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SuperLIB Project – Analysis of the Performances of the Hybrid Lithium HE-HP Architecture For Plug-In Hybrid Electric Vehicles

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Abstract

This paper represents the latest results of the FP7 European Project SuperLIB: Advanced Dual-Cell Battery Concept for Battery Electric Vehicles. The electrical characteristics of the proposed hybrid topology based on high power and high-energy cells are presented. In the framework of project, dedicated research work has been carried out in the field of characterization and modeling. From these characterization results advanced simulation models have been developed for investigation and prediction of the proposed hybrid concept in detail based on innovative simulation tool for evaluation and optimization of the power flow in the driveline.

From the simulation results have been concluded that the performances of the vehicle can be enhanced in terms of power capabilities and range extension. Then, the results also show that the abilities of the high-energy battery can be improved in terms of energy efficiency, voltage drop and heat development inside the battery.

Finally the comparative analysis illustrates that the SuperLIB hybrid architecture has several merits against the hybrid topology based on high-energy batteries and electrical double-layer capacitors in terms of weight and volume.

Keywords: High power batteries, high energy batteries, electrical double-layer capacitors, lifetime, modelling

1 Introduction

Since the beginning of the automobile era, the internal combustion engine (ICE) has been used for vehicular propulsion. In addition, motor vehicles powered by the ICE are significant contributors to air pollutants and greenhouse gases linked to global climate change [1,2]. As the global economy begins to strain under the pressure of rising petroleum prices and environmental concerns, research has spurred the development of various types of clean energy transportation systems such as Hybrid Electric Vehicles (HEVs), Battery Electric Vehicles (BEVs) and Plug-in Hybrid Electric Vehicles (PHEVs) [3,4]. But the establishment of the energy storage technology which can support the output power during acceleration, the efficient use of the regenerative energy and considerable life cycle are the critical aspects and no current battery technology can meet these often concurrent objectives [4-8].

In the last decennium Electric Double-Layer Capacitors have been considered as an interesting solution in BEVs and HEVs due to their excellent properties in the terms of power density and life cycle. However, the implementation of such system with the associated DC-DC converter is still expensive due to the high cost of the power electronics system.

In order to overcome the limitations of the battery system in BEV applications, a new project, called SuperLIB, has been launched in the framework of the European Seventh Framework Programme (FP7) addressing the combination of high energy and high power Li-Ion batteries for the enhancement of the overall system performance as presented by fig. 1, for the improvement of the battery lifetime, the reliability and the cost/performance ratio of the battery system [9,10].

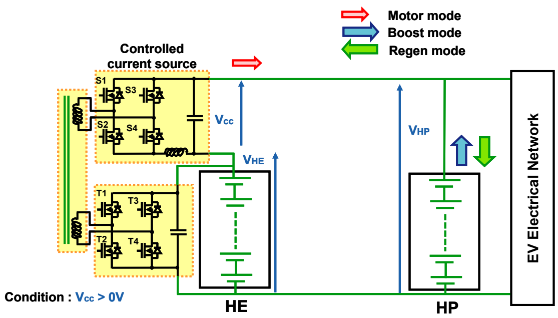

Figure 1. SuperLIB architecture concept [10]

The SuperLIB project addresses the combination of high energy and high power Li-ion batteries for the:

- Enhancement of the overall system performance,
- Improvement of the battery lifetime by 30%,
- Development of an advanced control system for the energy distribution within the battery
- Extending the useable energy content from 70% up to 90% depth of discharge,
- Development of smart control system for the highly integrated high energy/high power batteries,
- Increase of the reliability of the battery system,
- Cost/performance ratio of the battery system,

In order to achieve the above-mentioned objectives, a number of European research institutes and industrial stakeholders are involved in this project. Vrije Universiteit Brussel, which has a strong expertise in the field of modelling and estimation techniques for various rechargeable energy storage systems, together with IFPEN and Fraunhofer, will transfer the required scientific knowledge to the industrial oriented partners such as Volvo, CRF, AVL List, Bosch, European Batteries and Valeo.

2 Benchmark study battery performances

In the framework of this project, an extended benchmark analysis has been performed, assessing various lithium-ion battery performances against the performances of the SuperLIB dual cell architecture.

The SuperLIB battery architecture consists of a high-energy lithium iron phosphate battery (45 Ah) from European Batteries and high-power lithium iron phosphate battery (7 Ah) from EIG Batteries.

As we can observe in fig. 2, the SuperLIB dual cell concept has high performances in terms of power (1200 W/kg) and energy density (120 Wh/kg). Moreover, the proposed concept has the advantage that the used cell chemistry (lithium iron phosphate) is significantly safe and less expensive than other popular chemistries such as lithium nickel manganese cobalt oxide and lithium nickel cobalt aluminium oxide [8].

The energy density has been calculated based on the dynamic discharge performance load profile as indicated in the standard IEC 61892-2 from 100% SoC till 0% SoC [11]. The power performance has been investigated based on the Hybrid Pulse Power Characterization Test at 50% SoC.

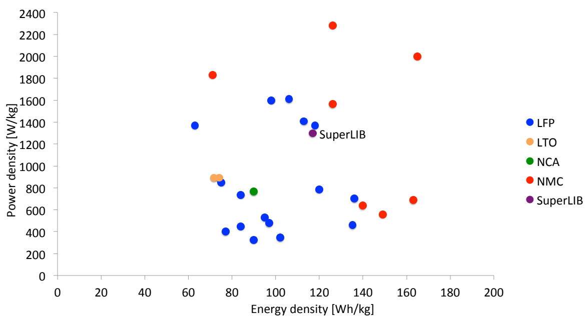

Figure 2. Comparison of various lithium-ion battery technologies against SuperLiB hybrid concept

3 Simulation model

In order to evaluate the performances of the HE-HP lithium-ion hybrid architecture, a simulation model in Matlab/Simulink has been developed as presented by fig. 3.

The simulation program is based on the “effect cause” also called the “wheel-to-energy source”. The simulation method goes upstream the vehicle components until it reaches the energy sources. It can simulate and optimize the power flow in HEVs and PHEVs.

Starting from a given speed profile, the model calculates the requested power from the energy sources.

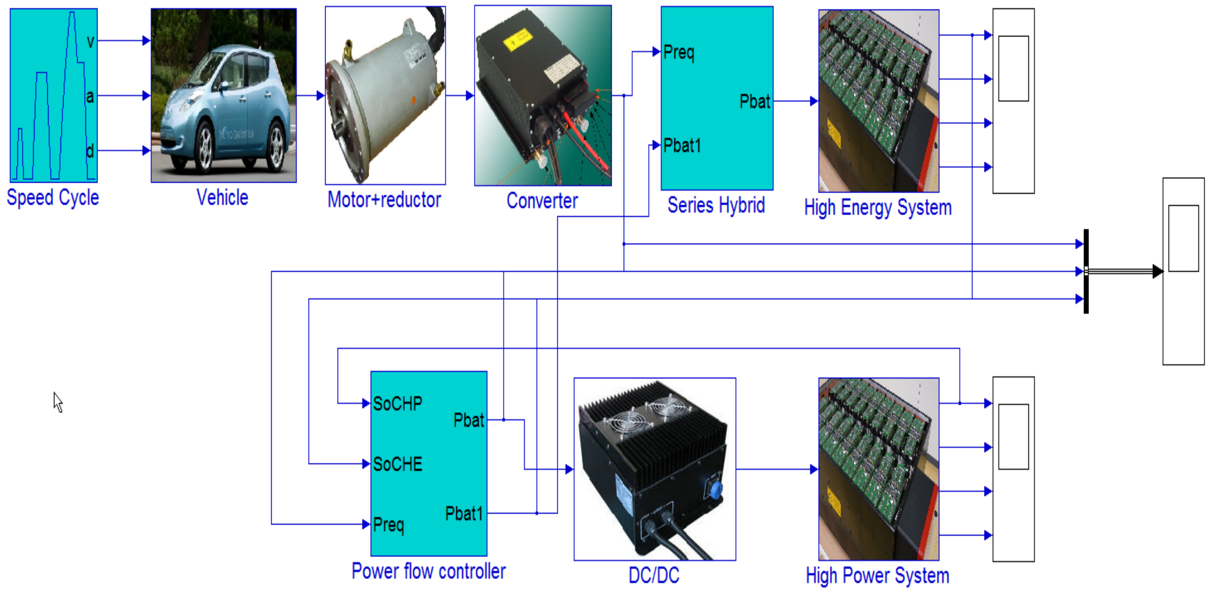

Figure 3. SuperLIB simulation model for a series hybrid electric vehicle

3.1. Battery model

The extended FreedomCar battery model as presented by fig. 4 has been used in the framework of this study. As we can observe the model exists of two variable ohmic resistances ($R_{o,ch}$ and $R_{o,dis}$), two variable polarization RC circuits composed of polarization resistances $R_{p,ch}$ & $R_{p,dis}$ and two variable polarization capacitors (C_{ch} and C_{dis}), a fictive capacitor OCV' and an open circuit voltage OCV. The indexes ch and dis represent the charge and discharge, respectively. The split up of the components in charge and discharge takes the hysteresis into account.

Furthermore, the models of the high-power and high-energy batteries include the state of charge (SoC), current rate and operating temperature dependency. This allows to investigate the power behaviour of the energy sources under different operating conditions.

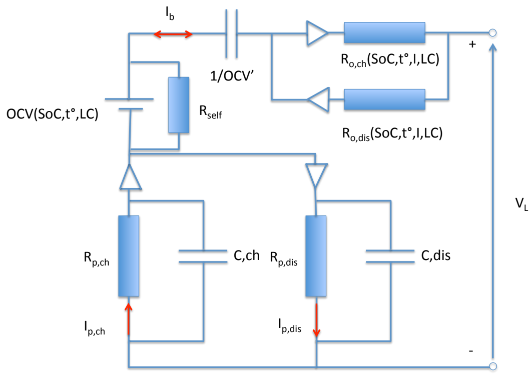

Figure 4. Extended FreedomCar battery model

The SoC has been determined based on the following relationship [12]:

$$SoC = 1 - \begin{cases} \int_{t0}^{tend,dis} \frac{I_b \cdot t_s}{C_{nom} \cdot 3600} \left(\frac{I_b}{I_{nom}}\right)^{k-1} \cdot dt & \text{if } I_b > 0 \\ \theta \cdot \int_{t0}^{tend,ch} I_b \cdot dt & \text{if } I_b < 0 \end{cases} \quad (1)$$

where I_b is the current through the battery (A), C_{nom} represents the nominal capacity of the battery (Ah), θ is the ampère-hour efficiency (%) and k corresponds to the Peukert number.

3.2. DC-DC converter

In this study, the DC-DC converter has not been simulated in detail. Since the objective of this study is to simulate the power flow in the driveline, the converter has been assigned an energy efficiency value equal to 95% as reported in [13].

3.3. Other components

Regarding the other components such as electric motor, converter and the redactor have been simulated by a fixed energy efficiency value equal to 93% [14].

3.4. Vehicle specifications

The considered vehicle in this study is Nissan Leaf. The specifications of the vehicle are presented in table 1.

Table 1. Chevrolet Volt vehicle specifications [15]

Property	Value	Unit
Vehicle mass (incl. battery)	1913	kg
Aerodynamic drag coefficient	0.287	-
Rolling resistance coefficient	0.01	-
Front area	2.16	m^2

3.5. Control strategy

In order to simulate the power flow in the proposed electric vehicle based on the SuperLIB architecture, there is a need for a dedicated control strategy for sharing the power between the high-power and high-energy battery systems.
Since the high-power batteries in the SupeLIB concept should supply the peak power during acceleration and recuperating of energy during braking events, the high-energy part is only responsible for the supply of the moving average power as presented by equations (2) and (3). Therefore in this study a control strategy has been implemented as presented in figure 5.

$$P_{high-energy} = \frac{P_{requested}}{\tau \cdot s + 1} \quad (2)$$

$$P_{high-power} = P_{requested} - P_{high-energy} \quad (3)$$

where

$P_{high-power}$: power of the high-power battery [W],
$P_{high-energy}$: power of the high-energy battery [W],
$P_{requested}$: requested power [W],
τ: time constant of the filter [s],

As we can observe, the control of the voltage of the high-power battery is carried out by implementation of a P controller, which generates an extra power signal ΔP in order to the voltage of the high-power battery to its reference value, which varies with the velocity of the vehicle. The objective of the voltage control is to be sure that the high-power battery is able to deliver power when the vehicle speed is low and to store power when the vehicle speed is high.

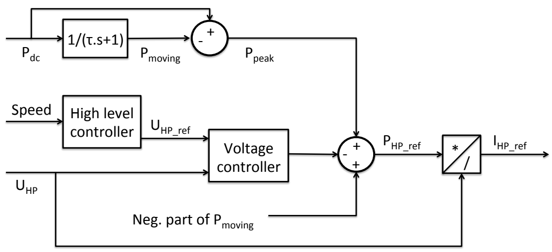

Figure 4. Implemented control strategy [16]

4 Simulation results

In order to evaluate the performances of the SuperLIB hybrid architecture against the stand-alone system and hybrid architecture existing of high-energy and EDLCs, a comparative analysis has been performed based on the New European Driving Cycle (NEDC), Highway Fuel Economy Driving Schedule (FWFET) and Federal Test Procedure Driving Cycle (FTP-75).
According to the simulation results, the hybrid architecture is able to enhance the overall vehicle system performances in terms of power capabilities as illustrated in figure 5.
As one can observe the high-energy battery only supplies the moving average, while the high-power battery acts as a peak power unit in providing peak powers during acceleration and recuperating energy during braking events. Due to this association, the energy efficiency of the high-energy battery can be enhanced from 86%, 83.6% and 86.3% (for stand-alone) to 90.2%, 86% and 88.1% (for SuperLIB hybrid architecture) based on NEDC, FTP-75 and FWFET driving cycles, respectively as can be seen in table 2.
Moreover, one can observe that the range of the vehicle based on the SuperLIB hybrid architecture can be extended by 14.2%, 18.1% and 13.2%

according to the NEDC, FTP-75 and FWFET driving cycles, respectively.
The time constant of the control strategy as presented by fig. 4 has been set up at 58s. This value has been derived based on fig. 6, whereby the range extension has been investigated at different time constants. From fig. 6, we can conclude that the highest range based on the NEDC is highest at 58s.

Furthermore, the analysis has been extended, whereby the evolution of the voltage over the high-energy battery based on the SuperLIB hybrid architecture and stand-alone has been investigated.
From this analysis we can observe that the voltage drop on the SuperLIB hybrid architecture varies between 330V and 306V against 352V and 295V for the stand-alone system.
The lower voltage drop over the high-energy battery has several advantages:

- The energy efficiency of the battery can be enhanced as illustrated in table 2,
- The heat development can be reduced due to the lower current through the battery,
- The lower voltage drop also will have a positive impact on the overall energy efficiency of the driveline and particularly on the efficient working of the electric motor [17,18],
- Due to the lower voltage drop, the battery will be able to provide longer time energy to the electric motor, which will extend the range of the vehicle as one can observe in table 2.

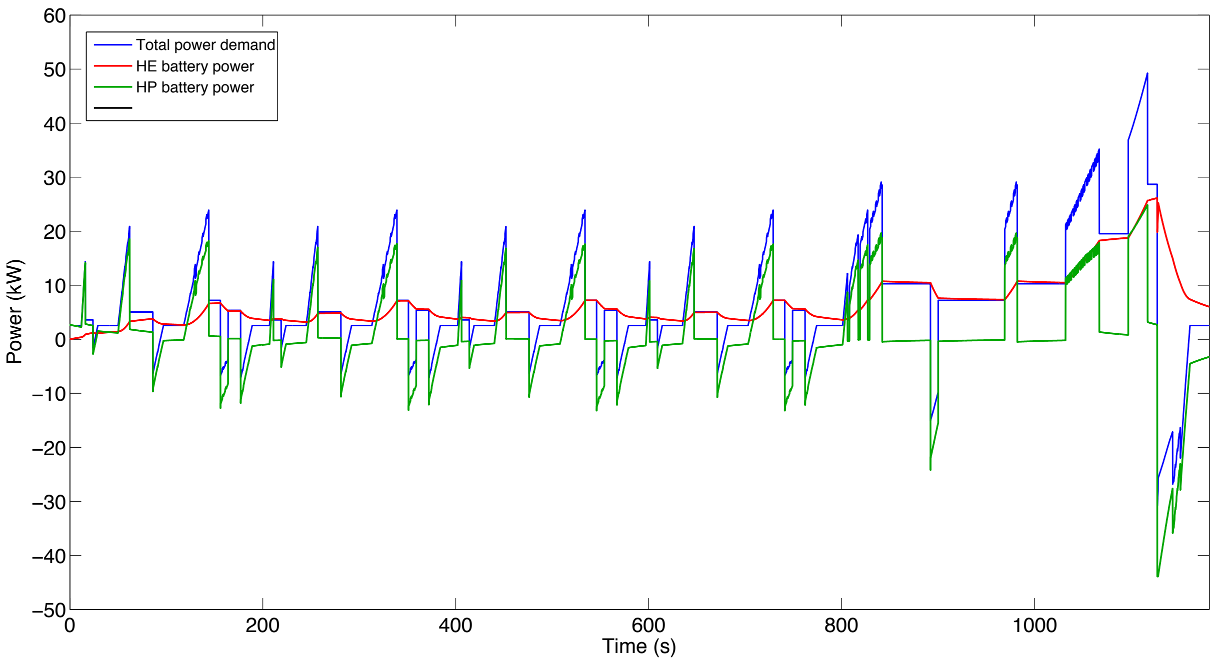

Figure 5. Power distribution between the high-energy and high-power batteries based on the New European Driving Cycle

Table 2. Simulation results based on 3 driving cycles

		AER (km)	Max & min voltage over HE battery (V)	η_{RESS} (%)
NEDC				
	Stand-alone	54,7	352-295	86,0
	HE-EDLC	57,7		92,4
	HE-HP	62,5	330-306	90,2
FTP-75				
	Stand-alone	55,1	345-294	83,6
	HE-EDLC	63,1		90,2
	HE-HP	65,1	330-313	86,0
HWFET				

Stand-alone	79,2	352-295	86,3
HE-EDLC	84,7		91,3
HE-HP	89,7	330-325	88,1

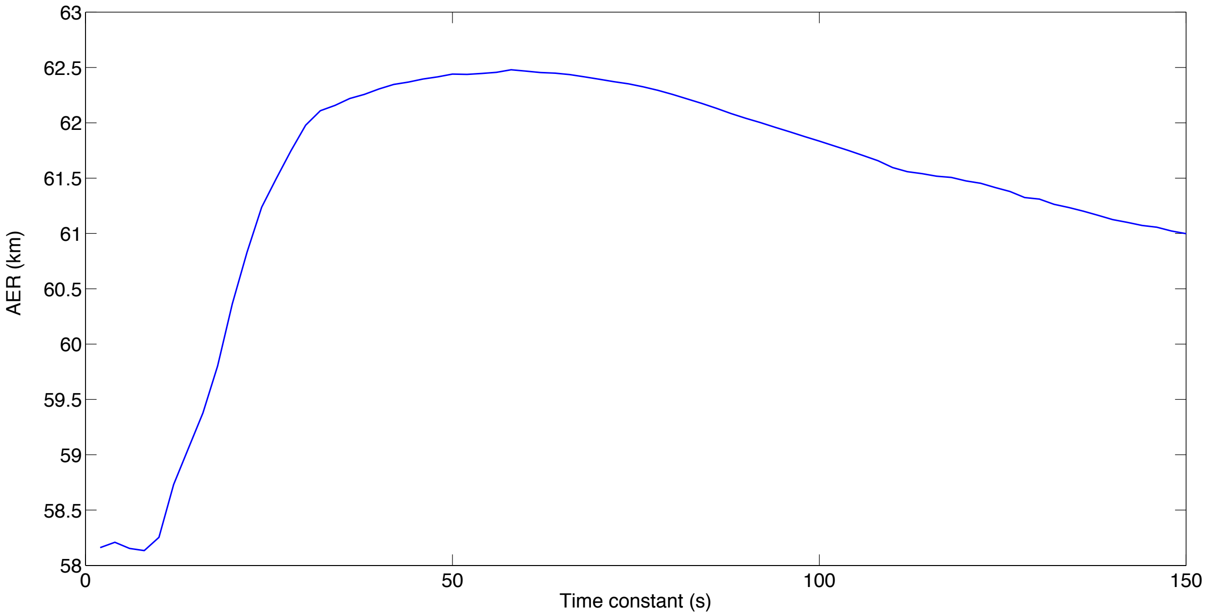

Figure 6. Evolution of the range as function of the time constant of the moving average controller strategy based on the New European Driving Cycle

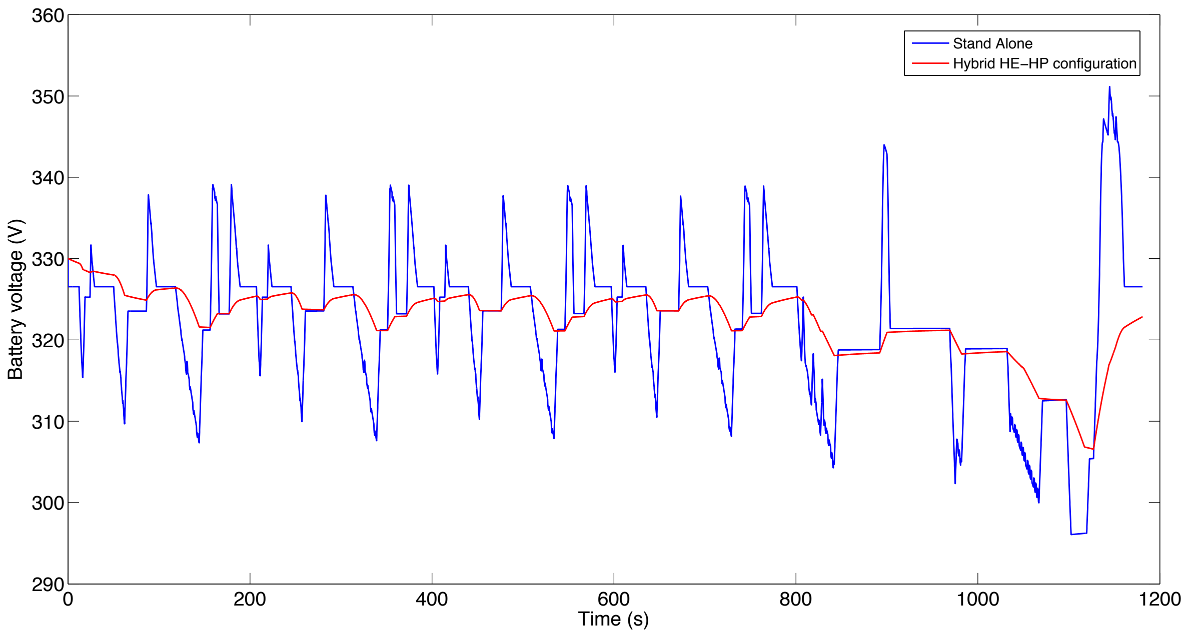

Figure 7. Evolution of high-energy battery voltage based on New European Driving Cycle

4.1. Weight & volume

In the field of electric vehicles, the weight and volume can be considered as key issues.
Therefore, in fig. 8 and fig. 9 the volume and the weight of the stand-alone, SuperLIB hybrid architecture and hybrid system composed of HE batteries with EDLCs have been compared and analysed.
In fig. 8, one can observe that the SuperLIB hybrid concept has significant advantages against the hybrid association based on HE batteries and EDLCs.
The total volume for the SuperLIB concept is $0.135m^3$ for SuperLIB concept and $0.248\ m^3$ for the other hybrid system.
These results indicate the main merit of the SuperLIB concept from the integration point of view of the energy storage systems in the vehicle.

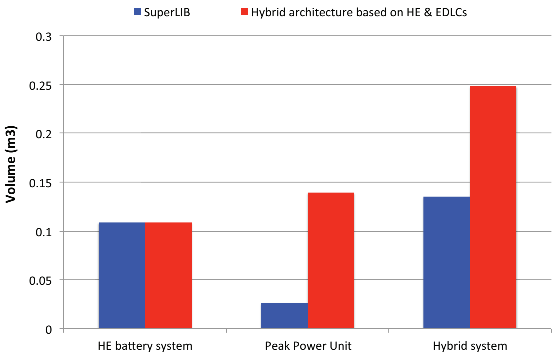

Figure 8. Volume comparison

Regarding the weight, the SuperLIB concept still shows improvement against the association HE and EDLCs. The weight of the total energy storage systems according to SuperLIB approach is 216kg against 292.7kg for the other hybrid system.
Here it should be noted that the total voltage of the EDLC system is 250V against 330V for the high-power battery system.

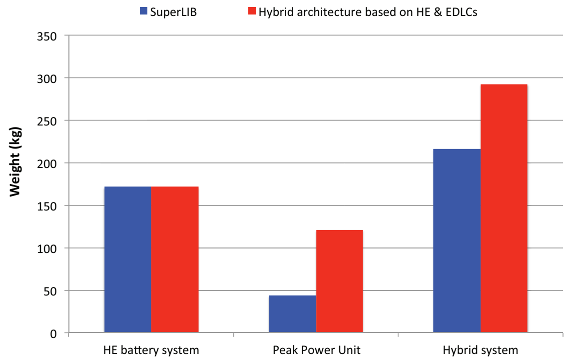

Figure 9. Weight comparison

Conclusions

In this paper, the last research results in the field of the innovative SuperLIB hybrid concept existing of high-power and high-energy are presented. Therefore, an extended benchmark study of the performances of existing lithium-ion batteries has been performed and compared to the SuperLiB dual-cell concept.
Then, a new simulation model has been developed for evaluation and optimization of the power flow in the driveline.
From the simulation results, we can conclude the that the SuperLIB approach has several merits against the conventional hybrid systems composed of high-energy and EDLCs, in terms of range extension, volume and weight, which can be considered as a key parameters in electric vehicles.

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References

[1] J. Van Mierlo, G. Maggetto, E. Van De Burgwal, R. Gense, Driving style and traffic measures influences vehicle emissions and fuel consumption, in Proceedings of the Institution of Mechanical Engineers, Part D, Journal of automobile engineering, Vol. 218, 2003, PP: 43-50

[2] J. Van Mierlo, G. Maggetto, et al., Comparison of the environmental damage caused by vehicles with different alternative fuels and drive trains in a Brussels context, in: Proceedings on the Institution of Mechanical Engineers, Part D, Journal of automobile engineering, Vol. 217, 2003, PP: 583-593

[3] J. Axsen, Burke, K. Kurani, Batteries for Plug-in Hybrid Electric Vehicles (PHEVs): Goals and State of the Technology, May, 2008

[4] N. Omar, B. Verbrugge, P. Van den Bossche, J. Van Mierlo, Power and Life Enhancement of Battery-Electrical Double Layer Capacitor for Hybrid Electric and Charge-Depleting Plug-in Vehicle Applications, Electrochimica Acta, Vol. 55, 2010, pp: 7524-7531.

[5] P. Van den Bossche, F. Vergels, J. Van Mierlo, J. Matheys, W. Van Autenboer, SUBAT: an assessment of sustainable battery technology, Journal of Power Sources, Vol. 162, 2006, pp: 913-919

[6] J. Axsen, K. S. Kurani, A. Burke, Are batteries ready for plug-in hybrid buyers, Journal of Transport Policy, Vol. 17, 2010, pp: 173-180

[7] N. Omar, M. Daowd, B. Verbrugge, G. Mulder, P. Van den Bossche, J. Van Mierlo, M. Dhaens, S. Pauwels, F. Leemans, Assessment of Performance Characteristics of Lithium-Ion Batteries for PHEV Vehicles Applications Based on a Newly Test Methodology, The 25th World Battery, Hybrid and Fuel Cell Electric Vehicle Symposium, November 5 9, 2010, Shenzhen, China

[8] N. Omar, M. Daowd, P. Van Den Bossche, O. Hegazy, G. Mulder, J. Smekens, Th. Coosemans, J. Van Mierlo, Rechargeable Energy Storage Systems for Plug-In Hybrid Electric Vehicles – Assessment of Electrical Characteristics, Journal of Energies, Vol. 5, pp: 2952-2988, 2012

[9] N. Omar, Th. Coosemans, J. Martin, V. Sauvant-Moynot, J. Salminen, B. Kortschak, V. Hennige, J. Van Mierlo, P. van den Bossche, SuperLib Project: Advanced Dual-Cell Battery Concept for Battery Electric Vehicles, EVS 26, Los Angels, 2012

[10] SuperLIB http://www.superlib.eu/ (accessed on 4 September 2013).

[11] IEC 61982-2: Secondary batteries for the propulsion of electric road vehicles - Part 2: Dynamic discharge performance test and dynamic endurance test http://webstore.iec.ch/webstore/webstore.nsf/Artnum_PK/29145 (accessed on 3 September 2013).

[12] N. Omar, Assessment of Rechargeable Energy Storage Systems for Plug-in Hybrid Electric Vehicles, PhD dissertation, Vrije Universiteit Brussel, September 2012.

[13] M. Al Sakka, J. Van Mierlo, H. Gualous, Ph. Lataire, Comparison of 30 kW DC/DC converter topologies interfaces for fuel cell in hybrid electric vehicle. In Proceedings of European Conference on Power Electronics and Applications, Barcelona, Spain, 8–10 September 2009.

[14] R. Barrero, Th. Coosemans, J. Van Mierlo, Hybrid buses: Defining the power flow management strategy and energy storage system needs. In Proceedings of the 24th International Battery, Hybrid and Fuel Cell Electric Vehicle Symposium (EVS-24), Stavanger, Norway, 13–16 May 2009.

[15] General Motors. GM Volt: specifications. http://gm-volt.com/full-specifications/ (accessed on 07/02/2013)

[16] J. Cheng, J. Van Mierlo, P. Van den Bossche and Ph. Lataire, Super capacitor based energy storage as peak power unit in the applications of hybrid electric vehicles, PEMD 2006, Ireland

[17] O. Hegazy, J. Van Mierlo, Ph. Lataire, Analysis, modeling and implementation of multidevice interleaved DC/DC converter for fuel cell hybrid vehicles. IEEE Transactions on Power Electronics Vol. 27, 2012, 4445-4458.

[18] O. Hegazy, J. Van Mierlo, Ph. Lataire, Analysis, control and comparison of DC/DC boost converter topologies for fuel cell hybrid electric vehicle applications. In Proceedings of 14th European Conference on Power Electronics and Applications, September 2011, Norway.

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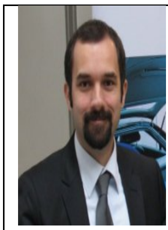

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