Mechanical Project of a Formula Student Electric Motor

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ABSTRACT

Self-developing their own motors is a new challenge concerning for Formula Student teams, there're not many solutions available on the market for this type of competition. FST Lisboa took this challenge and is working on their own motors with one prototype built. This work begins with the manufacturing, assembling and testing of a second-generation prototype. While manufacturing and assembling, problems that would limit the motor performance were found. Parallel to the manufacturing, a test bench was projected and built. With the motor assembled and the test bench operational, a battery of test was performed to determine the characteristics of the motor.

With all the knowledge acquired with every step before, 7 new concepts were modelled – four regarding electromagnetic concerns and three regarding the cooling of the motor. With finite elements models (electromagnetic and thermal) to analyze each concept, the best ones were chosen. This concept was developed, and a complete motor modelled, and major structural analysis was performed with finite element software to every critical component. Besides, there was a major emphasis on electrical and mechanical accommodation of every component. Also, a plan/tasks involved with the motor design and production are presented.

Keywords: Electric motor, Mechanical Design, Formula Student; Manufacturing

1. INTRODUCTION

1.1. FORMULA STUDENT

Formula student is an engineering competition at university level, where different groups of students build formula-type cars to compete against one another at official events sponsored by the industry.

1.2. STATE OF THE ART

Nowadays, most competitive electric teams in Formula Student are using AC Permanent Magnets Synchronous Motors (PMSM). There are two solutions available on the market designed specifically for the usage in Formula Student competitions. But some teams started to build their own motors, FST Lisboa is one of them.

The usage of PMSM allows regenerative braking and faster response times. This type of motor also has a higher torque/weight ration and are more efficient. Despite the advantages, this type of motors is more sensible to mechanical vibrations and high temperatures due to the possibility of crack formation or demagnetization of the Permanente Magnets (PM). They're also expensive than other motors due to the price of the PM.

Synchronous machines have the rotation of the shaft synchronized with the frequency of the supply current. They contain multiphase electromagnets on the stator which creates a magnetic field that rotates in time with oscillation of the supplied current, the rotor with usually permanent magnets creates another magnetic field. When current flows through the windings of the stator, it creates an electromagnet by the creation a magnetic field which rotates according to the current flowing from coil to coil over time. The magnetic provided by the PM on the rotor, is attracted to the stator rotating magnetic field, causing the rotation of the shaft and rotor. This represents one of the main forces responsible for rotation the shaft and rotor – Lorentz force. [1]

Inside PSMS we can find two different categories of rotor geometries – Surface Mounted Permanent Magnets (SMPM) or Interior Permanent Magnets machines (IMP):

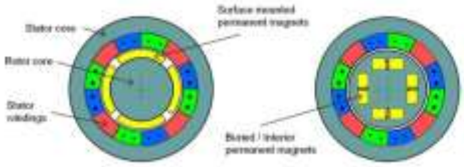

Figure 1.1 - SMPM Rotor (left) and IPM rotor (right) [2]

The motor built with this project and newest design have IPM due the advantage of allowing to concentrate magnetic flux inside the rotor, achieving higher airgap flux densities which leads to increased motor torque values.

1.3. OBJECTIVES

The purpose of this work is to manufacture, assemble and test the second generation of the motor. It's also intended to design the next one with all lesson learned, perform static and fatigue studies of critical components and deliver a plan of manufacture.

2. SECOND GENERATION PROTOTYPE

The second generation of the self-made motors was designed within the Powertrain team of FST Lisboa. It consists on a three-phased AC motor, PSMS with IPM arranged in a spoke geometry. The motor has a titanium alloy shaft, a rotor and stator made of s cobalt-iron – Vacodur 49 with enhanced magnetic properties, neodymium PM and housing components made of aluminum alloys. The motor is water cooled. Some of the motor subassemblies can be seen at Figure 2.1, for specific dimensions, the technical drawings can be found in the annexes. One encoder for shaft position reading and temperatures sensors, mounted on the smaller body above the main body, are also part of the motor.

Figure 2.1 - Second Generation Prototype

The prototype is composed by housing for the motor, cooling and electronics; a stator with coils and a rotor assembled to a shaft with the magnets inside. The second generation was designed to have the following characteristics:

Description	Value	Unit
Max Torque	18,6	Nm
Output power	29,4	kW
Ke (Voltage Constant)	27,7	(V/krpm)
Kt (Torque Constant)	0,325	Nm/A
L_d (d – axis inductance)	0,755	mH
L_q (q – axis inductance)	0,879	mH
Power factor	0,446	-

Table 2.1 - Second generation expected characteristics

2.1. MANUFACTURING

Rotor and Stator

The rotor and stator are made of *Vacodur 49*, a cobalt-iron alloy with excellent magnetic properties. The material is delivered in sheet 0,2mm thick covered with 2micron layer of an epoxy to later perform the stacking of the metal until the final shape wanted.

The metal sheets were laser cut to the desired geometry and recurring to self-made assembly JIG the stacking was done in a dry oven during one hour at 200ºC. This didn't work and it was found out that the metal sheets were lacking the epoxy.

Figure 2.2 - Stator and Rotor sheets with manually applied Epoxy

The epoxy was acquired and applied manually (Figure 2.2) what caused future problems and a reduction around 30% of the number of laminations to achieve the desired height.

Shaft

The shaft (Figure 2.3) was made of a Titanium alloy (Ti90/Ai6/V4) and it was manufacturing by two processes – EDM for the part where the rotor will be mounted and CNC machining for the rest.

Figure 2.3 - Machined Shaft

Housing

This component (Figure 2.4) represented the first attempt of joining the motor and the cooling housing in one major part. This led to using EDM to open the water circuit and CNC-machining for the rest.

Figure 2.4 - Machined motor housing

All other necessary components were machined with conventional machines or acquired.

2.2. ASSEMBLY

Rotor and magnets insertion

Due to the high velocities expected for the rotor, a forced fit was recommended (H7/u6) [3] but, with all the problems occurred during the stacking, the rotor didn't expand as expected with heating and had excess of epoxy in its interior. Submerging the shaft in nitrogen also didn't help. The solution was to for the shaft with a manual press (Figure 2.5). This caused small deformations on the shaft.

Figure 2.5 - Shaft insertion

The magnets had a sliding fit, but due to the excess of the epoxy this turned into a tight fit, risking breaking the magnets. To ensure they would not leave its place, they were glued to the rotor.

Stator Insertion

The stator, since it is a fixed part, didn’t require a fit so extreme has the rotor, the literature recommend a press fit (H7/p6)[3]. To do it, the stator was emerged in liquid nitrogen and with the help of a guiding jig, inserted into the housing. The process started ok but once 1/3 of the stator was in, it cracked and got separated in four pieces, with the biggest one inside the housing. Removing it damaged the inside a bit and repairing the stator was possible, but it lost 5% of its original height. This showed that the epoxy used in the stacking could not be operated in cold temperatures.

The stator was repaired and with a second attempt, but this time the aluminum housing was heated up, the stator was successfully mounted (Figure 2.6).

Figure 2.6 - Stator insertion

Winding

There were no companies that made coils for a motor this small, which led a homemade attempt of it. This resulted in coil with way to less wire than need.

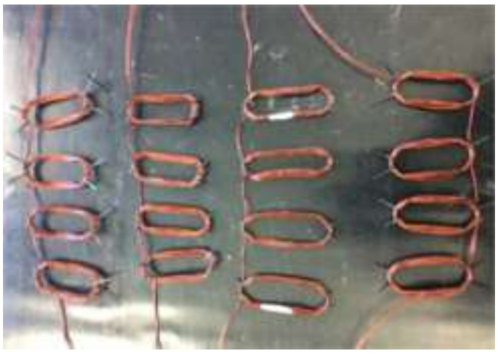

Figure 2.7 - Homemade coils

Eventually help was found and with the proper tools, the winding was done. But, a Vacuum Impregnation Process where the air is removed from between the wire and replaced with a varnish could not be done due to the motor size and lack of equipment for it.

Figure 2.8 - Coils inside the stator

After having all sub-assembly done, all that was missing was putting everything together. The bearings were inserted in the shaft following their datasheet instructions and with it the sub-assembly rotor and shaft was ready to be inserted inside the rotor. This was expected to be a problem due to the magnetic forces created by the magnets but turned out quite easy. The lids were screwed in place and finally the motor was ready to start test-benching. The encoder and its cover were mounted just to check for any problem, since it wouldn't be need for the first test, it was removed for safety.

2.3. BENCH TESTS

To perform the needed test on the motor a test bench was built:

Figure 2.9 - Test-bench under construction

General tests before starting the motor were done - visual inspections; checking for something loose – something was loose in the shaft; upon investigation the cause was a bearing wrongly positioned due to the shaft deformation mention before; earth continuity and resistant test; winding continuity and insulation test. When everything was okay with this test, the prototype was connected to one of the cars AMK motors.

No load tests

With the AMK moving at know speeds, the current and voltage values of the prototype were measured allowing to compute the voltage constant:

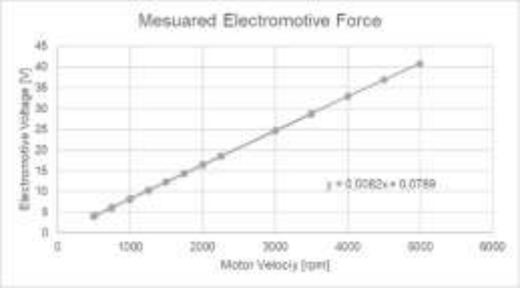

Figure 2.10 - Induced voltage - no load

$$Ke = 8{,}2\frac{V}{krpm}$$

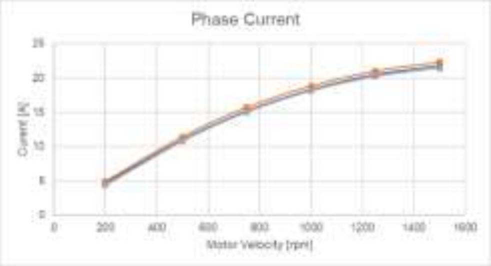

Figure 2.11 - Induced Current

Looking at the current values, saturating so early, it indicated a serious problem.

Shor circuit test

With the same conditions as the previous test but now with the prototype phases short circuited the torque constant could be estimated:

$$Kt = \frac{\tau_m}{Ia} \tag{2.1}$$

$$\frac{Kt\ AMK}{Kt\ Prototype} = \frac{\frac{\tau\ AMK}{Ia\ AMK}}{\frac{\tau\ Prototype}{Ia\ Prototype}} \tag{2.2}$$

Obtaining $Kt = 0{,}26\,\frac{Nm}{A\,rms}$, that confirmed the motor problems, this value only allowed an expected maximum torque of 1,94Nm.

Other tests were done using capacitor to determine the quadrature inductance obtaining $Ld = 0{,}354\ mH$.

Saturation Problem Testing

To check what was causing the saturation, the magnets and the iron were tested. The magnets were checked with a gaussmeter and they’re okay.

To test the iron, a transformer was built, and the B-H curve traced for comparing with the datasheet values. This was the problem, the only conclusion possible was that the *Vacodur* was sold without passing through a final annealing to achieve the best magnetic properties

3. DESIGN PROCESS

Designing an electric motor involves disciplines such as electromagnetics, mechanics, thermal, material science, electronics, tribology and mathematics.

Following an approach of subsystem/component where the motor is divided in smaller and simple components to study, the design process began resulting in four relevant concepts regarding electromagnetic aspects and three regarding thermal aspects.

Figure 3.1 - Design Concepts

4. ELECTROMAGNETIC ANALYSIS

Recurring to *FEA* commercial software, an electromagnetic model was used to estimate and compare the flux density and maximum torque each concept could provide. The best one was concept number for of the figure 3.1 with a max. torque of 26,2 Nm.

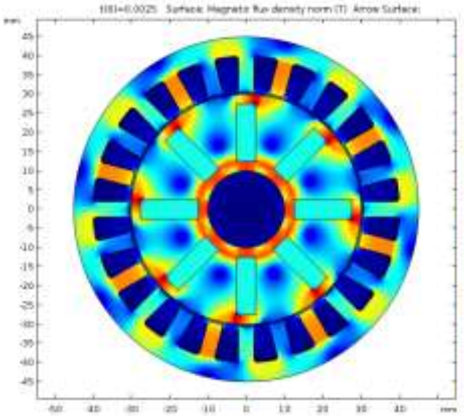

Figure 4.1 Flux density concept 4

5. THERMAL ANALYSIS

The same software was used for the thermal analysis with an appropriate model. In this case the temperatures of the rotor, stator, coils and water were the relevant variables to study.

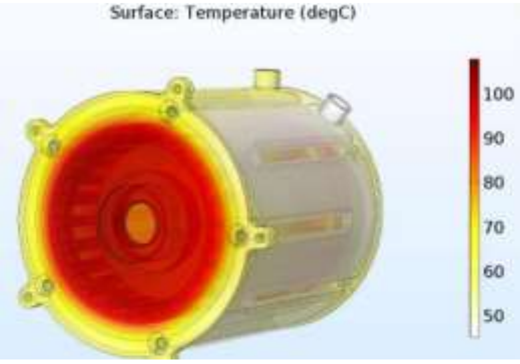

Figure 5.1 - Motor temperatures of concept 3

The chosen concept was the one that had the cooling circuit incorporated in the motor housing

6. MECHANICAL DESIGN

With the geometry of the stator and rotor defined and with the cooling design chosen, every other component was modeled. The materials were chosen considering restrictions by rules, economics reason and the properties that suited the best the components need.

The load cases considered for the static analysis consisted on applying the motor maximum expected torque into a shaft blocked (due to a transmission fail). It was also considered the force created by a possible road bump and the weight of the car.

For the shaft, the critical dimensions were computed to check if there was some incompatibility with the dimensions already defined by the rotor geometry. It was then analyzed recurring a commercial software following the von Mises criteria and safety factors check:

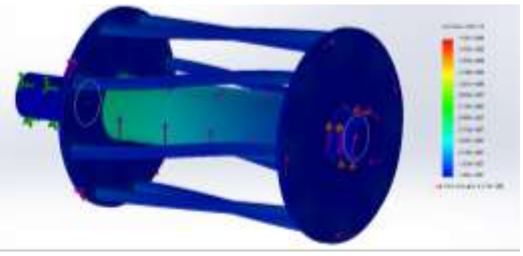

Figure 6.1 - Von Mises stress on shaft

All critical components followed this step and made sure all had safety factors above one.

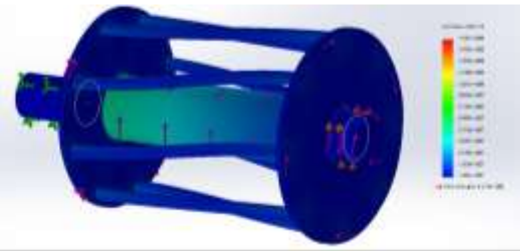

Figure 6.2 - Von Mises stress on rotor

One problem that exists one the commercial motors used by the team, it's the lack of place to use a mechanical fuse. This was corrected on this shaft and key and keyway included:

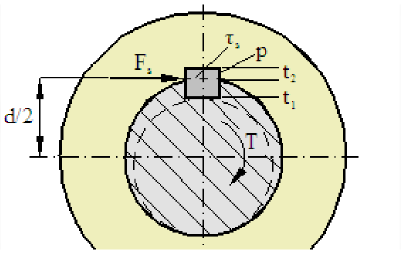

Figure 6.3 - Shaft keys and keyways

key width b	4mm
key height h	4mm
keyway depth shaft t_1	2.5mm
keyway depth hub t_2	1.8mm

Table 6.1 - Key dimensions

Also, regarding the shaft, its design considered the rotor manufacture, the way the shaft is composed (one main part, eight connecting rods, one cover and one connection to encoder) allows that the JIG for the stacking is the shaft itself.

Figure 6.4 - Exploded view of the final shaft version

For the stator this couldn't be done, so a specific JIG was modeled (Figure 6.5).

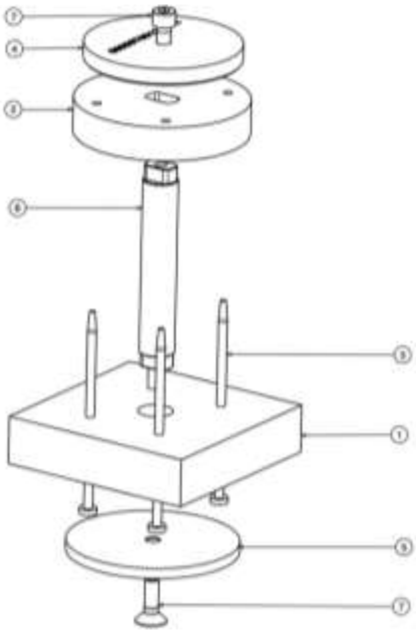

Figure 6.5 - Stator stacking JIG

Fatigue calculations were done following the modified Goodman Criteria, for supposedly being a more conservative approach. The critical components had a safety factor above one.

Stress analysis were also performed on the housing to check situations like dropping the motor on the ground:

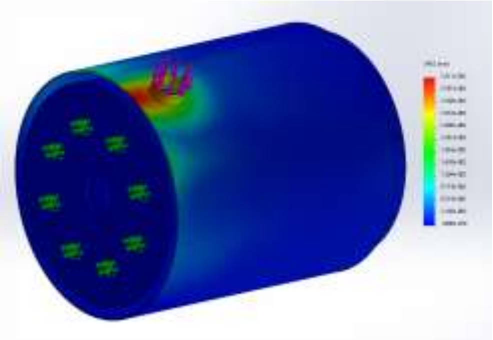

Figure 6.6 - Fall test housing deformation

All other missing components were modeled:

Figure 6.7 - Motor lids

Bearing and oil retainers were also selected taking the motor loads and speed into account. There's also the problem with conventional motor bearings, they can get "fried" by the electrical current passing through them, causing premature failing by electrical arcing. The solution for this problem is using ceramic ball bearings sealed. This type of bearing offers lower Maintence costs by expanding its service life. They have and extended grease life since they run colder because of the ceramic balls - 6201-2RSLTN9/HC5C3WT

The choice for the retainer was 12X19X5 HMS5 RG1 based of the diameter of the shaft and because it was the retainer available with higher operational speed.

The clearance fits between critical components were also defined:

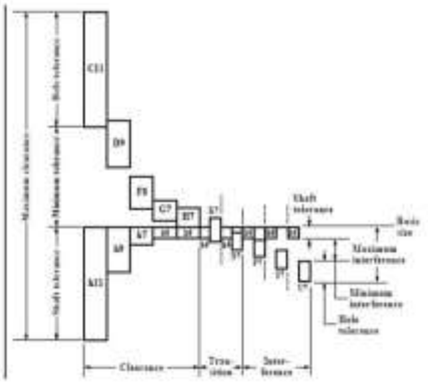

Figure 6.8 - Clearance fit shaft-hole

Stator – housing: This fit must hold the stator in place, but it cannot be too tight, or it will cause losses in the iron magnetic properties. It will be used a press fit with light interference - H7/p6.

Shaft rods – shaft bottom: The shaft rods need to be held in the right place so they can align properly the laminations for the stacking. A press fit is also the appropriate solution – H7/p6.

Magnets – rotor: The magnets will be inserted manually, from practical experience, they are too fragile to have any kind of interference fit. A sliding fit is recommended – H7/g6

Lids – housing: Once the motor is assembled, it's not supposed to disassemble again, but since it's still a protype a tight interference is need, but one that can be dismounted – fixed fit – H7/n6

Bearing – shaft: Recommended by seller – j5

Bearing – housing: Recommended by seller – H7

Retainer -shaft: Recommended by seller – g6

Retainer – housing: Recommended by seller – H8

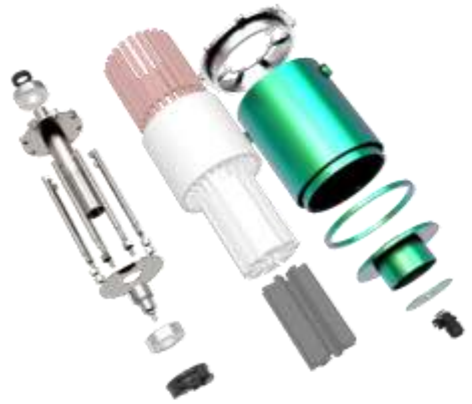

Figure 6.9 - Final CAD model exploded view

7. CONCLUSIONS AND FUTURE WORK

Building a prototype has an enormous importance. The lessons learned by it helped preventing future problems and they were many in the one built.

Manufacturing of the rotor and stator revealed severe problems for future motor generations: the material didn't have the epoxy to bond the laminations; this led to manually apply the epoxy which cannot be done – the already cut sheet are hard to handle, a lot were damaged and the layer of epoxy was too thick; the epoxy reacts poorly to cold; excess of epoxy covered slots in the stator and in rotor, reducing space for coils and magnets. The only positive aspect regarding this to components were the JIG built for its assembly.

The insertion of the rotor, that was another problem: the excess of epoxy and the damaged laminations due to epoxy hand application, ruined the tolerances for the previous dimensioned fit. This led to a poor process to assemble the rotor, pushing it with a hand press which cause small deformation on one part of the shaft.

Assembling the rest of the motor revealed no problem which led finally to testing. A bench test was designed, manufactured and assembled for it. The tests showed characteristics way too low from what expended.

With all that was learned, new concepts emerged. Electromagnetic and thermal analysis performed to choose the best and with that concept, the modelling and mechanical design of the rest of the motor done. The results show an oversized motor, but for this will be a validation tools that needs to endure bad handling.

For the future, the new design needs to be manufactured and tested. Also, the bench test needs improvements. It would also be interesting to find if processes like sintering are an option for the team and optimize components with that in mind.

REFERENCES

[1] A. Fitzgerald, C. Kingsley, and S. Umans, Electric machinery. McGraw-Hill, 2003, vol. 319, no. 4.

[2] "IPM and SPM machines," accessed on 13-02-2019. [Online]. Available: https://ei. uni-paderborn.de/en/lea/research/forschungsprojekte/electrical-drives-and-mechatronic-systems/ control-of-permanent-magnet-synchronous-motors-for-automotive-applications/

[3] A. Silva, J. Dias, C. T. Ribeiro and L. Sousa, Desenho Técnico Moderno – Lidel, 4ª Edição, 2004

[4] J. G. V. V. Sarrico, "Design and Implementation of a 20 kW, 12000 RPM Permanent Magnet Synchronous Motor (PMSM) for the IST Formula Student Powertrain," Master's thesis, Universidade de Lisboa, 2017

[5] P. M. de A. Fontes, "Refrigeração do propulsor elétrico de um veículo Formula Student," Master's thesis, Universidade de Lisboa, 2016.

[6] J. E. Shigley, C. R. Mischke, and R. G. Budynas, Shigley's Mechanical Engineering Design - 9th Ed., vol. New York,. 2002.

[7] SKF Group, “SKF Rolling Bearings Catalogue.” SKF Group, 2013.
[8] W. Tong, Mechanical Design of Electric Motors. CRC Press, 2014.