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European Competitiveness in Commercial Hybrid and Automotive Powertrains (ECOCHAMPS):

Effective Passenger Car Hybridization via a 48V DCT

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Abstract

The ECOCHAMPS project has addressed the topic GV-04-2014 Hybrid Light and Heavy Duty Vehicles of the Green Vehicles work program under Horizon 2020. This project realized, in a single, coordinated action, all the aspects of this call through the activities of a twenty-five member consortium representing of the European Automotive Industry. The overall objectives of the ECCHAMPS project are to achieve efficient, compact, low weight, robust and cost effective hybrid powertrains for both passenger cars and commercial vehicles, with increased functionality, improved performance, comfort, safety and emissions levels below Euro 6 or VI. In particular, to achieve 20% powertrain efficiency improvements and weight plus volume reductions with respect to the best in class vehicles on the market at the time of proposal (2013), whilst having a maximum of a 10% cost premium. At the time of the TRA in Vienna, the ECOCHAMPS project will just have been completed after three years of activity.

In Work Package 4 of the ECOCHAMPS project a 48V hybrid passenger car demonstrator is being developed. In this vehicle, the powertrain is fitted with an electrical machine directly coupled to a double clutch transmission (DCT). As such, the powertrain configuration gives the possibility to achieve hybrid vehicle functionality, e.g. regenerative braking, acceleration assistance and limited EV operations, whilst not detracting from the vehicle packaging and being a lower cost solution appropriate for rapid market uptake. Initially the powertrain has been developed with a state of the art electrical machine, rated at up to 15kW when running at 48V. However, an advanced electrical machine and power electronics have been developed, which demonstrate up to a 25 kW rating within the same practical package.

Results from the overall development and testing of the demonstrator vehicle and advanced electrical system will be presented in this paper. It will be seen that such a hybrid powertrain configuration offers an appropriate step for cost effective improved vehicle efficiency when compared to vehicles currently available. As a consequential impact of the ECOCHAMPS project, the uptake of hybrid vehicle technology in the European passenger car market is expected to be increased.

Topic: 3. Advanced Propulsion Systems

Keywords: Electromobility, Energy Efficiency, Decarbonisation, Emissions, Environmental Impact.

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Nomenclature

DCT	Double clutch transmission
E DCT	Electrified DCT
ICE	Internal Combustion Engine

1. Introduction

The ECOCHAMPS project has addressed the topic GV-04-2014 Hybrid Light and Heavy Duty Vehicles of the Green Vehicles work program under Horizon 2020. This project realized, in a single, coordinated action, all the aspects of this call through the activities of a twenty-five member consortium representing of the European Automotive Industry. The overall objectives of the ECOCHAMPS project are to achieve efficient, compact, low weight, robust and cost effective hybrid powertrains for both passenger cars and commercial vehicles, with increased functionality, improved performance, comfort, safety and emissions levels below Euro 6 or VI. In particular, to achieve 20% powertrain efficiency improvements and weight plus volume reductions with respect to the best in class vehicles on the market at the time of proposal (2013), whilst having a maximum of a 10% cost premium. At the time of the TRA in Vienna, the ECOCHAMPS project will just have been completed after three years of activity.

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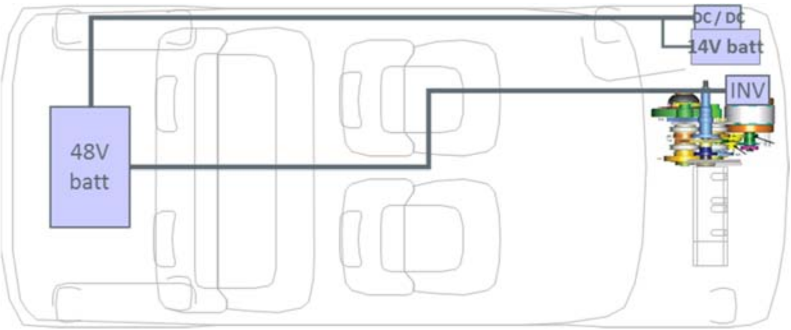
2. Principle of the 48V E DCT hybridization

To achieve the desired cost breakthrough WP4 intends to take advantage of

- 48 V components
    - No galvanic insulation necessary and no need of specific crash protection due to low voltage level.
    - Next coming mass production (components for 48 V belt starter generator as battery, DC-DC, plugs & connectors and related controls).
- A hybrid architecture that exploits the advantages of the double clutch transmission.
    - No additional component except one gear
    - High speed motor for a small size
    - Internal oil cooling for a high performance
- Careful sizing of electrical components that allows them to be kept as small as possible.

The figure below shows the electric topology of the demonstrator vehicle. As can be seen the 48 V battery is integrated in the rear of the vehicle while the DC-DC converter and the vehicle 14V battery are integrated within the engine room. The Inverter for the e-motor, which is integrated within the transmission, is connected directly to a side e-motor.



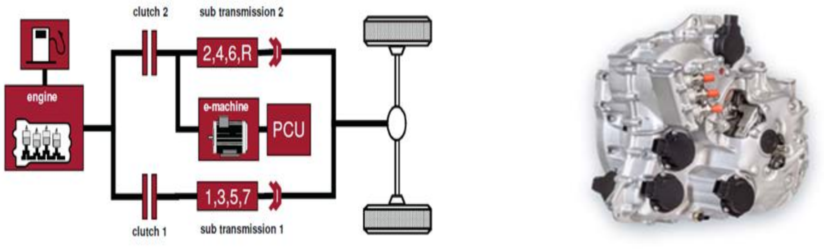


Figure 1: Diagrams showing the architecture of demonstrator vehicle and the layout of components, with an image of the eDCT (Source Getrag)

Regarding the electric power level, the figure below shows the percentage of the energy that can be recovered during deceleration for different drive cycles vs the E motor power.
It clearly illustrates that the potential energy that can be recuperated depends on the power rating of the e-motor and the type of drive cycle.

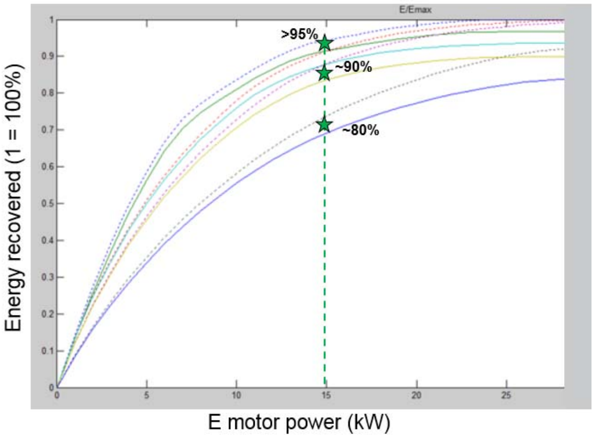


Figure 2: Projected energy recovery during deceleration vs regenerative electric power depending on usage

This figure shows that the targeted 15 kW rating covers between 80 % (highway) and 95 % (urban) of the total deceleration power that can be stored in the battery. This value of 15 kW is supposed to be achievable with a 48 V system.

3. Organization of the study

The E DCT study was divided into two parts:

- Stage 1: Proof of concept with a 48 V 15 kW powertrain
    - Theoretical CO2 potential evaluation
    - Powertrain test on bench
    - Integration in mule car for physical verification on test bed
- Stage 2: Investigation of the maximum power appropriate to a 48 V system (target 25 kW maximum)
    - Theoretical sizing
    - Prototyping and test of E motor on bench

The activity and the sharing of tasks between RICARDO, DAIMLER and RENAULT were organized as follows:

- DAIMLER has taken care of the hybrid powertrain integration and test
- RENAULT has integrated this hybrid transmission in the democar and tested it
- RICARDO had the charge of studying and prototyping the improved EM to reach 25 kW with a 48V electric network

4. Framing

The targets were set in the first phase of the ECOCHAMPS project, within the WP1 and were defined as follow:

Key Performance Indicator	**Target**	**Indicative value**
Cost (% over baseline)	Max 10%	10% (complete car)
Fuel Consumption & CO2 (% under baseline)	Min 20% of efficiency improvement (NEDC)	~ 20% (NEDC)
Maximum Speed (km/h)	As base vehicle	Same than normal Megane, i.e. 200 kph
Maximum EV Speed (km/h)	n/a for HEV	Not a target but 60 kph reachable (short operation) for the base version 15kW.
Acceleration Time (s)	As base vehicle	Normal Megane reference (0-60 km/h) = 5.6s
Braking	As base vehicle	Same performances than normal Megane
Grade ability	As base vehicle	Same performance as a normal Megane
EV Range (km)	No target	Not a target, but indicative value is 0.5 km
NVH Vehicle	Equal or better than Megane	Same or lower noise than normal Megane for serial application. See the before and after test in the target setting procedure.
NVH Gearbox & Differential		
NVH Traction Motor		
NVH Power Electronics		
NVH Engine		
Available Capacity	<0.1m3 loss	<0.1m3 loss

Figure 3: target and visibility for the 48V E DCT powertrain in Megane

5. Paper study and theoretical results

5.1. CO2 estimate:

The simulation of the hybridized double clutch transmission, based on a 7.5Ah lithium-ion battery and a 15 kW motor, gave the following results:

Item	**Megane with 48V EDCT simulation**	**Base ICE Megane simulation**
Length of NEDC (secs)	1180	1180
Fuel consumed (g)	371.4	472.4
Fuel consumption (L/100km)	4.5	5.8
Fuel economy (mpg)	62.5	49.0
CO2 emissions (g/km)	106.7	136.0
Powertrain efficiency (%)	26.5	18.8

Figure 4: Comparison of base ICE and initial hybrid versions of the Megane.

Therefore, the commitment taken into the frame of ECOCHAMPS, i.e. 20% efficiency improvement seemed theoretically feasible.

5.2. Cost estimate

Compared to the existing1 motor 2 clutch parallel hybrid on the market, the EDCT concept takes advantage of:

- Mechanical simplification (clutch removal)
- High speed E motor (small size)
- power limitation (~15kW)

- Use of 48V components (benefit of next coming high volume production)
- No galvanic insulation thanks to 48V level (more simple electric connections, simplified DC/DC)
- More simple battery (less cells than high voltage one)

Therefore, the premium cost achievable was estimated ~10%, in line with the ECOCHAMPS target.
The cost breakdown is shown below:

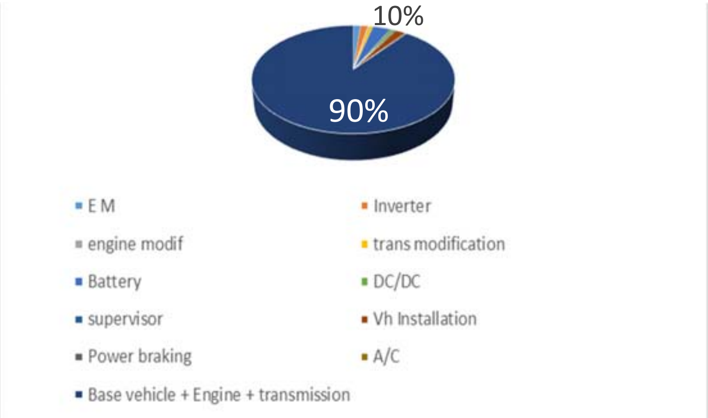


Figure 5: 48V E DCT cost premium estimate (dark blue: base vehicle, other colours: hybrid parts)

5.3. Packaging study

The general integration the hybrid components for a serial application should be as follow:

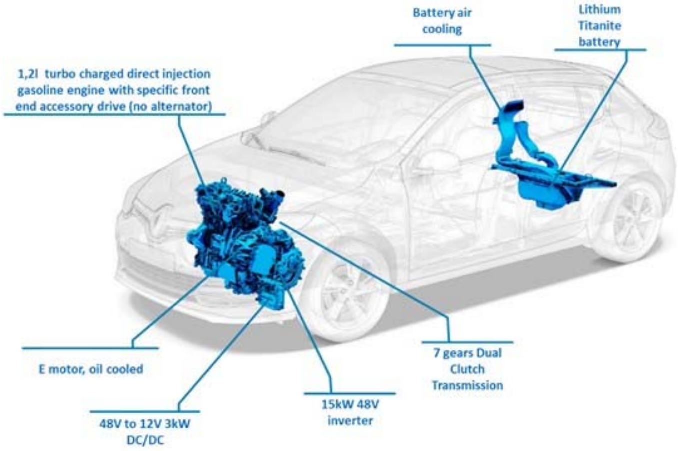


Figure 6: targeted component integration as foreseen for a serial production

Regarding the democar, the component integration was slightly different compared to the targeted final integration due to components availability.

The democar front integration was very close to the targeted one.
On the contrary, the battery integration was different. For prototyping, two 48V battery in parallel were chosen to get the requested power and energy as no big enough battery was available. In addition, the trunk of the democar had to host some additional components necessary for the measurements necessary on this car (additional 12V battery, on board computer, sensors).

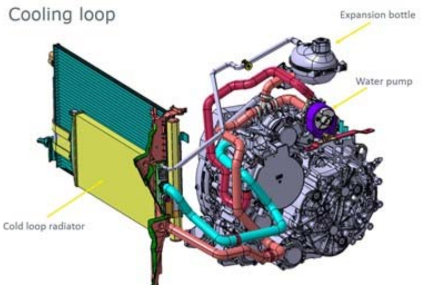


Figure 7: democar under hood integration

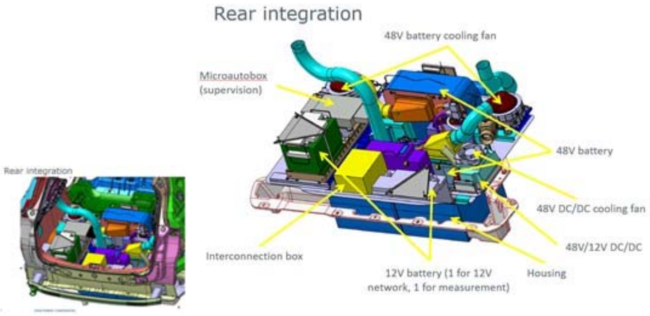


Figure 8: democar trunk integration

5.4. Control system

The basics of the 48V EDCT hybrid energy management is the same than any hybrids:

- ICE disconnection during regenerative braking for a better energy recovery
- ICE shut off at low load when the engine efficiency is low, using the electric drive
- ICE load shift to optimize the overall efficiency

Because of the limited power available at 48V, the electric drive area is reduced as shown below:

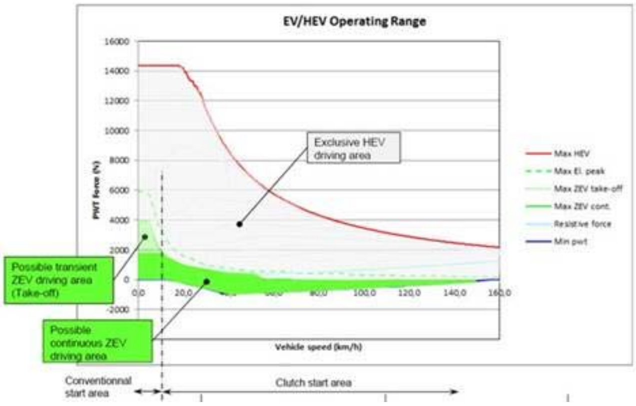


Figure 9: E Drive and hybrid area

As this electric drive area is limited, one of the key challenge is to manage smoothly the transition between the electric drive and the ICE restart as it occurs frequently.

The ICE restart is operated in two ways: at low speed, below 15 kph, it is restarted with the starter. At higher speed, it is achieved with a clutch restart. The clutch restart principle is to launch the ICE with a torque coming from the E Motor through one of the two clutches of the DCT. During that phase, the E motor provide an additional torque to compensate the ICE drag and maintain the electric traction.

6. Results on the democar

6.1. Transition electric drive ➔ hybrid drive

As mentioned at low speed, the electric traction and the ICE restart are two separated function, as the ICE is restarted with the starter. Above 15kph, to avoid a too frequent starter use, the ICE is restarted with the transmission clutch.

As the available electric power is limited, the ICE launch is slower than full hybrids, and the boost capacity to accelerate the car while the ICE is not operational is lower too.

As a result, the ICE restart sequence compared to full hybrids is not at the same level than the full hybrid competitors.

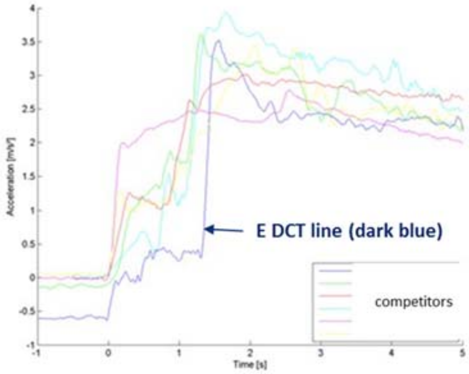


Figure 10: transition E Drive ➔ Hybrid of the 48V E DCT compared to full hybrids

Nevertheless, it was judged acceptable in particular for LCV applications as forecasted in ECOCHAMPS.

In addition, the study done to improve the power of the E Motor up to 25 kW will reduce the gap and improve the situation.

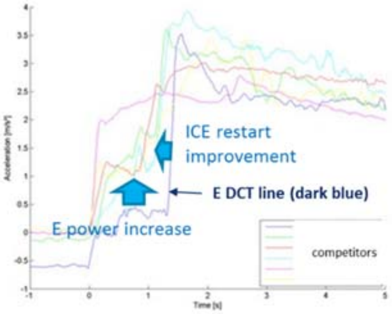


Figure 11: transition E Drive ➔ Hybrid improvement thanks to high power E motor

6.2. Emission compliance at NEDC cold conditions

The democar emissions has been measured on NEDC cycle.

Reminder of the regulation limit for Euro6b

	EURO 6b Emissions				
	HC [g/km]	CO [g/km]	NOx [g/km]	NMHC [g/km]	Particulate mass [nb/km]
NEDC Standard	0.1	1	0.06	0.068	6e12

Figure 12: NEDC Euro6b emission limits (reminder)

After tuning, the final emission results are as follow:

	Exhaust (bag)				
	HC [g/km]	CO [g/km]	NOx [g/km]	NMHC [g/km]	Particulates (Nb/km)
NEDC PT1_3020 06/11 BàR24	0.032	0.707	0.017	0.025	1.054^{E}12

Figure 13: NEDC emissions reached with the Democar

6.3. CO2 measurements at NEDC cold conditions

The raw result at bench is shown below:

	CO2 Bag	**SOC start/end**	**DCDC consumption**
NEDC PT1_3020 06/11 BàR24	111.1g/km (4.96L/100)	95% / 88%	3A

Figure 14: raw CO2 results reached at NEDC with Democar (cold condition)

Nevertheless, this value has to be corrected to take into account the battery SOC variation between the beginning and the end of the test and a deviation on the electric network balance.

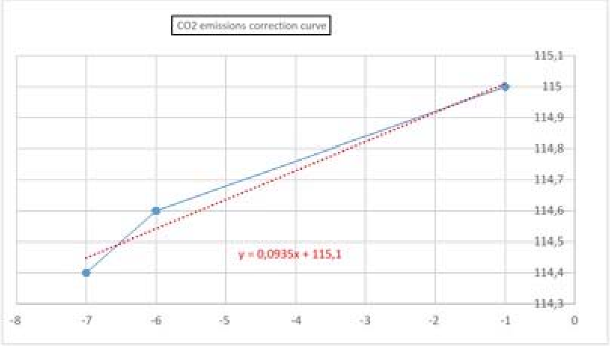


Figure 1 : CO2 correction vs battery SOC deviation

Figure 15: CO2 correction vs battery SOC deviation

Therefore, the final result is as follow:

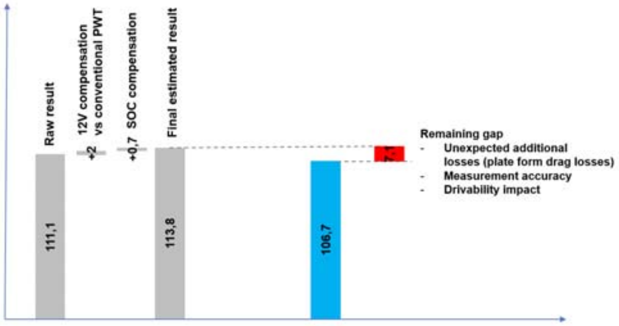


Figure 16: model change from raw NEDC results at test bed to targeted serial vehicle

The final result shows a significant gap of 7.1gr/km compared to the simulation.

Further investigations have been performed to identify the platform deviation (aerodynamic discrepancy compared to serial car, additional parasitic drag losses, tire deviation etc …) testing the democar with and without the hybrid energy management on a NEDC hot cycle.

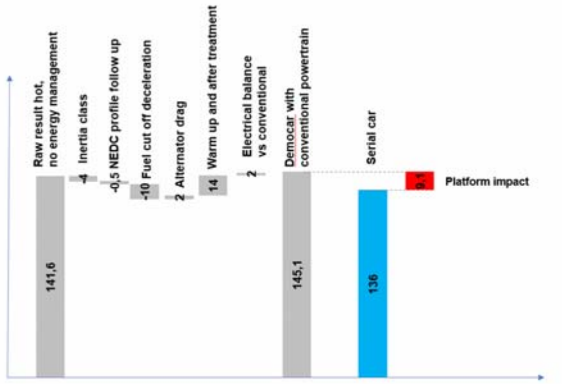


Figure 17: identification of the deviation between the democar plateform and the reference serial car

The final result shows the drag losses of the democar are higher the serial car of about 9.1 gr.

Applying this bonus to the democar, the serial car equipped with the E DCT should reach 113.8 – 9.1 = 104.7gr/km to be compared with the 106,7gr/km estimated target obtained by simulation.

This result, slightly better of 2 gr/km than expected should be tempered considering the precision of the measurements and number of correction done.
Nevertheless, it gives a strong confidence in the result and allows to rely on the commitment taken within the ECOCHAMPS project.

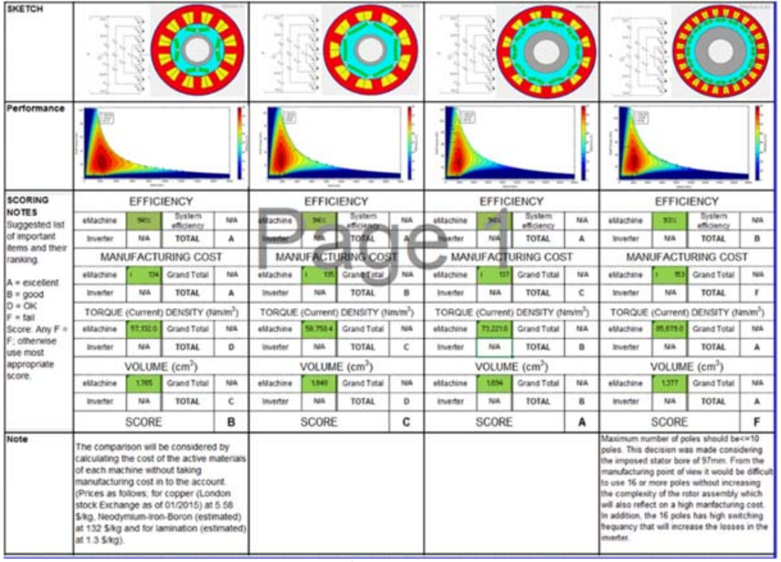
Therefore the final efficiency improvement of the powertrain can be considered as being above 27.4 %

7. Increased power EM study

As mentioned previously, the E motor power increase should close the gap between the full hybrid and the 48V hybrid for both

- Energy recovery
- Extended E Drive
- Faster transition between E drive and hybrid mode

A study was conducted to select the most appropriate E motor structure as presented below



SKETCH				
Performance				
SCORING NOTES Suggested list of important items and their ranking. A = excellent B = good D = OK F = fail Score: Any F = F; otherwise use most appropriate score.	EFFICIENCY eMachine 94% System efficiency N/A Inverter N/A TOTAL A MANUFACTURING COST eMachine 1 134 Grand Total N/A Inverter N/A TOTAL A TORQUE (Current) DENSITY (Nm/m^3) eMachine 57,132.0 Grand Total N/A Inverter N/A TOTAL D VOLUME (cm^3) eMachine 1,765 Grand Total N/A Inverter N/A TOTAL C SCORE B	EFFICIENCY eMachine 94% System efficiency N/A Inverter N/A TOTAL A MANUFACTURING COST eMachine 1 135 Grand Total N/A Inverter N/A TOTAL B TORQUE (Current) DENSITY (Nm/m^3) eMachine 58,750.4 Grand Total N/A Inverter N/A TOTAL C VOLUME (cm^3) eMachine 1,840 Grand Total N/A Inverter N/A TOTAL D SCORE C	EFFICIENCY eMachine 94% System efficiency N/A Inverter N/A TOTAL A MANUFACTURING COST eMachine 1 137 Grand Total N/A Inverter N/A TOTAL C TORQUE (Current) DENSITY (Nm/m^3) eMachine 73,221.0 Grand Total N/A Inverter N/A TOTAL B VOLUME (cm^3) eMachine 1,694 Grand Total N/A Inverter N/A TOTAL B SCORE A	EFFICIENCY eMachine 93% System efficiency N/A Inverter N/A TOTAL B MANUFACTURING COST eMachine 1 153 Grand Total N/A Inverter N/A TOTAL F TORQUE (Current) DENSITY (Nm/m^3) eMachine 85,679.0 Grand Total N/A Inverter N/A TOTAL A VOLUME (cm^3) eMachine 1,377 Grand Total N/A Inverter N/A TOTAL A SCORE F
Note	The comparison will be considered by calculating the cost of the active materials of each machine without taking manufacturing cost in to the account. (Prices as follows: for copper (London stock Exchange as of 01/2015) at 5.58 $/kg, Neodymium-Iron-Boron (estimated) at 132 $/kg and for lamination (estimated) at 1.3 $/kg).			Maximum number of poles should be<=10 poles. This decision was made considering the imposed stator bore of 97mm. From the manufacturing point of view it would be difficult to use 16 or more poles without increasing the complexity of the rotor assembly which will also reflect on a high manfacturing cost. In addition, the 16 poles has high switching frequancy that will increase the losses in the inverter.

Figure 18: comparison of E Motor structure to reach 25 kW

and led to select a 8 pole, 6 phases (2x3 phases) IPM design with a target short time rating of 25 kW.

Several prototypes were built to validate the mechanical, magnetic and thermal behaviour before starting the control definition. In parallel, several inverter were built to supply the E motor accordingly to its characteristics


Figure 12: high power E Motor prototype


Figure 13: high power inverter prototype

8. Conclusion

The study and the test conducted give a good confidence in the 48V EDCT concept for both

- Cost potential
- Integration
- Driveability
- CO2 savings

Furthermore, the power improvement forecasted should enlarge the scope of application reaching the area of the current full hybrids.

Acknowledgements

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