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# Cost Optimised Integrated Electric Powertrain Containing the First Silent Switched Reluctance Motor for Passenger Vehicles.

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## Summary

Within the ARMEVA-project[1] Punch Powertrain developed a switched reluctance based prototype integrated electric powertrain and tested in a vehicle. The choice for the Switched Reluctance Motor was based on the results of Multiphysics modelling of three different types of reluctance motors and the assessment of the modelling outcome. While a lot of SRM research and industry experts have tested the vehicle, nobody was aware of other SR motors with this low levels of NVH built for passenger vehicles.

*Keywords: electric drive, motor design, noise, powertrain, switched reluctance motor*

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## 1 The ARMEVA project

The target of the ARMEVA(Advanced Reluctance Motors for Electric Vehicle applications) project was the development of a rare-earth free, efficient motor for applications in electric and plug-in electric vehicles. The power target was set at 90 kW. Three different reluctance motor concepts (Synchronous Reluctance Motor, DC-Excited Flux-Switching Motor and Switched Reluctance Motor) were investigated by using multiphysics modelling tools. Siemens was able to support the system design via multi-physical simulations to address comfort issues usually associated with this type of machine, these predictions were later experimentally verified. The motors were assessed by their simulated performance for cost, efficiency over a drive cycle and noise. The selected motor, a Switched Reluctance Motor, and its electronics were further developed into a physical prototype. The integration of the motor into an integrated electric powertrain offered clear advantages with respect to cost, efficiency and packaging as well as interfacing in the vehicle.

To allow the motor demonstration in a vehicle, a compact integrated powertrain hosting the motor, the electronics and the transmission were developed, built and integrated into a BMW i3. The first test rides for functional testing showed a drastic reduction of motor noise when compared to earlier Switched Reluctance Motors.

## 2 Multiphysics modelling

Developing an optimal drive inherently requires using a multi-attribute approach for the design process. The multiple domains of competences necessary for a coherent electric vehicle design were gathered in a closely-collaborating consortium[2]. A set of vehicle requirements were set at first, bearing in mind every physical specific requirement.

## 2.1 Requirements modelling

The full electric vehicle was modelled in the Siemens 1D software LMS.AMESIM and included multi-physics aspects such as vehicle dynamics, aerodynamic resistance, road slope, driver control unit (PI), vehicle control unit, gearbox, electric motor, battery state of charge (SOC). From the maximum speed requirement of ARMEVA, outputs such as vehicle structural properties, maximum torque, power and battery storage energy were computed by ensuring the vehicle achieves the requested requirements for specific drive cycles, both type approval (NEDC and WLTC) and real world drive cycles (MOL and recorded trip of EV Vans).

## 2.2 Motor design modelling

Developing an optimal drive inherently requires using a multi-attribute approach for the design process. A design platform was created to have a closed loop optimisation including the electromagnetic properties of the motor design, the winding configuration, the control strategies and the power electronics. The cost function contains cost, efficiency and NVH. This holistic approach is the only way to get a more optimized design compared to designing in domain loops where one domain is optimised while assuming the other domains are constant.

## 2.3 Concept assessment modelling

The electromagnetic simulations also provide magnetic flux variations at the air gap location. The radial magnetic forces are further calculated using the Maxwell stress tensor. By acting on the stator teeth with spatial and time signature characteristics, they induce vibrations of the motor that themselves travel towards the outer surface of the stator. The vibrating structure creates pressure differences over time and space which are directly translated to acoustic perturbations and noise. Figure 1 illustrates this multi-physics phenomenon. The structural and acoustic responses were performed using 3D Finite Element methods. The laminated stator core was modelled using isotropic material properties with a proper mesh, i.e. relatively fine to capture the fundamental behavior accurately and efficiently. A structural modal analysis from 0 to 5,000 Hz was performed to collect the natural frequencies and mode shapes of the structure. The previously computed forces were conservatively mapped from the electromagnetic mesh towards the structural mesh and a forced response analysis using modal superposition technique was utilized to obtain the output vibrations at the outer surface of the core. Finally an appropriate acoustic mesh transferred the vibratory energy to the targeted 1 meter distant microphone through the air medium. This provides the acoustic pressure signature in the frequency domain at a steady-state speed. The simulation flow was followed for a set of 40 speed cases ranging from 500 to 20,000 Hz by intervals of 500 Hz and for the three machine types. The SRM gave the best acoustic results and this result therefore contributed to the final choice on the SRM topology in comparison with other machines.

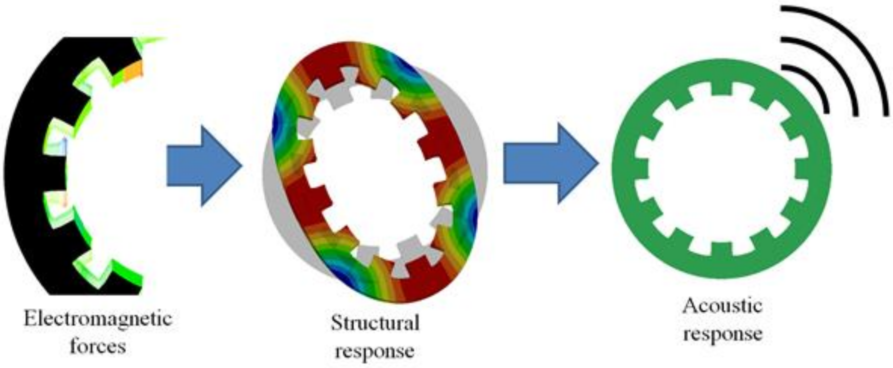


Figure 1: Electromagnetic force to acoustic response

# 3 The Switched Reluctance Electric Drive

The Switched Reluctance Electric Drive comprising the motor and the inverter was further developed into a working prototype. Special attention was given to NVH, efficiency and cost.

## 3.1 The motor

The multiphysics modelling yielded optimal main dimensions of the lamination geometry for rotor and stator. Most modifications with high impact result from the high speed operation of the motor (up to 20000 rpm). The losses in a motor with high speed that need to be investigated are:

- Iron losses
- Copper losses
- Windage losses
- Friction losses (bearings and seals)

The iron losses were improved by investigating the lamination material. Several material grades were considered. Next to the thickness also different bonding techniques between the lamination sheets were investigated. The latter also has a high impact on the NVH, as can be expected.

To reduce the copper losses, intensive study was carried out with  simulation of the proximity losses and skin effects. Novel wires and winding techniques were investigated and successfully implemented in the prototype.

Friction losses are reduced by contact free seals to replace the classic lips seals. Further investigation was conducted to find the best trade-off between cost and reliability for the bearing types. Luckily high precision bearings could be avoided by a novel oil lubrication technique.

The salient structure of an SR motor results in high windage losses when not appropriately addressed. Different methods were investigated to transform the rotor into a cylinder.

To achieve an increased stiffness of the rotor construction simulations were performed to find the the maximum shaft diameter without a negative impact on the magnetic performance. At the same time, the impact of a hollow shaft on the stiffness was assessed. The hollow shaft allows providing oil to the bearing opposite of the transmission. The oil flow also cools rotor, which increases efficiency at no cost.

The stator is inserted in a cooling jacket. The assembly is adapted to use stator potting instead of the classic impregnation. The stator potting provides a more consistent quality and fixes the windings into the winding slots without the use of slot liners. The potting increases the thermal conductivity allowing a continuous power well above the requirement.

## 3.2 The Inverter

Due to the consequences of a high speed motor, a fast responsive system is needed in the inverter. A previous generation SR inverter was reworked with high bandwidth current sensors and a FPGA was used to implement the time critical control strategies. This resulted in a prototyping platform that is programmed with model based designed SW. The platform was used to assess all different relevant state of the art control techniques [3] for each working point as can be seen in Fig. 2 :

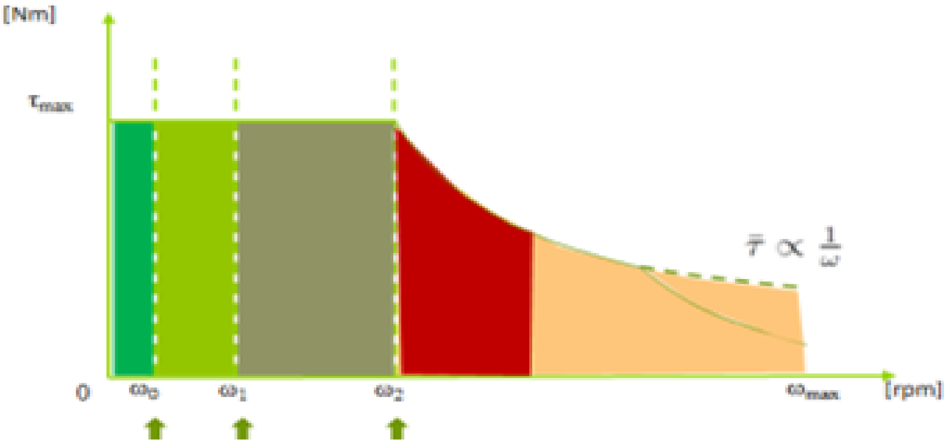


Figure 2: control strategy selection overview

The investigated control strategies are:

- Direct instantaneous torque control (DITC)[3]
- Continuous conduction mode (CCM)
- Direct instantaneous force control (DIFC)
- Direct average torque control (DATC)
- Average torque control (ATC)
- Powertrain anti surge torque actuation (PASTA)

The FPGA is part of a system on chip (SoC) device. That is a processor combined with a FPGA. The current state of model based design and automatic code generation allows engineers with limited expertise of VHDL code implementing controls algorithms for these SoC devices with a limited effort. The advantage of the model based approach is that all models (controls, validation, simulation) can be reused throughout the V-cycle. This leads to a high reliability of the software and the optimisation tools while reducing cost and lead-time.

The platform is also used to validate the downscaling of the effective hardware that is required when developing further towards mass production..

## 4 The Integrated Electric Powertrain

The previous electric powertrain design at Punch Powertrain was not integrated and existed of a separate motor bolted on a transmission and combined with an inverter. An integrated housing was developed for transmission, motor and the inverter as shown in Fig 3. The interfacing between these subsystems represents a substantial part of the total cost while the packaging in the vehicle implies suboptimal use of space and unnecessarily complex assembly.

The same lay-out of motor and transmission was used and the power electronics subsystem were positioned around one of the shafts going to the wheels and next to the motor. An integrated housing was developed for transmission, motor and the inverter with a size of 427x409x304mm. Special attention was paid to the cooling channels. A set of parallel cooling channels first cool the power electronic components and then the electric motor. A smart design of the parallel channels provide a large contact surface between housings and coolant while drastically reducing the back pressure. The low back pressure reduces coolant pump power.

The integration allows a direct connection of the motor phases to the IGBTs. Consequently the cost of the external cabling with connectors is completely eliminated. Other cost savings relate to a reduced parts count. Another cost advantage is at the customer. The interfacing of the powertrain is largely reduced and limited to high voltage cabling from the battery, CAN-bus and 12V connector, coolant in and out, powertrain suspension and drive shafts.

Further efficiency gains are realized by collecting oil thrown upwards by the gears in a reservoir. From the reservoir oil is distributed by gravity all over the integrated powertrain. This eliminates the churning losses and the need of an oil pump. The replacement of some tapered rolling bearings by ball bearings also reduces transmission losses.

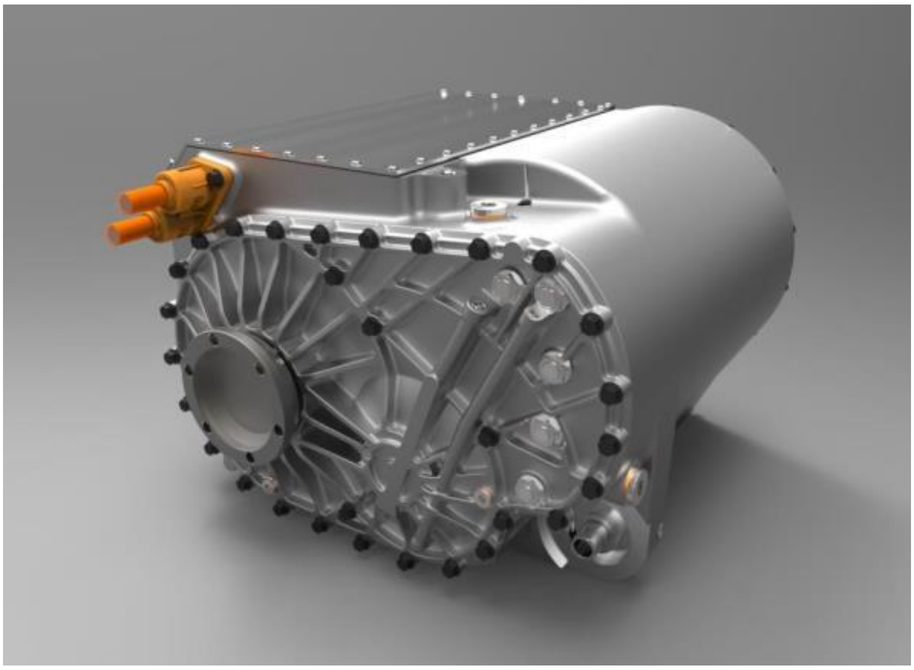


Figure 3: Integrated Electric Powertrain

# 5 Testing and characterization

The developed SRM was mounted on the test bench available at Punch Powertrain. Through the test bench the operation characteristics of the SRM were obtained and analysed. Figure 4 shows the efficiency of the motor using ATC. As expected, the range of high efficiency is spread over a very wide operating range. The efficiency over a drive cycle will be measured and presented on the conference.

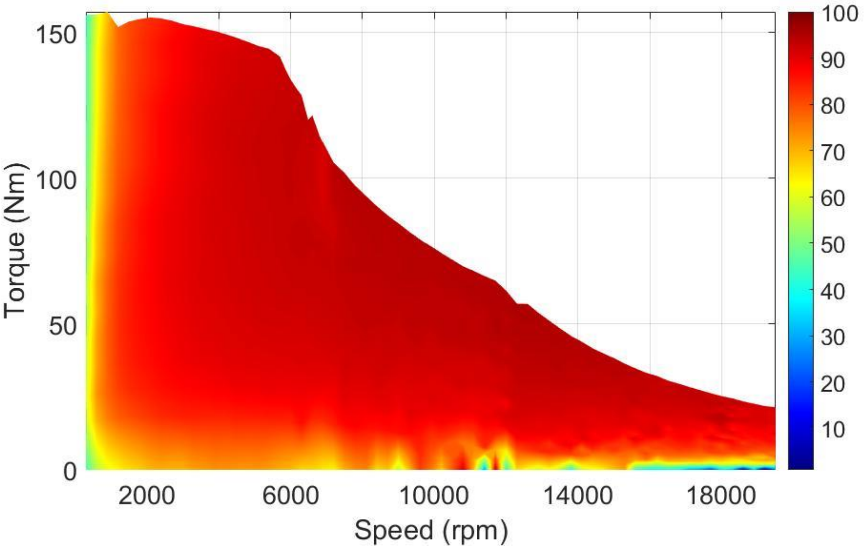
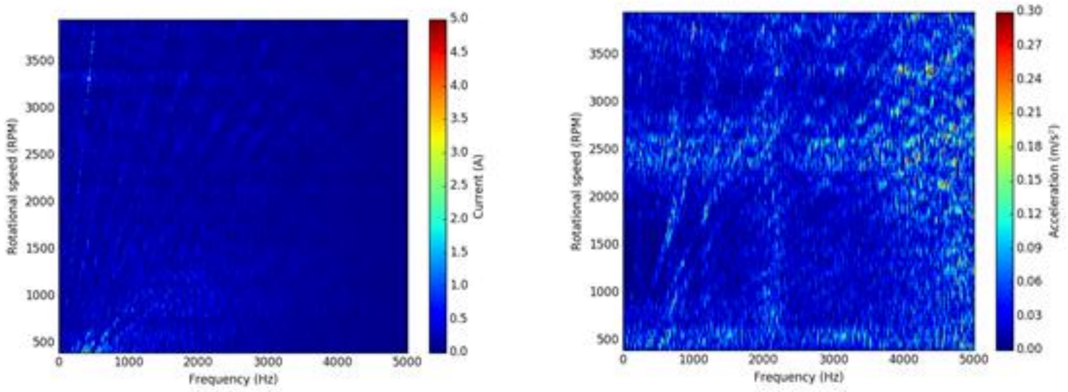


Figure 4: Motor efficiency using ATC

The NVH tests consisted in imposing different operating situations on the machine and measure the resulting vibrations and noise generated. Several different operating conditions were imposed on the machine to get a better understanding on its NVH behavior.

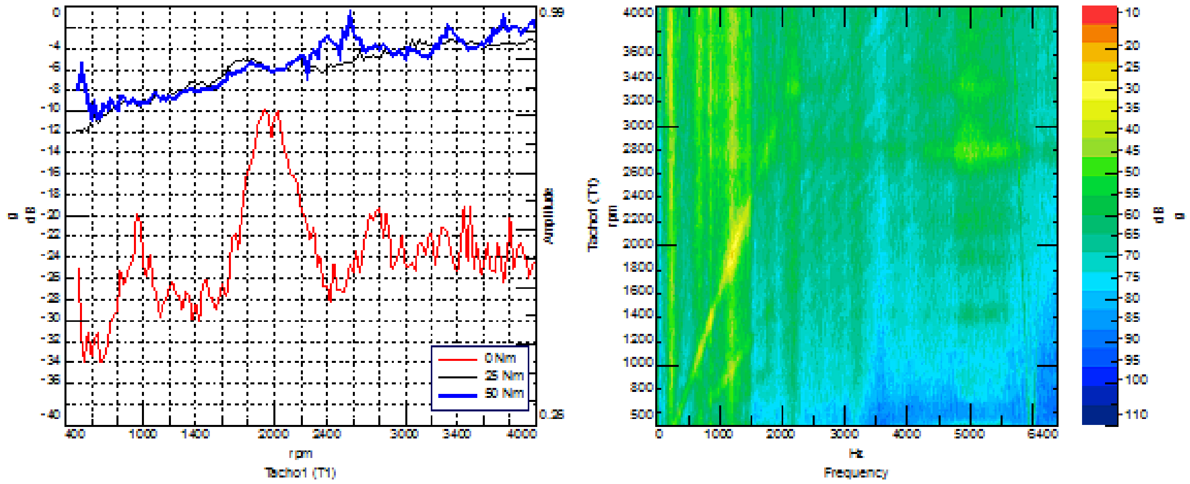
Run-up and coast-down operating conditions showed that the transient difference present between the two were not affecting the NVH of the electric machine. The method adopted here to compare the performance of the machine consisted of subtracting the spectrogram obtained by the run up and by the coast down. In this manner it is possible to check whether there is any significant difference between these two transient conditions of the machine. Figure 5(a) and Figure 5(b) show the result subtraction of the spectrogram of the current and acceleration in a certain position resulted during the run up and the coast down, respectively. One can notice that despite the presence of some non-zero values most of the spectrogram is null. The maximum difference observed for these plots is less than 5 %. Based on these results we can assume that the NVH performance of the machine is very similar during a run up and a coast down.



(a) (b)

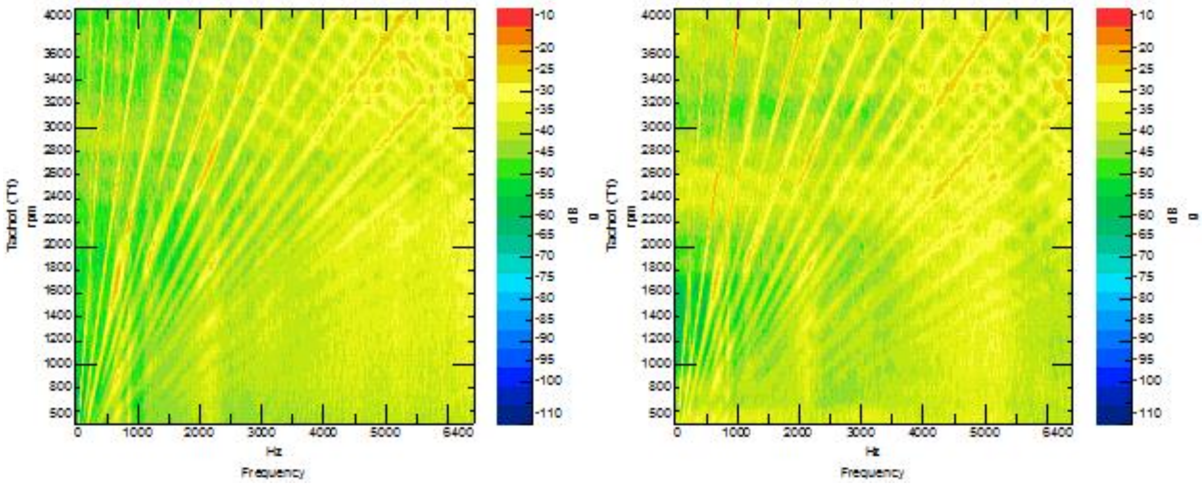
Figure 5: Spectrogram obtained by the subtraction of the (a) current in phase A and (b) acceleration in the normal

The input shaft load was varied as well to identify possible operating points where the load plays a significant role. Since the higher the load, the stronger the force, one expected higher vibrations and acoustics for increased loads and it was validated with this test bench tests. Figure 6 validates this phenomenon by depicting the results of the output vibrations in radial direction for 0, 25 and 50 Nm torque loads, together with the RMS acceleration values for the three operating load conditions. Similar results come with the acoustic pressure data, but are not shown here.



(a) RMS value

(b) 0 Nm



(c) 25 Nm (d) 50 Nm

Figure 6: Vibration in the radial direction for different load cases

A last check was to use different control strategies for the same operational torque and speeds. The first is a Direct Instantaneous Torque Control (DITC), which was used during the previous analyses, and an Average Torque Control (ATC). The resulted acoustic performances for these two types of control strategies are shown in Figure 7. Especially around speed cases where important orders were about to excite a structural mode, i.e. 2,100 rpm and 2,400 rpm, significant performance differences were noticed with much higher noise output using the ATC control drive scheme.

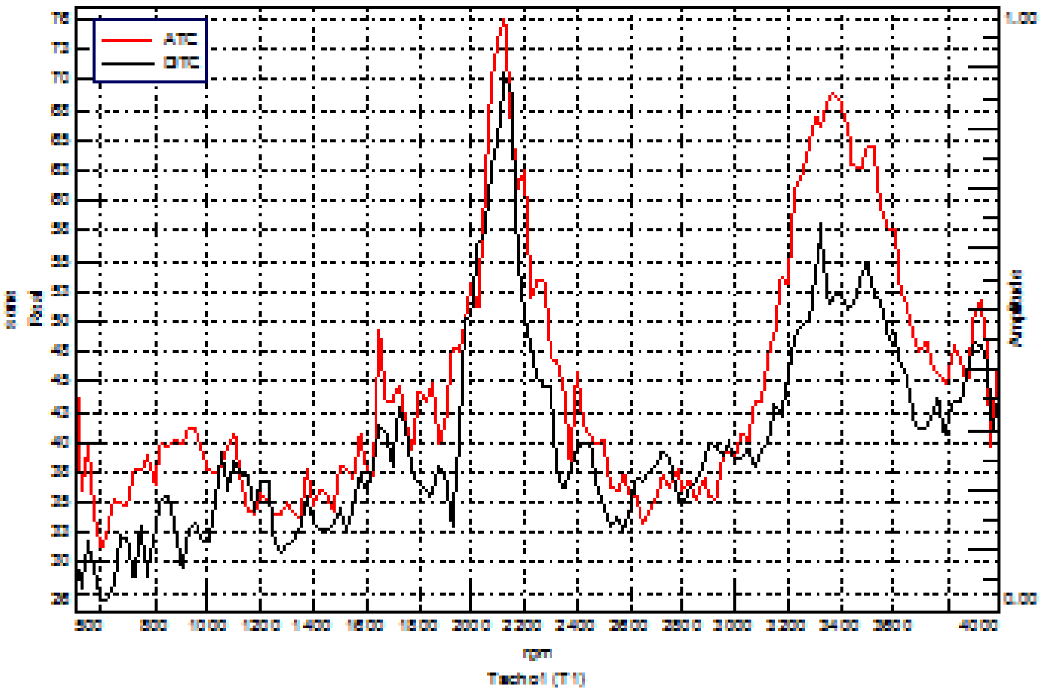
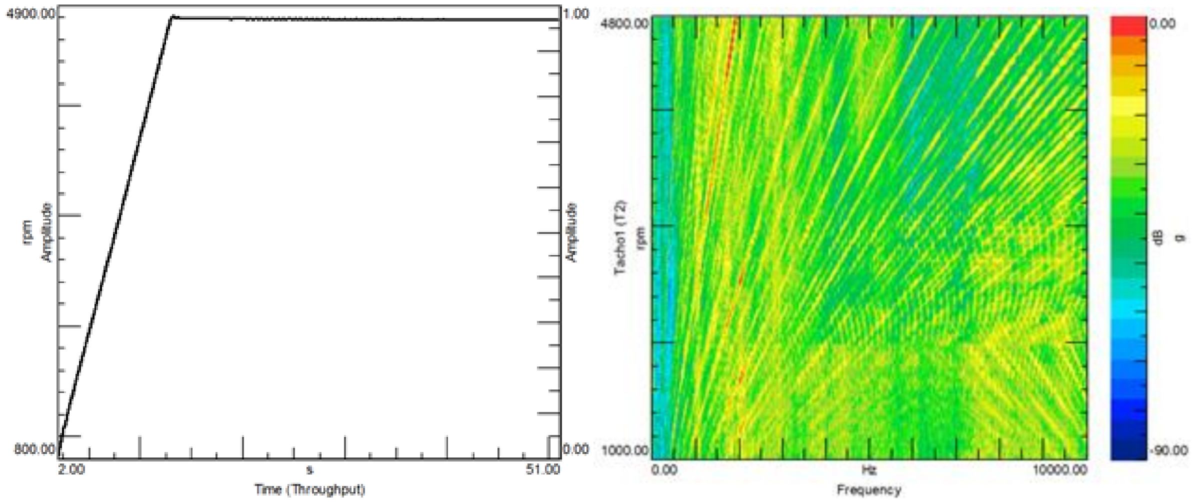


Figure 7: Overall level of the noise measured with ATC and DITC control strategies

# 6 Demonstrator

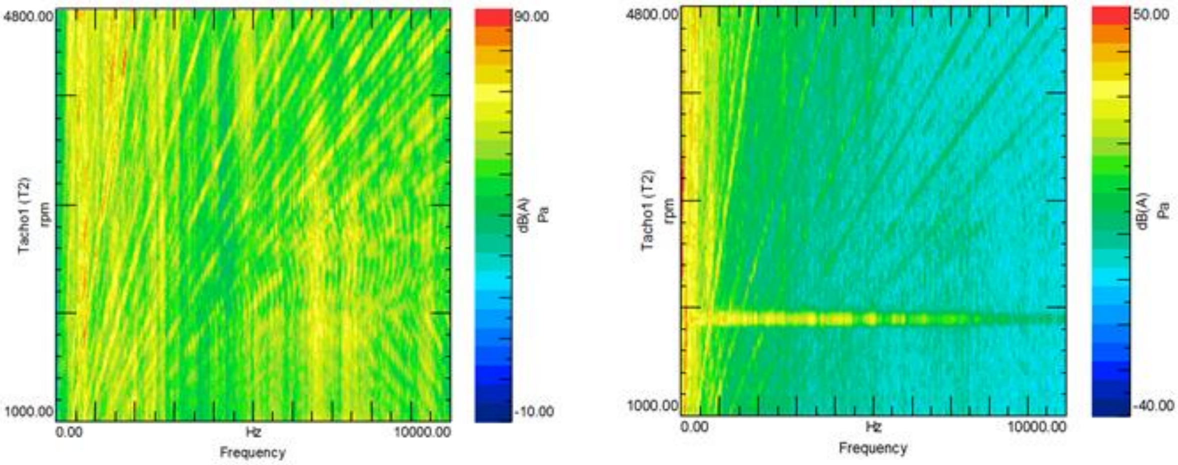
The integrated electric powertrain was integrated into a BMW i3. An existing EV was selected to reduce the conversion and integration effort. After performing some reverse engineering, the required CAN signals were identified. The motor control was adapted for using these signals of the i3.

A characterization of the NVH performances was done at the vehicle level as well. The BMW i3 with the newly designed ARMEVA SRM was instrumented on real road situations, chassis dyna and output vibration and acoustics data were collected for different operation cases. This consequent NVH study allowed defining critical transfer paths (Transfer Path Analysis technique) where vibrations and acoustic signatures were travelling through from the electric powertrain. More importantly, the NVH tests proved the quietness of the implemented machine design. Indeed the experiments on the chassis dyno captured an interesting quantifying phenomenon. Figure 8 shows the speed of the vehicle drive shaft, the acceleration at a motor position, the acoustic noise emitted inside the engine bay and in the car cabin. Just before 2,000 rpm, one can notice a peak of amplitude along all the frequency bandwidth, that actually corresponds to the noise emitted by the door locking system. Knowing the commonly non-noisy nature of such locking features, one can assess on the NVH performances of the developed electric motor.



(a) Rotational speed on motor’s shaft

(b) Acceleration on the motor – direction Z



(c) Overall noise level measured inside engine bay

(d) Overall noise level measured inside car cabin

Figure 8: Vibroacoustic results obtained on the complete car concept

The vehicle was demonstrated on the same day as the final ARMEVA workshop. Workshop participants were offered a test drive. All test drivers were impressed by the silent and shock free operation of the electric drive. While a lot of SRM research and industry experts were present, nobody was aware of other SR motors with this low levels of NVH built for passenger vehicles.

## 7 Conclusions

With the development of the Switched Reluctance Electric Drive in the ARMEVA-project a large step forward in compact, powerful permanent magnet free motors was realized. While the power level increased

to more than twice the power of the previous generation of SR motor at Punch Powertrain, the cost of the electric drive has decreased. A substantial part of the cost saving was realized by integrating the powertrain subsystems into one unit.
At the same time the SR NVH emission has been drastically reduced to a level that was assumed not possible by many motor experts.

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TEKSHIFT GMBH..

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Steven Bervoets is working as a systems engineer for Punch Powertrain for 8 years. He started as a controls engineer with migrating legacy C-code into Simulink models for code generation for the transmission control unit. Soon he took the lead in the hybrid controller development. Since 2010 he has guided the development of 4 generations of Switched reluctance motors and controllers. The last years, he is responsible for the development of a switched reluctance based electric vehicle powertrain.

Patrick Debal
Patrick Debal, Powertrain Expert Advanced Development, graduated as master of Science in Mechanical Engineering at the University of Leuven in 1985. Patrick joined Punch Powertrain in late 2006 to develop hybrid powertrains. Initially he was project leader of the development project. Once it transferred to applications Patrick became the Hybrid Powertrain System expert. Today, Patrick is Powertrain Expert within Advanced Development.

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Saphir Faid, manager Advanced Development, received the degree of Master in Electromechanical Engineering in 2004 from Group T University College, Leuven, Belgium. He led several innovative electric vehicle projects including an electric concept vehicle and hydrogen racing vehicle, before joining Punch Powertrain in 2008. He was involved in several transmission and hybrid powertrain projects, and since 2010 he is leading the development of SRM technology. His field of experience covers electric vehicle components including electric motors and batteries as well as project management

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Dirk has previously worked on low carbon vehicle projects such as electric vehicle conversions and harbor cranes, fuel cell vehicle conversion, fuel cell control and electric motor testing. In 2015 he received his PhD from the University of Sunderland in which he focused on power and energy management optimization strategies for series hybrid electric vehicles. Since 2016 he manages the new electric powertrain developments at Punch Powertrain. These powertrain developments involve both Permanent Magnet and Switch Reluctance motors.

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Fabien Chauvicourt received the M.Sc. degree in Mechanical Engineering specialized in Industrial Acoustic and Vibration from the Université de Technologie de Compiègne, Compiègne, France, in 2014. He is currently an Early Stage Researcher within Siemens Industry Software NV, Leuven, Belgium, as a Fellow of the ADEPT Project, which is a European Commission ITN Marie Curie Programme. He is also candidate for a joint Ph.D. degree at the Katholieke Universiteit Leuven, Belgium and the Université Libre de Bruxelles, Belgium.

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Cassio Faria is a Sr. Project Engineer for R&D at Siemens Industry Software NV and his work focus on NVH of electric machines, design of smart structures, nonlinear controller design and virtual sensing techniques. He earned his PhD in Mechanical Engineering from the Virginia Polytech Institute and State University (Virginia Tech) in 2013 and later did his Postdoc at the Aerospace Engineering department in the University of Michigan.