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48V drivlina, FFI konceptstudie	
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48V powertrain, FFI concept study	
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Nyckelord: 5-7 st 48 V motor drive, Electric Vehicle, WLTP cycle, benchmarking, in-conductor cooling, high current	

Förord

The concept study, 48V powertrain, has been funded by the Swedish Energy Agency, STT Emtec and Mid Sweden University and has mainly been carried out at Mid Sweden University in Sundsvall. Chalmers has participated in the project by evaluating the results and calculations that the project has resulted in. STT Emtec AB has begun work on adapting its testing operations of drivelines to include electric drivelines for future projects and for other commercial actors. Volvo Cars AB has followed the project and participated in meetings to feedback the project's results into their organization.

STT Emtec participates in the project in discussions and evaluation and prepares investments to test upcoming prototypes and other electric powertrains in its commercial operations.

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Sammanfattning

Denna konceptstudie syftar till att ge en genomförbarhetsöversikt av en 48V drivlinan för elektriska fordon. Projektet arbetade främst på en konceptuell nivå för att studera fördelar och nackdelar med att använda en lågspännings drivlinje i helt elektriska fordon. Några viktiga områden som projektet undersökte på en mer detaljerad nivå är motor, inverter, kablar, kontakter, batteri och laddningsstrategi.

Resultaten indikerar att en 48V drivlinjedesign är konkurrenskraftig mot modern högspänningsdesign när det gäller effektivitet, prestanda, storlek och vikt, och det är möjligt att hantera hög ström i drivlinan genom att använda vatten glykol 50/50 som kylvätska design med födande kylvätska i ledarna.

Vi har också föreslagit en ny batteripaketarkitektur med serieladdande parallellkörningsfunktion, vilket kommer att säkerställa framtida 48 V EV att ha kompatibilitet med befintlig högspänningsladdningsinfrastruktur. Vi har utfört prototyper och börjat preliminära tester på denna nya arkitektur.

Summary

This concept study aims to provide a feasibility overview of the 48 V powertrain EV design. The project mainly worked at a conceptual level studying, the pros and cons of utilizing a low voltage powertrain in fully electric vehicles. Some key areas that the project investigated at a more detailed level are motor, inverter, cabling, connectors, battery and charging strategy.

The study results indicates that our novel 48 V powertrain design is competitive against state-of-the-art high voltage design in terms of efficiency, performance, size and weight, and it is feasible to handle high current in the powertrain by the utilizing water glycol 50/50 as coolant and having in-conductor direct cooling design.

We also proposed a new battery pack architecture with series-charging parallel-driving capability, which will ensure future 48 V EV to have compatibility to existing high voltage charging infrastructure. We have conducted prototyping and started preliminary testing on this new battery pack architecture.

The overall conclusion of this study is that it indicates a high efficiency and high performance 48 V powertrain for future EV which could also benefit from higher safety and lower costs.

Introduction / Background

Today's electric cars work at high voltages between 300-500 V and the trend is to raise the voltage further. The main driving force for this is to improve efficiency and cost by reducing the cross-sectional areas of the conductors. However, the high voltage is a clear safety risk. All workshop personnel must be certified, rescue personnel in case of accidents cannot put out fires or rescue trapped persons without imposing special restrictions. Under no circumstances may the car owner come into contact with the high voltage, at home, in the event of minor interventions or accidents. A relatively large cost in today's cars is linked to managing risks related to electrical safety.

There are some initiatives to construct a low-voltage electric driveline below 60 V which is thus not associated with the danger of life to come into contact with electrical conductors for e.g. workshop staff or in case of accidents. Volabo [1], which is a spin-off from Bundeswehr University Munich, happens that with their 48 V driveline, you could achieve 20% better fuel economy than existing solutions on the market. Mid Sweden University has also been working with low-voltage motors for a few years and has shown promising forecasts.

This project intends to make a system-level analysis of motor, inverter, cabling, connectors, battery and charging strategy, and benchmarking state-of-the-art high voltage EV powertrain against our 48 V design in WLTP drive cycle.

The most efficient EV on the market now is Tesla Model 3, which has a 350 V battery pack. The rear-wheel drive version has a 6-pole PM motor with peak power of 211 kW and top speed of 16000 rpm at a weight of 46 kg. It uses oil cooling inside the motor for both the stator winding and lamination stack which then goes through oil filter and then heat exchanged to water glycol coolant to the rest of the vehicle. Their three-phase inverter utilize state-of-the-art 650 V SiC MOSFET from ST Microelectronics which has a customized package with two dies inside. It has a nominal Rdson of 8 mΩ and is rated for 250 A, and a max junction temperature of 200 °C. It has a junction-to-case thermal resistance of 0.19 °C/W. The inverter uses totally 24pcs of SiC MOSFET in the three phase half bridge, which is 4pcs in parallel in all six sides.

Although we know this PM motor in Tesla Model 3 is probably the most efficient design on the market, unfortunately we cannot use it in our benchmarking. Because we can’t find any published info on its detail winding design and material specification. So as the alternative, we used 2014 Tesla Model S induction motor for the benchmarking. It is a 3 phase 4 pole copper-cage induction motor with additional rotor internal cooling, and it has a peak power of 340 kW at a nominal 366 V DC link. It has an active diameter of 254 mm and an active length of 153 mm. Its lamination weights about 45 kg and its copper weights about 16 kg. Its max phase current is 900 A at a current density of about 21 A/mm^2.

Implementation

In the feasibility study for a 48 V driveline project, several activities have been carried out to evaluate the concept. 1) Design and simulations of motor performance, 2) Experimental evaluation of cooling in the motor winding, 3) Modeling of performance during a drive cycle and 4) Design of battery systems for charging in existing infrastructure.

The motor design has been implemented in CAD tools and simulated its performance to extract efficiency at different torques and speeds.

Results

Our 48 V Motor Design

In this study, we have demonstrated a truly high efficiency and high performance 48 V motor drive concept design: an Ethylene Glycol Water 50/50 (EGW50/50) in-conductor directly cooled 45 phase permanent magnet assisted synchronous reluctance motor integrated with 60 V MOSFET inverter. Simulation showed the motor has an efficiency map with a wide area of better than 98%. The whole drive unit has a dry weight of about 57 kg and can continuously deliver 510 kW at a power density of 34 kW/L and a specific power of 8.9 kW/kg. It has an active diameter of 225mm and an active length of 150mm. It uses 2.5 kg of permanent magnet of grade N42UH. The copper inside this motor drive weighs only 8.5 kg, not more than a stator winding of a similar size high voltage motor. Our concept design has also included an in(around)-conductor EGW50/50 cooled battery-to-drive two-terminal cable with screw-on connectors. It has a dual-purpose design to deliver both power and coolant through the drive. The cable uses 500 mm^2 stranded copper wire in each terminal that can deliver at least 10 kA of DC current through it. This cable and connector design shows that it is feasible to handle high current in the 48 V system and the whole drive unit will not take more space or weight than high voltage designs.

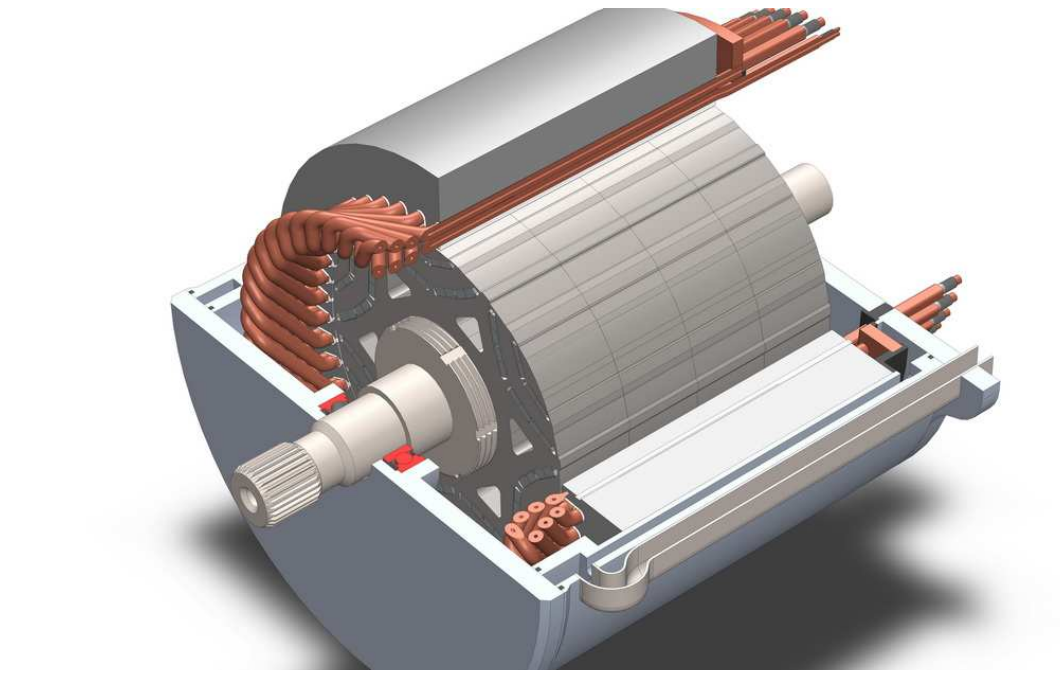


Figure 1. The concept drawing of our 48 V PM motor.

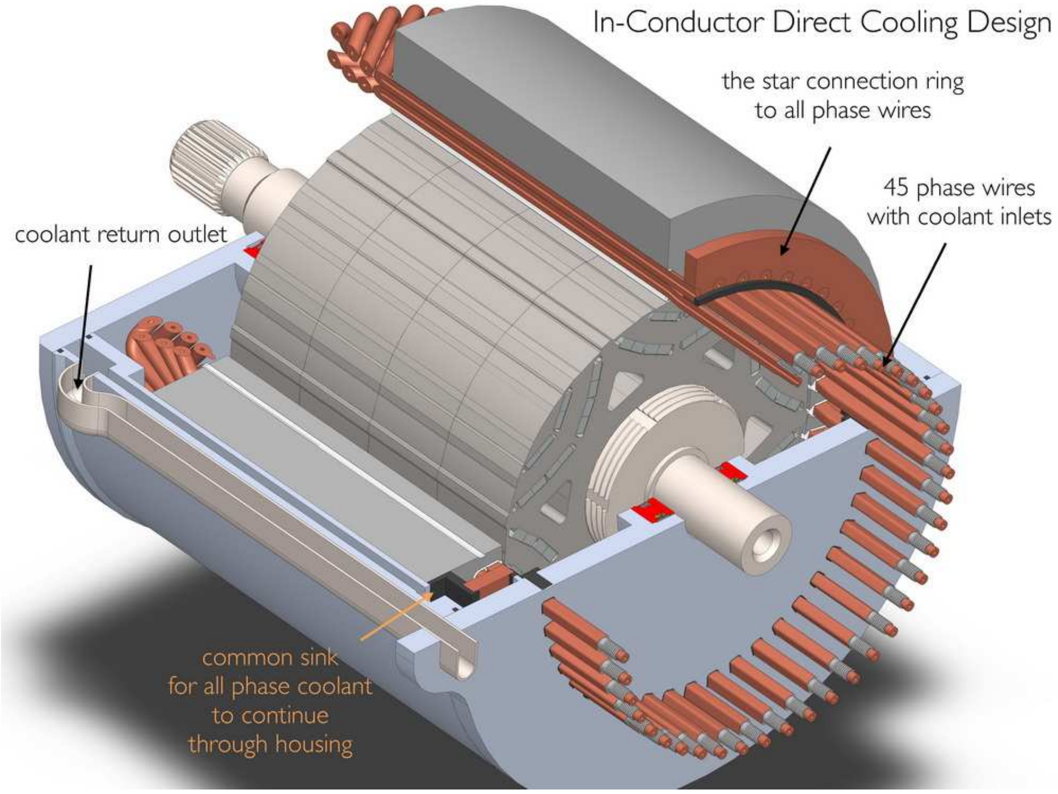


Figure 2. The in-conductor direct cooling design of our 48 V PM motor.

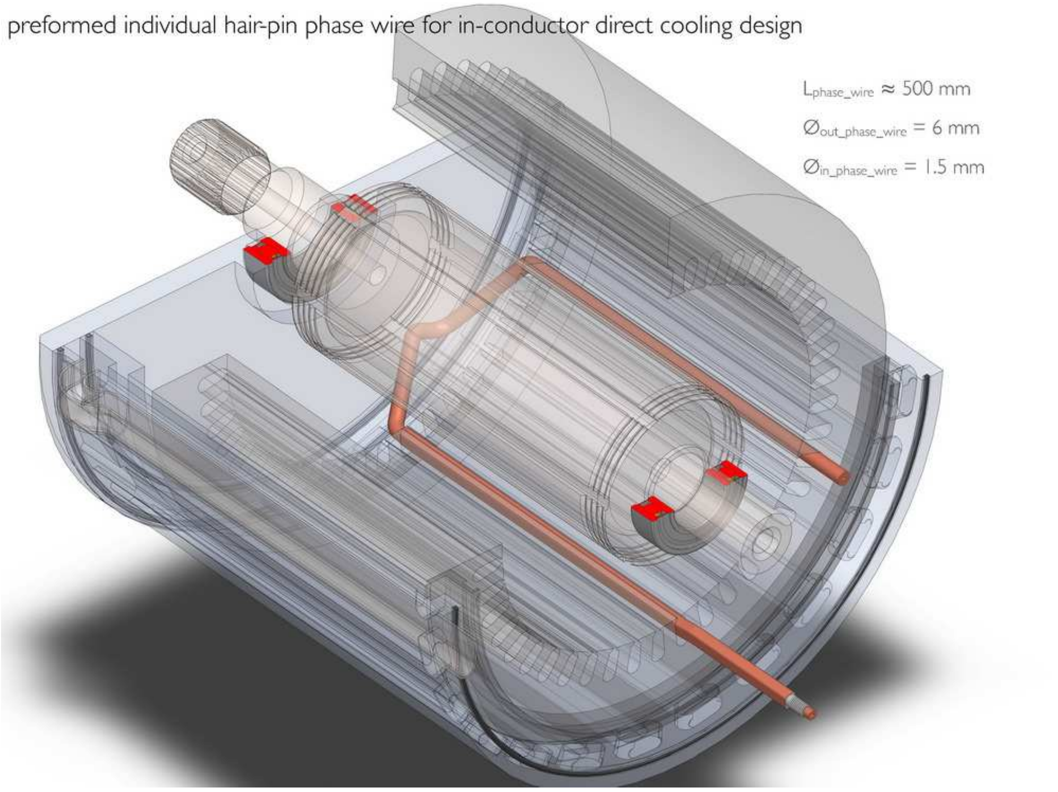


Figure 3. The preformed hair-pin wire for the winding of our 48 V PM motor.

Our Drive Design

The 60 V MOSFET used in our multiphase drive has similar theoretical power density and efficiency to that of the 650 V state-of-the-art SiC MOSFET from STMicro used in the Tesla Model 3 inverter. But it can be cooled from both sides and is 4.4 times better in cooling performance than the SiC MOSFET. Our inverter design fully utilized this key advantage and further incorporated in-conductor direct cooling to these 60 V MOSFETs, which resulted in a 48 V drive that can outperform the state-of-the-art both in terms of power density and efficiency.

Because of the multiphase nature of its design, our drive has massive built-in redundancy. This feature significantly improves the robustness of the drive and the safety of the vehicle. So even if several MOSFETs fail, the drive could still function, although at a reduced capacity. Because of the 48 V and the redundancy from the multiphase design, all the MOSFET drivers in our inverter don't require galvanic isolation and can be a lot simpler and cheaper. By interleaving the multiphase drive through its control algorithm, it also has the potential to further reduce the DC link capacitor current, and hence either increase the capacitor reliability or further reduce the drive cost.

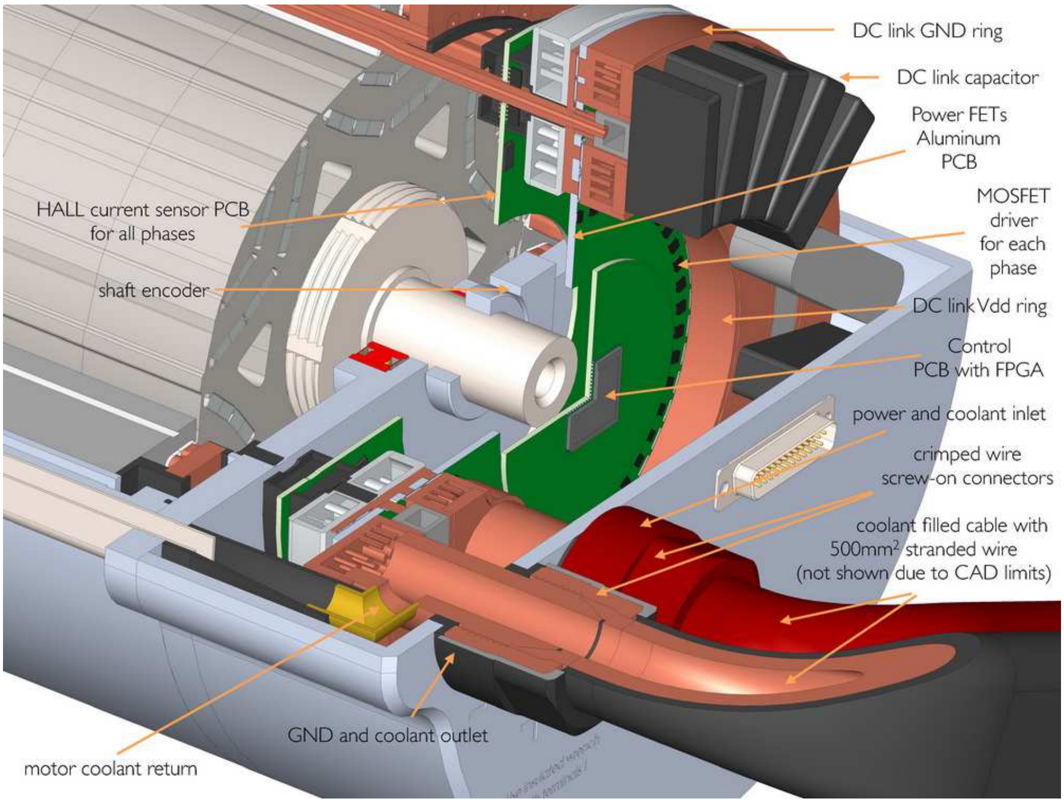


Figure 4. Our multiphase inverter design.

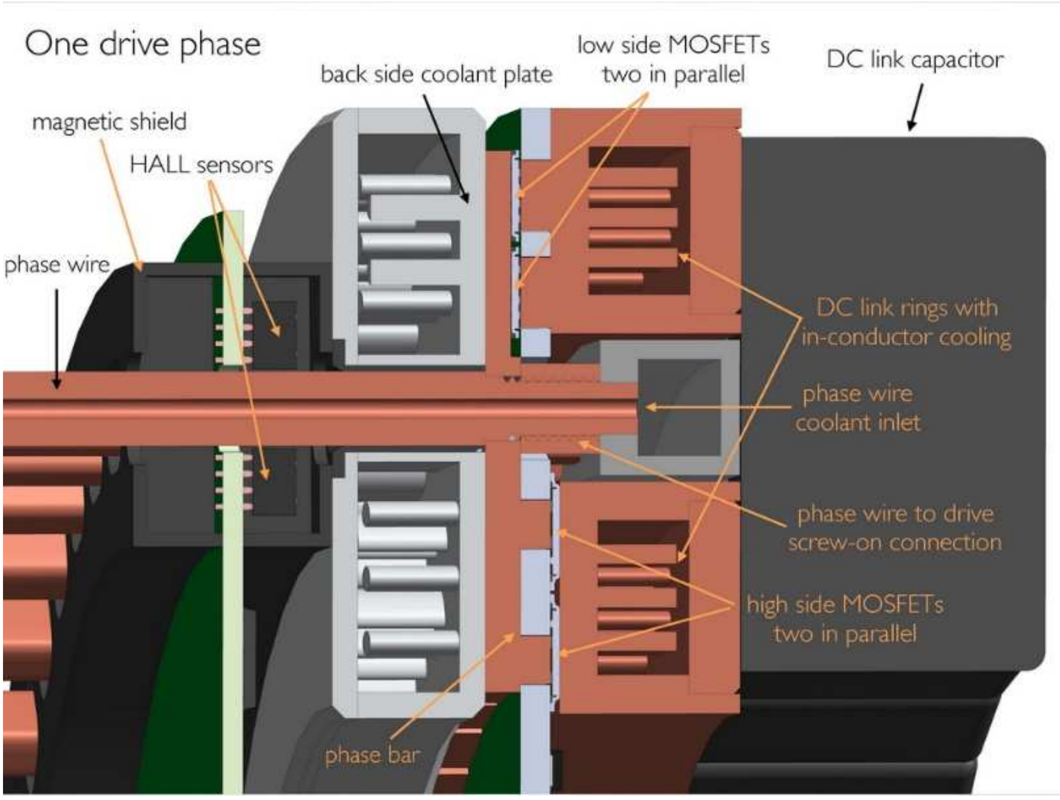


Figure 5. The direct copper bonding of MOSFETs in our inverter.

Thermal Management

Compared with conventional high voltage motor designs, our 48 V counterpart can achieve better efficiency and performance primarily because it has a major technological advantage: in-conductor direct cooling using EGW50/50, which is a method of passing the best performance cooling fluid through hollow conductors of the stator winding in order to directly cool the winding where most heat generates. This cooling method vastly out-performs all other conventional methods. Our earlier studies have indicated that this method enables a copper conductor continuous DC current density of 50 A/mm^2 inside the motor slot by utilizing a small hole of only 6.25% cross-sectional area. Such a high continuous current density is unheard-of to our knowledge. However, this advantageous method is not used in any high voltage EV motor design. It is impractical on small high voltage motors, both for the conventional stranded windings that have thin wires, and for the more recent hair-pin windings that need laser welds at the ends and go through an impregnation process.

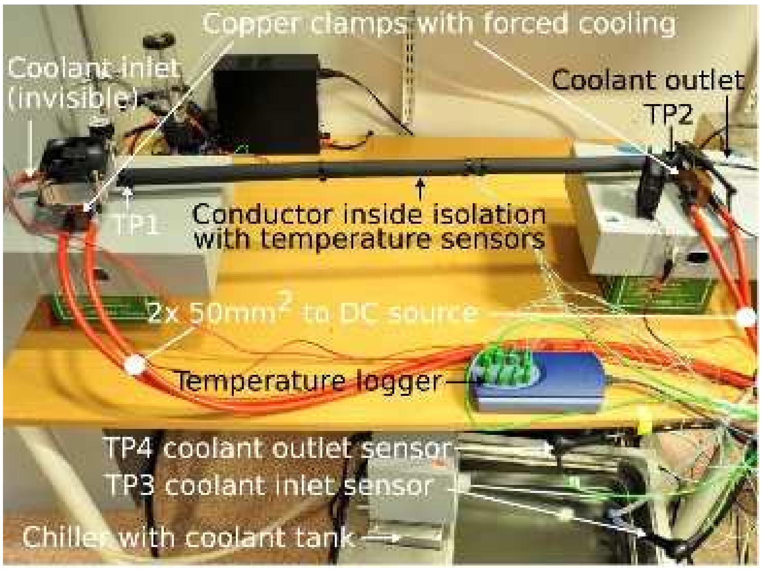


Figure 6. The preliminary testing and verification of in-conductor direct cooling design.

Motor Performance Simulation

We have simulated both 2014 Tesla Model S induction motor and our PM motor and the following efficiency map shows the obvious advantage of our design. The simulation used maximum 900 A_{rms} at a current density of about 21 A/mm^2 for the phase current of Tesla IM at a DC link voltage of 366 V, and maximum 884 A_{rms} at a current density of about 33.4 A/mm^2 for the phase current of our PM motor at a DC link voltage of 48 V.

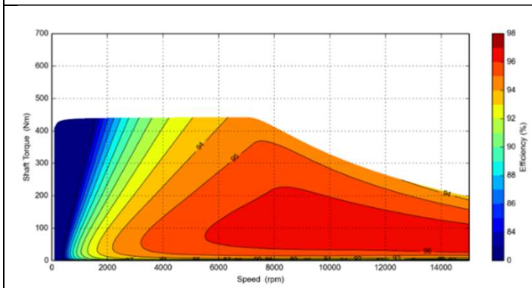
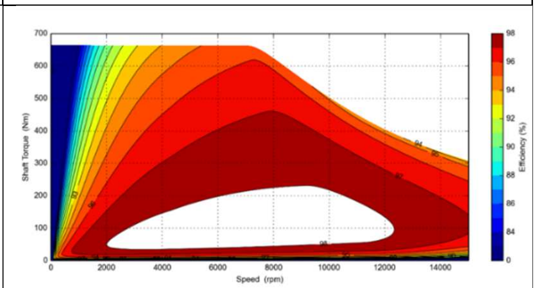
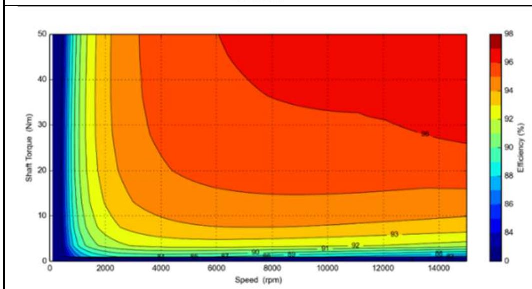
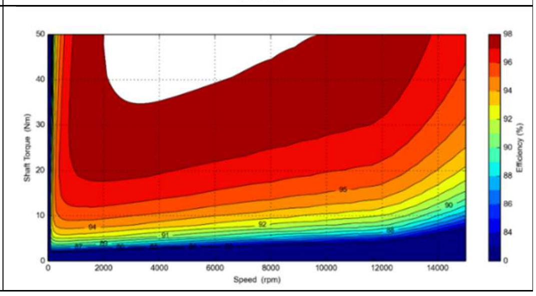
2014 Tesla Model S induction motor	our PM motor
	
	

Figure 7. The efficiency map comparison between Tesla induction motor and our PM motor, in both full torque range and below 50 Nm.

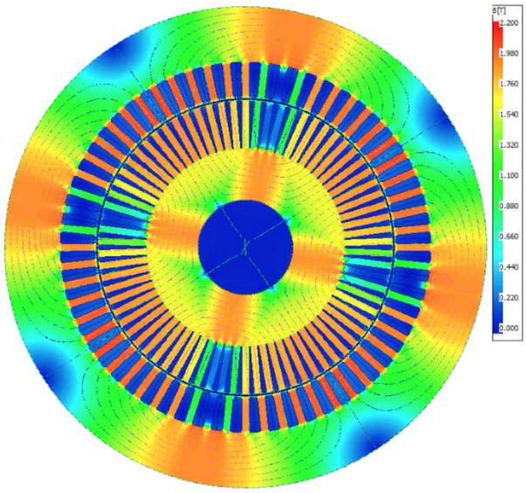


Figure 8 The Tesla induction motor fully loaded.

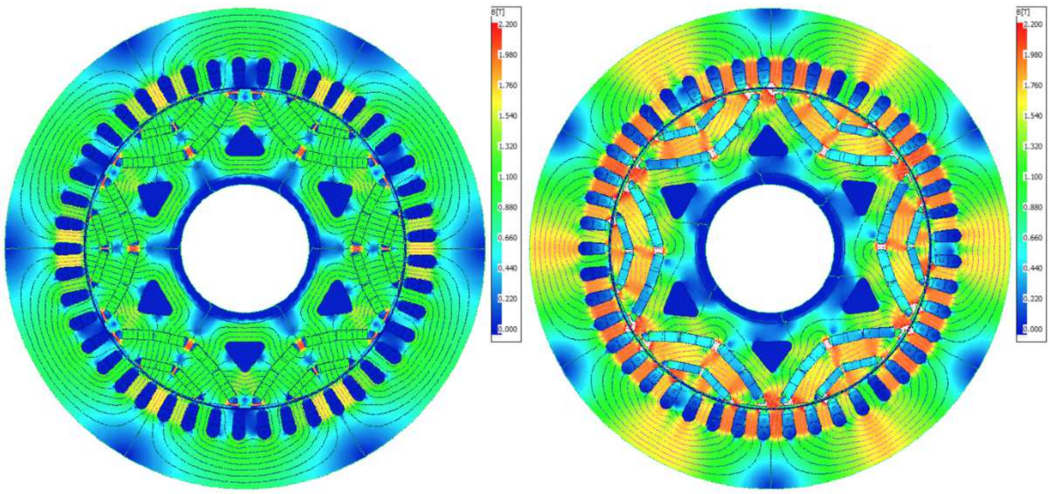


Figure 9 Our pm motor no load and fully loaded.

Feasibility Benchmarking

In this study, we used 2014 Tesla Model S induction motor driven by their 2017 Model 3 SiC MOSFET inverter as the state-of-the-art to be benchmarked with our 48 V drive design in WLTC Class 3B drive cycle on three different vehicles sizes: a Tesla Model 3 RWD LR, a mid-size sedan and a full-size SUV. The result on the vehicle size of Tesla Model 3 RWD LR is shown below as the example.

The system parameters used in the benchmarking for the vehicle sizes of Tesla Model 3 RWD LR:

	Tesla Model 3 RWD LR
Static mass (including driver):	(1730 + 80) kg
Frontal area	2.22 m^2
Drag coefficient	0.23
Rolling resistance coefficient	0.015
Tire size	235/45 R19

The common powertrain parameters used in the WLTP benchmarking:

	Tesla 2014 Model S IM + 2017 Model 3 SiC MOSFET inverter	**our PM motor + our 45phase MOSFET inverter**
Gearbox ratio	9	9
Gearbox efficiency & additional frictional load in drivetrain to the motor	97 % 0.5 Nm	97 % 0.5 Nm
Motor temperatures	winding 100 °C rotor cage 90 °C stator lamination 90 °C rotor laminations 90 °C	winding 80 °C rotor magnet 90 °C stator lamination 80 °C rotor laminations 90 °C
Battery pack	366 V with $R_{bat\ pac}$ = 5 mΩ	48 V with $R_{bat\ pac}$ = 0.08 mΩ
Interconnect resistance, drive to battery pack	1 mΩ	0.29 mΩ
Drive design	3 phase with 650V SiC MOSFETs	45 phase with 60V MOSFETs
Switches in each drive phase	4 in parallel, each at R_{dson} = 9.6 mΩ	2 in parallel, each at R_{dson} = 1.4 mΩ
Interconnect resistance per phase in drive	0.5 mΩ	0.5 mΩ
Drive switching loss model	20 kHz ideal sine wave current without ripple	20 kHz ideal sine wave current without ripple

Here is the summary from the benchmarking which shows that our 48 V powertrain has a range improvement of 2% for the vehicle as TM3 RWD LR:

	Tesla 2014 Model S IM + 2017 Model 3 SiC MOSFET inverter	**our PM motor + our 45phase MOSFET inverter**
Ideal loss in kWh/100km (exculde powertrain losses)	11.85	11.85
Overall energy efficiency	81.06 %	82.74 %
Overall range efficiency in kWh/100km	14.62	14.32
Mean motor losses in Watt	531	275
Peak motor losses in Watt	2327	880
Mean drive losses in Watt	277	303
Peak drive losses in Watt	1287	1867
Overall range improvement	0	**2.09 %**

Here is the WLTP case results for TM3 RWD LR on state-of-the-art:

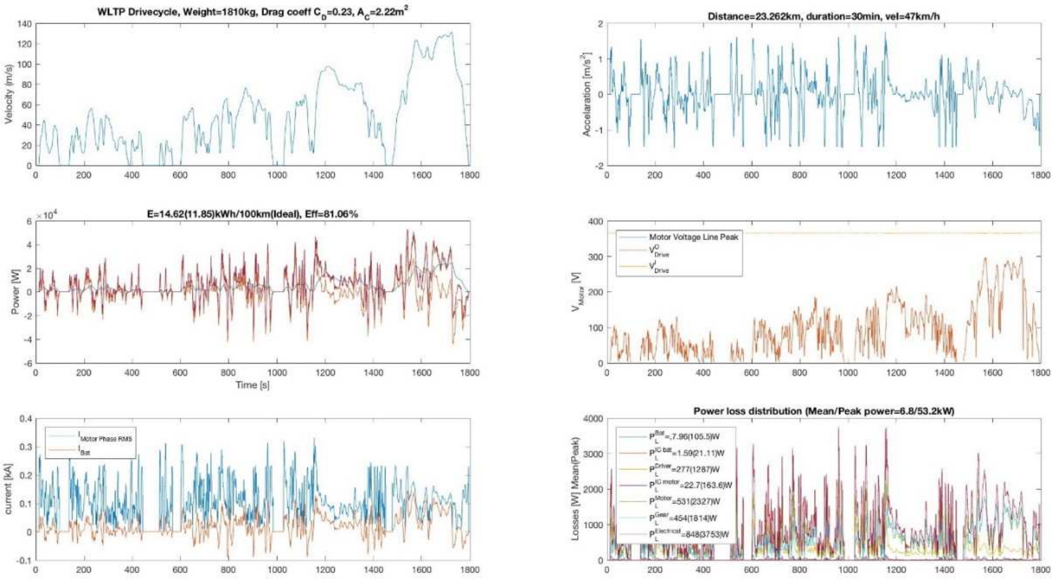


Figure 10 The WLTP results for Tesla IM + SiC MOSFET inverter.

Here is the WLTP case results for TM3 RWD LR on our motor drive:

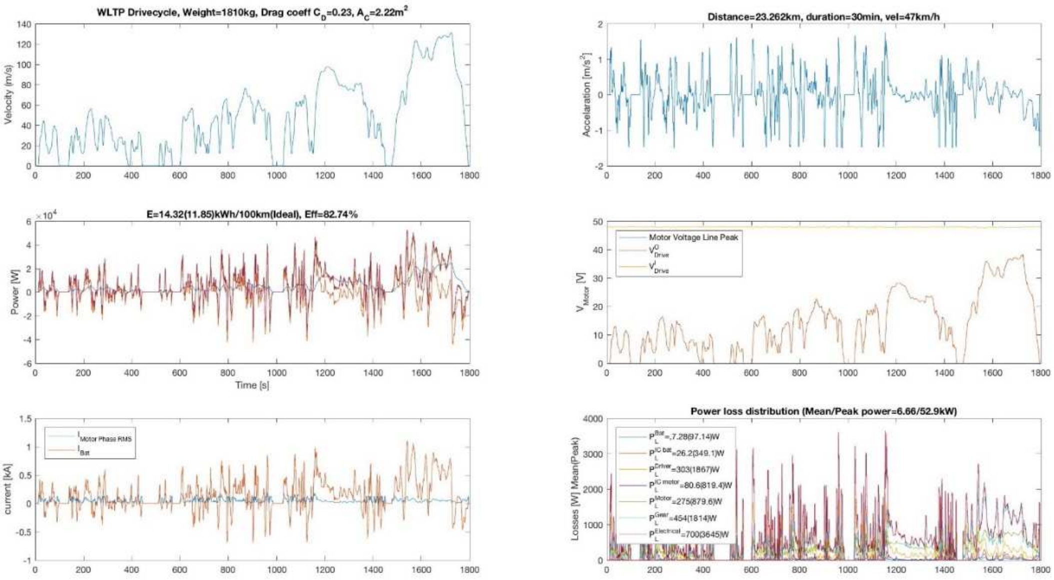


Figure 11 The WLTP results for our motor drive.

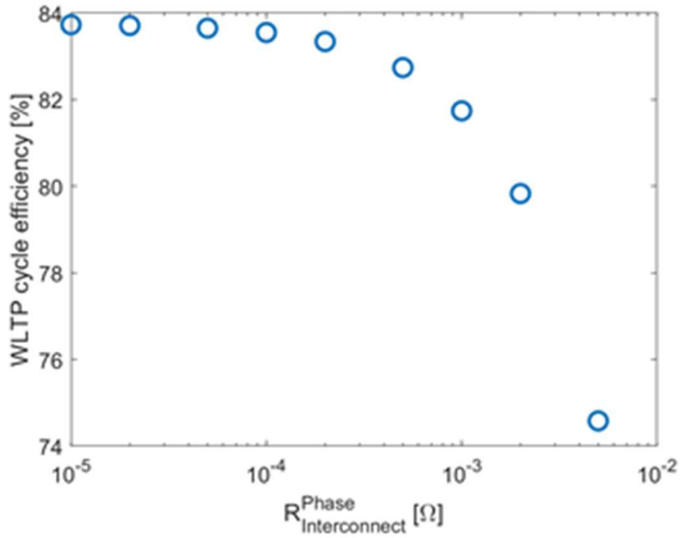


Figure 12. Effect of interconnect resistance per phase in inverter

From Figure 12, it can be seen that the interconnect resistance per phase should be less than 0.5 mΩ to have a negligible (<1%) degradation of the efficiency. We have used 0.5 mΩ in our benchmarking as we know that is easily achievable.

Cables and Interconnects

The low voltage approach requires very high current handling capabilities, so the cables and interconnects are very important to consider both from efficiency and thermal point of view.

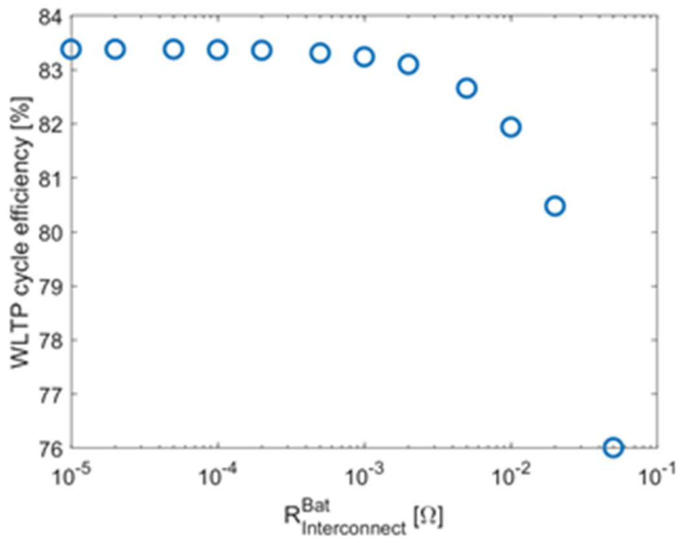


Figure 13. Effect of line resistance between 48V battery packs and the inverter.

From Figure 13, it can be seen that the cable resistance between the 48 V battery pack and the motor drive should be less than 0.5 mΩ to have a negligible (<0.1%) degradation of the efficiency.

Assuming a battery-to-drive one-meter long cabling length having in(around) conductor liquid cooling design. Target max load current of 10 kA while limit max current density down to 20 A/mm^2. This will require two cables having 500 mm^2 copper cross-section area. Assuming additional 10% increased resistance from contacts, and a copper temperature of 60°C, this yields a total resistance of 0.192 mΩ (we used 0.29 mΩ in our benchmarking). At 10 kA, the total power loss is 8575 W, which is 1.79% of the 480 kW power that go through. At 2 kA (more than enough for a full-size SUV at 150km/h), the total power loss is 343 W, which is 0.36% of the 96 kW power that go through. Copper weight in this cabling including connectors is 9.5 kg, so estimated total cabling weight should be < 12 kg. The Tesla IM in this comparison is about 21 kg heavier than ours. The Tesla Model 3 PM motor is rated at 211 kW peak and is about 46 kg. Their high-voltage cabling should add another 2 to 3 kg. So, our 48V drive can be similar in weight compared to state-of-the-art while providing significantly better performance.

Battery Pack and Charging

There is currently a high voltage infrastructure rolled out in the society and it would be crucial for a low voltage vehicle to utilize this. This challenge can be addressed by either integrate DC/DC converters in the vehicle or reconfigure the batteries during charging. To allow fast charging very high power DC/DC converters would be required that would add extra cost and weight. Power modules such as Vicor RFM modules shows that the 48 V / 10 kW modules can be quite compact but the related cost probably quite high if it should be scaled to fast charging power levels of 50-300 kW. The approach by having reconfigurable 48 V battery blocks connected in parallel during normal operation. During charging, eight blocks in configured in series and charged in a normal fast charging infrastructure. The following diagram shows the architecture of the series-charging parallel-driving design. Designing such system there is a tradeoff between how much such system cost to implement and how much it degrades the system performance. In the project it is estimate that the cost for such a battery system would increase 3.5% and degrade the vehicle energy efficiency with 0.2%. These values should only be seen as indicative as the system can be optimized further and the cost level for an EV producer will differ from what is publicly available from retail distributors, such as Farnell and Digikey.

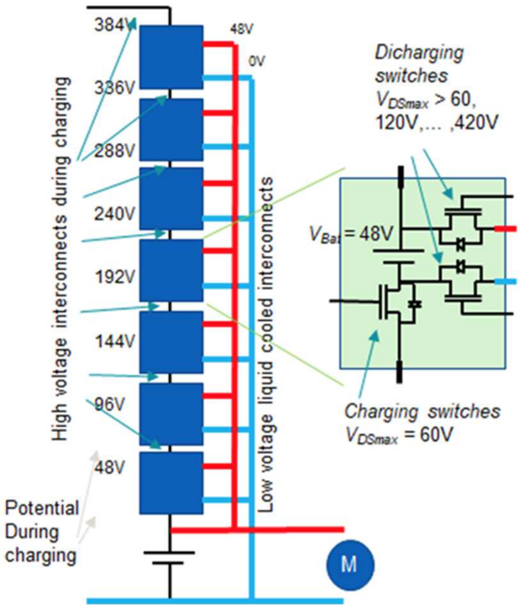


Figure 14. The series-charging parallel-driving battery pack design

Discussion

These results have shown that it is indeed feasible to have a 48 V powertrain for the fully electric vehicle, and that it could be competitive to state-of-the-art high voltage design both in terms of efficiency and performance. And it is possible to utilize existing high voltage charging infrastructure to charge such 48 V vehicle.

Publications

[1] S. Haller, J. Persson, P. Cheng and K. Bertilsson, "Multi-Phase Winding with In-Conductor Direct Cooling Capability for a 48 V Traction Drive Design", published in *International Conference on Electrical Machines 2020*.

Referencesor

[1] www.molabo.eu

Attachments

Attachment 1. Administrativ Bilaga

Attachment 2. Publication [1]