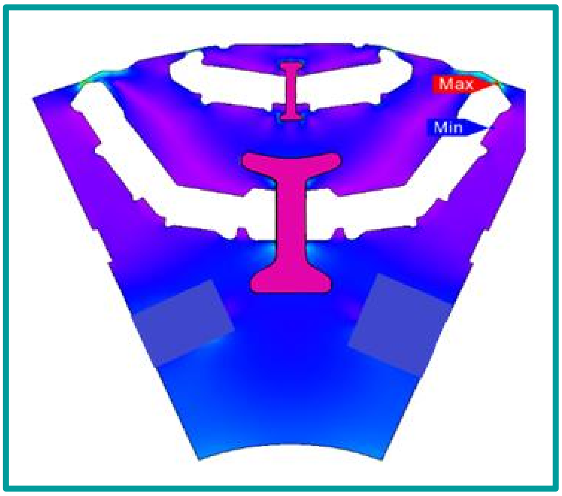

Figure 3.4-Previous concept

3.3 Dog-bone anchor solution

3.3.1 Brainstorming steps

The analysis of the base design and of the previous concept, with the discussion about the bridges characteristics, is fundamental to arise two possible solutions for the retention of the rotor elements without any bridges. The former is to develop the previous solution, so six different designs of the anchor upper part in the U-shaped flux barrier are considered and analyzed both from the stress and the electromagnetically point of view as shown in figure 3.5. Reflecting on the analyses the conclusion is that a single anchor is not enough to retain the two rotor elements that form the U-shaped flux barrier.

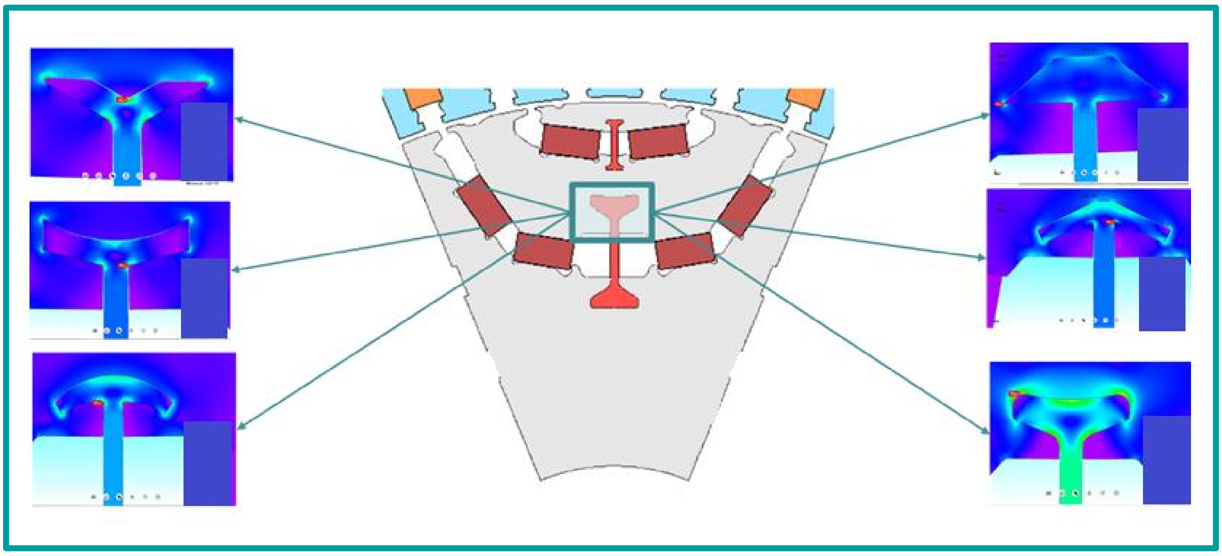

Figure 3.5-Brainstorming steps

3.3.2 Three dog-bone anchor solution

3.3.2.1 First design

Considering the bending of the U-shaped flux barrier a change in the position is applied, instead of a one single big anchor in the center of the rotor, two smaller anchors are in the outer part of the U-shaped flux barrier between the couple of the magnets. To leave enough space between the magnets and the anchor, the magnets were moved, so the two anchors positioned in the most outer part of the U-shaped flux barrier are moved of 1.5 mm in an outer position and the ones closed to the center of the flux barrier are moved more inner of 1.5 mm.
To resist to the centrifugal force a design with its own axis sloped with an angle α with respect to the upper end of the U-flux barrier is considered and the shape of the anchor is substitute by a circular shape for the two ends of the anchor, transforming it in a like dog-bone shape, as shown in figure 3.6.

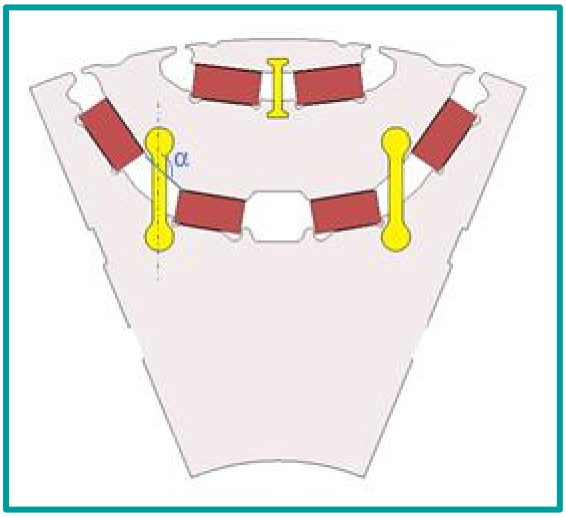

Figure 3.6-First design

The stress analysis of this first design, performed by means of JMAG© and shown in figure 3.7, reveals that the stresses
reveals that the higher stresses are localized in the e-steel around the left upper part and in the right bottom part of the dog-bone ends. This is due to the bending and the shear stress that the centrifugal force is generated in these two area, where the area is not enough big to resist to the force, as it is reduced by the presence of the flux barriers.

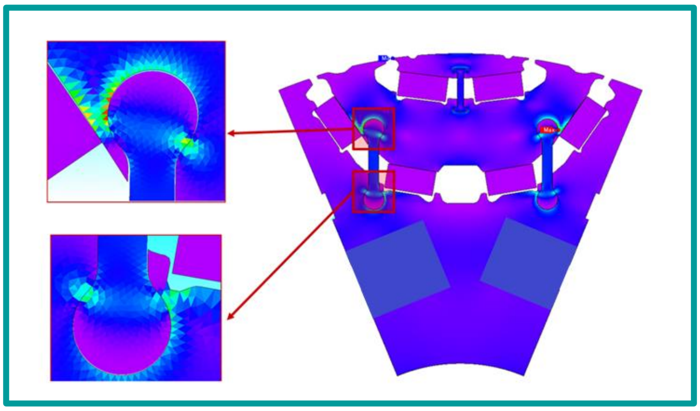

Figure 3.7-First design stress analysis

The electromagnetic analysis shows, in figure 3.8, that the flux short circuit in the outer and central bridges are no more present. It is of interest the fact that with the presence of the right anchor in the U-shaped barrier an oversaturated area is created, that is not going to affect the electromagnetic performance, but instead is beneficial.

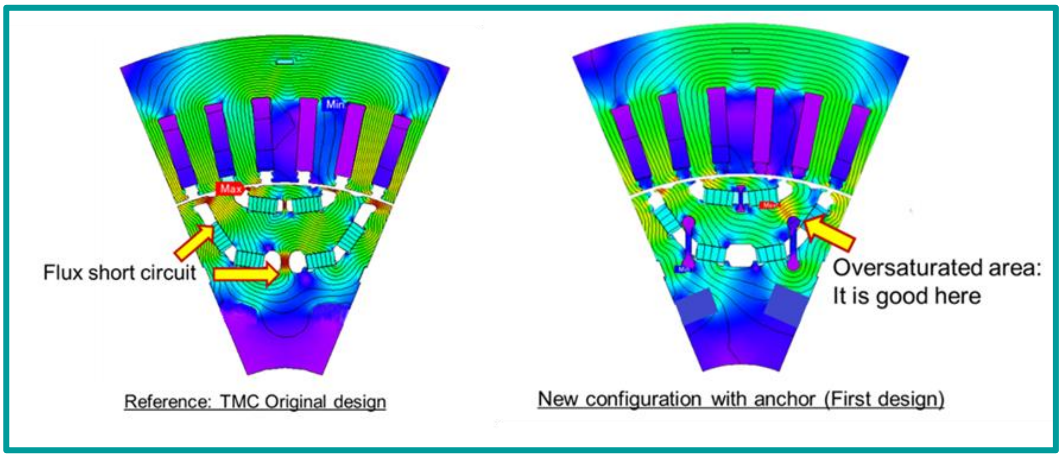

Figure 3.8-Electromagnetic analysis first design

Thanks to this design it is possible to reach higher value of torque and a reduction in torque ripple, improving the electromagnetic performance, but from the stress point of view the target value is still far from the original design value, that it is the reference one. The comparison in percentage is shown in the table 3

	Average torque [Nm]	**Torque ripple [Nm]**	**Stress [MPa]**
Design 1 vs original	+8.24%	-9.24%	+337%

Table 1-First design

3.3.2.2 Second design

The first design has the drawback, to have very high stresses and the impossibility to move in the right and left ends the anchor as its circular ends are too close to the U-shape flux barrier and the magnets. The improvement in changing the position are so small, rather, changing the position, increases them, due to the increase of bending and shear stresses. A first change in the design is done considering this aspect. The anchor is sloped in a different way,as it is possible to see in figure 3.9, so now the angle α is perpendicular to the upper end of the U-shaped flux barrier.

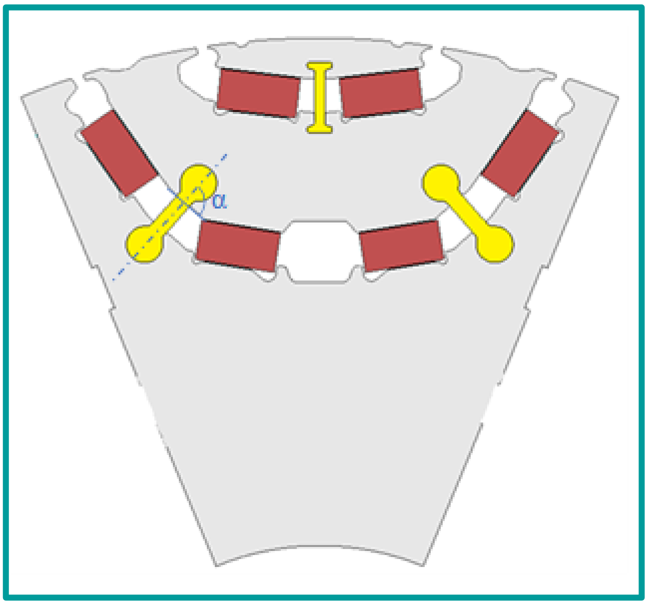

Figure 3.9-Second design

Considering the stress analysis there is an relevant decrease in the stress value, but it is still too high, in particular in the lateral part of the circular end that results to be the most affected by the centrifugal forces, as shown in figure 3.10.

The electromagnetic analysis confirms the good results that have been already present in the previous analysis, as shown in figure 3.11.

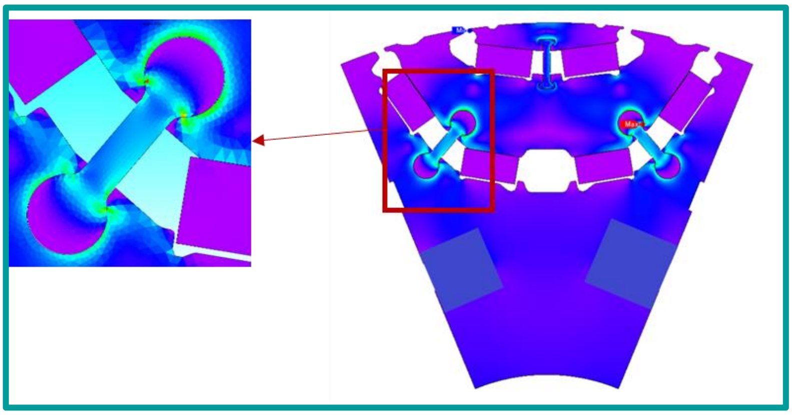

Figure 3.10-Stress analysis of the second design

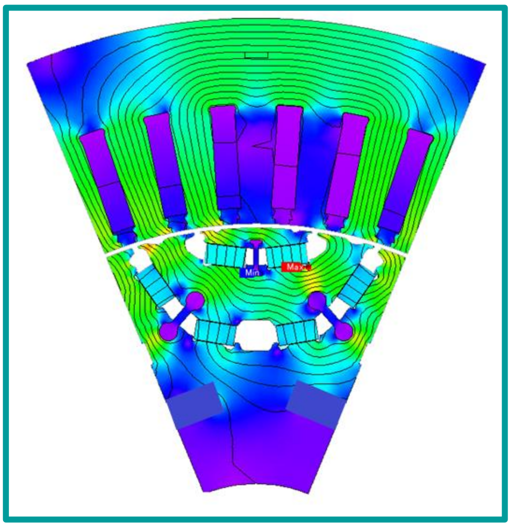

Figure 3.11-Electromagnetic analysis of second design

	Average torque [Nm]	Torque ripple [Nm]	Stress [MPa]
Design 2 vs original	+8.25%	-9.24%	+214.5%

Table 2-Second design

Thanks to this first change in the design the stress value is decrease and the overall performances of the motor are confirmed, as shown in table 4.

3.3.2.3 Third design

Considering the previous design, the position of the anchor is confirmed thanks to its beneficial effect on the stresses, but the circular shape seems to be not capable of resist to the stresses that arise from the centrifugal forces. In this third design the focus is on the shape of the ends of the anchor. Analyzing the previous stresses and because the anchor is subject to a tensile stress, the idea is to increase the area of the anchor end to distribute the stresses. By this consideration the anchor end shape is change in an ellipse one, as shown in figure 3.12, that, with an increased surface, can resist more to the tensile stress.

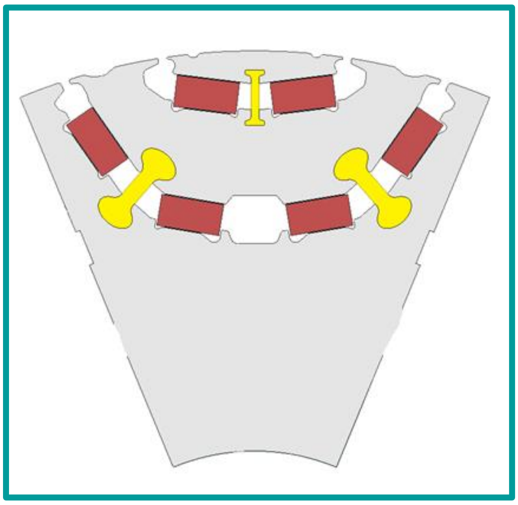

Figure 3.13-Third design

Considering a stress analysis, the idea is confirmed and the value with respect to the original design is decreased a lot, comparing it with the previous one. The higher stresses are now localized in the minor radius of the ellipse.

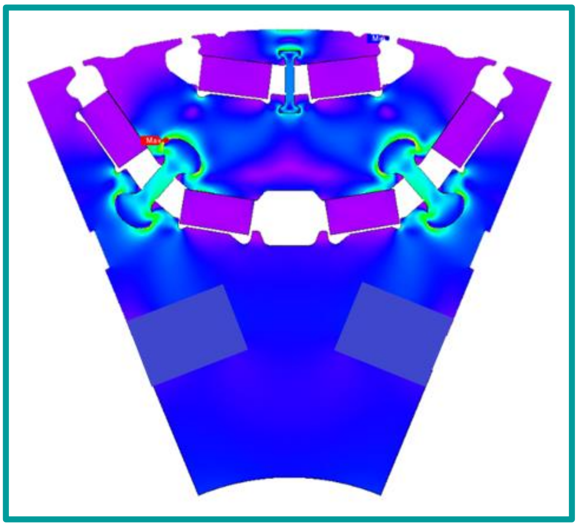

Figure 3.12-Stress analysis of the third design

The electromagnetic analysis results for this configuration changes as with respect to the original design, the torque value increase of +7.24% but the torque ripple have a higher beneficial effect of -10.58% as shown in table 5

	Average torque [Nm]	**Torque ripple [Nm]**	**Stress [MPa]**
Design 3 vs Original	+7.24%	-10.58%	+87.1%

Table 3-Third design

3.3.3 Torque and Torque ripple analysis

At this point of the project and having this change in the torque and torque ripple value in the last design, the focus of the analysis is to try to understand which part of the anchor design can affect more these two essential parameters of the project.

3.3.3.1 Bottom end of the anchor analysis

Considering the bottom end of the anchor in the U-shaped flux barrier, the study is performed trying to enlarge the major and the minor radii with different magnitudes and to change the slope of the ellipse with respect to the central part that remains always perpendicular to the U-flux barrier end.

Making different designs, the focus is on three designs that show in a more evident way how the torque and torque ripple values are affected by these changes. The first one is the third design of the previous chapter, the second one considers a bigger major radius and the third one a bigger major and minor radius.

In these three designs, shown in figure 3.14, it is possible to observe two areas around the anchor that are changing with the change in the design. Analyzing the upper area, it is possible to see that, transforming the bottom end of the anchor, it starts to be less saturated, as the color in the analysis change becoming light yellow, instead in the bottom end the area change from green to yellow color that means that the intensity of the magnetic flux density is increasing. These changes causes a variation in the torque, that now with respect to the original design is respectively +2.3% and -0.1%. Regarding the torque ripple the values with respect to the original design are -36% and -31%. From the observation of the analysis and the values of torque and torque ripple, it is possible to assume that the enlarging of the bottom part has two effects: the former is to decrease drastically the benefit effect in torque that is aquired with the previous design and the latter is to decrease up to -36% the torque ripple, that means that this design will have less vibrations and noise with respect to the original design.

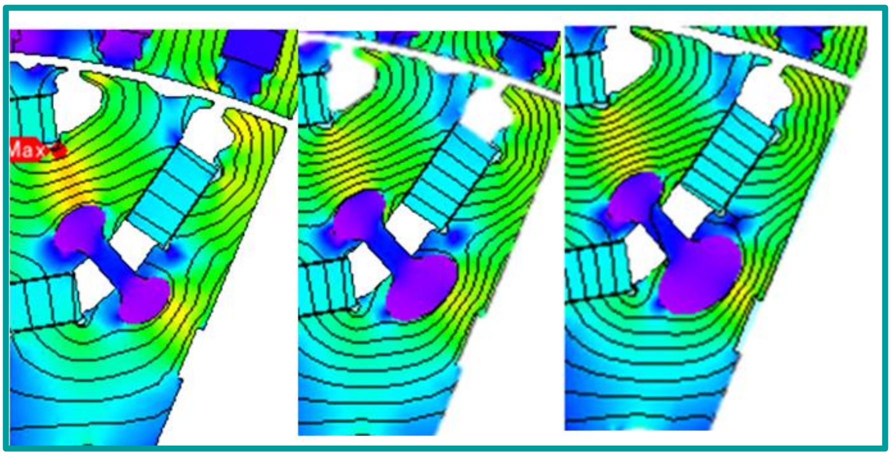

Figure 3.14-Bottom end analysis

3.3.3.2 Upper end of the anchor

Considering the upper end of the anchor, the same analysis of the bottom end is performed, enlarging the minor and major diameter of the upper ellipse. Three cases are observed the first one is the third design of the previous chapter, the second one has the major radius that is enlarged and the third one has bigger major and minor radius of the ellipse. The three cases are shown in figure 3.15.

It is possible to notice that augmenting the ellipse diameters the effect is to increase the magnetic flux density value and area, creating a bigger and darker red area that means that the e-steel is changing to the oversaturated zone, that is inert from a magnetic point of view. For this reason, the torque value of the last two cases decreases more and more if it is compared with the third design of the previous chapter. Also, for the torque ripple it is possible to notice that the performance decreases, as they increase up to more than the original design.

The torque of the last two cases with respect to the original design varies of +4.88% and +3.88%, while the torque ripple are respectively -2.6% and +1%

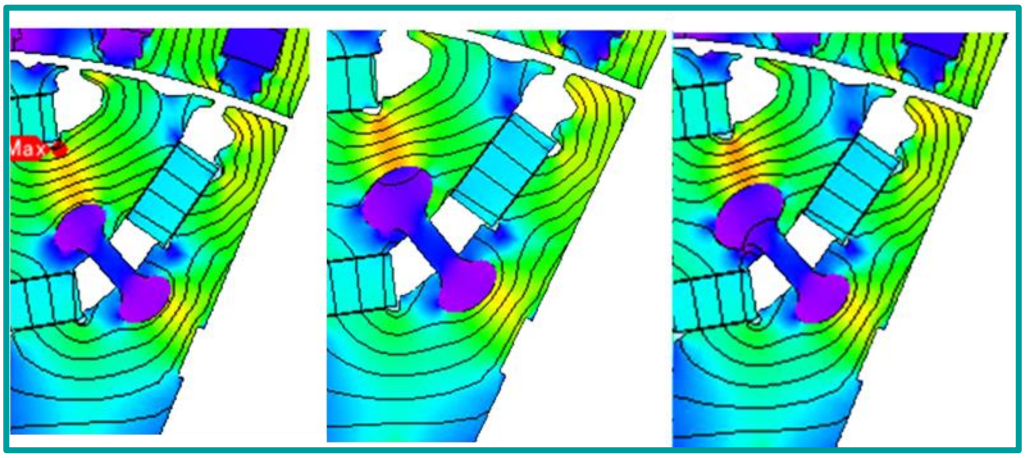

Figure 3.15-Upper end analysis

3.3.3.3 Sloped ellipse

A last torque and torque ripple study is performed considering an ellipse design sloped with respect to the central portion of the anchor. This solution is also the one that reaches the lowest value of the stresses for the three anchors solution, but considering the torque and torque ripple their value worse more, achieving for the torque -1% and for the torque ripple +4.4% comparing with the original design. This behavior is explained considering the areas in upper part and bottom part of the anchor, that are both oversaturated.

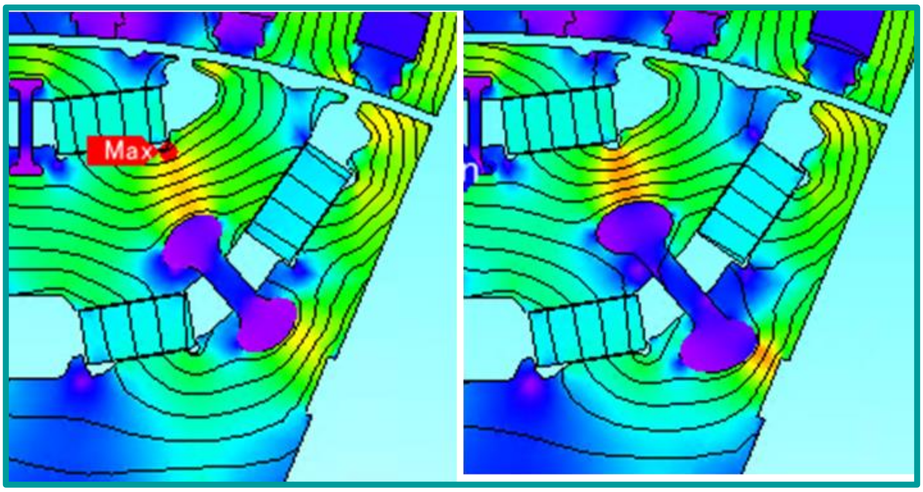

Figure 3.16-Sloped end analysis

3.3.4 Three anchors solutions conclusion

The three anchors solutions present valuable results considering the torque and torque ripple values, comparing them with the original design, but what is difficult in this design to reach is the stress target. To reduce the stress value one possible solution is to increase the dimension of them, as the areas affected by the highest Von Mises stress are the ones that undergo to tensile stresses. Increasing the dimension, however, there is a huge cons related to the torque and torque ripple values, because, as it is shown in the previous paragraph, these two parameters are linked to the dimension and shape of the bottom end of the anchors worsening their performances.

At this study level two scatter plots are created to analyze all the created designs.
The first graph is a Von Mises vs torque graph, figure 3.17, where it is possible to visualize a trend of the technology. This trend shows that, if the target is to have high torque, the Von Mises stresses increase, while, if it is to have low Von Mises stresses to reach the original stress target, also the torque decreases, nullifying the beneficial effect of this solution.
The second scatter plot, instead, figure 3.18, is related to the torque ripple vs torque values. In this graph it is possible to see that most of the points are located between two boundary values.

Taking into account these considerations, the final conclusion about this technology that is not possible to reach the target stress value, without compromise the beneficial effect of the torque and torque ripple, so a new solution is needed.

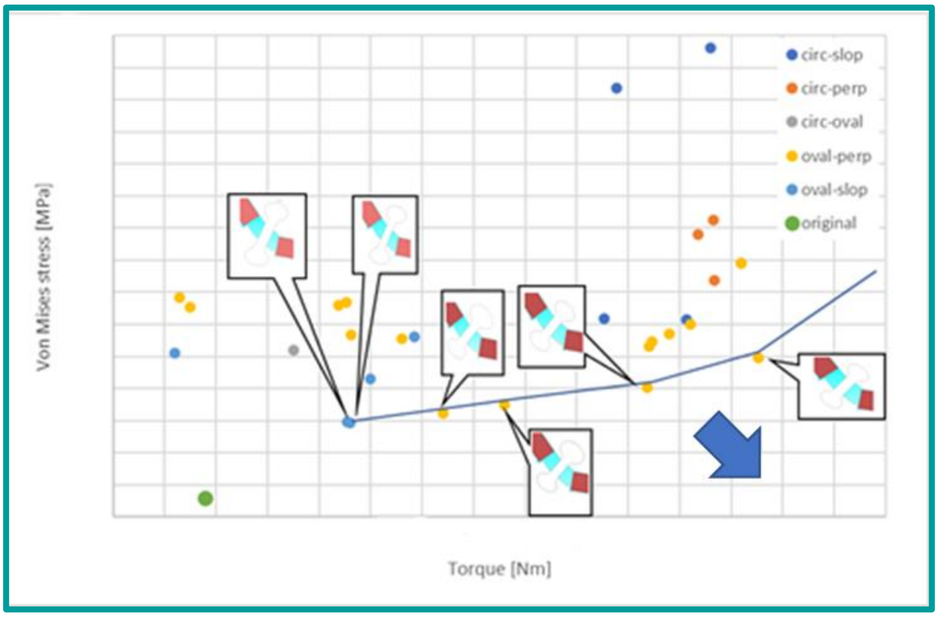

Figure 3.17-Von Mises vs torque

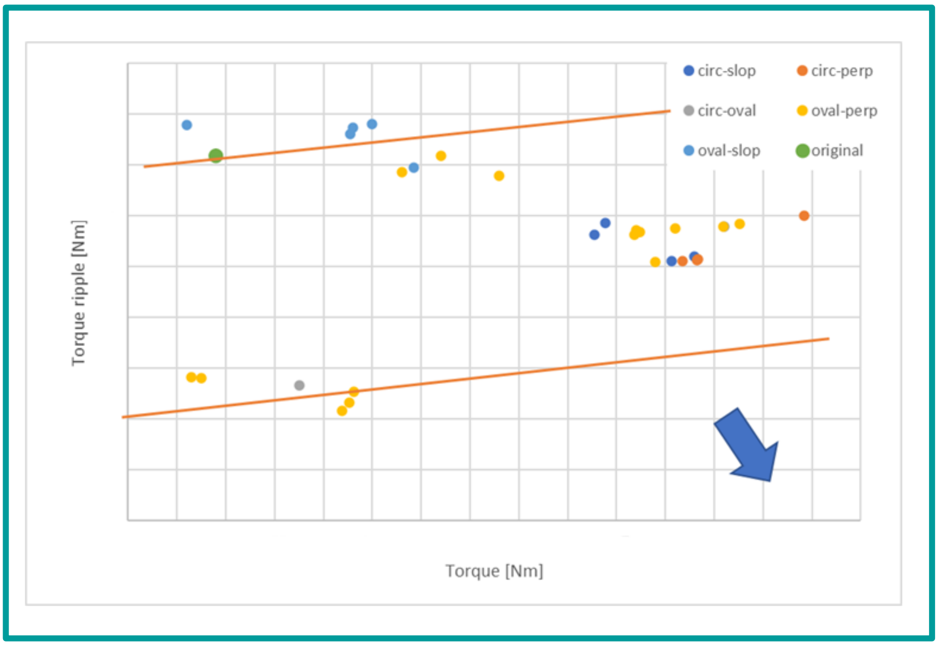

Figure 3.18-Torque ripple vs torque

3.4 Four anchors solutions

The previous chapters shows that the three anchors solutions are a valuable solution for the torque and torque ripple point of view, but it is not enough to retain mechanically the rotor, so a new solution is developed.
The explication of this is to add a fourth anchor to the rotor in the central part of the U-flux barrier, as it is possible to see in figure 3.19.

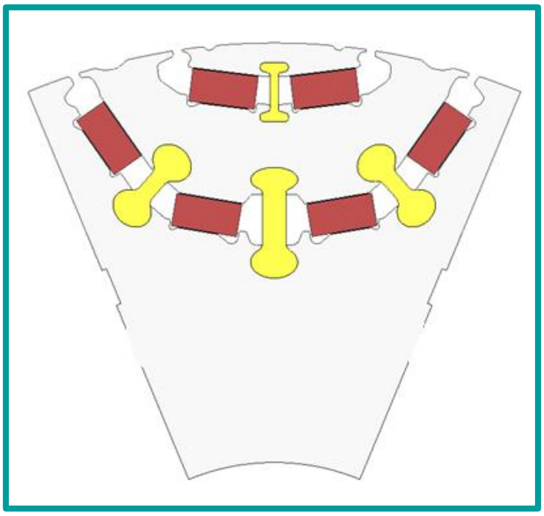

Figure 3.19-Four anchor solutions

Performing a stress analysis on this new solution, the results shows that the anchors in the U-shaped barrier and the rotor surface close to them reach the value of the original design. By adding a new anchor is possible to retain the two elements of the rotor that are forming the U-shaped flux barrier. In the Von Mises analysis it is displayed that, now, the highest stresses are in the top anchor of the V-shaped flux barrier and they are over the target value, as shown in figure 3.20. At this stage the focus of the study is to the upper part of the rotor to retain the other two rotor elements that are shaping the V-flux barrier.

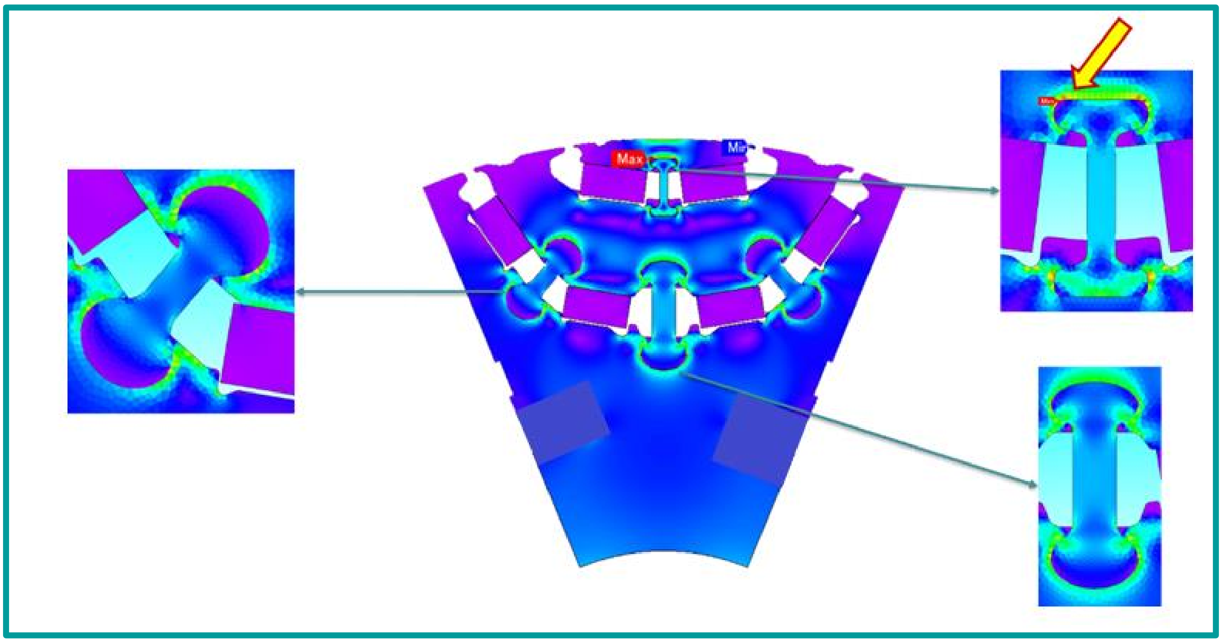

Figure 3.20-Stress analysis of four anchor solution

As presented in table 6, considering the electromagnetic analysis adding the fourth anchor, the torque is achieving a +7.4% more than the original design and the torque ripple are decreased of -10.37%. Comparing these results to the third design of the three anchors solutions both parameters remain around the same value, so this means that the fourth anchor is not affecting the electromagnetic performance of the rotor.

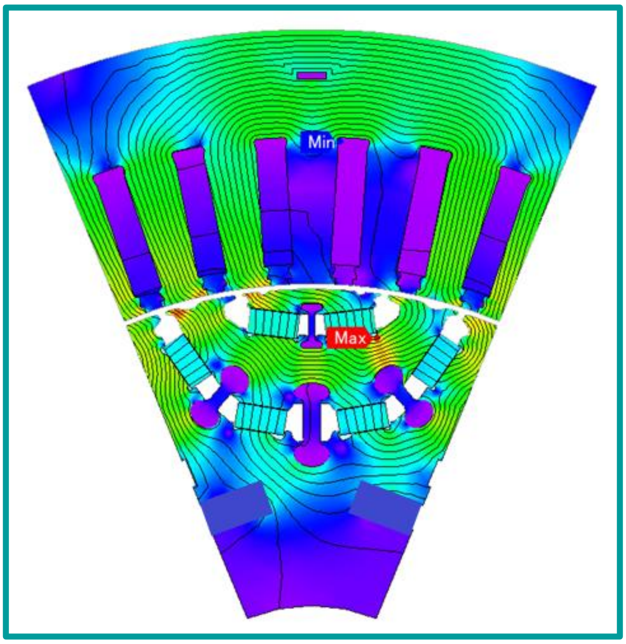

Figure 3.21-Electromagnetic analysis of the four anchor solution

	Average torque [Nm]	Torque ripple [Nm]	Stress [MPa]
Design 4 vs Original	+7.4%	-10.37%	V-shaped +29.24%
			U-shaped -2.46%

Table 4-Four anchor solution

3.4.1 Top anchor

The focus now of the study is to design an anchor located in the V-shaped design that is capable to retain the two elements of the rotor and achieve better results for the torque and torque ripple. Two possible shapes are analyzed: the former has the end with the ellipse shape and the latter has a pillar shape.
With the ellipse shape is possible to decrease the stresses, but to reach the target value it is needed to increase its top end. Examining the electromagnetic analysis, the dimension increase of this end has a counter effect on the torque ripple values as they pass from -10.37% to -1.6% of decrease. This effect is not wished as the scope of this study is to have the greatest possible decrease in torque ripple to have less noise and vibrations.

For these reasons, the latter solution is analyzed and the anchor shape is changes to the pillar one. Considering the structural analysis, the stress values are lower than the ellipse one and they reach the target value, so from the structural point of view this solution is the perfect one for retaining the rotor elements. Performing the electromagnetic analysis, with this design the torque is increase of +6.2% that is lower of 1.2% than the previous design, but still with a valuable advantage with respect to the original design. The torque ripple in this design achieves a -14% of decrease, that is the best obtained value considering all the designs done until this stage of the study.

Comparing the analysis of these two designs in figure 3.22, the best one is the pillar one that is also the chosen one.

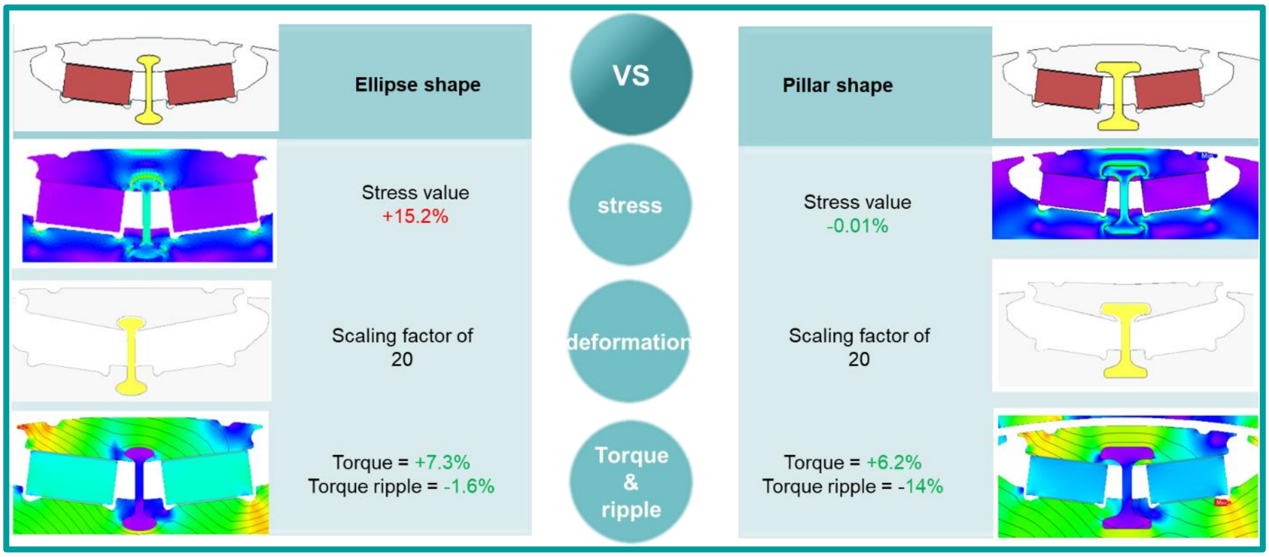

Figure 3.22-Top anchor

3.4.2 Final design

A last design is performed to optimize the shape and make lighter the anchors reducing their central area and making smaller their ends, in this way the two solutions of the U-shaped and V-shaped flux barrier, that were studied separately, are integrated together and it is possible to achieve better performance results.

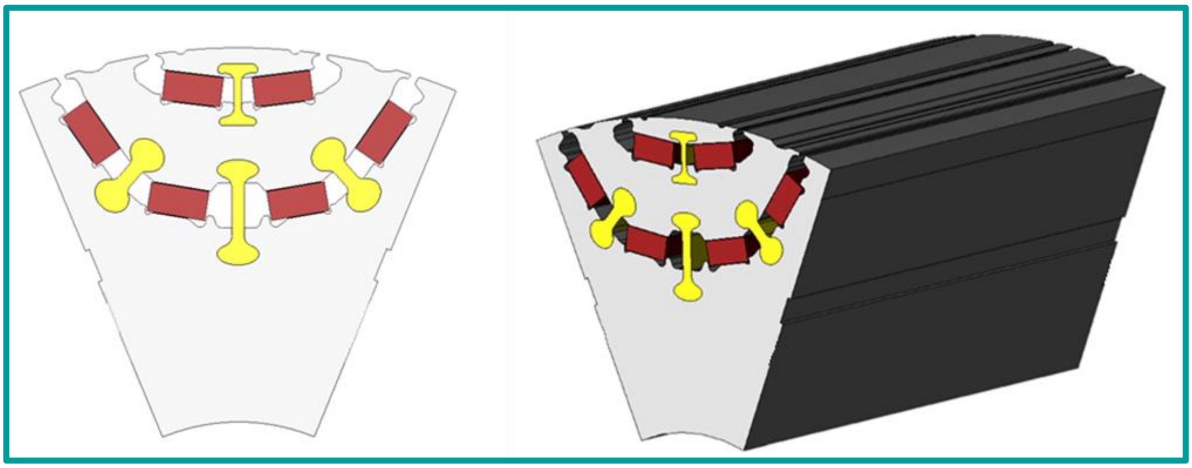

Figure 3.23-Final design

Performing the structural analysis, shown in figure 3.24, even if the mass of the anchors is reduced, the Von Mises stress are still in the target value of the original design.

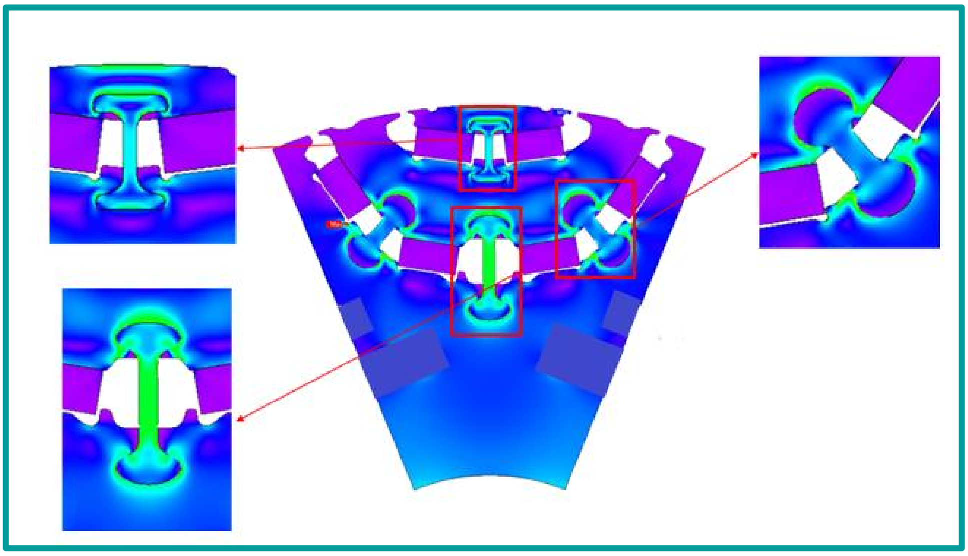

Figure 3.24-Stress analysis of the final design

	Stress [MPa]
Design 4 vs Original	-1%

Table 5-Final design vs Original stress

The electromagnetic analysis confirms the results achieved in the previous design, with a small additional decrement for the torque ripple that now achieve a value of -14.4%.

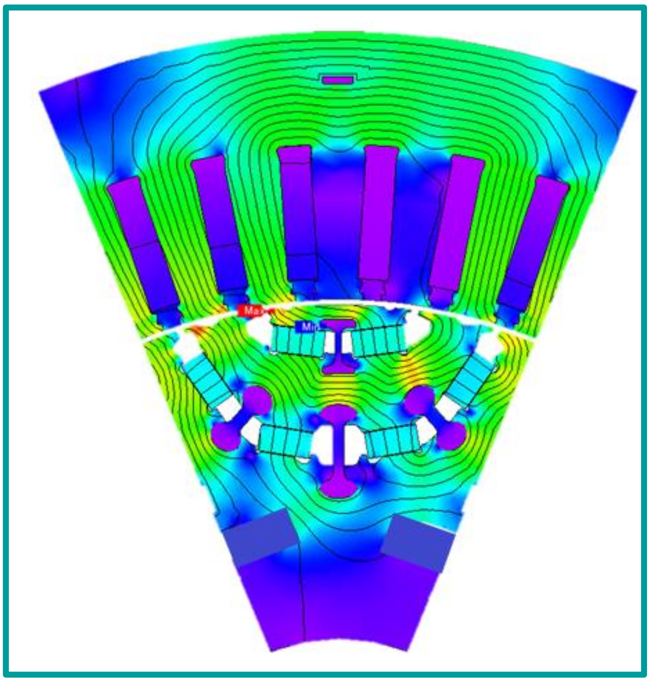

Figure 3.25-Electromagnetic analysis of the final design

	Torque [Nm]	Torque ripple [Nm]
Design 4 vs Original	+6.2%	-14.4%

Table 6-Final design vs original torque and torque ripple

3.4.2.1 Electromagnetic analysis with different current values

All the previous analyses are performed considering a specific value of the current. The next ones are considering different current values classified in low, medium and high values. This analysis is done to verify the sensitivity for the current.

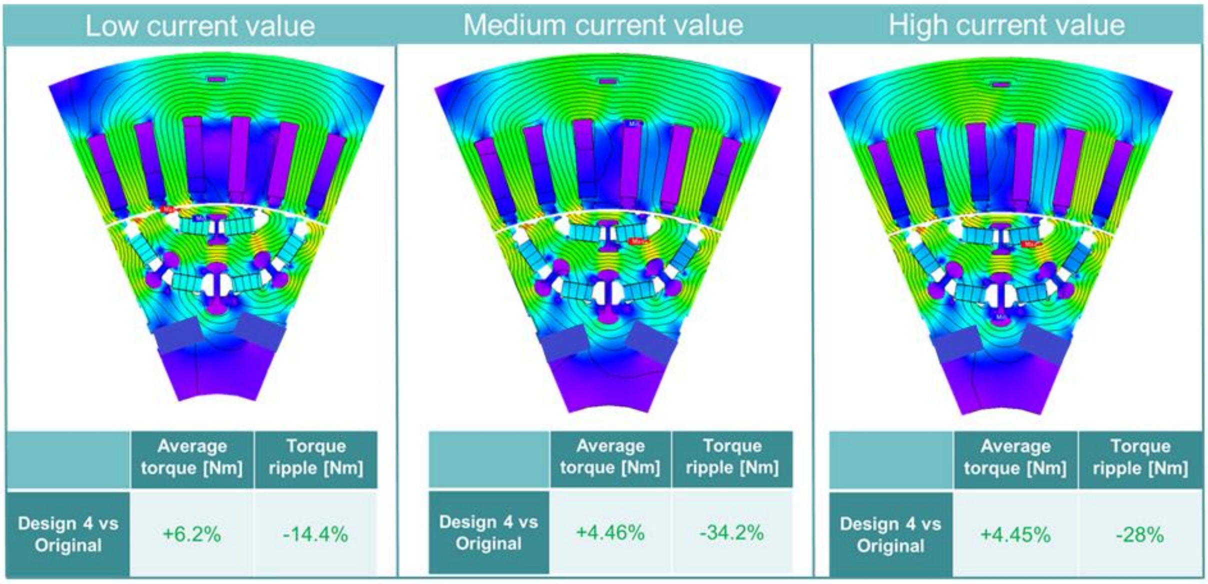

Figure 3.26-Different current values

As it is possible to see in the figure 3.26, this design is beneficial for all the three current configurations, in the decrease of the torque ripple, that reaches the highest value for the medium ampere value with -34.2%.

3.4.2.2 Reluctance torque and inductance analyses

In the IPSM motor the torque is generated by two components: magnet torque T_m and reluctance torque Tr.

$$T = T_r + T_m \quad (1)$$

For the magnet torque each stator current produces a torque component in association with the permanent magnet magnetic field across the air gap. Since the permanent magnets have almost the same magnetic permeability of the air, the reluctance and the inductance computed along any direction is constant. The permanent flux tends to align the rotor with the magneto motive forces generated by the stator. Considering the mathematical equation it is dependent on the pair of poles P_n, on the magnet flux Φ_a and on the component of the current along the q-axis i_q.

$$T_m = P_n * \Phi_a * i_q \quad (2)$$

The reluctance torque instead is the property of a magnetic circuit of opposing the passage of magnetic flux lines, equal to the ratio of magnetomotive force to the magnetic flux.

$$T_r = P_n * (L_d - L_q) * i_d * i_q \quad (3)$$

To understand the improvement in torque that the anchor design has, an analysis where the two components of the torque, reluctance and magnetic, are considered, is performed for all the three current configurations.
Examining the graphs, it is possible to notice that the magnetic torque is the one that increases more comparing it with the original design, this means that it is the one that most affect the total torque increase.
Considering the reluctance torque, it has the peak values that are slightly moved in the higher current phase angle value. This is due to the inductance Lq that, as it possible to see in the following graphs, figure 3.27 and 3.28, is higher than the original design.

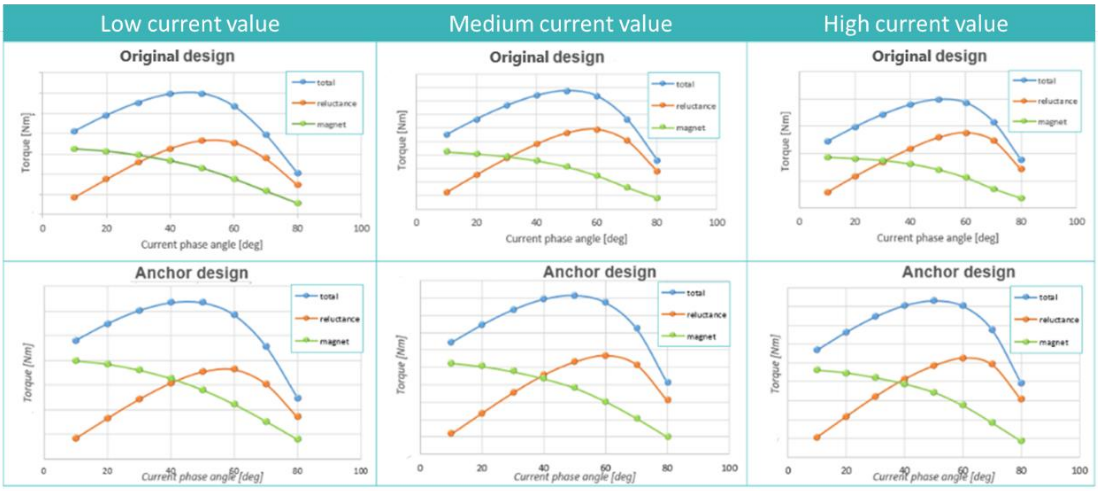

Figure 3.27-Torque vs current angle

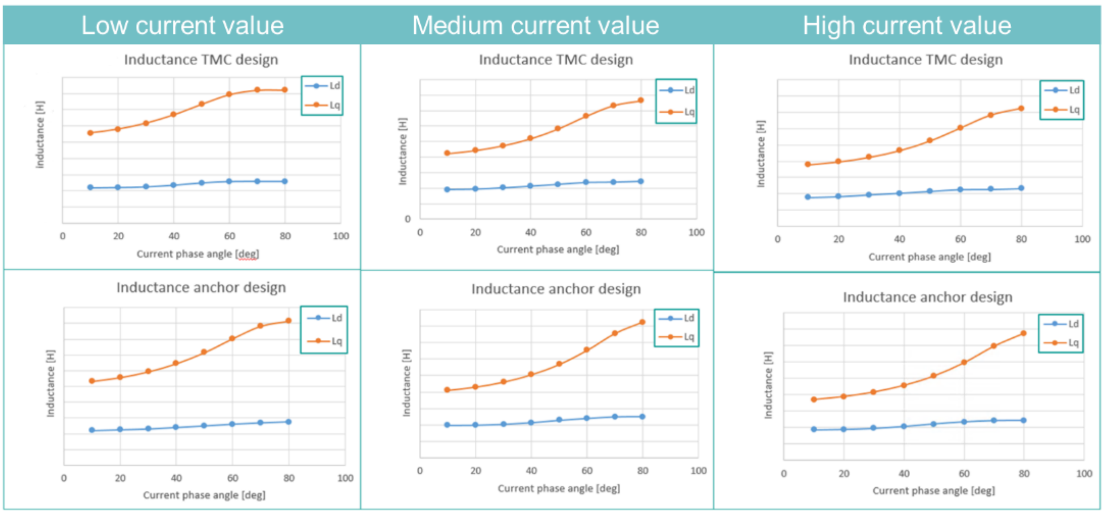

Figure 3.28-Inductance vs phase angle

3.4.2.3 Efficiency map

The efficiency map of a motor drive system is important design information as it gives system engineers a picture of the overall efficiency of the drive and what operating point to operate at for maximum efficiency.

Considering the last design the efficiency map is performed by means of JMAG© software with some simplified assumptions:

- no PWM losses
    - no PWM iron losses
    - no PWM magnet eddy current losses
- no AC losses
- constant value of the inverter voltage

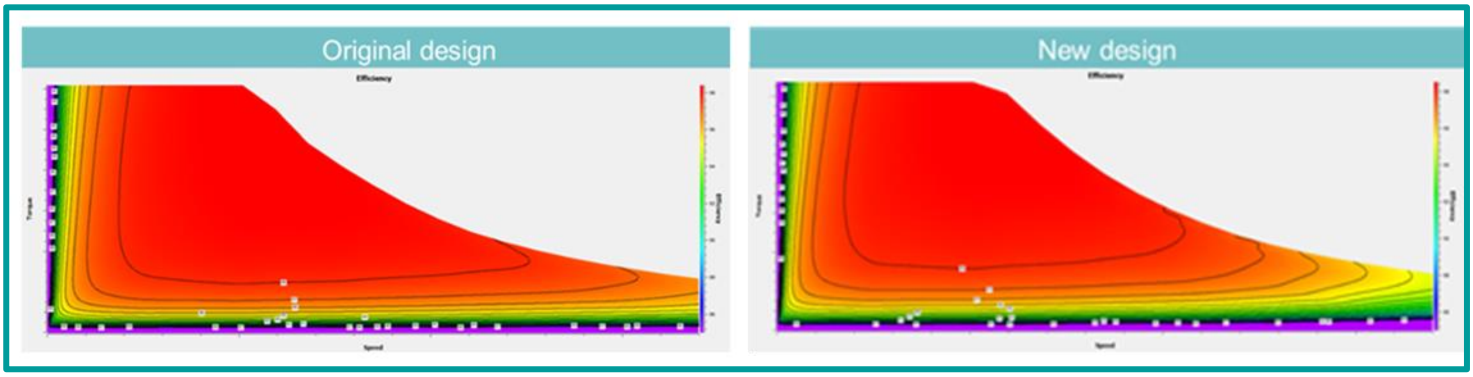

Figure 3.29-Efficiency maps

It is of interest to compare these two efficiency maps to see which design is better. As it is possible to see in figure 3.30 the peak efficiency of New Design was improved by 0.1 percentage point over Original Design.

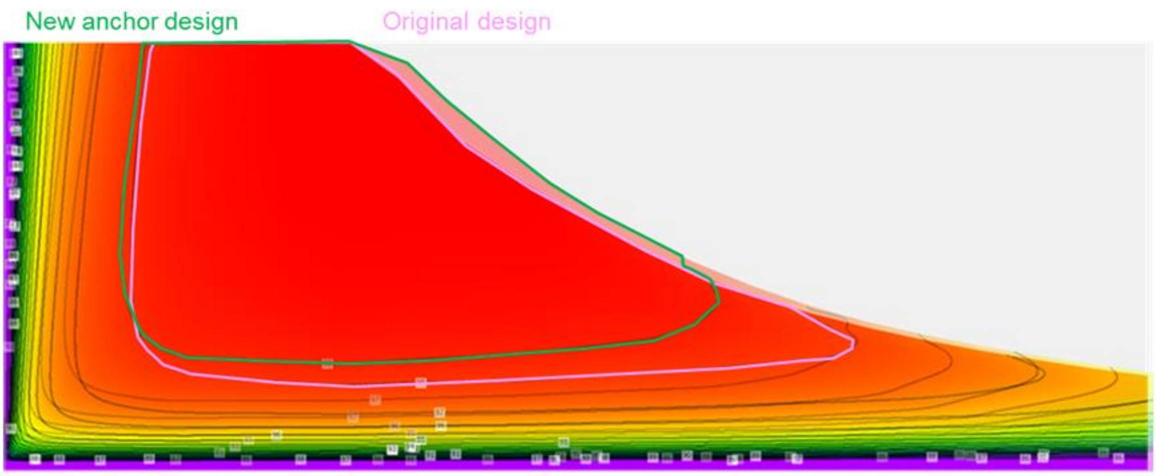

Figure 3.30-Comparison between the efficiency maps

3.4.2.4 Magnet reduction study

Nowadays one of the most important targets in the development of the e-motor is reducing the magnets dimension and utilisation, as they are significant from an environmental and cost point of view. This design gives the possibility to consider a magnet reduction, as it is possible to use the additional acquired torque to decrease their dimensions. The target is to bring back the torque at its original value reducing the magnet. This analysis reveal that it is possible so save 21.43% of the mass of the magnets, as presented in table 9.

a

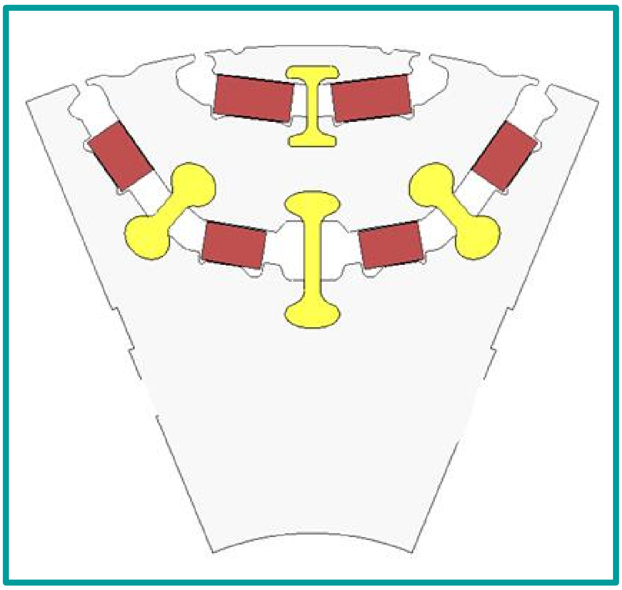

Figure 3.31-Reduction of the magnets

	Average torque [Nm]	Torque ripple [Nm]	Mass [g]
Reduction vs original design	-0.1%	-0.06%	-21.43%

Table 7-Reduction of the magnets

3.5 Conclusion

A bridgeless rotor design for a PMSM is proposed with 4 anchors that provide mechanical strength against centrifugal forces. This rotor has better torque and better torque ripple than the base design.

To obtain the bridgeless design, the starting point is the previous design with a single anchor located for each flux barrier. Then from this it is developed the three anchors solution, with two anchors in the U-shaped flux barrier and one in the V-shaped flux barrier. This solution achieves beneficial effects for the torque and the torque ripple, but it is not enough strength to retain all the rotor. The final design considers four anchors, re-adding the central anchor in the U-shaped barrier. With this design it is possible to retain the rotor and to have +6.2% in torque and -14.4% in torque ripple with respect to the original design.
Other advantages of this configuration are the possibility to remove the magnets after end of life, to have a safer assembly to keep the coating on the magnets without any scratching, to avoid the resin glue and to have a potential reduction of the magnets mass.
Suggestions for further work consist of a study of the impacts for industrialization, in particular in mass production, a thermal analysis, a more detailed efficiency map, a study for a different kind of retention of the magnets, as resin is not more possible to use, and an additional investigation on the oversaturated area.

Figure list

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Siteography

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- Technical specs, dimensions, fuel consumption of cars (ultimatespecs.com)
- https://ev-database.org/

Acknowledgements

This is the end of my University chapter, started on an Autumn day in 2014 with a lot of expectations, the desire to get involved, the curiosity of finally studying one of my strongest passion and see that one of the desires of a little me could be closer to becoming reality.

From the beginning, this long journey is not as expected and a lot of things in University and in my life were very hard and all the expectations, this desire and my passion became, at a certain point, an heavy weight on my shoulders. What should be a university exam done with study, become more a life test done with doubts and low self-confidence.
It was not easy, but I pushed hard and learned from everything, both good and bad things, and grew. Not all was bad, but it was certainly a roller coaster, happiness and sadness, easy and difficult things, pain and relief, loneliness and togetherness take turns, as life is.

The end arrived, in an unexpected way, and, if I was able to close this incredible chapter, is also thanks to all the people who were part of this incredible adventure, make things more difficult, make me in trouble, support me, get angry with me, stand beside me, leave me. All of you, with life, were the reason of my growth in these years and if I reached my goals, it is also your credit.

My gratitude goes especially to Elena and Franco, my parents. I know all the sacrifices that you made for me, all the work hours in your job, the tiredness and the strength that you spent to give me this chance for all these years. We had to do a lot of sacrifices and things did not go as we wanted in most of the time, but we reach it and now it is time to celebrate together our goal.

To Cecilia, my sister, thank you to be supportive and tolerate me, to resist to all the F1 and MotoGP races on Sunday and to grow our different passions together, even if we are the opposite, we always find the way to learn from each other.

To Anna Maria, Maurizio, Lucia, Ezio and Maria Teresa, my family, when we are in difficulties you were here for us, to help and support us, without asking, you were here. You suggested me when I was in doubt and helped me to be a better me and this goal is also yours.

To my friends, firstly to the oldest ones, we grew together, it is incredible to see how far we go together and that you are still with me, enjoying our successes and supporting each other in the bad days as we have done from the elementary and high schools.
To the ones met in University, it was really hard Politecnico di Torino, but all the projects, the hours spent in studying, the exams and the celebration for the good results gave us a boost to continue, to not give up and reach our goals together.
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To Toyota Motor Europe, especially Raf Schuermans and Takahito Endo, thank you to give me this chance of doing this internship and thesis together, to be kind and patience with me, to give me the possibility of having new opportunities and to teach me so much, thanks to this my passion was rekindled again for what I love to do.

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I am so glad to have met all of you and thank you to be part of this journey, to be with me.
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Letizia Mesiti