

Design of a gearless wheel hub motor for BEV based on a switched reluctance machine

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Summary

This contribution deals with the topic of developing a gearless wheel hub motor for traction purpose of full or hybrid electric vehicles based on a switched reluctance machine (SRM).

The main focus of this research is given by the construction of a SRM that is able to be competitive to a conventional permanent excited synchronous machine (PSM), to be independent of the material needs for a PSM like rare earth elements, and therefore creating an electric motor that is able to be dedicated as "price-stable" in the future.

Main target of the presented work is the integration of an electric machine into the given space inside a wheel of a conventional vehicle without influencing the wheel hub, the friction brake or other already given parts, to create the big advantage of having full flexibility in terms of new vehicle concepts. Due to this the needed power electronic will be integrated, too. Additional the developed wheel hub drive should be robust, high-efficient and powerful to satisfy high automotive standards nowadays.

Starting with a feasibility analysis of the intended machine using FEA-Calculations this paper allows a look on its design-process and construction and presents the results of the first prototype (evo 0) including a comparison to the previous simulations.

Furthermore, the design of the 2nd prototype (evo 1) as a consistent development from the gained experience with the first prototype will be presented.

In future, NVH behavior as well as drivability due to comfort and agility targets will be the objects of the investigation.

Keywords: wheel hub motor, Switched reluctance machine

1 Introduction

Energy efficiency and active safety in vehicle dynamics control systems are increasingly becoming a central topic for the automotive industry. In addition to the customers who demand low-consumption, cost-saving

and environmentally-friendly vehicles, state regulations and guidelines for reducing CO₂ emissions also force the automotive industry to think about alternative vehicle and drive concepts, as well as to continually increase road safety. In order to reach the Federal Government's goal of bringing 1 million electric vehicles to Germany's roads by 2020, the price of this type of vehicle has to fall sharply. However, the increased use of permanently excited electrical machines by the use of rare earth leads to new ecological problems in their production and to economic dependence on China, as the major supplier of magnetic materials.

Wheel hub motors are already available as PSM, developed for various applications [1,2,3,4], but none is available for the customer market, nor independent from rare earth elements.

The switched reluctance machine can help to solve this problem since its rotor carries neither a winding nor a permanent magnet [5]. However, their NVH behavior is very problematic, which has so far hindered their use in the automotive sector. This problem and the problem of the unsprung masses of a wheel hub motor [9] consistently countered is the declared goal of the wheel hub drive to be investigated on the basis of the switched reluctance machine.

In addition, commercially viable electric road vehicles are usually equipped with a conventional drive train, which means that an electric machine drives the vehicle via a differential gear. They thus offer the driver, compared to the competition with an internal combustion engine, no driving dynamical added value which could relativize their cost disadvantage. However, the single-wheel drive with the developed wheel hub motor offers a clear added value in terms of vehicle dynamics and safety as well as vehicle design through the advantages of a "distributed" drive such as torque vectoring, variable installation space selection, etc. Figure 1 shows one possible topology of a BEV equipped with four SRM wheel hub motors including distributed power electronics.

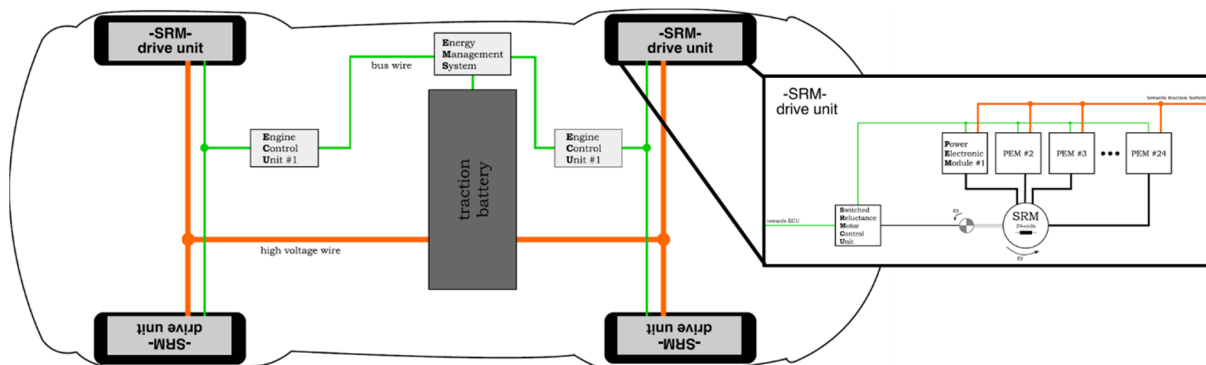


Figure 1: Vehicle topology [6]

2 Machine design 1st prototype (evo 0)

The overall target when designing the first wheel hub machine was a fully functional prototype that can be used to gain as much experience as possible in terms of:

1. verifying the magnetic FEA-Calculations,
2. Vibrations and Harshness of a low phase SRM wheel hub motor,
3. Gaining knowledge about mechanical design and build-up of such a machine,
4. Feasibility study of a full integration into the given circumstances of an already existing vehicle platform.

Therefore, a first prototype was built up, to test various scenarios in a safe environment on a test-bench and figuring out limitations, before designing the next evolution (evo 1) machine that will be implemented in a project-demonstrator vehicle.

After starting the development of evo 0 in June 2016 the first proof of concept motor spun at the end of that year the first time. More than 80% of the motor parts including power-electronics, pcb's and windings had been produced inside the universities facilities. The result of that work is shown in fig.2.



Figure 2: first proof-of-concept motor

To figure out the boundaries of a SRM wheel hub motor in terms of NVH-behaviour, ev0 was built up as a two-phase machine with 24 stator and 36 rotor poles. Therefore 12 stator teeth are able to produce a tangential force at the same time, leading into a high torque density of the machine. Figure 3 shows three characteristic points during the machine rotation movement anti-clockwise:

1. 0 degree: unaligned position (unstable status, no torque is produced)
2. 2.5 degree: rotor & stator teeth are half aligned, approx. max torque production
3. 5 degree: aligned position (stable status, no torque is produced)

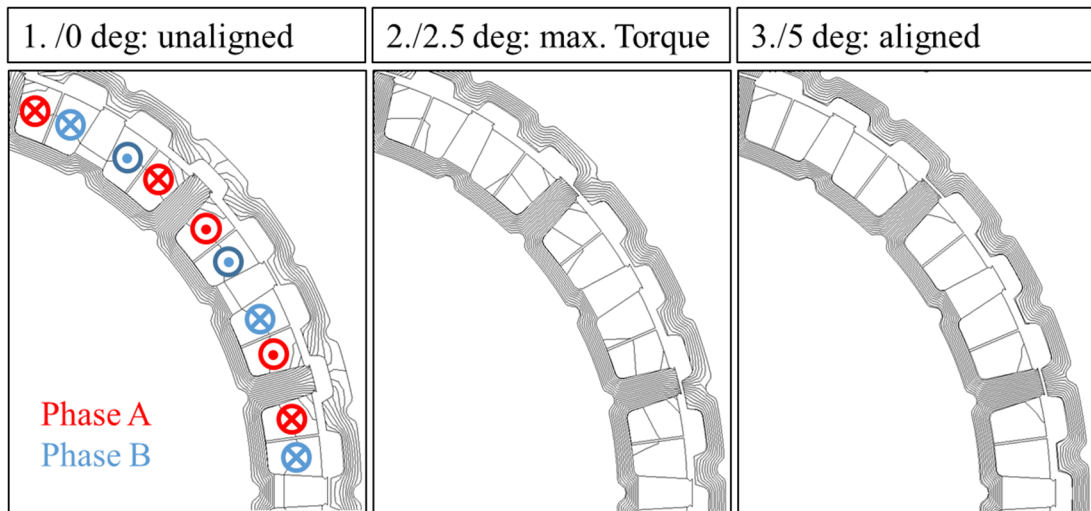


Figure 3: Different rotor-positions 2-phase

At position No.3 latest, Phase-B must be excited to produce a constant movement, using the rotational inertia of the rotor. By using the winding concept shown in Fig.3 at position No.1, short flux paths are produced to maximize the SRM's power and efficiency. Due to the fact, that during the unaligned & the aligned position neither phase A nor phase B can produce traction torque a two-phase SRM has the main disadvantage of a 100 % torque ripple. In additional, there is a minimal angle position (0 or 5 deg) where the SRM is not able to start up on its own because no torque is available. This effect can be compensated by having two or even four machines (fig 1.) mounted on a vehicle, where it is very unlikely that all of them are coming to a standstill at the same rotor angle. Nevertheless, a 100 % torque ripple and the NVH-consequences must be analysed during the dyno-runs.

Furthermore, the first proof of concept was built up as an air cooled machine with lower current-densities to perform a feasibility study, if a pure active air cooled wheel hub motor is applicable inside a vehicle using forced air from the under tray of the car to maintain a stable temperature level.

3 Test results & lessons-learned from evo 0

To be able to perform all different static and dynamic tests with the first machine, a test-bench with sufficient measurement-equipment including a speed-controlled load-machine was built up. A high-precise torque & speed sensor between the load machine and the device under test (DUT) as well as an electric power analyser in additional with a rapid-prototyping ECU to simulate the vehicle, helps to perform a deep machine analyse.

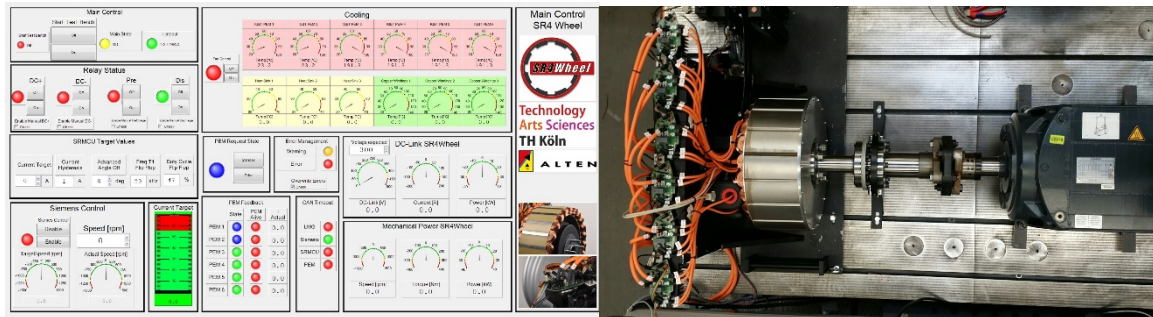


Figure 4: GUI for test-bench control & device under test

3.1 Standstill measurements

To verify the FEA-simulated torque and inductance as function of the machine angle, the machine rotor had been fixed in defined positions and different levels of current had been applied to the windings. The result of the measured (blue) vs. the simulated (red) torque as well as the machine inductance can be seen in fig.5.

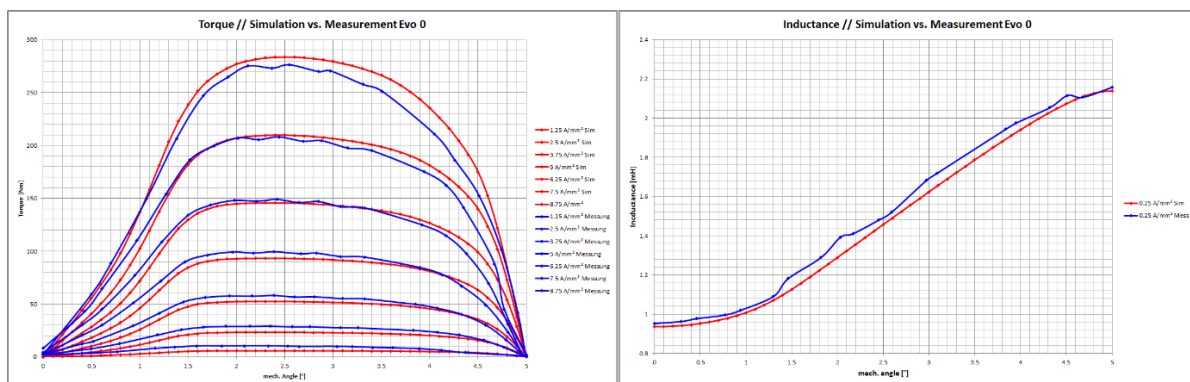


Figure 5: Simulation vs. Measurement // evo 0

Clearly noticeable is the, over wide ranges, small gap between simulation and measurement. Due to this, the FEA-simulation results can be stated as trust-worthy, and a lot of different mechanical approaches can be analysed virtual before building up the next prototype. In detail the difference between simulation and measurement can be identified in table 1 & 2.

Table 1: Comparison between measurement & simulation // torque

Current Density [A/mm ²]	Simulation [Nm]	Measurement [Nm]	Difference [%]
3,75	36,8	39,3	6,9
5	65,5	67,1	2,4
6,25	102,2	99,8	-2,4
7,5	148,7	140,1	-5,8

Table 2: Comparison between measurement & simulation // inductance

Current Density [A/mm ²]	Simulation [mH]	Measurement [mH]	Difference [%]
0,25	1,47	1,50	2,1

For comparing Simulation and results, in both cases, the mean-value of torque & inductance was calculated.

Furthermore, the inductance as well as the standstill torque was measured when overloading the machine in terms of current density. Clearly noticeable is a good saturation of the material when applying higher currents, as well as a peak torque of >700 Nm was reached.

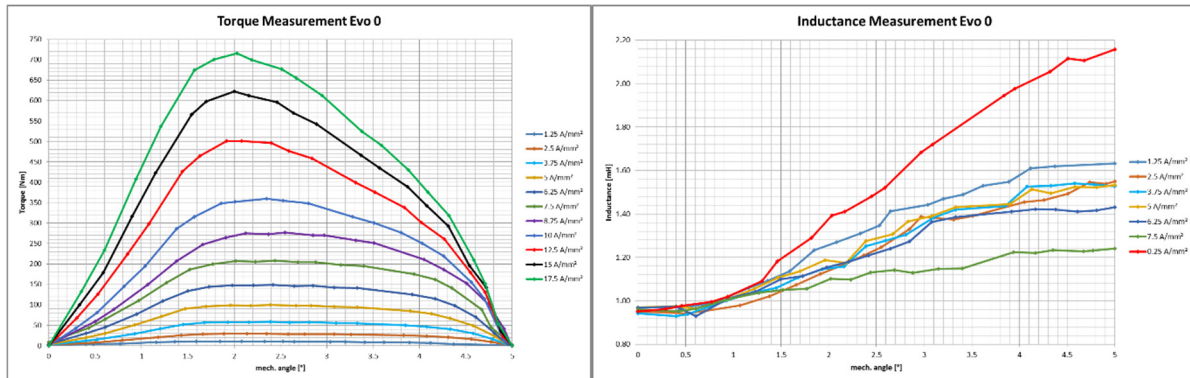


Figure 6: Full standstill motor mapping

3.2 Dynamic measurements

For analysing the SRM, a dynamic motor mapping table with coil-current over speed with in total 300 measurements points was implemented. Within each Measurement point, the power-electronics and motor efficiency as well as torque, power, speed and several other important values had been measured.

Each load point had been speed controlled by the load machine (fig.4) and several different current levels had been applied to the machine.

It quickly turned out, that the vibrations, especially during low speed operation of the machine at higher currents, raised to unacceptable levels. A safe operation of the machine could not be guaranteed further. Investigations results into high axial forces inside the air-gap when heading the aligned position between rotor and stator and therefore elastic movement of the whole rotor which even leads into contact between rotor and stator during movement.

Thus, it was not possible to perform a full mapping of evo 0, but it was clearly identified that a multi-phase SRM in combination with a maximal stiff rotor is necessary to guarantee safe operation inside a testing vehicle.

Besides that, all developed control algorithms could be tested and optimized successful.

3.3 Thermal measurements

To figure out, if a forced air cooling could be sufficient to maintain a stable temperature level, the DUT was equipped with several temperature sensors placed at sensitive positions in- and outside of the machine. In addition, an IR-camera was installed to get a clear overview of temperature distribution. Different critical scenarios (like low-speed uphill drive) had been tested, and the results had been compared to a multi-body-temperature simulation which was built up previous using MATLAB-Simulink. The simulation matched the results well (max. difference for all different simulated bodies < 4 °C), but no stable temperature level inside the copper windings could be reached. Fig.7 shows a constant (nominal) load till 550 seconds, and a cool down phase afterwards (thick lines are measurement data, thin lines simulated). Clearly noticeable is a non-saturation of the copper windings (blue) and therefore the statement that a forced air cooling inside the car will not be able to maintain the temperature at the defined nominal load point of the SRM wheel hub motor.

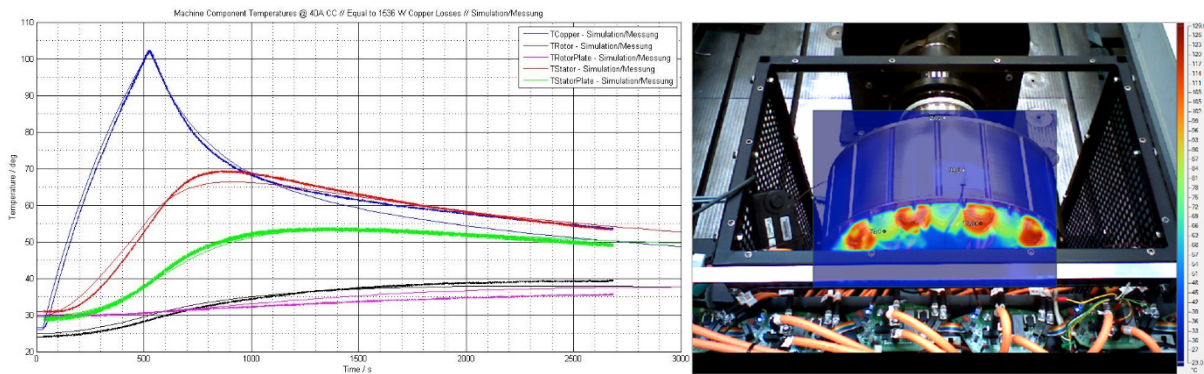


Figure 7: Temperature measurements vs. simulation

3.4 Consequences from evo 0 testing for next evolution

After the full standstill and the dynamic analyse of the first proof of concept machine the following important points could be identified for the further development of a SRM wheel hub motor.

1. A multi (>2) phase machine in combination with a maximum stiff rotor is needed for high torque at low speed,
2. A liquid cooling system is needed to maintain a stable temperature level for high current densities,
3. The mechanical integration into the given circumstances (original brake, wheel hub and bearing could be kept) was successful,
4. The power electronics incl. software development was successful, the integration into the machine not yet,
5. The machine design is not ready to be implemented into harsh environments (water, dirt, vibrations) yet,
6. The FEA-simulation as well as the temperature-simulation are trust-worthy and can be used in the future for machine development.

4 Machine design 2nd prototype (evo 1)

Gaining wide knowledge from evo 0 design, built up and testing, the next machine had been designed.

4.1 Mechanical design and integration

The overall target when designing the next wheel hub machine, is a full integration into the given circumstances of an already existing vehicle platform. Therefore, the friction brake, the wheel hub and the suspension were kept untouched, while using the given space between the original rim and the friction brake to integrate a gearless outer rotor switched reluctance machine. By adding a stator-holder plate (yellow) between wheel-hub and wheel bearing and in addition adding a rotor-holder (blue) between wheel-bearing and the rim the foundation for the active stator (green) and rotor (magenta) is already given. Furthermore, the active rotor-material is no longer used as mechanical load path, but inserted into radial stiffness optimized carbon fibre rotor holder (blue). This holder provides the opportunity to create a complete capsuled machine, by integrating a machine-cover (orange) at the back in combination with a sealing (grey). Therefore, point No.5 from chapter 3.4 is fulfilled. In Addition, the original rim is independent from the wheel hub motor which gives on the one hand the customer the opportunity to change the rim-tire combination without opening the machine and on the other hand decouples all vibrations and load-movements of the rim from the machine. Thus to this, the air-gap of the machine can be decreased to 1mm, to increase the power-density and efficiency of the machine.

The power electronics are located direct next to the machine coils to maximize integration possibilities. In addition, a liquid cooling system is placed between the critical copper windings, and the power-electronics, to maintain a stable temperature level. Neither the original wheel hub nor the brake and the wheel bearing has been modified and the final target of a highly integrated machine is reached. This provides a great flexibility e.g. when converting ICE cars into (P)HEV or BEV.

Wheel hub motor solutions developed in the past, where either integrated into the given space, without modifying original parts [7], or did modify the wheel hub and the brake system to integrate the power electronics [8], but so far none was able to combine both, a full integration including power electronics. Besides that, all available solutions are based on PSM.

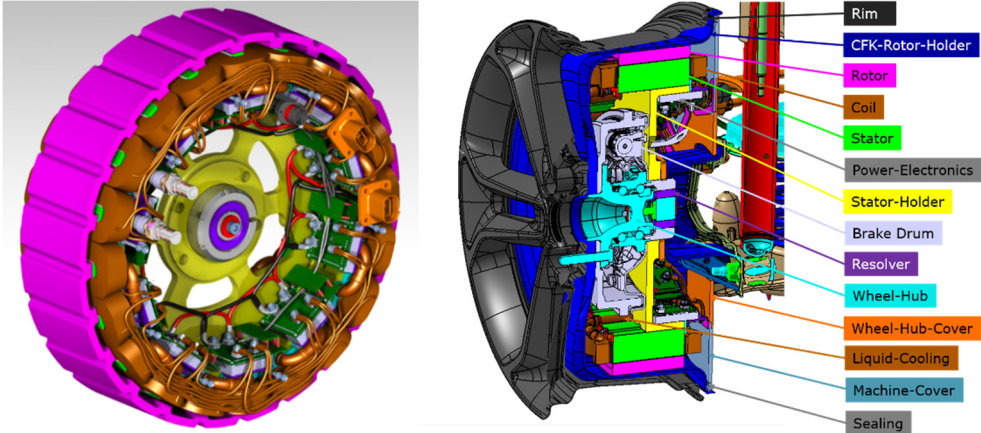


Figure 8: Mechanical concept of evo 1

4.2 Electrical design

Due to the knowledge gained from operating a two-phase SRM, several different mutli-phase machines had been investigated. Three, four and five-phases machines each with various combinations of stator-and rotor-teeth had been simulated and compared with each other. For an objective comparison, all boundaries like volume, current density inside the windings etc. had been kept and torque quantity as well as torque quality (torque ripple) had been analysed. For each possible combination a complete torque over speed mapping was created.

The final result leads into a five-phase machine with 20 stator and 24 rotor teeth, which was identified as the best compromise between all investigated solutions. By innovative orientation of the coil winding direction ultra-short flux-paths could be created. As shown in fig.9, different phases are producing tangential forces together. Due to the mechanical fact, that there is an overlapping of multiple stator-rotor teeth combinations in all mechanical positions the five-phase 20/24 machine is able to produce torque in all positions, which leads into a small torque ripple and starting ability in all positions. Furthermore, it is possible to switch off a phase before the rotor-tooth reaches the aligned position without an overall lack of torque, which reduces the radial forces of the rotor-tooth drastically and increases NVH-quality.

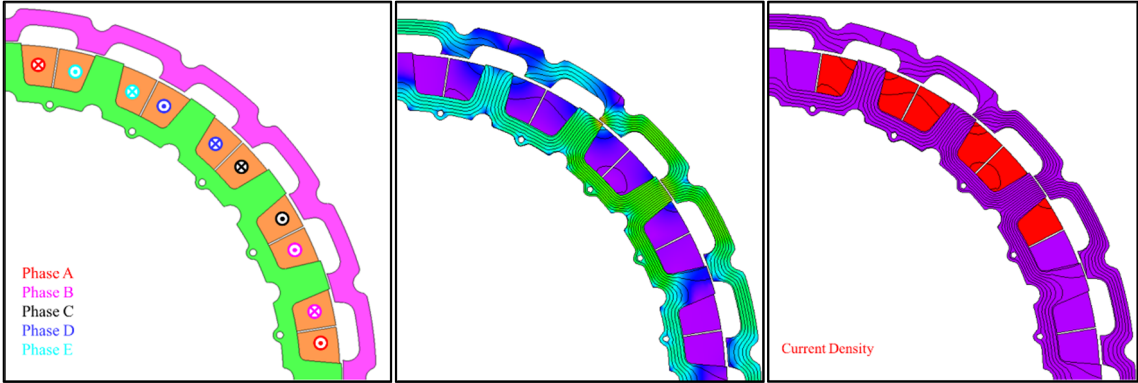


Figure 9: FEA-calculations five-phase machine

After finding the, for this application, optimal number of phases and stator-rotor teeth combination, various degrees of freedom by designing the final cross-section could be identified. In total 9 different mechanical parameters could be varied, to optimize the torque and efficiency behaviour of the machine. The outer as well as the inner diameter of the machine remain unchanged to keep constant constraints. With these limitations,

all parameters had been modified within a reasonable range to identify the final value. Fig 10. shows the available parameters, and the gain of torque after identifying the optimum for an example working point (nominal torque at 600 rpm).

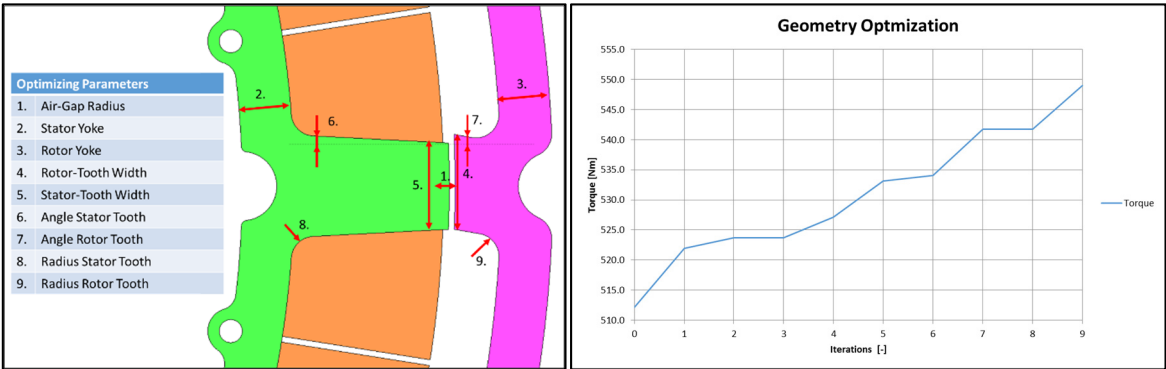


Figure 10: Optimization of evo 1

Due to the geometry optimization, the mean torque in the shown working point could be increased from 512 Nm up to 549 Nm by > 7%. At the same time, the number of turns per Coil was decreased from 68 to 56 which leads into a smaller inductance. This is helpful, especially at higher speeds, to be able to produce high torque, cause the current-slope is higher, and therefore the time, till the target current in the winding is reached is shorted. In additional, the target current can be applied longer, due to the fact that the falling current slope and therefore the time for demagnetization is shorted as well. This leads into a, over a wide speed range, torque-stable machine. Last but not least, the overall weight of stator, rotor and coils could be kept.

By designing an unsymmetrical rotor tooth (see fig.10), the machine can be optimized for a specific rotation-direction, in this case anti-clockwise. By doing so, the switch-on and switch-off points of each phase could be adjusted for optimal smooth torque production, and it is possible to reach mechanical angles where three phases in parallel are producing traction torque (see fig.9 right and fig. 11 left). At minimum there are two different phases producing torque at the same time, which can be identified in fig.11. This figure shows the current-profiles and the resulting torque at 600 rpm.

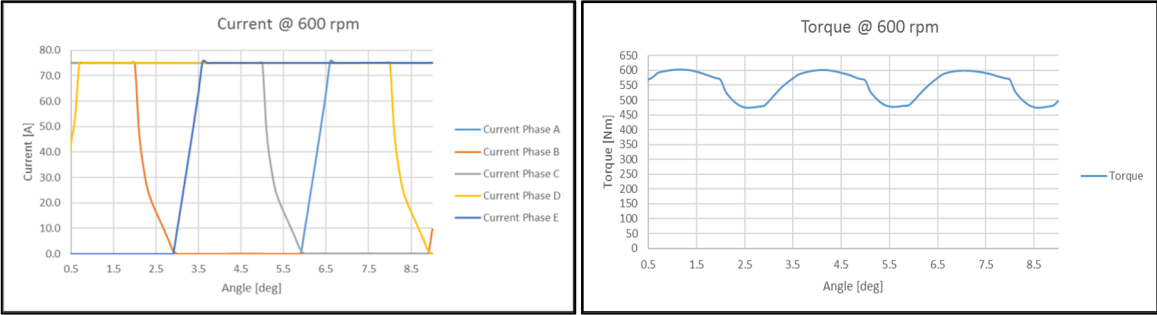


Figure 11: Current profiles & torque at 600 rpm

The fact of a higher torque ripple and less overall-torque when driving clock-wise can be accepted due to the small percentage of use driving the machine backwards. There is no need to produce specific right and left rotors cause the active rotor material can be twisted before being inserted into the CFK rotor holder.

A comparison between the first two-phase motor (blue) and the new five-phase machine (red) shows the drastically impact on the torque ripple in fig.12. Both machines had been compared under the same boundaries (equal speed, current density and volume of machine). Table 3 shows the achievements:

Table 3: Torque comparison 2- vs. 5-Phase

	2-Phase	5-Phase	Difference (%)
Mean Torque [Nm]	596	546	-8,4
Torque Ripple [Nm]	975	135	-86,2

By lowering the mean torque by < 10% the torque ripple could be decreased by >85% which is a great achievement with respect to driveability at low speeds and NVH-behaviour of the machine.

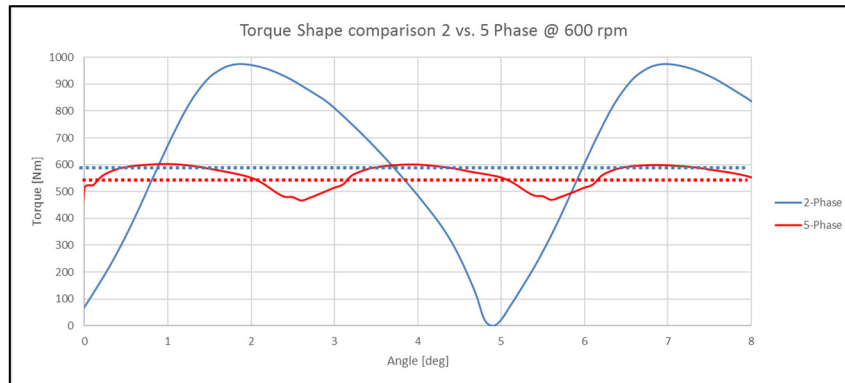


Figure 12: Torque shape comparison

4.3 Cooling design

After the knowledge gained with the first proof of concept machine, a liquid cooling system was designed. With the help of the thermal multi-body simulation built up with MATLAB-Simulink, an already validated model (refer to fig.7 left), the cooling pipe location, diameter, shape and flow could be evaluated. Target when designing the cooling system was a stable coil temperature at approx. 120 °C in nominal operation (15 A/mm²) to keep a safety margin to the max. allowed 155°C for overloading the machine e.g. for fast acceleration of a vehicle (>20 A/mm²). In addition, the cooling system was integrated in such a way, that it is able to cool down the integrated power electronics at the same time and maintain a stable temperature level for the semiconductors. Figure 13 shows the integration of the cooling inside the machine and the simulated temperature behaviour of the machine at nominal load for 5000 seconds.

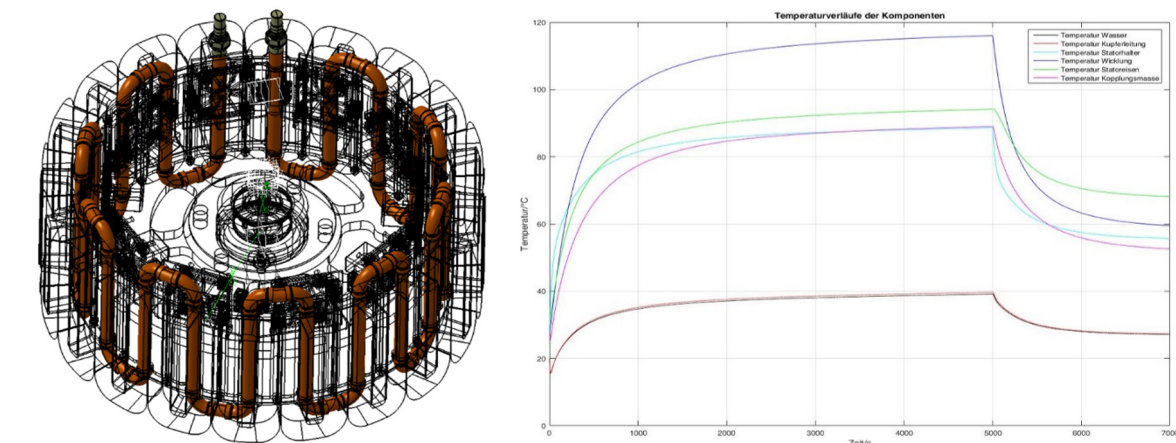


Figure 13: Cooling integration and simulation

A stable coil temperature at <120°C could be reached with the following parameters:

Table 4: Cooling parameters

	Value	Unit
Cooling Flow Rate	6	l/min
Pressure drop @ 6/lmin	209	mbar
Water Inlet Temp.	45	deg
Pipe Diameter	10	mm
Pipe Length	3,05	m

The shown curves have to be validated during the operation and testing of the next prototype, but results from the first machine had shown a trust-worthy model.

4.4 Expected performance and key values

Due to the in chapter 4.2 shown electric development, the designed SRM wheel hub motor is able to produce a smooth and stable torque over its whole speed operating range. This leads into the following torque- and power-curve.

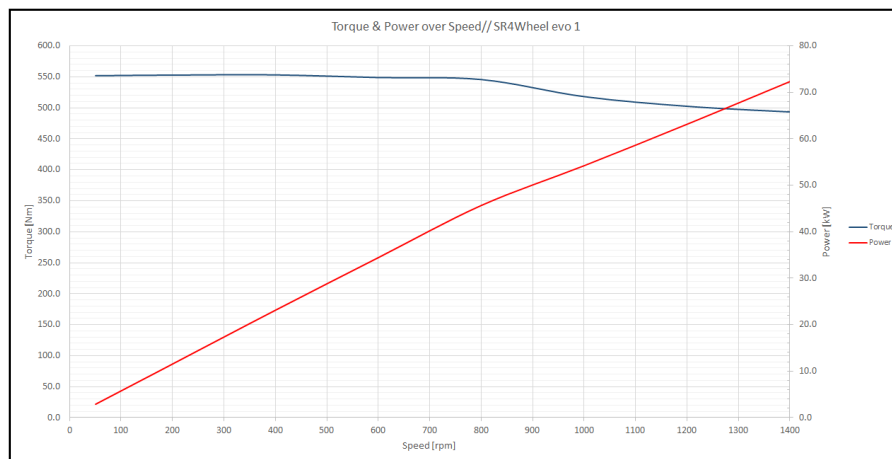


Figure 14: Torque & power over speed

A summary of the key values of the next machine prototype can be found in Table 5:

Table 5: Key values of evo 1

	Value	Unit
Machine Type	SRM	-
No. of Phases	5	-
No. of Stator Teeth	20	-
No. of Rotor Teeth	24	-
Outer Diameter	430	mm
Active Length	100	mm
No. of Turns per Coil	56	-
Air-Gap	1	mm
max. Torque @ 0 rpm	553	Nm
max. Power @ 1400 rpm	72,6	kW
Weight	<50	kg
overall Efficiency	>90	%

Note: All values are preliminary and have to be verified during test-bench operation in Q4/2017.

5 Summary and Outlook

5.1 Summary

With the shown concept in chapter 4, a fully functional and highly integrated SRM wheel hub motor is designed. The developed machine is able to be integrated without any mechanical changes on the rear-axle of the project-demonstrator vehicle, a Ford Focus electric. Due to this, it shows its great potential for the conversion of ICE-cars into (P)HEV or BEV. Furthermore, the machine is user-friendly, cause rim-tire combinations are easily changeable and the machine itself is maintenance-free. Fig. 15 shows the final integration on the rear-axle of the project-demonstrator.

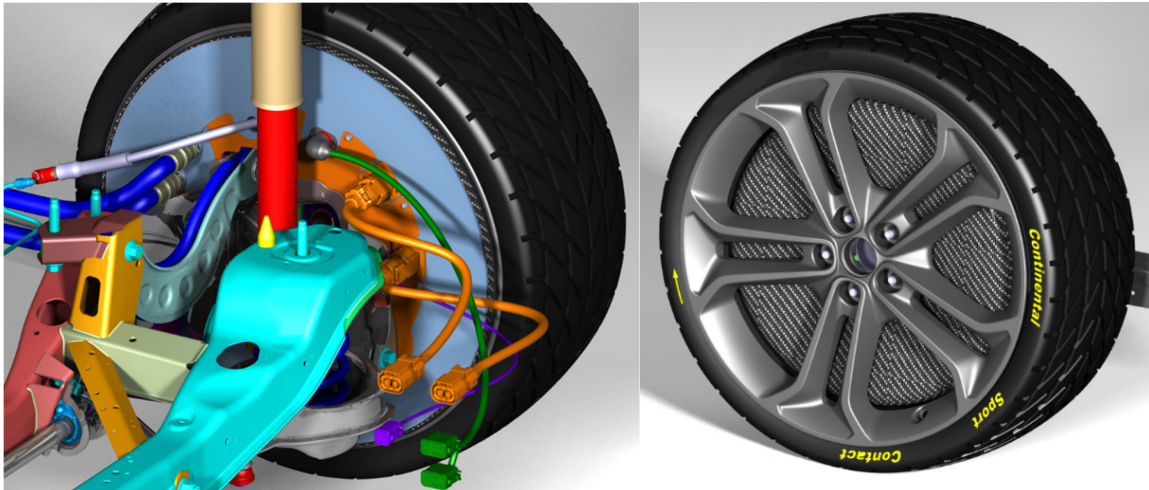


Figure 15: Integration inside vehicle

Finally, with its starting torque of $>550\text{Nm}$, maximum power of $>70\text{kW}$, and maximum speed of $>1400\text{rpm}$ two machines are already sufficient to drive a mid-size passenger car. By installing four machines (fig.1) on a vehicle, good vehicle performance and great opportunities in terms of lateral vehicle dynamics control (e.g. torque vectoring) can be achieved.

5.2 Outlook

Currently two of the in chapter 4 shown machines are in production. After completion, one machine will be installed on the test-bench, shown in fig.4. A detailed testing program, including tests of various control algorithms, will be applied before installing both prototypes on the rear axle of the project-demonstrator in Q4/2017.

First test drives are planned for end of this year, which afterwards leads into a detail testing program including harsh environments, driveability studies with the respect to unsprung-masses [9], and efficiency as well as reliability tests.

All gained knowledge from this test-phase, will lead into the final machine design (called evo 2) which will be started already during the testing-phase of evo 1 beginning of 2018. This final machine design will go into production mid-2018, in the total amount of four machines, which will be installed into all four wheels of the car. Afterwards a test-program of > 8 months will help to push the developed machine to its boundaries, and getting closer to the overall target of a “price-stable”, mass-producible machine for future (P)HEV and BEV.

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Mr. Vosswinkel made his bachelor degree in the field of automotive engineering before extending his knowledge with a master-degree in mechatronics. During his bachelor & master-studies, he gained experience in the sector of electric cars by various activities such as CTO of a formula-student-electric-team, or scientific employee in a research project building up a complete PHEV. After his master-degree Mr. Vosswinkel was working e.g. for an Formula-e team before returning to the university to start his PhD-program by developing the described machine.



Prof. Dr. Ing. Andreas Lohner

After completing his doctorate at the Institute for Power Electronics and Electrical Drives at the RWTH Aachen University of Technology in the field of battery management systems, Prof. Dr.-Ing. Andreas Lohner has been the head of the "Drive Control Development" group in the systems development department of Vossloh Kiepe GmbH in Düsseldorf. Since 1 December 2004, he has been teaching automation engineering and electrical drives at the Cologne University of Applied Sciences. His research area ranges from power electronics and drive train to the traction battery of a BEV.