EMIL

The White Paper

The ideal automotive motor without rare earth-magnets

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The Mission

The goal of Emil Motors is simple. Building an electric drivetrain without any rare earth magnets, that performs as well as state of the art motors with permanent magnets.
Rare earth magnets cause a variety of problems. They are sourced almost entirely from China and prices are extremely variable. Due to political tensions, the supply of these materials is not safe at all. Mining of rare earths is questionable as well, causing catastrophic damage to large areas of land and violating human rights in some cases.

A large part of the industry has realized this problem and is trying to fix it. But how? The reasons for using rare earths in the first place make sense when looking at automotive applications.
The drivetrain must be compact, lightweight, efficient and cheap. Strong magnets can enable such power dense and efficient designs, while being reasonably cost effective.
An alternative electric motor without magnets should offer the same benefits.
That's where innovation is required.
It should be noted that the whole drivetrain needs to be considered when comparing different motor technologies. A drivetrain consists of the electric motor, inverter and gearbox. The drivetrain must be cheap, efficient and power dense as a whole unit. Not just one part of it.

Large OEMs are already proposing solutions to the rare earth problem. Let's look at the different motor designs, that function without any magnets at all. We will not consider motors with non-rare earth magnets, like ferrite magnets. Ferrite magnets are massively weaker compared to rare earth magnets and are also overwhelmingly sourced from China. So, there are no real supply chain advantages.

1. *The Synchronous Reluctance Machine (SynRM):*
   A magnetic system tends toward the state of lowest reluctance, which is a measure of "magnetic resistance". By using this physical phenomenon and designing optimized reluctance rotors (the rotating part of an electric motor), it is possible to obtain usable torque. However, this torque is relatively low, resulting in a very large motor or low power output. There are alternative designs which require very high RPM to obtain good power output. This will increase gearbox size and weight, reducing gearbox efficiency. Motor bearings will spin faster, resulting in reduced bearing life and worse reliability. For those reasons, we disregarded the SynRM as a viable option.
2. *The Externally Excited Synchronous Machine (EESM):*
   When removing magnets from the rotor of an electric machine, you can replace them with electric magnets. An electric magnet or solenoid is just a coil with a direct current passing through it. However, passing a current requires some kind of electrical connection. These coils are located inside the rotating part of the motor, making a connection much more difficult. Brushes are usually the answer, requiring additional maintenance and increasing motor cost and complexity.
   In addition, more power electronics are required to create the DC current for the rotor. Overall the complexity and cost of the motor is increased. The current inside the rotor results in higher resistive losses as well, in other words heat. This requires complex cooling solutions for the rotor. Although multiple OEMs are actively pursuing EESMs as an alternative to permanent magnet motors, we believe in a less complex solution.

3. *The Induction Machine (IM):*
   This type of electric motors is one of the oldest electric motors. It is widely used in the industry, in fact over 80% of all electric motors are induction motors.
   It works as the name implies. The magnetic field in the rotor is not created by permanent magnets, instead it results from induction. Induction occurs when a changing magnetic field passes through a conductor. This changing magnetic field is created in the stator and results in induced current inside the rotor cage.
   The rotor cage is an electrically conducting part inside the rotor, made from aluminium or copper. This current inside the cage creates the rotor magnetic field, resulting in a magnetic force and thus torque.
   Induction machines are famous for their simple construction, high power, and good efficiency, but it isn't quite good enough for modern electric vehicles.
   The main drawback of induction motors is their lower torque density, resulting in a larger motor. Furthermore, the losses in the rotor create more heat, but in contrast to the EESM, the induction motor can run the rotor hotter, resulting in higher thermal headroom and overload capability.
   The main problem is the lowered torque density compared to other motor alternatives. In terms of manufacturing complexity, material cost and robustness, the induction motor is hard to beat.

This comparison makes it obvious that there is no perfect alternative to permanent magnet motors right now. We propose an innovative solution to this issue. In essence, the induction motor is very close to being the ideal electric motor for electric vehicles. In fact, the manufacturer Tesla has used induction motors for most of their existence and they are still being used as front axle boost motors. But how could the torque density of an induction motor be improved?

We would like to introduce you to our Axial Flux Induction Motor (AFIM). Axial Flux motors are becoming a topic of interest, due to their higher torque output. Due to their geometry, axial flux motors have a higher leverage for the magnetic force, resulting in higher specific torque output. However most companies are focusing on axial flux permanent magnet motors.
In fact, lots of people automatically associate axial flux motors with permanent magnets, but that's not correct. Most types of electric motors can also be built in axial flux geometry, including the induction motor. This mitigates the biggest drawback of the induction motor. The lacking torque density.

The image below illustrates the effect of the increased rotor radius. Torque of an electric motor is roughly proportional to radius squared, but for an Axial Flux machine it is radius cubed. The 25% bigger radius, as seen in the image, would result in a much higher torque compared to a radial flux machine. Of course, this is an oversimplified example, but the principle is correct.
The results from actual simulations reveal that the torque density of our AFIM design is significantly higher compared to radial flux induction motors.
Individual comparisons and detailed numbers are available in this document.

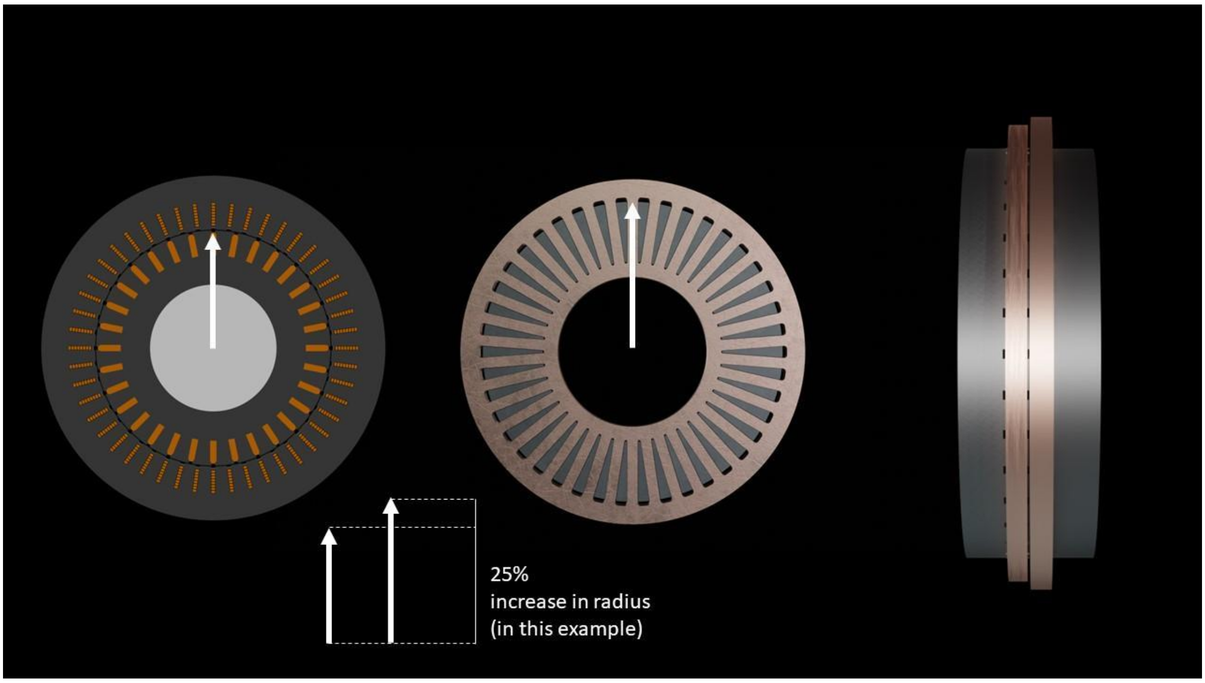

Figure 1 - from left to right, section view of a conventional radial flux machine, frontal view of our axial flux rotor, side view of our axial flux motor

All of this is great news, because the materials inside of an axial flux induction motor are the same compared to a conventional induction motor. This results in a very cheap and simple motor construction, just like the conventional induction motor. In addition to that, the increased torque density makes it possible to decrease the active material weight to make this version of the induction motor even cheaper, while maintaining the same torque output.

We believe that our AFIM bears great potential to be used in all kinds of electric vehicles. In fact, we can match conventional permanent magnet motors in their performance, by using our technology. Without using any magnets, without requiring a complex rotor construction or a complex cooling solution. Even the power electronics remain very simple in comparison to an EESM, where additional power electronics are required to supply the rotor with current.

Even the gearbox could be simplified using our motor design. Due to the higher torque capability of our motor, one stage of the gearbox could be eliminated, increasing efficiency and reducing size and weight.

The following pages will reveal more details.

Comparison

In this comparison we will compare our motor with existing state of the art electric motors, which are in production. We will be comparing the torque density, peak efficiency and low load efficiency (very relevant for WLTP range). Low load efficiency is defined as 10kW of power at 5000RPM in this case. All these numbers are just considering the motor, without gearbox or inverter losses, because numbers for the whole systems are hard to find.

AFIM – Axial Flux Induction Motor, IPM – Internal Permanent Magnet, IM – Induction Motor
Active weight is just the weight of stator and rotor, no case, no shaft, no gearbox, etc.

Product	Technology	Peak Torque	Peak Power	Active weight	Torque Density	Peak efficiency	Low load efficiency
Emil M220	AFIM	600 Nm	250 kW	33 kg	18 Nm/kg	97,6%	96,98%
Tesla Model 3 Motor	IPM	432 Nm	193 kW	32 kg	13,5 Nm/kg	97,79%	~96%
Old Model S Motor	IM	636 Nm	391 kW	~65 kg	9,78 Nm/kg	~98%	~97,5%
Old Model S Front Motor	IM	331 Nm	190 kW	~38 kg	8,7 Nm/kg	?	?
AUDI ATA320	IM	355 Nm	165 kW	>60 kg	<6 Nm/kg	~97,5%	~97%
BMW i3 Motor	IPM	250 Nm	130 kW	34 kg	7,3 Nm/kg	97%	~96%
Nissan Leaf old Motor	IPM	280 Nm	80 kW	~40 kg	7 Nm/kg	97%	93%

Lots of numbers, but what is the takeaway? First some clarification. These performance numbers are very hard to find and may have some inaccuracy to them, but it’s the best information available. There are still some obvious trends in the data. Overall efficiency is very close between all the motors, with a variation of less than 1%. Just the Nissan Leaf motor exhibits poor efficiency at low load. The older Tesla Model S induction motor is the surprising efficiency king in this table, but also the heaviest motor. The weight stems from a high usage of copper and steel, which enables the high torque and high efficiency. But this also results in higher production cost and performance loss due to the higher weight.
Unsurprisingly our Emil M220 motor features the highest specific torque at 18 Nm/kg. This is to be expected, because of the Axial Flux architecture. The main drawback with our motor is the lowered max RPM. Because of the higher rotor diameter, we are limited to 12.000RPM. The other motors in the table can spin anywhere from 15 to 18.000 RPM.

But the lower RPM together with increased torque result in almost identical motor performance, while being able to reduce the reduction ratio in the gearbox. This makes it possible to eliminate one stage of the gearbox (one shaft with two gears and two bearings), improving system efficiency and lowering overall cost.

Overall, we are the lightest motor together with the Tesla Model 3 motor. That’s great news, because we can also match the Model 3 motor in power and torque. Something that used to be impossible with induction motor technology. Looking at the Audi and Tesla induction motors from the table, they aren’t anywhere near the torque or power density of the Model 3 motor.
And although we are very slightly worse in efficiency compared to the Model 3 motor, we can compensate that fact, by removing one stage from the gearbox.
This will result in system efficiencies identical to the Model 3 powertrain.

That’s an impressive feat, considering the Model 3 drivetrain is acknowledged to be one of the best in the industry.

When it comes to overall cost, we have the best prerequisites: simple and cheap material usage (copper and steel), no magnet handling in production and simplified gearbox with eliminated parts.

Motor design

Axial Flux motors can be built in different fashions. Here are the three most common geometries.

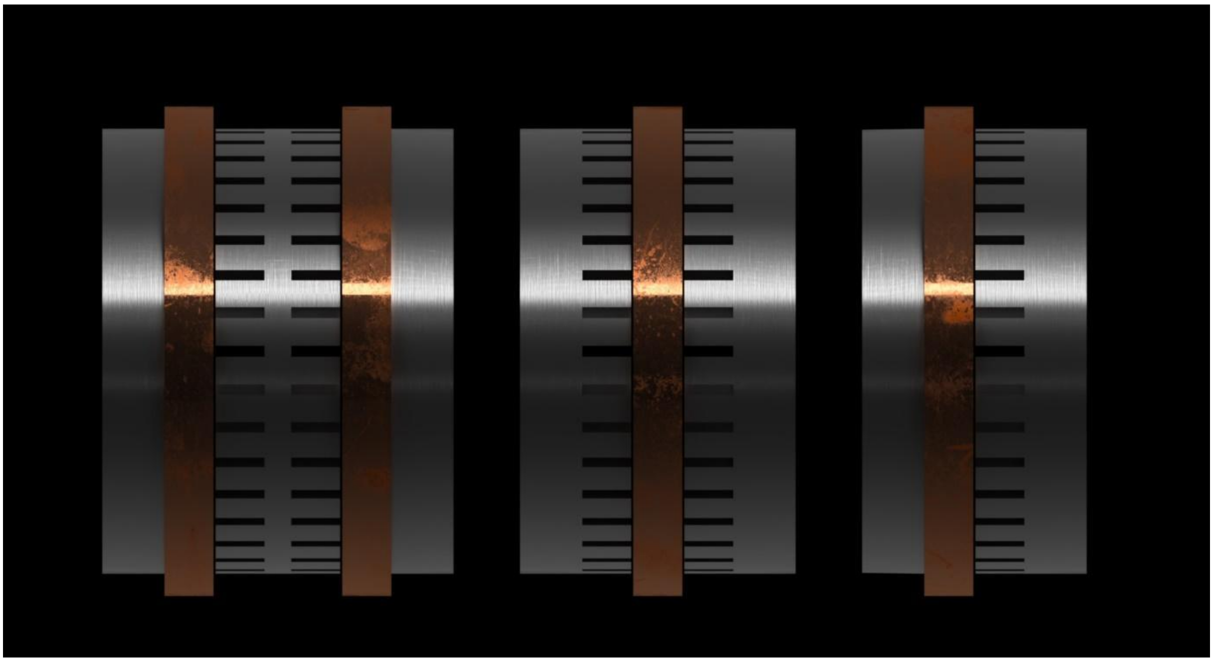

Figure 2 - left to right, yokeless stator double rotor, yokeless rotor double stator, single rotor single stator.

Mechanical differences, manufacturing differences and electrical differences should be considered when choosing between one of these geometries.
The design with a single rotor and stator bears multiple problems. The main problem being a very high axial force. Under load the rotor and stator try to pull each other together. In the single stator/rotor design this force is not cancelled and must be supported through the usage of a thrust bearing. For larger, more powerful motors, that’s a difficult task and prone to long term reliability issues.

In addition, the rotor requires a yoke on the back for the magnetic flux to close its loop. That increases rotational mass and mass moment of inertia.

The first option with the stator in the middle and two rotors is even worse in terms of mass moment of inertia, because two rotors with two yokes are spinning. Furthermore, the manufacturing, assembly and cooling of this option is much more difficult.

That’s why we settled on the middle option. Double stator, single rotor. The axial forces cancel out and the rotational mass is minimal. Due to the aligned flux inside the rotor, grain oriented electrical steel can be used for this part. Cooling is straightforward, because the stators are easily accessible from the back.

The material choice for the stator is nothing special, we are using non-oriented electrical steel with a copper winding. The winding design itself is special but will not be published in this document. In the rotor we use a copper cage to increase conductivity and reduce losses. Inside that copper cage, grain-oriented steel inserts are utilized to conduct the magnetic fields. The manufacturing of these inserts and the cage is also proprietary and will be revealed in our patent application.

As shown, the rotor would be quite weak mechanically. To increase the strength of the rotor structure, various features and techniques may be used. Without any reinforcements the max. RPM of the rotor would be less than half of the desired RPM.
The exact reinforcement features we use in our high RPM design, will be disclosed in our rotor patent, once that is unveiled to the public.

We do not use any active rotor cooling methods, no in shaft oil cooling or similar. With our current design, thermal simulations point to it being unnecessary.

Gearbox design

So far, I have mentioned the benefits of a simplified gearbox multiple times. But let's go into more details on that. In simpler terms, our motor produces lots of torque but cannot spin as fast as conventional motors.

Some benefits are immediately apparent, like the lower rotational speed of the motor bearings. A lower speed means a higher bearing life and better reliability.
Losses inside the bearings also decrease with a lower RPM. But for the major benefit we must look at a state-of-the-art EV gearbox.

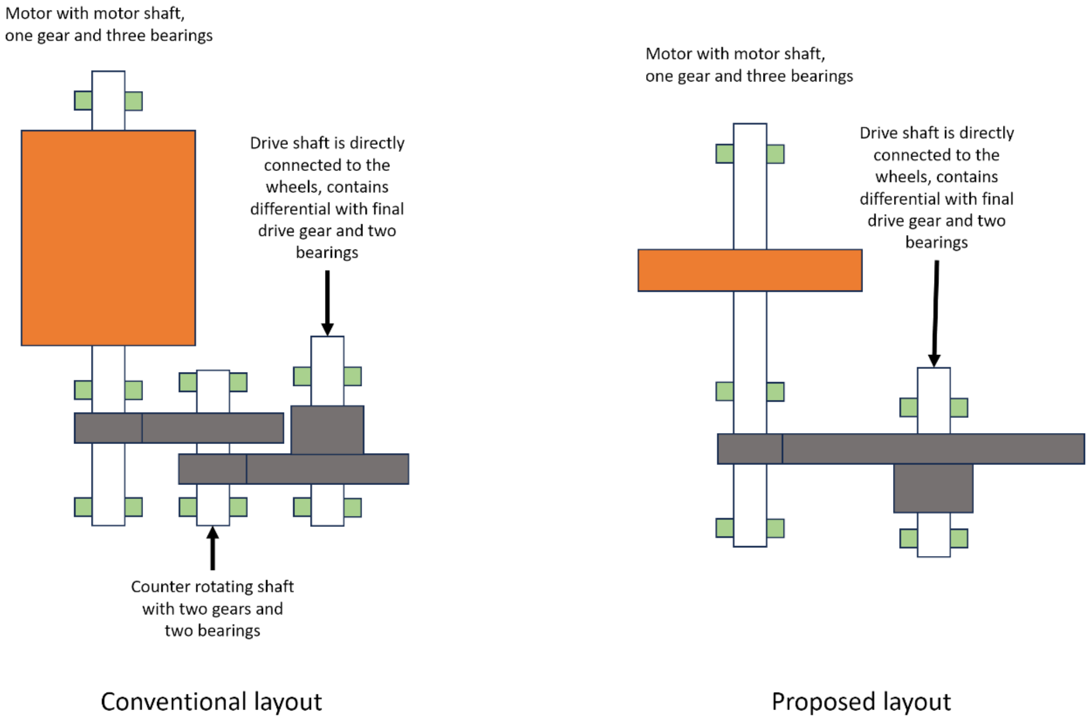

Figure 3 - Conventional gearbox on the left, proposed layout on the right, bearings in green, rotor in orange, gears in grey

The conventional gearbox on the left features the electric motor and two additional shafts. In total there are four gears plus differential and seven bearings.
In terms of gear contacts, there are always two. One between the motor shaft and the counter rotating shaft and another between the counter rotating shaft and the drive shaft.

This design is necessary because of the high gear ratios required. Anything between 7 and 10, depending on the car, the performance requirements and motor characteristics.

With our motor a gear ratio around 5 would be suitable, sometimes even lower. At this point it is possible to remove the counter rotating shaft and rely on just one gear contact.
The final drive gear will get much bigger, but it is still reasonably sized and removing all the parts from the counter rotating shaft will save weight overall.

Now we have achieved what every engineer wants to achieve, we have deleted five parts. Two gears, one shaft and two bearings. Eliminating these bearings and reducing the gear contacts to just one will result in a noticeable impact on system efficiency. An EV gearbox has an overall efficiency between 90% and 98%, depending on load and RPM. With our simplified setup you can achieve an efficiency up to 99% and especially at low load the improvement will be significant.
Less moving parts is always a good thing, it keeps weight down, reduces cost and improves efficiency.