High specific power batteries for racing applications: The HI-ZEV vehicles

Within the “Industria 2015” Italian framework program, the HI-ZEV project has the aim to develop two high performance vehicles: the first one full electric, the second one hybrid. This paper deals with the electric energy storage (EES) design and testing of such vehicles. Different applications mean different storage: the hybrid battery storage has been designed to be able to supply the maximum power of the electric motor, without requirements in terms of energy, while the electric has the energy (and range) as main requirement

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The object of the HI-ZEV Project is the implementation of two vehicles with high performance and low environmental impact. One vehicle will be a pure electric vehicle (Zero Emission Vehicle, targeted to the United Arab Emirates market), the other one a plug-in hybrid, targeted to EU and USA market).

The final design of the hybrid prototype is a 4x4 sport car powered with an internal combustion engine (maximum power: 300 kW) at rear axle and an electric motor with a maximum power of 150 kW at front axle. It is equipped with a 400 V, 15 Ah storage system with high maximum discharge currents (up to 35 times the nominal current). The electric prototype has the same chassis, equipped with the same electric engine at front axle, but with 2 electric motors at rear axle with 100 kW each instead of the internal combustion engine (ICE) and 24 kWh of energy on-board (two batteries of 12 kWh for each axle).

Even though both vehicles have the same chassis and the same powertrain for the front axle, the energy storages have completely different requirements to be met. High specific power is the main requirement for the hybrid vehicle: it must supply all the motor power (150 kW plus losses) but there are not many requirements for energy (about 30 km in electric mode) so low energy storage can be installed on board. The electric vehicle, instead, must supply the same motor power (for example

the battery of the front axle), but the requirements in terms of energy are more important: as a result, the storages of the vehicles are totally different: 6 kWh OCCL Li-Ion batteries for the hybrid version and two 12 kWh KOKAM Li-NMC batteries for the electric one.
Since performance, cost and durability of the electric energy storage (EES) are critical for the overall feasibility, such demanding performance requires a very careful design, especially with respect to the thermal management of the Li-Io cells, very sensitive to high temperatures, also for safety reasons. Therefore a model of the storage system has been developed, simulating each module like an electric generator with more RC circuits in series. To take account of the heat transfer, a forced convection model has been used too, with the air speed proportional to the vehicle speed.
The paper reports the choice, design and preliminary testing of the EES of both vehicles; for the hybrid vehicle, the critical issue is the power response and thermal management: smaller storage systems (compared to electrics vehicles) are chosen in order to control the vehicle weight so high power request could create problems to control the module temperature. The temperature is critical also for the electric vehicle: high power has proportional losses, and forced convection is the choice for this battery.

The vehicle lay-out

The vehicle is thought of as a high-performance sports car with all-wheel drive, two seaters and careful aerodynamics. The vehicle management system has a supervisor who manages the operation of the subsystems traction& electric energy storage, and deals with the integration of torque and power.
The hybrid vehicle design was developed by studying different configurations. The schematics about arrangement of the engine are different, each with very specific characteristics [1-2].
Since the goal of the project was to have a maximum of similarity for the "pure electric" and the hybrid version, a different configuration, a "split" hybrid (Figure 1) was chosen. A split hybrid is a four-wheel traction vehicle with two independent traction systems, a conventional (based on an internal combustion engine) and an electric one. The front axle has an electric traction and the rear has a classical thermal engine configuration. The "pure electric" configuration differs in having both axes electrified.
This configuration makes mechanical installation simpler, while the handling of the torque must be careful, to avoid unpleasant effects in accelerating during cornering.
The hybrid electrical traction system consists of a 150 kW motor controlled by an inverter which also shares the liquid cooling system. The PTM coordinates messages between INV and BMS and has an important role in checking the battery status and regulates the power availability of the inverter. The cooperation strategy of the two axes is defined by a parallel-hybrid state-control, with special features in thrusting and braking. The battery modules are arranged on both sides of the vehicle, near the driver's seat, and are air-cooled.
The vehicle also has an electric parking brake installed, an electro-actuated gearbox and clutch, an electric power assisted steering and other systems that manage data logging and displaying.
The electric vehicle is a 4-wheel-drive with the chassis of the hybrid one, the same front axle, but with 2 YASA 100 kW at rear. There are two batteries (equal), each one is connected to an axle powertrain (Figure 2).
The maximum power is then 350 kW with a weight of about 1300 kg.
The Table 1 summarizes the specifications of both vehicles. A num-

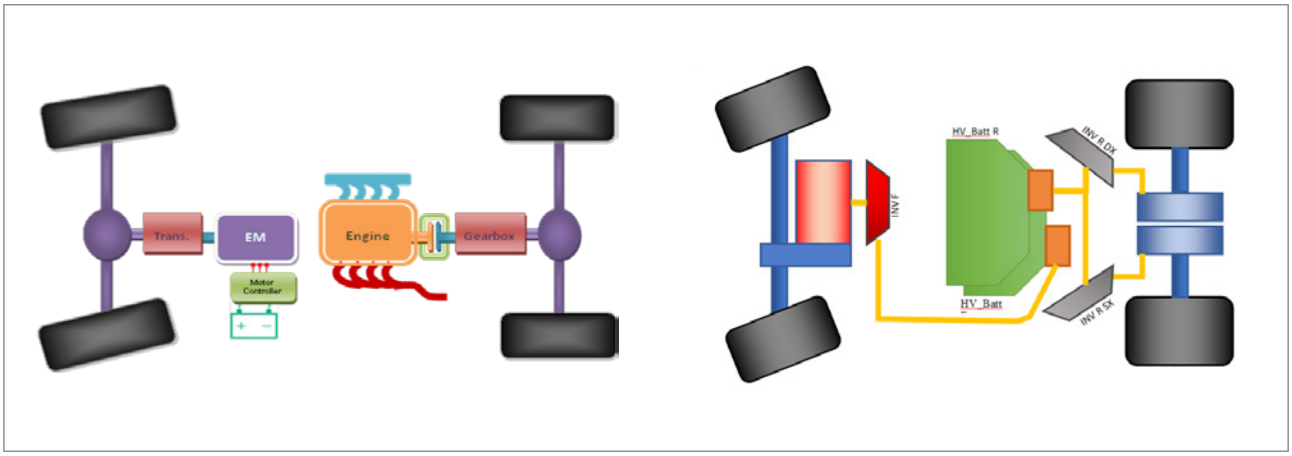

Fig. 1 and 2 Hizev hybrid layout (left) and Hizev electric layout (right)

ber of data are reserved because the design is covered by an intellectual property by the consortium owner of the project.

Different choices for the electric energy storage (EES)

Designing a vehicle all the interesting parameters need to be fixed: then the designer has to choose the ones to be used like input data, the remaining ones will be the output of a verifying session. This type of approach is correct for all electric or thermal vehicles; for example, by fixing the mass and the requested acceleration it is possible to calculate the engine output power. Then it is possible to carry on the design, compute speed, evaluate consumptions and emissions level and, finally, verify vehicle performances, put in the pre-established (design) cycles into the model [3].

For a hybrid vehicle, the designer has one more degree of freedom because it is possible to choose the way to share the (required) total power between the electric motor(s) and the thermal engine.

Moving on the extremes of the operative range, the designer can start from the diesel-electric propulsion, often used in railway and naval fields, in which the batteries have an auxiliary rule because the electric motors are fed by the motor-generator, to the "range extender" hybrids, in which the generator is very small and it is used only to recharge the batteries, that are dimensioned to power by the traction motor(s) (P) alone for the requested "pure electric" range (E).

The choice of these design parameters leads the project development to the next step. In fact, the pulse discharge power (Ppeak) and the total available energy (E), are the input to correctly design the vehicle storage system [4].

In our case, the vehicle specifications are shown in Table 2.

A P/E ratio can be calculated for any kind of storage device by dividing its specific power (W/kg) by its specific energy (Wh/kg). For instance, available traction batteries have a P/E ratio between 1 and 4, that is good for pure EV but far too low for hybrid applications.

High power Li-Io batteries offer more adequate P/E ratios, approx. 10 W/Wh, with specific power and energy of about 1000 W/kg and 100 Wh/kg. SCs benefit from higher P/E ratios exceeding 100 W/Wh since the specific power is very high, up to 1000 W/kg, and the specific energy is less than 5 Wh/kg [5].

Conceptually speaking, a storage system having the P/E ratio required by the typical mission of the considered hybrid vehicle, would have all the power needed for the cycle power peaks without storing more energy than necessary.

The normal Li-Ion cells or SC are not compliant with these characteristics. So the EES has to be composed by ultra-high power Li-Io cells, i.e. Demon OCCL.

On the basis of the previous hypotheses high-performance Li-Ion modules have been adopted, the Demon OCCL (Oxygen – Cobalt – Carbon – Li-Po) Nanotechnology with a capacity of 5 Ah.

The characteristics of such modules are compliant with the maximum power that the electric motor must supply: 70C of maximum continuous discharge current (70 times the nominal capacity, 350 A) and 5C of charge current (25 A). Every mod-

	HIZEV Hybrid	HIZEV Electric
Wheelbase	2700 mm	
Mean track	1716 mm	
Weight	1118 kg	
Front suspension	Double A-Arm, with pull rod link to the damper, torsion bar	
Rear suspension	Double A-Arm, with push rod link to damper, torsion bar	
Steering	Crank-pinion, with power assistance	
Brakes	ABS, carbon-ceramic ventilated discs	
Calipers	6 pistons on front, 4 pistons on rear	
Aerodynamics	Cx: 0.26; Flat bottom and rear diffuser	
Wheels	235/35 ZR 20 88Y/ 295/35 ZR 20 101Y	
Front Axle Power Unit	Brusa Electric 150 kw from 4300 rpm Rpm max 13000 rpm	Brusa Electric 150 kw from 4300 rpm Rpm max 13000 rpm
Rear Axle Power Unit	Rear: ICE:1750 cc 400 hp @ 8000 rpm (nominal)/max 8000	Rear: 2 YASA 100 kW
Storage	400V – 15Ah 6kWh	2 packs 400V –31Ah 12Wh

Table 1 Specifications of the vehicles

ule is composed by 6 cells in series with a nominal voltage of 22.2 V. The storage system is composed by 18 modules in series (nominal voltage: 399.6 V) and 3 in parallel (capacity 15 Ah), with a total energy of about 6 kWh. With such a storage system, the maximum discharge current (at the minimum allowable Voltage of 350 V) is 500 A, so every module has to supply 167 A (33 times the nominal capacity), below the maximum discharge current of the module.
A single module has been tested on a battery cycler in order to check if it can really work with such high currents without an excessive increase in temperature. Several tests have been made on a single module, discharging it with a constant current from 1 to 25C and re-charging it with a constant current up to 5C. The environment temperature has been controlled and set to 23 °C and the module is cooled with natural convection (Figure 3 left).
A battery thermal model has been developed in order to evaluate the modules temperature during some driving cycles of the vehicle, one is the ARTEMIS driving cycles, simulated to be run in electric mode, and the other is a racing driving cycle, run in hybrid mode. The module has a tester to calculate the OCV (Open Circuit Voltage) and the internal resistances (discharge and charge) as a function of the SOC (State of Charge).
In Figure 3 the comparison between the measured and the calculated voltages is reported, and there is good accordance between the two set of data, especially when the discharge is not too long (first discharge at 25 A, 10-40 s), while for longer discharges (400-600 s) there is a little underestimate of the internal resistance. To improve the accuracy also in this condition, a series of RC in the circuital model of the battery circuits could be useful, but for an in-vehicle application the steady-

	Requested	Unit
Electric motor peak power, P	150	kW
“Pure electric” range	30	km
Specific consumption	0.2	kWh/km
Needed energy storage, E	6	kWh
Power/Energy ratio	30	1/h

Table 2 Electric subsystem specification

state conditions are not present and then not used.
The model [1] uses an electrical circuit in which the battery is represented as an electrical generator (OCV, open circuit voltage), an internal resistance R and an RC (a resistance and a capacitor in parallel) circuit, the values of the resistance R and the RC circuits are those that best fit with the experimental data.
The model is divided into two parts: the first uses the first law of thermodynamics for a single module, to calculate the module temperature when exchanging heat with the box at different box temperatures, the second one uses the first law of thermodynamics to calculate the box temperature, taking a forced air cooling of the box into account.
In Figure 3 (right), results are reported: for high discharge currents (the module has been discharged in about 160 seconds) the thermocouples show different behaviors. In the figure the maximum and minimum values are reported: the highest one grows from 14 degrees to 34 at the end of the discharge while the lowest grows from 14 to 24. The thermal model has been calibrated with the highest value and it can be seen that there is a good accordance with experimental data.
Once calibrated the model for a single module, the complete battery pack installed on a box has been simulated using the first law of thermodynamics; it is represented as a volume with all the modules inside, with a steady-state flow that enters and exits from such volume and a heat generation due to the power losses from the modules.
To verify the performances of the storage system, two configurations have been simulated: the first running in "pure electric" with a driving cycle representative of the real vehicle usage, and the second one in hybrid mode running an "uphill race" driving cycle.
In Table 3, a summary of the results is reported. The instantaneous power supplied by the power unit (thermal engine and the electric motor) is calculated as a sum of the friction (tires), aerodynamic and inertial forces, also taking into account the driveline mechanical efficiency (0.9) and the traction motor efficiency, as reported above else in the text. In the electric mode all the power is supplied by the motor and during brakes only the 50% of the energy is recovered. In the hybrid mode, a simple model to calculate the power from the two units has been developed: the power supplied from the electrical motor is a fraction of the total, where the ratio is the ratio of the maximum electric motor power to the thermal one. In our case such ratio is 0.33: the thermal engine is 300 kW (maximum power) and the electric motor power 150 kW.
In the electric drive the ARTEMIS Driving cycles (urban, rural and motorway) have been simulated; these cycles are obtained from a large database of real driving cycles and they are much realistic than the type approval procedure driving cycle.
In Figure 4, the driving cycles are reported: the first part, the urban cycle, has lower speeds and lower power requirements, the rural part has higher values and the motorway has the highest values of power and speed (up to 150 km/h). In the electric mode the vehicle is not able to run all of the three driving cycles

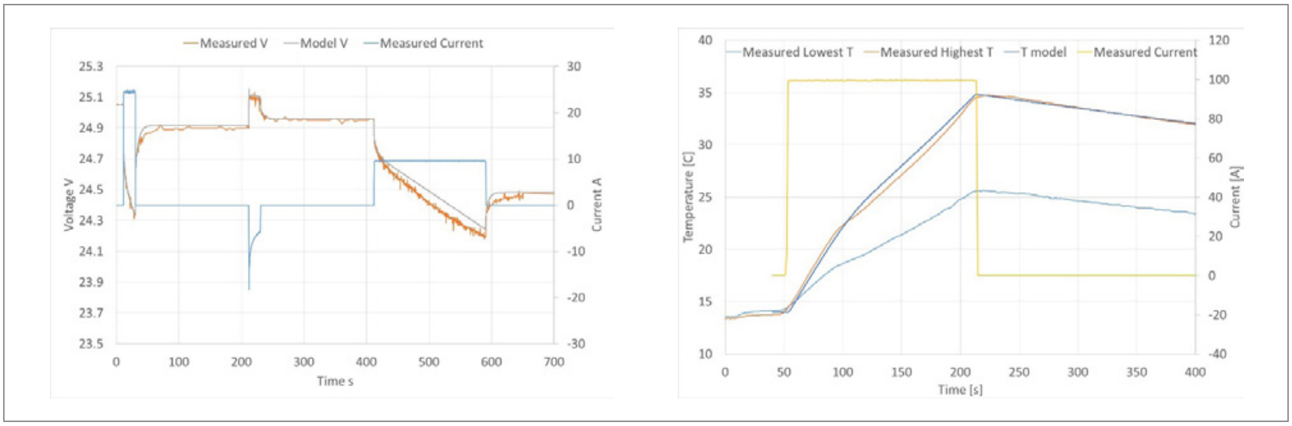

Fig. 3 Comparison between measured and calculated voltages during the test to measure the internal resistances of the module (left); Discharge at 20C current with forced convection and gas speed at 20 m/s (right)

(during the motorway part there is no more energy to continue) and the range is about 41 km (SOC limit: 10%). The average power of the cycle is about 8.6 kW so the electric storage is not much stressed by these driving cycles: the battery temperature increase is about 1 degree. The energy consumption is 126 kWh/km.

In the uphill race driving cycle, the electric motor supplies power in a fixed ratio to the thermal engine power and regenerative braking is able to send to the battery a maximum of 30 kW (only one axis has the electric traction and there is a limitation in maximum charge current, 5C i.e. 25 A). The electric average power of the cycle is more than 60 kW, much higher than that obtained on the Artemis driving cycles, therefore the maximum temperature (differential temperature of 11 degrees) is much higher, but without exceeding the limits.

The energy consumption is 0.32 kWh/km and the range is 14 km, typical for an uphill race (generally 10 km).

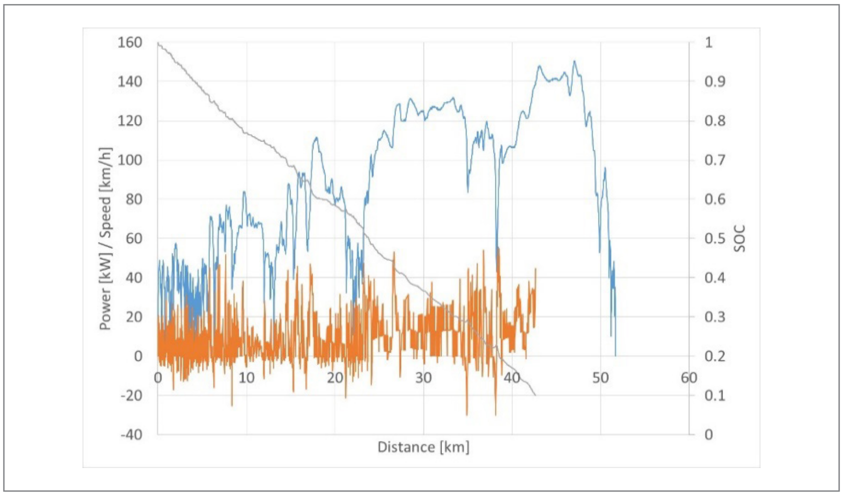

Fig. 4 Artemis Driving Cycles run in electric mode

The electric vehicle

The design phase for the electric vehicle is quite different than the hybrid one. The critical issue is no more the maximum power, but the range starts to have a big importance. The purpose of such vehicle is the uphill race, but with the possibility to run in the street with a reasonable range. An uphill race has a length of more or less 20 km run at maximum power, and for a daily usage the suggested range of the vehicle can be around 150-200 km.

With the vehicle model used also for the hybrid vehicle, a 24 kWh storage can have a range of about 180 km (on the NEDC driving Cycle) for the vehicle. The maximum power for each battery to be supplied is about 150 kW plus Losses, then a C rate Current <15.

The cell technology to guarantee such performances is li NMC produced by KOKAM and specifically the cells SLPB78216216H with the following characteristics:

	Artemis Electric	Uphill Race Hybrid
Range	41 km	14
Electric Consumption kWh/km	0.126	0.32
Delta temperature degrees	1	11
Electric Average absolute Power	8.6 kW	60.1 kW

Table 3 Summary of the results with the two solutions tested

- Capacity: 31 Ah;
- Maximum continuous discharge rate: 8C;
- Maximum pulse discharge rate: 15C;
- Energy density: 158 Wh/kg:
- Weight: 072 kg.

Each battery is then composed by 96 cells in series with a nominal Voltage of 352 V.

The HIZEV electric model has been tested on different driving cycles, starting from the NEDC and its subparts (UDC and EUDC), passing from ARTEMIS driving cycles and the WLTC, up to an uphill race driving style. The NEDC is used as a reference and the 184 km range can be assumed as a good value. However, a strong dependence on the consumption (and then range) with the driving cycle average speed can be observed: in the urban environment, there are the lowest values (0.1 kWh/km), as the speed increases the value passes to 0.141 for the EUDC driving cycle and 0.229 for ARTEMIS Motorway up to 0.721 for an uphill race (Figure 5).

Driving Cycle	Average Speed [km/h]	Range [km]	Consumption [kWh/km]
UDC	18.3	235	0.102
EUDC	64.2	170	0.141
NEDC	32.26	184	0.13
ARTEMIS Urban	17.6	181	0.132
ARTEMIS Road	57.2	179	0.134
ARTEMIS Motorway	99.7	105	0.229
WLTC Class 3	46.5	157	0.153
Race	125	33	0.721

Table 4 Consumption and range results for different driving cycles for the HIZEV electric

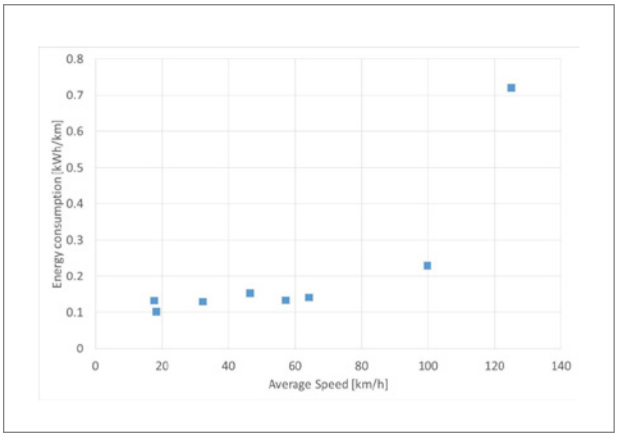

Fig. 5 Influence of the average speed on consumption for HIZEV electric

Once the cells are chosen, the cooling method has to be designed and the maximum operating temperature has to be measured.

Conclusions

Within the "Industria 2015" Italian framework program, the HI-ZEV project has the aim of developing two high-performance vehicles: one full electric and one hybrid. This paper deals with the electric energy storage design and testing.
The design of the electric storage of a hybrid and an electric high-performance vehicle has been designed and a model of the storage system has been developed, simulating each module like an electric generator with more RC circuits in series. To take account of the heat transfer, a forced convection model has been used with the air speed proportional to the vehicle speed.
Such vehicles have been simulated on different realistic driving cycles, in real world cycles, but also on uphill races. The hybrid vehicle in electric mode and an uphill race driving cycle in hybrid model have been simulated in order to check the storage system capability to satisfy the range specifications (30 km in electric mode and 10 km in hybrid mode during a race driving cycle), without exceeding temperature limits (50 degrees for the maximum temperature). The electric vehicle can have a range of 184 km during the NEDC driving cycle and run the race driving cycle for 30 km. The results have shown that for all the tested cycles the designed battery packs are able to run safely, not exceeding the limit temperature and meeting the requirements for the range; the model so developed and validated can be a useful tool in the design phase of a battery pack system.

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