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Design, Production & Verification of a Switched-Reluctance Wheel Hub Drive Train for Battery Electric Vehicles

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Summary

This contribution deals with the topic of the consistent further development of a wheel hub motor for Battery Electric Vehicles (BEV) based on the principle of an outer rotor Switched Reluctance Machine (SRM).

Based on the experience made by first prototype Evolution 0 (EVO 0), developed in the Laboratory for Automation Engineering, Power Electronics and Electrical Drives of the Cologne University of Applied Sciences (CUAS), the test results of EVO 1 as well as the redesign of EVO 2 is being presented in this paper. The prototype EVO 0, a first proof of concept leads to several optimizations and lessons learned for the predecessor model EVO 1.

The overall target of developing such a gearless outer rotor wheel hub motor is the fully integration of the complete machine including its power electronics into the given space between the original friction brake and the rim. Furthermore, due to the additional integration of the power electronics, great opportunities in terms of new vehicle design as well as retrofitting capabilities of already existing vehicle platforms can be achieved. Thereby further drive train assembly space like the engine compartment is no longer necessary. The SRM does not require magnets for torque production which leads to independence to the changeable commodity prices on the rare earth element markets. This paper presents the developing process, testing and verification of the innovative drive train concept starting with the final CAD of EVO 1. During the testing and verification process a machine characteristic mapping is performed on a drive train test bench and subsequently the results of a Finite Element Analysis (FEA) are plausibility checked by the test bench results. The process continues with energy conversion test scenarios of the project demonstrator vehicle on a roller test bench focused on NVH Behavior and Efficiency. As a conclusion, the gained knowledge by evaluating two EVO 1 prototypes on the rear axle of the test vehicle, the design for the front axle drive train EVO 2 will be presented. As a major task on the front axle the limited space due to the big disc brake can be identified and solved.

Keywords: wheel hub motor, switched reluctance machine, BEV (battery electric vehicle), electric drive, EV (electric vehicle), finite element calculation, powertrain

1 Introduction

As the latest political and industrial discussions and decisions show, the reduction of CO2 emissions are no longer a topic located dedicated to the future but now. The actual generation living on our planet earth is the first one, which can feel and see the implications of global warming and at the same time it is the last generation that has the chance to counteract against the global warming.

The diesel affair impressively shows that even the biggest OEMs have to redefine their product platform and their powertrain family as well as their development philosophy faster than ever happened in the past.

Customer requirements such as economic efficiency, environmental sustainability, energy efficiency, and high driving ranges cannot be met by actual BEVs. New technologies and cost saving solutions have to be introduced to the market to satisfy customer needs in the future.

Research papers prove that the production of a BEV can produce as much CO2 emissions as the production of Internal Combustion Engine (ICE) vehicles including its first 80.000km [1]. Therefore, simple mass production of BEVs will not be the key to counteract against global warming.

One of the highest ecological and economic problems by producing different kinds of BEV is the extraction of rare earth elements for the magnet production, which are essential for the most common electric motor used in BEVs: the Permanently Excited Synchronous Machine (PESM). More than 90% of this commodity is located in Asia which causes high economic dependency.

The SRM can help to overcome this problem since its rotor carries neither a winding nor permanent magnets [2]. Due to a high Noise Vibration Harshness (NVH) problem and a complex control algorithm the SRM is still waiting for the breakthrough as an electric traction drive for passenger cars.

The dedicated goal of this research project is to overcome the disadvantages of the SRM to use it as a traction drive and additionally prove the possibility of an integration of the complete electric machine including power electronics into the given assembly space of a wheel. There by great layout flexibilities for future BEVs are examined. Furthermore enhanced vehicle control algorithms like torque vectoring can be researched.

2 Machine Design 2nd Prototype (Evolution 1) and Construction

The analysis of the first SRM Wheel Hub Drive Train (WHDT) prototype EVO 0, presented in [3] gained a lot of knowledge for the design process of the predecessor model EVO 1. The overall target of the integration of the WHDT into the given assembly space of a standard vehicle wheelhouse is being held successfully. This leads to the improved drive train design shown in Figure 1.

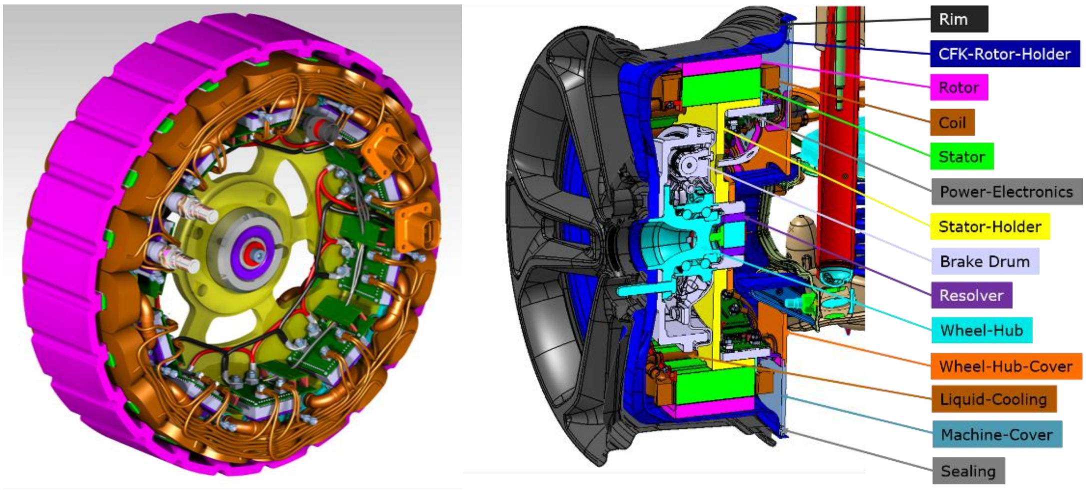

Figure 1: Mechanical concept of Evolution 1

The high requirements to a WHDT such as high power density and mechanical robustness could be met by redesigning the power-electronics (grey), integrating a liquid cooling system (brown) and using a carbon fibre rotor holder (blue) with an integrated sealing system. The key values of EVO 1 can be obtained in Table 1.

Table 1: Key values of Evolution 1

	Value	Unit
Type of Machine	SRM	-
Number of Phases	5	-
Number of Stator Teeth	20	-
Number of Rotor Teeth	24	-
Outer Diameter	430	mm
Active Length	100	mm
Number of Turns per Tooth	56	-
Air Gap	1	mm
Torque @ 0 rpm	520	Nm
Power @ 1400 rpm	60	kW
Weight	<50	kg
overall Efficiency	up to 90	%

3 Production of Evolution 1

Two fully useable prototypes have been built up based on the design shown in chapter 2 by using almost only internal resources of the CUAS production possibilities. The achieved results can be seen in Figure 2 and Figure 3.

Figure 2: Back & front EVO 1 + integrated power electronics

4 Test Bench Results & Finite Element Analysis Verification of Evolution 1

After performing several kinds of static and dynamic measurements with no load conditions, EVO 1 had been tested against a speed controlled ASM to analyse and optimise each single working point (variation in speed and torque). A high speed measurement system (with 1ms timestamp) including torque and speed measurements had been installed. In parallel, all voltage and current signals were logged with a precision power analyser to generate a view of EVO 1 machine characteristics with high resolution.

While EVO 0 was only able to generate 25 % of its maximum designed torque on the test-bench through high radial deformation, the extreme stiff carbon fibre rotor of EVO 1 is able to show the full machine performance while maintaining the air gap of 1mm. This leads into a starting torque of 523 Nm with a previos design goal of 520 Nm, refer to Table 1. In Figure 3, the basic overall efficiency of the whole wheel hub drive train including 10 power electronics modules (PEM) is shown:

overall Efficiency [%]																			
100	35,9	45,9	54,6	59,9	64,7	69,4	73,4	76,0	78,7										
90	38,3	48,9	56,7	62,9	67,3	71,2	74,3	76,8	79,9										
80	42,3	51,9	59,6	64,2	68,8	72,7	75,6	78,3	80,1										
70	45,3	54,8	61,4	67,1	71,3	74,3	77,7	78,9	80,5	82,2									
60	47,9	56,7	64,0	69,1	73,0	76,2	78,4	80,2	80,7	82,6	84,5	85,9							
50	51,1	59,9	66,9	71,4	74,6	78,0	78,4	81,3	80,7	82,4	84,2	85,8	86,6	86,5					
40	53,8	62,5	68,0	73,8	76,2	78,4	80,0	81,5	79,3	82,5	84,2	84,6	85,9	86,3	86,9	87,1	87,1		
30	54,8	62,4	68,8	73,8	77,2	77,2	78,3	80,3	80,5	82,1	84,7	84,4	85,0	85,4	86,1	86,3	86,5	85,8	84,9
20	55,3	61,6	67,1	72,1	73,9	77,2	76,5	80,6	78,9	78,0	81,4	80,9	82,6	83,1	82,6	82,9	83,6	83,5	84,3
10	49,9	56,1	59,8	64,1	72,1	72,9	72,7	75,0	76,6	75,3	76,6	76,8	79,1	78,5	77,3	78,7	78,5	79,7	79,3
Current [A] / Speed [rpm]	100	150	200	250	300	350	400	450	500	550	600	650	700	750	800	850	900	950	1000

Figure 3: overall efficiency Evolution 1 // basic machine mapping

Running only a basic machine mapping, the target of up to 90 % efficiency (power electronics & SRM) could almost be achieved (max. 87.1 %). A more detailed efficiency analyse will be performed in chapter 6.2.

Simultaneously to the efficiency analysis a comparison of simulated and measured torque had been performed and shows satisfying results. By maintaining a difference between simulation and reality of <5% in almost all working points the FEA simulation could be validated with great confidence. Figure 4 shows the machine torque versus speed curve for three different phase currents:

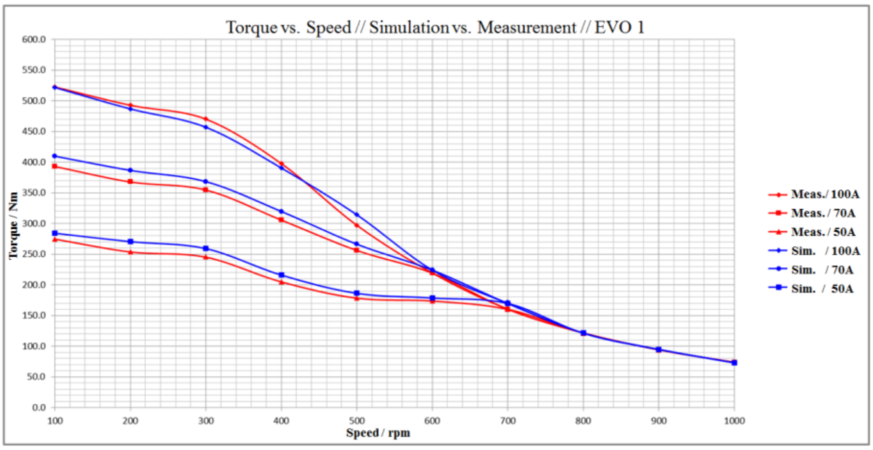

Figure 4: torque measurement vs. simulation comparison // Evolution 1

By validating the simulation with real measurements a powerful tool is now available to perform deep machine analysis based on simulations, before testing new parameters in the project demonstrator vehicle.

5 Installation in the Project Demonstrator and Testing of Evolution 1

After a successful validation on the test bench, the first two prototypes had been integrated into the project demonstrator vehicle. Showing its great capabilities of retrofitting this machine into the given vehicle both machines had been integrated in less than 2 hours.

The result of the WHDT integration into the wheelhouse can be obtained in Figure 5.

Figure 5: Integrated EVO1 in project demonstrator

To have maximum logging and control functions, a CAN display with bidirectional communication had been installed inside the vehicle. With this interface, it is possible to record all machine data while performing tests on the roller test bench and on the street. Thereby, it is possible to switch between different machine controls setting, and it gives a comfortable opportunity to test different control algorithms while driving on the street without the need to reprogram the Switched Reluctance Motor Control Unit (SRMCU).

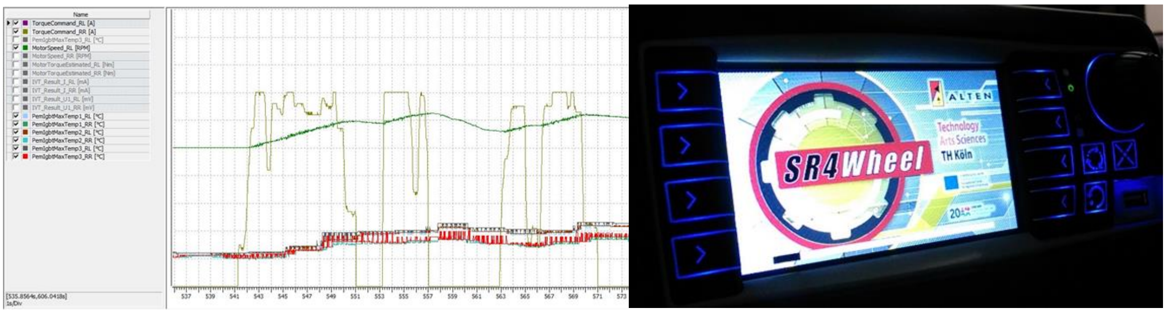

Figure 6: Recorded data during test drive & Human Machine Interface

After the successful high voltage and logical integration of both rear axle machines into the Ford Focus Electric test vehicle and a tested robust Vehicle Control Unit behaviour, the project demonstrator had been undergoing several different tests on the laboratory roller test bench, described in chapter 6.

6 Driving Test Results

Main focus during all tests scenarios on the roller test bench was maximum reliability of the WHDT and repeatable behavior. Furthermore two of the SRM natural disadvantages like the NVH behavior and efficiency should be analysed and optimised in detail.

Figure 7: Project demonstrator on roller test-bench

6.1 Noise Vibration Harshness Optimisation

For a detailed view of EVO1 sound characteristics, audio recordings with wide frequency spectrum microphones had been performed. By transferring the recorded data by a Fast Fourier Transformation (FFT) into a frequency over time diagram, several different working points like low *speed - high torque / high speed - low torque* had been analysed. Two different frequency ranges could be identified:

1. Switching frequency in current hysteresis control (stable over complete machine operation),
2. Basic switching frequency of the five different phases (proportional to machine speed).

Furthermore it turned out that different basic switching frequencies are able to induce the harmonics of the resonance-frequencies of the carbon fibre rotor carrier and therefore higher vibrations inside these points could be obtained.

By reanalysing these working points at the simulation a high torque ripple at exact those points due to the chosen *switch-on*, *switch-off*, so called “firing angle” points could be identified.

The SRMCU controls the firing angle of each phase, based on the measured machine speed and the target hysteresis current control value e.g. at 400 rpm and 50 A current, *Phase Switch On* at 0.2 deg after unaligned and *Phase Switch Off* 1.5 deg before aligned position. These firing angle values are simulated previous testing via FEA, verified on the machine test bench, and stored via 2d-look-up tables at the control unit.

For improving the NVH characteristics a new firing angle machine mapping is developed by trying to reduce the overall machine torque ripple inside the natural resonance-requency points of the rotor carrier. By changing the *switch-on switch-off angles*, an optimal “handshake” in terms of torque transfer between the demagnetisation of the *switch-off* phase and the magnetisation of the *switch-on* phase could be realised. Figure 8 shows an example working point at 400 rpm, and 50 A which proves, that an ideal synergy of the different phase currents leads to minimum torque ripple while maintaining the torque amplitude.

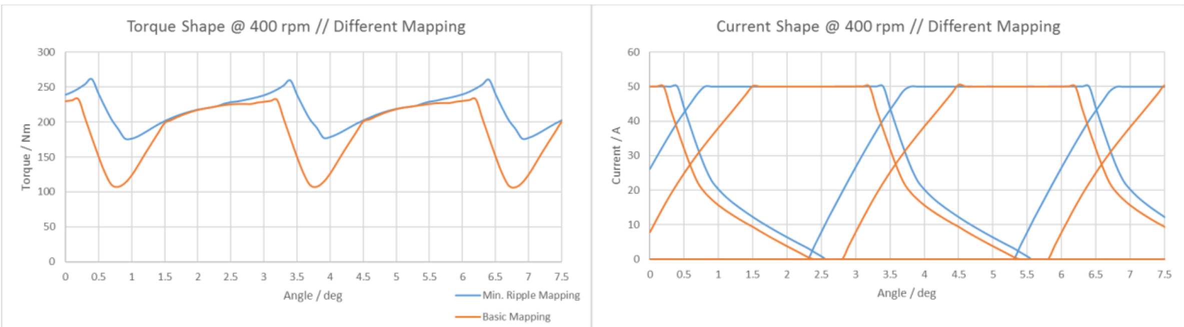

Figure 8: Different firing angles for minimum torque ripple

By evaluating the optimum switching points for On/Off by the help of FEA calculations the torque ripple inside the shown example point had been significant reduced:

Table 2: Parameter minimum torque ripple

	Basic Map	Min. Ripple Map	Unit
Switch On Unaligned	0.5	0	deg
Switch Off Aligned	3.6	3.4	deg
Torque Ripple	54.2	32.6	%
Average Torque	191.4	219.4	Nm

The torque ripple had been reduced by >20 % while the average produced torque gained 14 % by changing the *switch on* point 0.5 deg and the *switch off* point 0.2 deg.

The comparison between both acoustic measurements (basic versus min ripple map) at the example working point proves that by reducing the ripple, the noise behaviour of the machine can be improved.

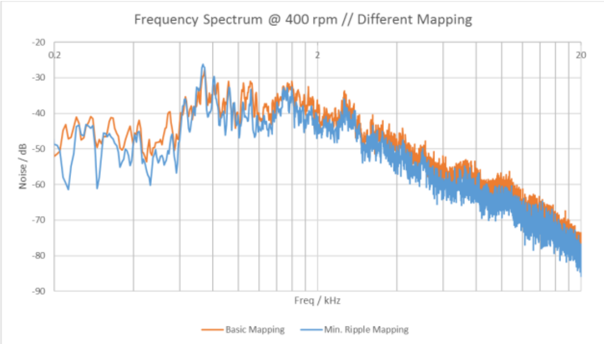

Figure 9: Frequency spectrum for two different machine maps

Calculating the average noise amplitude for both measurements at the same working point shows that the noise amplitude of minimum ripple mapping is reduced by -3.2 dB, for human ears a subjective reduction of 50 % loudness by parallel adding 14% torque. Using the described working process for the noise reduction of the machine, a new “NVH-friendly” machine mapping for all working points had been developed. These maps are stored in the SRMCU and can be controlled by the bidirectional CAN display inside the car.

6.2 Efficiency Optimisation & New European Driving Cycle Test results

After focusing on NVH behavior of the new WHDT, the machine efficiency improvement was identified as a second working package during test drives on the roller test bench. For a plausible comparability between the developed wheel hub drives automotive OEM drive trains, a fast-logging and high resolution current- and voltage probe had been inserted on the output of the vehicle battery. Therewith several NEDC cycles had been performed with the original OEM drive train on the roller test bench to use the logged data as a reference. After installing the two new motors on the rear axle of the car and uninstalling of the original drivetrain these drive cycles had been repeated using the standard machine firing angle map. Due to the fact, that the measurement device and the test environment on the roller test bench had been identical, the results could be directly compared.

First results had been shown, that especially under partial load points (Target current <50A) in the range of <400 rpm, the developed SRM has a poor efficiency. Please refer to the efficiency table in Figure 3 for a detailed look. These load points are very common inside the NEDC, whereby the targeted efficiency improvements were focused on this area.

When requesting a certain specific drive torque to accelerate the vehicle, from machine mapping point of view, there are three degrees of freedom: 1. *Switch On Phase*, 2. *Switch Off Phase* & 3.*Current Amplitude*. There are almost infinity combinations of these three parameters by producing the same requested torque at a given speed.

Using this freedom, the FEA calculation had been used to identify the combination of the parameters for each partial load point. Figure 10 illustrates, that the same amount of torque can be produced by decreasing the time of current inside the coil but increasing the amplitude. To keep the example easy, only the copper losses are compared.

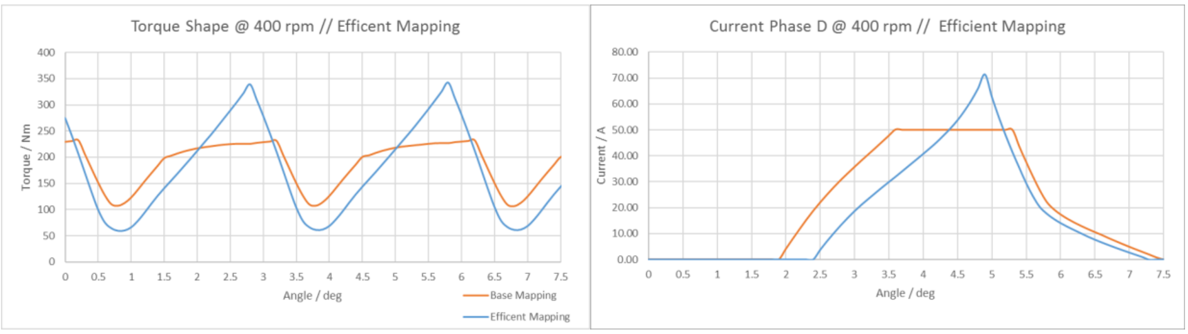

Figure 10: Different current shapes for identical torque

Using the coil resistance and time of current inside the coil, the energy losses can be compared, illustrated in Figure 11:

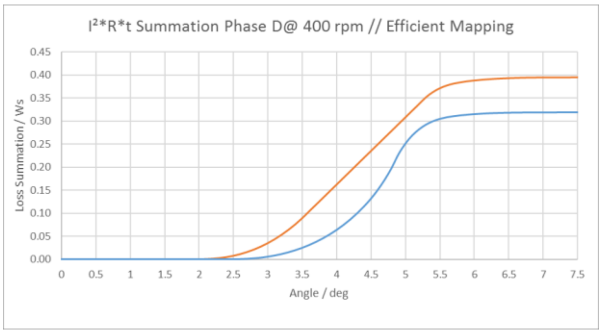

Figure 11: Energy loss comparison

Table 3: Parameter Maximum efficiency map

	Basic Map	Max. Eff Map	Unit
Switch On Angle	0.5	1	deg
Switch Off Angle	3.6	4	deg
Current Amplitude	50	70	A
Average Torque	191.4	190.7	Nm
Energy Loss	0.395	0.319	Ws

Considering the example point, the energy losses had been reduced by almost 20 % by keeping the requested torque stable at 191 Nm.

On the other hand it is obvious that this efficiency gain has to be “payed” by an increased torque ripple from 54.2 % in Standard Basic Mapping to 82.4 % in efficiency mode (remember 32.6 % in NVH mode) which directly leads into a poor NVH behavior if running the efficiency map.

Depending on the operation point, e.g. the driver torque request the best compromise between NVH, efficiency and torque production has to be identified and implemented inside the machine mapping.

After proving that it is possible to maximise the efficiency of the WHDT all working points had been optimized and stored at the SRMCU to be activated as “efficiency driving mode” via the display. Repeating the NEDC drive cycle with the new mapping (blue) and comparing it to the base mapping (yellow) as well as with the original Ford Focus Electric drivetrain (orange) and the theoretical needed power of a 100% efficient drivetrain (green) the new mapping showed its capability to safe energy.

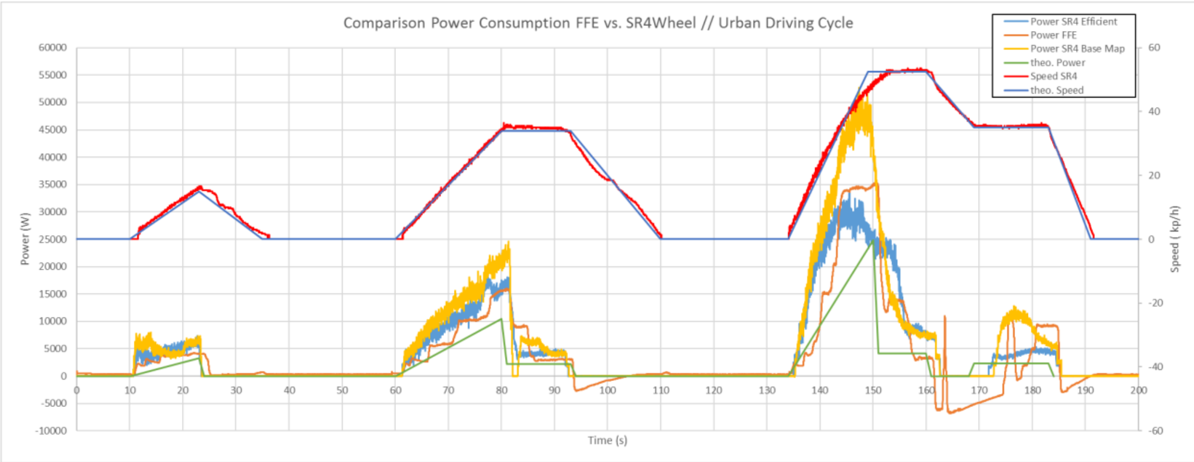

Figure 12: Test result: original Ford vs SR4Wheel rear axle vs ideal power consumption

While consuming more power during acceleration periods the new SRM motor turned out to be more efficient during periods of constant speed. As a result the new motors are almost able to reach the energy consumption efficiency from the original OEM powertrain equipped with a single PESM driving the same NEDC profile.

Table 4: NEDC results

	SR4Wheel	Ford Focus w/o Recuperation	Unit
NEDC Distance	9,91	10,3	km
Energy consumption	2297,6	2313,5	Wh
Rated at 100 km	23,19	22,46	kWh / 100 km
Rated Energy Consumption	103,2	100	%

These results are able to show, that a well suited and parametrised SRM is able to be competitive to a PESM in terms of overall efficiency under identical circumstances.

7 Machine Design 3rd Prototype Evolution 2

Simultaneously to the successful installation and testing of two EVO 1 machines on the rear axle, a final switched reluctance wheel hub motor for the front axle of the project demonstrator had been developed.

Keeping the overall goal of zero modification to the original vehicle including disc brake, upright and wishbones, the integration of a suitable machine turned out to be even more complex compared to EVO 1.

Through the drum brake on the rear axle with a diameter of 270mm and a 19 inch rim (diameter: 430mm) EVO 1 had an radial installation space of 80mm. Adapting this calculation to the front axle, EVO 2's integration is much more complicated. The size of the disc brake with a diameter: 334mm let the radial installation space decreases to 48mm, which is 60% of EVO 1.

Furthermore the moving parts at the front axle suspension like lower wishbone and steering link has to be taken into consideration when designing EVO 2. Due to the limited space, the power electronics of the front axle had to be outsourced into an extra housing. From electro-magnetic point of view, the EVO 2 drive train adapts all lessons learned from EVO 1 and thereby leads into a design with 20 stator teeth, 24 rotor teeth, outer rotor; five phased switched reluctance machine. Figure 13 shows flux and current density when phase D & E are energised as an example operating point.

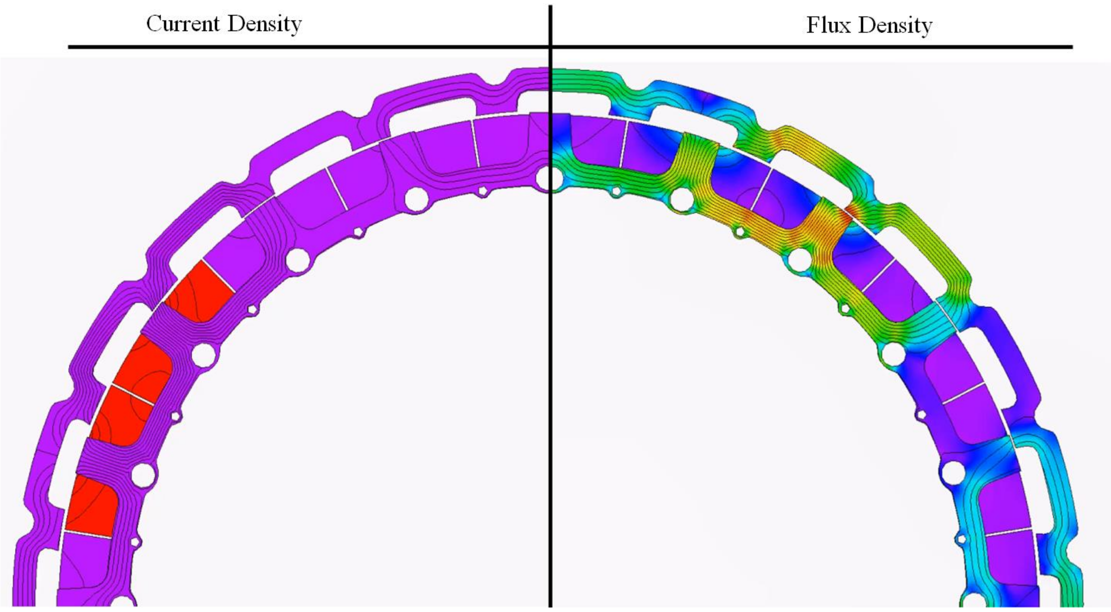

Figure 13: Flux and current density distribution EVO 2

Due to the high current density the liquid cooling is placed even closer to the windings directly in the stator teeth compared to EVO 1, c.f. Figure 13. The final CAD construction is shown in Figure 14:

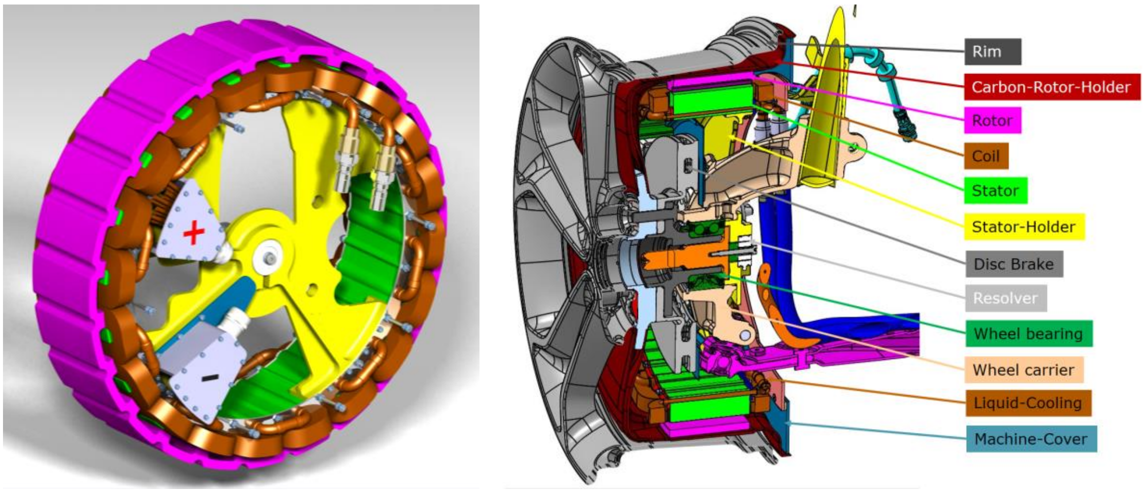

Figure 14: Mechanical concept of EVO 2

Comparing EVO 2 to EVO 1 additional 11kg of machine mass could be saved, which leads to a weight reduction of 22%.

The torque-speed characteristic of EVO 2 was designed to match perfectly the behaviour of EVO 1 on the rear axle: producing less launch torque at lower speeds (due to the limited installation space) EVO 2 can produce more power at higher speeds to compensate the rear axle which performs a power drop at >700rpm.

Overall the EVO 2 drive train is even 8 % more powerful, at 22 % less weight at the same time. Figure 15 shows the comparison of front and rear machine over speed:

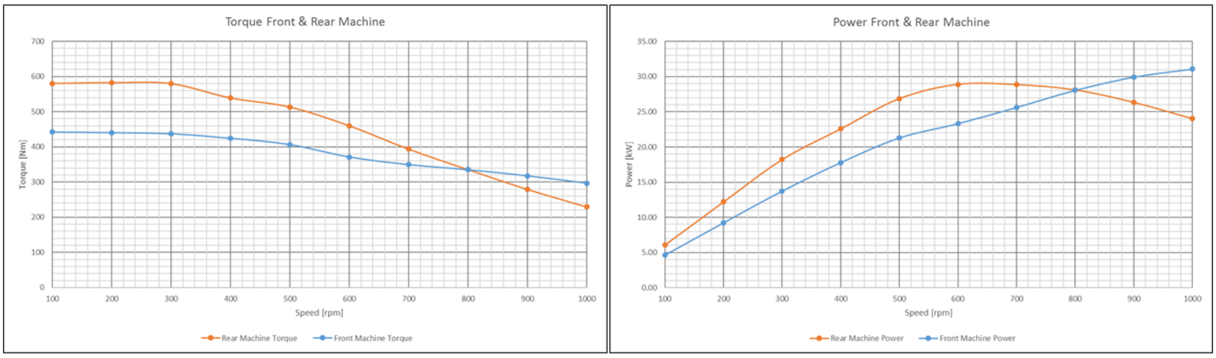

Figure 15: Torque & power front and rear machine

Thanks to the gained knowledge producing wheel hub SRMs, the manufacturing and assembly process of EVO 2 could be completed without problems. Figure 16 shows the complete ready to install drive kit for the front axle. Clearly noticeable in the left Figure is the unaffacted original disc brake inside the machine. The overall goal of integrating the machine into the given installation space on the front axle could be achieved.

Figure 16: Back & front view of EVO 2

8 Summary and Outlook

8.1 Summary

As shown in the previous chapters, the successor model of EVO 0, the model EVO 1 had been successfully installed and tested at the project demonstrator vehicle. The EVO 1 drive train is able to produce >500Nm launch torque, and reaches efficiency levels that are close to the original PESM with 3.2 % difference inside the NEDC. By developing the power electronics as well as the control unit including its software at the laboratory, a high degree of freedom for the machine controls can be reached c.f. chapter 6. By designing and manufacturing EVO 2 as a logical advancement of EVO 1 for the front axle, the project demonstrator can be equipped with four SRM wheel hub drives. The original drivetrain is removed and the complete empty space in the engine compartment of the car demonstrates the great flexibility of the new drivetrain in terms of vehicle platform concepts.

The installed power and torque, using all four machines at a battery voltage level of 300 VDC can be identified in Figure 17.

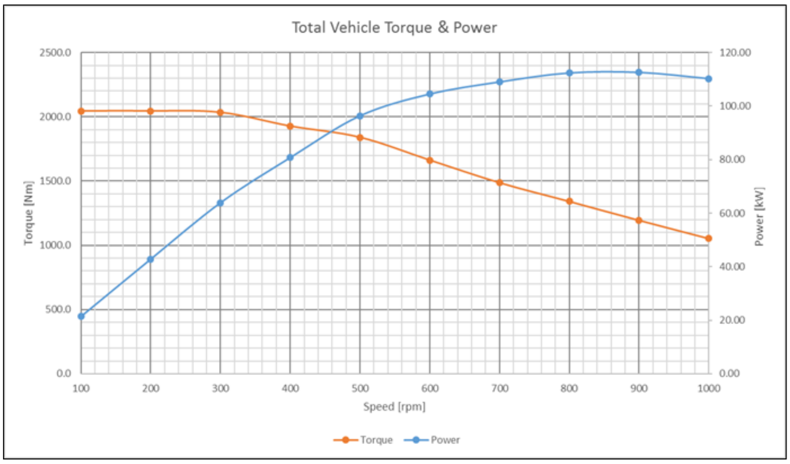

Figure 17: Full vehicle performance with four SRM

A launch torque of >2000Nm, and a constant power plateau of >100kW at >600 rpm shows the good synergy effects between front and rear axle and leads into a vehicle acceleration performance of 8,6 sec. from 0-100 km/h.

Table 5 summarises the most important key values of the three developed wheel hub motors.

Table 5: Final machine comparison

	EVO 0	EVO 1	EVO 2	Unit
Number of Phases	2	5	5	-
Active Length	122	100	95	mm
Outer Diameter	430	430	430	mm
Air Gap	1.5	1	1	mm
Peak Torque @ 100 rpm	169	523	442	Nm
Peak Power @ 300VDC	5,8	28,1	31,8	kW
Peak Efficiency Drive Train-System	80,3	87,1	>90	%
Weight w/o Power Electronics	54,6	50,4	39,2	kg
Torque Density	3,1	10,4	11,3	Nm/kg
Power Density	0,11	0,56	0,81	kW/kg

Clearly noticeable is the gained knowledge about Wheel Hub SRM's during the design process from EVO 0 as a first proof of concept at the beginning of the project, designing a reliable 5 phasis SRM with included power electronics for the rear axle EVO 1 with a power density of already 0,56 kW/kg coming to the final machine EVO 2 for the front axle with a >40% higher power density of 0,81 kW/kg.

Notice: The Potential of running the machines at 600 VDC, e.g. in other vehicles would almost double their power.

8.2 Outlook

Both EVO 2 front axle machines will be installed and initially tested by end of April 2019 inside the project demonstrator. Until the project SR4Wheel will come to its end in July 2019, several tests under real load conditions, such as maximum power test, reliability drives and application of the specific developed dynamic vehicle control algorithms will be performed. Furthermore bachelor thesis and master thesis as well as a dissertation will take a deeper look into more advanced control algorithms for better NVH behaviour and efficiency as well as better torque density even after the finishing point of the official project.

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Authors

Martin Vosswinkel M.Sc

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 a 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.

Volkmar Platte M. Sc.

After his apprenticeship degree in Information Electronic in 2006 he had been collecting experiences in the electric engineering department of Oerlikon Barmag. He received his Master degree in Electrical Engineering from CUAS in 2018.From May 2016 until December 2018 he has been a research associate at the Institute of Automation at the CUAS. His research interests include the field of switched reluctance motor control. Since Jan. 2019 Mr. Platte is working at ELEKTRISOLA Dr. Gerd Schildbach GmbH & Co. KG as Application Engineer. In the Business Unit Litz Wire, beside the daily operations he is especially responsible for the electric mobility research and development part.

Tobias Hirche B.Sc.

In 2015, Mr. Hirche was team member at the undergraduate student challenge IEEE International Future Energy Challenge (IFEC) during his electrical engineering studies. The topic was to develop a High-efficiency Wireless Charging System for Electric Vehicles and other Applications. He graduated a bachelor's degree in 2016. His bachelor thesis deals with the topic of a high frequency switching GAN-half bridge power electronic at 1 Mhz. Since October 2018 he is employed as a scientific assistant at the Institute of Automation at the CUAS taking responsibility at the SR4Wheel project for power electronics and programming.