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In-Wheel Traction Motor: a Case Study for Formula SAE Electric ⋆

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Abstract: This paper discusses in-wheel electric tractive systems, bringing as a case study the finite element design of a Fractional Slot Permanent Magnet Synchronous Machine with non-Overlaping Winding (FSPMSM) for an all-wheel drive Formula Student powertrain. The goal is to obtain a system that fits a 10" rim wheel, with a high power density that enables a 280 kg vehicle to accelerate over 75 meters in less than 4 seconds. Iterating the design method to maximize the output torque, the simulations indicate that a single 12,000 rpm machine can provide continuous 17.7 kW at the 600 Vdc system.

Keywords: In-Wheel Motor, PMSM, Formula Student, Power Density, Electric Vehicle

1. INTRODUCTION

In 2018, the global electric vehicle fleet exceeded 5.1 million, almost doubling the number of new electric car sales (IEA, 2019). Irle (2020) indicates 7.5 million at the end of 2019. As world's largest vehicle market, China kept the boom lead, coming from 600,000 units sold in 2017 to 1.1 million in 2018, accounting for 55% of the global market. Brazil, on the other hand, when including hybrids, sold 3,900 units in this year, which made a 0.16% share of total national market (Riato, 2019). With worldwide sales increasing, the development of technology for electric mobility is driven to face challenges that are still present.

There are different arrangements of propulsion systems for electric (VE) and hybrid (HEV) vehicles. These may vary according to the number of propelled axles and the number of electric motors. There are simple solutions that use only one traction motor per axle, either on the front (Front-Wheel Drive), on the rear (Rear-Wheel Drive), or on both axles, known as All-Wheel Drive (AWD) (Momoh and Omoigui, 2009; Kebriaei et al., 2015). Even though these solutions are the most used in vehicle propulsion systems, the flexibility of electric motors makes it possible to implement more sophisticated arrangements with independent motors per wheel (Mutoh and Takahashi, 2009). In this distributed solution, the AWD vehicle will have four electric motors, two per axle. This technological solution leads to a precision gain in control and dynamics, in addition to better energy management (De Filippis et al., 2016).

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From this independent arrangement, it is possible to act on the torque in an order of ten times faster than with hydraulic braking, enabling performance gains in Traction Control Systems (TCS), Anti-lock Brake Systems (ABS) and Electronic Stability Control systems (ESC) (Murata, 2012; Wu et al., 2014; Akaho et al., 2010). Akaho et al. (2010) showed an improvement of 3% in the TCS and 7% in ABS. With regard to greater flexibility in energy management, this factor alone can increase efficiency by achieving up to 3% reduction in consumption (De Filippis et al., 2016). Further efficiency increase can be made with the removal of the mechanical differential and reduction gears. Compared to a vehicle model equipped with an axle motor, the independent solution is capable of providing gains of up to 8% in consumption (De Filippis et al., 2018). These gains represent an increase in autonomy or a reduction in battery costs.

An independent wheel powertrain can be implemented in two different ways. The first, and most common, is called In-Board Motor (IBM), characterized by incorporating the motors into the chassis. The focus of this work, is centered on the second technological concept: the In-Wheel Motor (IWM). In this arrangement, the traction motors are accommodated directly in the vehicle's wheels.

It is noticed through the proposal and developments found in literature, that the IWMs are gaining prominence in the scenario of technologies for vehicular electrification in recent years, once this technology provides additional benefits to the advantages of independent motorization.

The first additional benefit is the internal space gain. In the case of HEV this gain is more critical, mainly in the hybridization of conventional vehicles, since they already need to deal with space restrictions. It is also possible to have a dimensional reduction in new vehicle designs, mostly in purely electric ones, making them more suitable for urban centers.

There is also a reduction in the powertrain mass, which can reach 36%, as presented by Murata (2012). This value was obtained with a transition from a single IBM to the IWM solution. Without the low driveshaft natural frequency, it is possible to take advantage of motor response, also making the system easier to perform maintenance and replacement of the components, due to its location outside the body and chassis structure.

In addition to these arrangement characteristics, there are different variations of electric motors technologies. The vehicle tractive systems are made with three main topologies: Inductions Machines (IM), Switched Reluctance Machines (SRM) and Permanent Magnet Synchronous Machines (PMSM). The selection process depends on the application, as there is no ideal machine topology for all scenarios.

In the general context of vehicle electrification, it can be said that the motors often used were adaptations of existing industrial solutions. However, over the past few decades, these technologies have been optimized for this specific niche. There are countless research and development projects that have been promoting technological advances. The main requirements for the machines are robustness, low cost, high power density, wide speed range, low noise, little maintenance and ease of control.

The IM and SRM are cheaper and present moderate performance, while the additional cost of PMSM is correlated with their higher power density (Sokolov, 2017; Hashemnia and Asaei, 2008; Lebsir et al., 2013). PMSM lack of coils in the rotor grants them higher efficiency peaks, but a high speed operation increases their stator core magnetic losses. Comparatively, this can make the IM more efficient at cruise speed, once their magnetic field can be lowered (Rippel, 2007). From the perspective of In-Wheel motorization technology, PMSM are predominant due to its high power density.

One of the applications that featured PMSM In-Wheel systems as a great solution is the student competitions with high performance vehicles, such as Formula Student Electric and Formula SAE Electric, where the possibility of controlling the wheels torque dynamically and individually grants great benefit. This paper presents a design of a PMSM for an AWD Formula Student application, as seen in Figure 1. The 280 kg prototype, with the power limitation of 80 kW, must accelerate in a 75 meters track in less than 4 seconds, and do an Endurance test of 22 km of winding track in about 30 minutes.

Figure 1. NK319: Fórmula Tesla UFMG 2019's prototype.

2. STATE OF THE ART

2.1 In-Wheel Motor - Development

Different works report the challenges and uncertainties related to the use of IWM technology. It is important to highlight here the factors that bring challenges to the application of this powertrain solution.

There is an aspect of uncertainty that is linked to dependence on rare earth minerals. These minerals used for the production of magnets are fundamental to obtain the high torque and power density requirements demanded for the application. However, the price volatility of this raw material can be observed in the period between 2011 and 2013, when the Neodymium achieved an appreciation of approximately 800% (Office of Energy Efficiency & Renewable Energy, 2017).

The effort to reduce dependence on these minerals is noticeable. In the fourth generation of the Toyota Prius, for example, the rare earth elements used in the powertrain were reduced by 15% (Taniguchi et al., 2016). Research was carried out to develop engines with Non-Rare Earth Materials, looking for topology optimization for the design and manufacturing process. The use of magnetic materials such as ferrite, electric steels with a higher silicon index, and new production techniques are some examples (Office of Energy Efficiency & Renewable Energy, 2017).

Another aspect that adds a challenge to the IWM solutions is the dynamic behavior of the vehicle's unsprung mass. To clarify this issue, different studies are being conducted. From this perspective, the effort is focused on the lifespan of the motors and suspension, and on the users comfort requirements.

Studies suggest that for commercial small passenger-carrying vehicles, the increase in unsprung mass should not exceed 40 kg per wheel, also pointing to the need to redesign the suspension (Bravo et al., 2012). This change is necessary to ensure that there is no loss of tire contact with the pavement under transient damping conditions. In another study, vehicles with similar mass and suspension coefficients characteristics were evaluated. These authors pointed out that an increase of 50 kg per wheel is not able to alter the natural frequencies to the point of impairing passenger comfort levels (Van Schalkwyk and Kamper, 2006).

In the scenarios of the IWM, Luo and Tan (2012) propose the use of bushings to reduce the effects of vibration and lateral and vertical forces in the deformation of the magnetic gap. The results point to a reduction in the deformation of the magnetic gap and improvements in comfort for vehicle driving. These efforts can also impact the IWM bearings. Damage to this component is critical because it can affect the operation of the motor. To minimize this impact, Biček et al. (2020) proposes a methodology for defining the structure and geometry for IWM bearings.

From the perspective of damage to the suspension set, Kulkarni et al. (2016) concludes that the adoption of IWM on the vehicle wheel does not result in damage or reduced component lifespan. Rojas et al. (2010) presents suspension systems with the ability to mitigate possible effects of the discomfort that the increase in unsprung mass may cause. In the scenarios evaluated in simulations, the authors suggest a 40% increase in comfort and safety in relation to the passive damping system.

Bičeka et al. (2019) evaluates commercial IWM technology in Ingress Protection (IP) tests. The results show that the solution reaches levels with IP68 and IP6k9k, resisting high pressure jets and submersion of up to 1 m. The authors also conclude that the evaluated IWM technology can operate on ambient temperature of -40 to 85 °C without damage to the lifespan.

Therefore, it is possible to conclude that there are viable ways to deal satisfactorily with the increase in the unsprung mass brought by the In-Wheel Motors. Although adaptations and conversions are more complex and limited, vehicles that implement the solution from the design stage increase IWM viability.

2.2 In-Wheel Motor - Benchmarking

There are different companies that have developments presented in IWM technology. Among them are Protean Electric, Elaphe Ltd., Printed Motor Works, ZIEHL-ABEGG, Magnetic Systems Technology (Magtec), ZF Friedrichshafen AG. BE, Emrax and AMK Arnold Müller GmbH Co. KG. The solutions target a wide range of vehicles, from compact for two occupants to public passenger transport vehicles. There are also models for heavy duty application, as transportation, agricultural and even military solutions.

The commercial search conducted counted twenty models, from seven different manufacturers. The main focus was on commercial solutions for light vehicles, including passenger and cargo transportation and heavy duty. Bicycles, motorcycles and conceptual literature technologies were disregarded.

All models found are PMSM, mostly with water cooling, linked to the power density benefits. Approximately 28% of the companies listed also offer very few air-cooled models, with consequently lower power density. Regarding the flux orientation, 62% are radial and 38% axial. Figure 2 shows some of the models found.

Power converter modules integrated to the motors were found in 20% of the IWM solutions, a strategy adopted by 42% of the companies. 100% of the IWM technologies found for application on light passenger vehicles and public transportation, are direct driven: without reduction gear. Those IWM solutions identified are in the 17 to 40 kg mass range. Heavy-duty IWM represents a point outside the curve, with a mass of up to 465 kg.

It is noticeable that there are several solutions for applications in conventional vehicles, such as for personal use and transportation, and the available solutions are robust to critical conditions due to humidity, dust, ice, mud, as well as mechanical impacts, vibrations and mechanical stresses on the three axes (Bičeka et al., 2019).

Figure 3 shows the rated power density characteristics as a function of the rotation speed of the commercial solutions

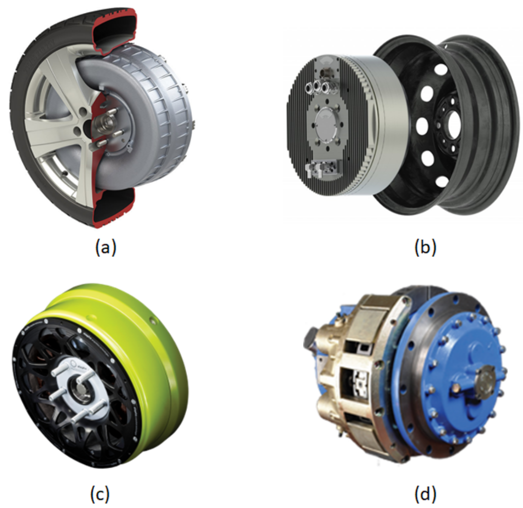

Figure 2. In-Wheel Motor commercial solutions (a)Protean Eletric, (b)Printed work, (c)Elaphe, (d)MagTec.

available. The up variation means the maximum power density that can be achieved in transient mode.

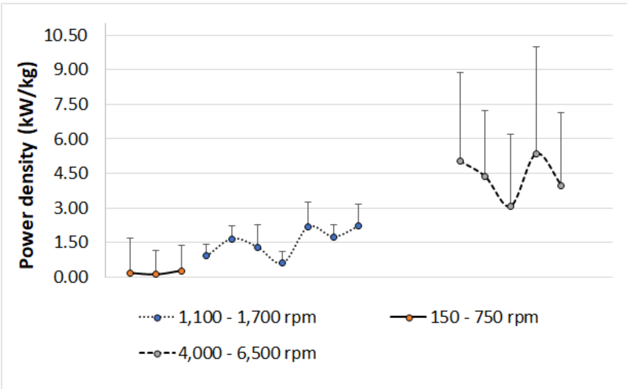

Figure 3. In-Wheel Motor power density on speed range.

For performance vehicles, such as the Formula Student, the torque and power density indices are even more relevant. These single-occupant vehicles are compact and have limited space. Since the application is very specific, there is not much variation in the motors used, generally presenting powertrains made with adaptations of aircraft industry systems. The three most relevant solutions use PMSMs from the manufacturers YASA, Emrax and AMK. In Brazil, due to budget limitations, some teams use IM from the manufacturer WEG.

Among all the solutions found worldwide for Formula Student, the only ones that presented IWMs with relevant success were with AMK motors. These are radial high-speed motors that can reach 20,000 rpm and peaks of 10.4 kW/kg. The teams develop planetary gearboxes to match the required wheel torque. The use of machines from another manufacturer was only found with a Turnigy Power Systems motor in the work of Hooper (2011), where he proposed a similar system with less power.

3. PROBLEM DESCRIPTION

Given the advantages of the IWM and the PMSM topology, the design of this system seems suitable for Formula Student application. The vehicle used in this case study is the NK319, third prototype from Fórmula Tesla UFMG, the Federal University of Minas Gerais team. The current powertrain uses independent dual rear IM traction, with a total power of 12 kW nominal and 36 kW peak, see Figure 4. Electronic differential was developed to enable the independent control of the machines. This entire system weighs 57.6 kg.

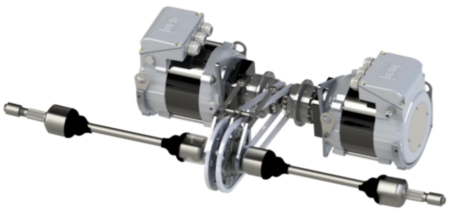

Figure 4. Prototype NK319 current powertrain.

Before the machine's design discussions, this work will proceed to an analysis of the constraints imposed by the competition regulations, the demands for torque and power, and the remaining mechanical constraints.

3.1 Formula SAE Constraints

The first contraints of the machine project comes from the Formula SAE Rules. Any type or quantity of electric machines are allowed, but the power drained from the batteries is limited to 80 kW and the instantaneous DC bus voltage to 600 V.

Selecting the operating voltage is a complex issue, since increasing it can lead to unwanted side effects, such as higher controller switching losses, overall insulation mass and safety concerns. Despite the downsides, reaching the 600 Vdc limit can be considerably rewarding, lowering direct current losses and overall mass in components like conductors and protection systems. Once all needed components are also commercially available at this voltage, the design decision was to operate using the maximum allowed range.

Unlike the discussion on operational voltage, the power limit issue will be addressed below, together with the analysis and modeling of demands.

3.2 Torque and Power Demands

The design of the electric machine is carried out in order to reach certain values of torque and power, which define the electromagnetic constraints. Different analyzes can be made to obtain these values for a Formula Student, which will depend on the characteristics of the current prototype and the results obtained by its competitors.

Among the various events made in the competition to evaluate the vehicle dynamically, the Acceleration Event is the one that most requests peak characteristics, and the Endurance Event has the longest duration, being viable to obtain nominal values. Among the 1000 total points used to evaluate the team, these events represent 10% and 27.5% of the score, respectively.

The Acceleration Event takes place on a 75 meter track, having the simplest analytical modeling, since any lateral forces can be neglected. Therefore, the longitudinal model can obtain the acceleration of the vehicle by Newton's Second Law, from the calculation of the tractive force in each wheel, taking into account the opposite forces of aerodynamic resistance and rolling resistance. The current vehicle data was used, along with an iterative calculation process for load transfer and traction limits.

Once the model calculates the time that the vehicle performs the event, this value is inserted in a formula provided by the competition, along with the shortest time obtained by the competitors, allowing to calculate the team's final score. The methodology was to fix the nominal speed at 12,000 rpm, which was the maximum value considered feasible for the available manufacture, and to vary the torque observing the score results. It is also important to point out that, as the design uses a PMSM topology, the most conservative decision was made, not considering field weakening operation, in order to avoid demagnetization.

Iterating the model with the track times of 2018, the vehicle won the Event with an AWD peak torque of 275Nm per wheel, as shown in Figure 5. The results depend heavily on the complex analysis carried out on the tire-to-ground adhesion coefficient, which is not part of the scope of this paper. Reaffirming the dependence of the score on the performance of the other teams, it was obtained that the same torque value would reach only 80% of the score in 2017, where the competitors achieved shorter track times. The simulated results for the actual IM powertrain, peaked at 67% of the 2018's score and 44% of the 2017's score.

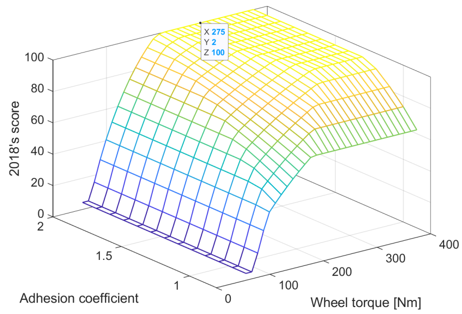

Figure 5. Acceleration score simulated for 2018 competition with AWD IWM system.

Once the IWM reaches the nominal speed, the 275 Nm represents about 31 kW per wheel. If the ideal distribution of instantaneous power were balanced between axles, this value would exceed the imposed limit of total power. However, the load transfer effect generates a dynamical optimal power distribution. In acceleration, it is better to have more power in the rear axle, and in regenerative braking, greater recharge is obtained with large peaks of power in the front axle. Since the power is not evenly distributed, the limit that the competition imposes to be drained from the batteries is lower than the ideal total power of the machines.

After analyzing the demands for peak torque and power, the Endurance Event was used mainly to define nominal values, since it is the longest dynamic event. The methodology used was to directly extract the results from the drive cycles measured in previous competitions. The nominal torque of 100 Nm per wheel, reaching 250 Nm peak was considered ideal. The power demand is from about 7.5 kW per wheel, with 15 kW peak. The Table 3.2 summarize all the demands results.

Table 1. Final output torque and power demands per wheel.

Nominal Torque	100 Nm
Peak Torque	275 Nm (4s)
Nominal Power	7.5 kW
Peak Power	31 kW (4s)

3.3 Mechanical Constraints

The SAE Rules do not present many limitations for the electric machine dimensions and mass, defining only that it has to have a minimum housing thickness, which depends on the material, and must be protected from moisture in the form of rain or puddles, recommending a IP65 rating.

The use of 13" and 10" rims are common in the category, with rare self-developed 8" rims. This tendency to reduce the wheels is driven by the performance gain obtained in acceleration with less wheel rotational inertia, better handling with less yaw moment, along with the overall mass reduction of the vehicle. The UFMG's team is actually using 13" rims, but plans to transition to 10" rims, leaving a wheel interior radial dimension of 241.3 mm.

The system have more axial dimension freedom. After taking the brake disc and wheel hub into account, the electric machine can have an axial dimension of 285 mm.

4. DESIGN PROCEDURE

The design of an electric machine is multivariable and iterative. Since the electromagnetic demands and constraints of the application are set, this paper proceeds to the flux orientation and topology dicussions, also presenting the finite element design.

4.1 Flux Orientation and Reduction Gear

The electric machine flux orientation can be radial or axial, each one presenting their advantages to the application.

Most commercial in-wheel machines are axial without reduction gear, since their disc format fits the wheel interior, the rotor diameter can be used to store inertial energy, and it usually can reach the desired output torque. Direct coupling increases the system efficiency, and reduces the complexity and cost of all project, manufacture, fabrication and tests procedures. The technology has advanced considerably in the path to overcome the intrinsic difficulties of the model, such as the assembly of the machine and maintaining the uniform gap (Gieras et al., 2008).

While the commercial applications usually can vary from 12" rims to 22" rims, the smaller Formula Student rims can present a decision shift to radial topologies with reduction gear. Since there is no high-speed axial solution for direct comparison, the Table 2 compares the Formula Student IWM solutions found in Benchmarking with a high torque density axial machine that can fit in a 10" rim. All calculations considered the mass of the motor and gearbox into account.

Table 2. Solutions comparison for Formula Student in-wheel 10" rim. Values given are final outputs per wheel. (Hooper, 2011; Aune, 2016)

Motor	Emrax 228	Turnigy CA120-70	AMK DD5-14-10
Reduction Gear	none	6.6:1	15.5:1
(Motor+Gear) Mass (kg)	12.3	2.61+1.77	3.55+1.48
Peak Torque (Nm)	230	132	326
Peak kW/kg	5.04	3.35	7.36
Flux Orientation	axial	radial	radial

A factor that increases the power density of the AMK radial solution, is that the motor has a high speed design, surpassing nominal 15,000 rpm. Besides the negative factors, such as increased losses, operating at higher speeds means that high power is achieved with low torque and consequently with low motor weight. The planetary gearbox is built inside the upright, also contributing considerably to weight reduction. Thus, this work continues with the decision to develop the machine for a tractive system with a similar topology: radial with reduction gear, which is in fact the main solution used among the worlds most prominent Formula Student teams.

4.2 Further Topology Discussions

Stating that the topology is PMSM radial, does not sufficiently define the machine, since there is a large variety of design decisions that need to be made, such as the use of iron stator core and slots, the winding type, poles-slots configuration and magnets position.

Coreless and slotless machines use non ferromagnetic materials for the stator magnetic flux path. These options are usually applied based on its cheaper large-scale manufacture. The downside that makes these topologies unsuitable for Formula Student application, is that it is hard to increase the amplitude of flux density (Song et al., 2019), which significantly decreases the power density.

The winding type selection problem is more complex, and also affects a wide list of parameters in the machine, such as harmonics generation, cogging torque and Joule losses. Even if some types can reach a unit winding factor, such as the full pitched type, this work opted by the fractional slot non-overlapping winding. The advantages are a simpler and cheaper manufacture, low cogging torque, good fault tolerance, large constant power region and high fill factor possibility (Petrov et al., 2014). Furthermore, this solution reduces the coil head, which also reduces Joule losses and the total machine length, affecting efficiency and mass. The topology nomenclature is Fractional Slot Permanent Magnet Synchronous Machine with Non-Overlapping Winding (FSPMSM), also known as Tooth Coil Winding Permanent Synchronous Machines (TCW PMSM).

The poles-slots configuration was based on the Cros and Viarouge (2002) work. The higher winding factor of 0.996, can be obtained with different combinations, but the 10-poles 12-slots was chosen since it has the simpler manufacture.

Jamil et al. (2015) indicates that in a 10-poles 12-slots machine, the single-layer version present a cogging torque reduction compared with the double-layer, without having a signficant impact in the mean torque. This option also increased the fault tolerance, since each slot only has conductors of one phase.

Finally, the magnet position chosen was the surface-mounted magnets, which avoided the need to create rotor slots. The downside is that the magnets are subjected to intense radial forces, making necessary to have a higher caution with their adhesion to rotor.

4.3 Finite Element Electromagnetic Design

The machine was simulated with the aid of Finite Element Method Magnetics (FEMM), externally controlled. The design method was iterative, evaluating the saturation effects in each sector of the stator and the results of torque, mass, voltage and harmonics, see Figure 6.

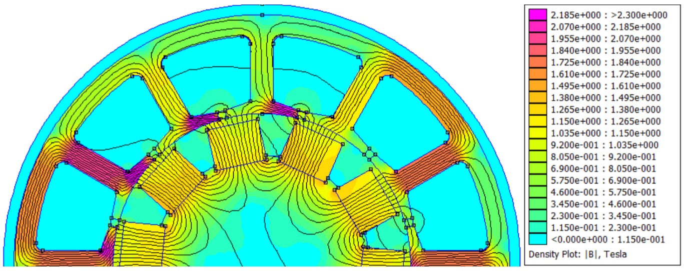

Figure 6. Nominal load magnetic field distributions.

Since the results are considerably affected by the current density and slot fill factor, it is necessary to briefly discuss the considerations made. An electric machine current density depends on a wide variety of factors, but mainly on the cooling method. In this work, liquid cooling was used around the stator to obtain a high power density: method known as water cooling jacket or water stator jacket. According to Yang et al. (2016), the current density in liquid cooled motors varies between 10 and 30 A/mm^2. Ponomarev et al. (2013) was more specific about the method used, indicating 6 to 14 A/mm^2 for the water cooling jacket. In this work a safe value of 7.85 A/mm^2 was used.

In regards to the slot fill factor, there are two types. Both are area relations, but one considers only the copper area and the other includes the area of the conductors insulation. The designations in this work were $f_{f,cu}$ and $f_{f,cond}$, respectively. Raabe (2014) indicates that with 20 AWG and IEC 100/2.80 slot, $f_{f,cond}$ = 0,5484 to 0,6018. Di Tommaso et al. (2017) found with round conductor values of $f_{f,cond}$ = 0,49 to 0,641. Without considering the paper insulation in a slot, Torezzan et al. (2009) indicates a maximum theoretical value of $f_{f,cond} = 0.9069$. The value of 0.7 was used based in manual winding tests.

Inserting the current density and slot fill factor values in the iteration process, the simulations readly indicated that FeSi solutions for the stator core were not suitable, since reaching the desired torque was only being achieved with the increase in mass. The material was changed to an 49% Cobalt-Iron (FeCo) alloy named Vacodur 49, which the manufacturer points to a high magnetic saturation of up to 2.3 T.

The design procedure maintained the nominal speed of 12,000 rpm, without field weakening operation, as stated in Section 3. By reinserting this value in the iterative model of longitudinal performance, an ideal reduction of 11:1 was obtained, leaving for the machine a torque demand of 9 Nm nominal and 25 Nm peak. Even with the FeCo stator core, a machine with 5.5 kg could not reach 25 Nm without saturation, as shown in Figure 7. The nominal cogging torque is shown in Figure 8. Future developments are expected to increase the output torque.

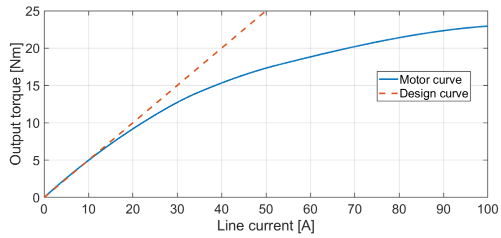

Figure 7. Output torque in variable line currents.

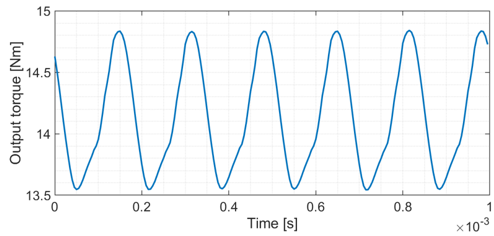

Figure 8. Machine's nominal torque profile.

The machine efficiency was calculated based on analytical models from the work of Gieras (2002). The efficiency was evaluated in four current values, considering operation with Sevcon HVLP20 controller: inverter nominal current (26.5A), machine's nominal current (35A), inverter peak current (53A) and ideal proposed boost current (100A). The results are shown in Figure 9.

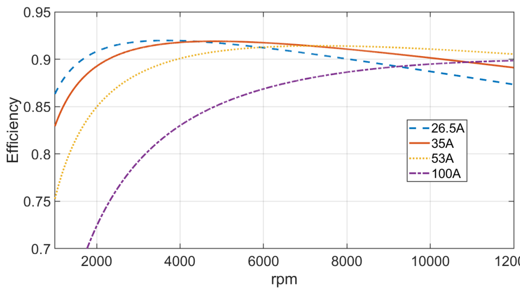

Figure 9. Machine efficiency with line current variation.

Results of the design procedure are shown in Tables 3 and 4, with the final system CAD shown in Figure 10. Following the best power density solutions, the reduction gear was designed inside the upright.

To analyze the performance of the developed system, Figure 11 presents a power density comparison of the solution with other Powertrains of Formula SAE and Formula Student. To make the comparison relevant to the competition, power was limited to 80 kW and the

Table 3. Final dimensions and mass.

Dimensions (mm)	
Stator outer diamenter	95
Stator inner diameter	57
Air gap	1
Rotor diamenter	55
Stator length	85
Magnets depth	8
Magnets width	10
Slot opening	1.2
Stator yoke	4
Teeth width	4.5

Mass (kg)	
Shaft	1.057
PM	0.503
Core	1.638
Copper	1.512
Frame	0.702
Additional	0.094
Total	5.506

Table 4. General and nominal output variables.

General	
Connection	Delta
Slots	12
Pole Pairs	5
Current Density	7.85 A/mm^2
Slot fill factor	0.7
Conductor	26 AWG
Insulation Class	H
Parallel cond.	20
Cond. per slot	53
Phase Resistance	0.234 Ω
Lamination	Vacodur 49

Nominal Output	
Power	17.77 kW
Torque	14.14 Nm
Efficiency	0.89
Power Factor	0.9
Line Current	35 A
DC Voltage	600 V

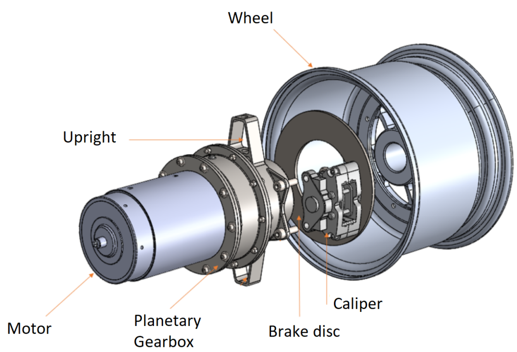

Figure 10. Final system with planetary gearbox.

mass considered was the sum of motors, transmission and reduction gears. The up variation means the limited peak power density.

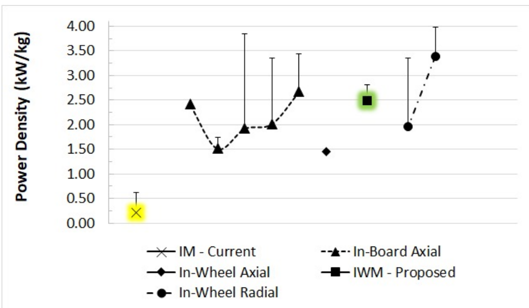

Figure 11. Powertrain power density of Formula SAE/Student solutions.

As expected, the use of the current IM In-Board proved to be considerably below the performance of the competitors. The AWD axial direct IWM possibility was also below what it could, since this only viable commercial solution found presents a nominal speed considerably above the wheel speed, which can be seen by its reach of the 80 kW limit already at nominal power. Even though the developed system has not reached the power density of the best solutions found, compared with the previous IMs the gains are considerable: using this AWD system with a Sevcon HVLP20 controller reduced the overall vehicle mass in 34.9 kg, which represents 12.5% of the current prototype mass. A relative impact of 248% peak power and 117% peak wheel torque. This results can be further increased if a 100 A line current controller is used, reaching 322% peak power and 143% peak wheel torque.

5. CONCLUSIONS

In this work, a Formula Student in-wheel AWD application was analysed, including the State of the Art, problem description and the final finite element design of a Fractional Slot Permanent Magnet Synchronous Machine.

The developed system reached power density levels close to those of the best commercial solutions used in Formula SAE/Student. While the power demands have been met, further development should focus in mechanical optimization for mass reduction. The replacement of the current powertrain by the developed one, presents a considerable improvement in the vehicle performance. The promising characteristics obtained need to be experimentally evaluated with manufacturing and testing procedures.

If the vehicle present a future overall mass reduction, the torque demand is directly affected, allowing to also adjust the machine with another design iteration.

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