EVS24
Stavanger, Norway, May 13-16, 2009

Supercapacitor enhanced electric power systems for personnel transport systems

ing. Frederik Van Mulders[1], ing. Noshin Omar[2], ing. Bavo Verbrugge[1]
prof. dr. ir. Joeri Van Mierlo[2], prof. dr. ir. Peter Van den Bossche[1]
[1] *Erasmushogeschool Brussel, IWT, Nijverheidskaai 170, B-1070 Anderlecht, fvmulder@vub.ac.be*
[2] *Vrije Universiteit Brussel, IR-ETEC, Pleinlaan 2, B-1050 Elsene*

Abstract

As energy efficiency becomes one of the key points in the design of most of today's power hungry applications, new and energy efficient approaches and associated technologies find their way towards the customer. Electric double layer capacitors, also known as supercapacitors, are one of these new and interesting products creating new possibilities and solutions to some of today's questions concerning energy efficiency in certain applications. This paper will have a look at the implementation of supercapacitors as peak power unit and energy reservoir in personnel transport system applications, particularly elevator applications. Elevators were and still are built with an energy dissipating resistor to convert the electric braking energy into heat. In the present energy saving economy, this sounds as an inappropriate loss of energy requiring an alternative.

Current research involves the use of supercapacitors in elevators to replace this energy dissipating resistor and store the energy in supercapacitors. The saved and stored energy can then be reused to power the elevator (e.g. smooth power peaks) or to send energy back to the main power net. This paper presents a basic simulation model along with comments on the supercapacitor pack dimensioning. A cost-benefit analysis, based on the rudimentary model and measurements, concludes the paper.

Keywords: EDLC, regenerative braking, energy recovery, electric drive

1 Introduction

A typical traction system consists of two main components, an energy reservoir (e.g. a battery or generator) and an energy converter (e.g. an electric motor). In many cases traction systems are subjected to dynamic loads so the energy converter should be able to deliver the required energy at any time. If only one energy reservoir is available, optimal use becomes difficult. In order to respond to energy peak demands these energy reservoirs are often overdimensioned, resulting in suboptimal energy yield in regime conditions.

Energy reservoirs are defined by two key parameters, the energy density and the power density. Ideally an energy reservoir should offer both a high energy and a high power density. A typical energy reservoir has a high energy density, but a limited power density, whereas new components, such as supercapacitors, offer low energy, but high power density [1]. Supercapacitors are electrochemical energy storage components and offer new solutions in various

applications. Combining supercapacitors with a relatively low power energy reservoir could result in a more efficient energy storage system.
In systems using a battery as energy storage unit, the use of a supercapacitor peak power unit could result in significant improvements [2]. As traction batteries were designed for low power density applications, high load conditions result in large internal losses and short cycle-life. Because a supercapacitor unit can be used to relieve the battery system from peak loads, the battery unit can be dimensioned and optimized for regime load conditions, resulting in better energy management and longer battery cycle-life. Furthermore, the supercapacitor unit has an added bonus because not only can it supply high-power peak demands, it can also be charged very quickly. This energy can come from the available energy reservoir, the battery, or from the traction system working as a generator. This energy saving regenerative feature can be applied wherever braking energy (in vehicles, elevators, etc.) can be recovered.

Batteries have a high energy density, but a limited power density, whereas supercapacitors offer low energy, but high power density, as shown in Figure 1 [3].

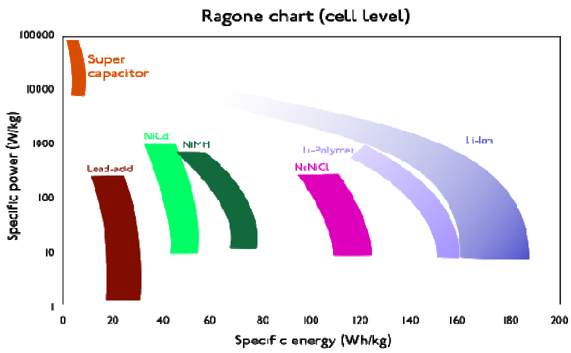

Figure 1 - Ragone chart comparing battery types and supercapacitors [3]

Furthermore a battery's life cycle is very limited compared to the long life cycle of a supercapacitor [4]. It would thus be convenient to create a combination with both a potential high power and energy density, as well as a longer life cycle.
Key point when using supercapacitors in an energy system is the usable energy. The total energy stored in a capacitor, E_{tot}, is a product of the capacitance, C, and the square of the voltage, U:

$$E_{tot} = \frac{1}{2} C \cdot U^2$$

In a practical energy-storage system that combines batteries and supercapacitors, the supercapacitor's total stored energy will almost never be fully used due to the fact that the converter necessary to accommodate such a wide potential difference range would be too complex for most applications. Moreover, when discharging a supercapacitor to 50% of its state of charge (SoC) voltage, already 75% of the energy stored in the supercapacitor will have been released. With the addition of the necessary voltage boundaries, the usable energy is given by:

$$E = \frac{1}{2} C \cdot U_{max}^2 - \frac{1}{2} C \cdot U_{min}^2$$

The useful stored energy of the supercapacitor is defined by the potential difference. For optimal use of the available energy, a two-way DC-DC converter between the supercapacitor unit and a DC-bus is advisable.

2 Usage in personnel transport systems

The proposed paper will have a look at the implementation of supercapacitors as peak power unit and energy reservoir in personnel transport system applications, particularly elevator applications. The solutions are however relevant for all electric and hybrid drive systems where energy efficiency is desired and where energy losses may be alleviated through the introduction of power-oriented electricity storage systems.

Elevators were and still are built with an energy dissipating resistor to convert the electric braking energy into heat, as illustrated in Figure 2. In the present energy saving economy, this sounds as an inappropriate loss of energy requiring an alternative.

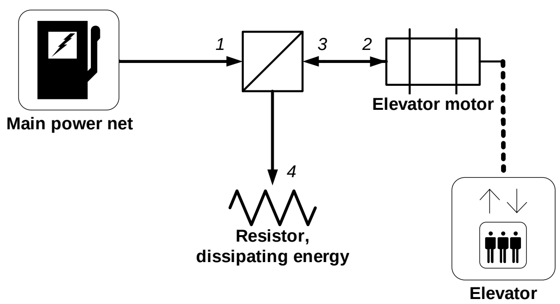

Figure 2 – The configuration of a conventional elevator

Current research involves the use of supercapacitors in elevators to replace the energy dissipating resistor and thus store the energy in the supercapacitors, as illustrated in Figure 3. This saved and stored energy can then be reused to power the elevator (e.g. smoothing power peaks) or to send energy back to the main power net. The use of supercapacitors instead of batteries is dictated by the expected lifetime of the elevator systems and the number of charge/discharge cycles [5, 6].

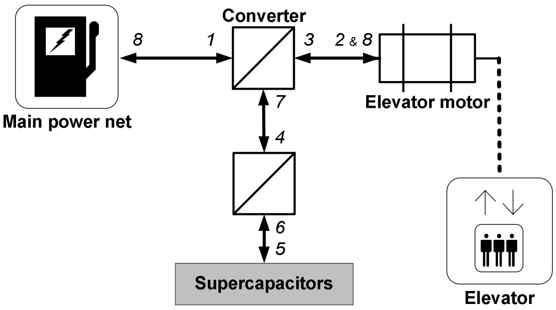

Figure 3 – The configuration of the alternative elevator

Previous research by A. Rufer concerning the use of supercapacitors in elevators stated that *"Considerable improvements can be achieved with respect to the power demand of such a system from the primary distribution network"* [7, 8]. While the results were based on a car elevator, this paper will focus on different passenger elevators for several environments.

Example measurements of the dissipated energy in the resistor of an available elevator (12.7kW synchronous motor, 1120kg cage, 1620kg counterweight and 1150kg lift capacity or 12 people) over travelling several floors are represented in Figure 4.

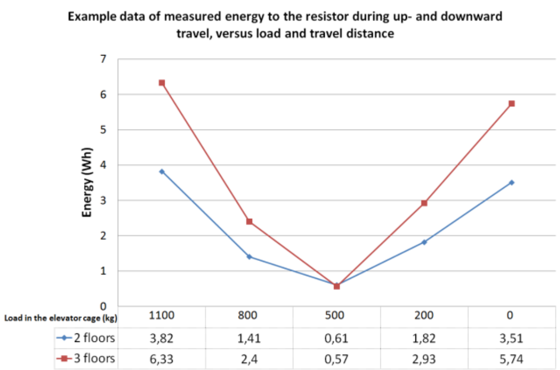

Figure 4 – Energy dissipated in the elevator resistor during up- and downward travel, versus load and travelled distance

These are small energy amounts, but when travelling over more floors, a heavy use cycle and/or load profile, the amount of energy that can be recycled over time becomes interesting.
These different load profiles and usage cycles of a passenger elevator need to be taken into account when dimensioning a supercapacitor pack for the elevator (e.g. the use of an elevator in a hospital is different from the use of an elevator in a typical office building).

The paper will present a simulation model along with comments on the supercapacitor pack dimensioning. A cost-benefit analysis, based on the rudimentary model and measurements, concludes the paper.

3 Methodology and elaboration

Figure 2 already illustrated the energy path for a conventional elevator. Figure 3 illustrated the energy path of the proposed alternative setup. In this setup the energy can flow to the supercapacitors (through points 3, 4 and 5) where it can be stored and, if necessary, energy can be withdrawn (6 and 7), which can be used to power the motor or to be send back to the mains.

Points of interest are the amount of energy that can be stored in the supercapacitors and the amount of usable energy present after discharge at the input of the motor controller (7).

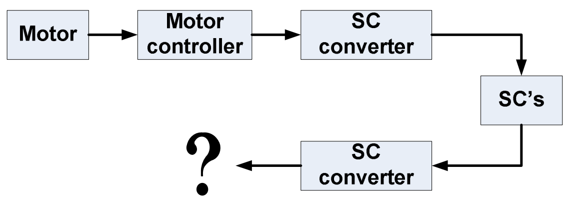

Figure 5– Energy path at generator working point of the elevator motor in the proposed alternative structure

Figure 5 illustrates the primary obstacles the energy must travel through (each with their own efficiency) to reach the motor controller where this energy can be utilized according to a certain predefined and situation dependent strategy (illustrated by the question mark and not the subject of this paper).

The energy dissipation resistor in the conventional structure was replaced by a supercapacitor converter and packet. The example measurements, illustrated in Figure 4, were performed at the input of the resistor and are the base for the calculation of the braking energy at the motor controller output. So it is safe to state that at least the same amount of energy can be presented at the input of the supercapacitor convertor input.

3.1 Energy equilibrium and efficiency of the supercapacitor unit

$$V_{SCpack,\max} = \%_{high} \cdot n_{cells} \cdot V_{cell,\max}$$

$$V_{SCpack,\min} = \%_{low} \cdot n_{cells} \cdot V_{cell,\max}$$

$$C_{tot} = \frac{C_{cell}}{n_{cells}} \text{ (if all cells are series connected)}$$

$$E_{SCpack,tot}(Joule) = \frac{1}{2} C_{tot} \left(V_{SCpack,\max}^2 - V_{SCpack,\min}^2 \right)$$

$$E_{SCpack,tot}(Wh) = \frac{E_{SCpack,tot}(Joule)}{3600}$$

Of course, one must not forget to check if the selected supercapacitors are a match for the delivered or demanded currents. For this purpose one can consult the supercapacitor's datasheet.

3.2 The case study

This simple and preliminary case study analyses several configurations to check when (in years) a break-even point in costs and benefits can be reached.

Ideally measurements or statistical data about the occupation and frequency of the elevator rides would be at hand for cases such as office buildings, hospitals and others. As these data were not at hand, this case study will only comply with a primitive elevator cycle. This cycle mainly consists of an elevator with constant load travelling between the same floors.

Also the inclusion of load in time could be interesting (e.g. no usage at night, in the morning the elevator travels up loaded and down unloaded (no recuperation), is then used little and by the end of a working day travels down loaded and up unloaded (lots of energy recuperation possible)).

As not to overcomplicate this problem, this stage of research will only analyse the effect of a monotone elevator travelling profile.
Generally all mass going up has to go down over the same number of floors. Only the division over time can be irregular.
Also, this case study will not incorporate a thorough cost-benefit analysis including simulations of interest rate, maintenance costs, variations in energy cost, etc.

Since only the energy to the dissipating resistor was measured to serve as an example, other parameters will be estimated to the best of our ability to have an idea regarding costs (e.g. cost of the supercapacitor installation, load in the elevator, elevator cycle profile, etc.).

At first only one case is studied. It will give a first indication of the recoverable energy, being the energy that can be offered to the motor controller. The long term cost benefit effect can then be assessed. If this analysis comes up too negative, further research might be unnecessary.

The remainder of this paper will elaborate the following points (to be concluded by the most important point):

- After how much supercapacitor pack cycles will the break-even point in cost-benefit be reached?
- With what time span does this correspond (after how many years the break-even point is reached)?
- For a given period, how much supercapacitor cycles will be done (this must be smaller than the maximal possible amount of cycles, specified in the supercapacitor's datasheets)?
- After a given period, how much energy (kWh), and thus euro, can be saved?

3.2.1 After how much supercapacitor pack cycles will the break-even point in cost-benefit be reached

The number of elevator movements during one supercapacitor cycle (to completely charge them) is given by:

$$n_{displ,SCfull} = 2 \cdot \frac{E_{SCpack,tot}(Wh)}{E_{\text{brake,measurement, at load x kg}} \cdot \eta_{converter}}$$

Given the assumption that what goes up, must also come down using the same elevator load, only in one of both cases energy can be recuperated. To compensate this, the formula above was multiplied by two (so one brake action corresponds with two displacements).
The total energy output of the supercapacitor converter after charging, storage and discharging is given by:

$$\mathrm{E}_{\text{tot,out}}/_{\text{SC cyle}} = E_{SCpack,tot}(Wh)\cdot\eta_{converter}$$

$$\text{or} \quad \frac{n_{displ,SCfull}}{2}\cdot E_{\text{brake,measurement, at load x kg}}\cdot\eta^2_{converter}$$

A break-even point in cost-benefit is reached when the costs and earnings become equal:

$$Cost = Earnings$$

The total energy, after input and storage, which can be output by the supercapacitors with converter, is given by:

$$\mathrm{E}_{\text{tot,out,breakeven}}(kWh) = \frac{n_{SCcycles,breakeven}\cdot E_{SCpack,tot}(Wh)\cdot\eta_{converter}}{1000}$$

In this formula $n_{\text{SCcycles,breakeven}}$ is the number of supercapacitor cycles needed to reach the break-even point. This is an unknown parameter that can be found by the completion of:

$$Earnings = \mathrm{E}_{\text{tot,out,breakeven}}(kWh)\cdot \mathrm{E}cost\left(€/_{kWh}\right) = Cost$$

This gives:

$$n_{SCcycles,breakeven} = \frac{1000\cdot €_{\text{cost installation}}}{E_{Cpack,tot}(Wh)\cdot\eta_{converter}\cdot \mathrm{E}cost\left(€/_{kWh}\right)}$$

3.2.2 After how much time the break-even point is reached

$$t_{n_{SCcycles,breakeven}} = n_{SCcycles,breakeven}\cdot t_{1SCcycle} = n_{SCcycles,breakeven}\cdot t_{n_{displ,SCfull}}$$

$$t_{n_{displ,SCfull}} = n_{displ,SCfull}\cdot t_{1displ}$$

$$t_{1displ} = t_{\text{1displ,at load x kg,from measurements}} + \mathrm{t}_{\text{buffer, load- \& unloadtimes}} + \mathrm{t}_{idle}$$

The time after which the break-even point is reached is thus given by:

$$t_{n_{SCcycles,breakeven}} = n_{SCcycles,breakeven}\cdot n_{displ,SCfull}\cdot t_{\text{1displ}}$$

$t_{\text{ndispl,SCfull}}$ is a time that should be limited. The longer energy is stored on a supercapacitor, the bigger the losses will be due to the self discharge of the supercapacitors.

3.2.3 For a given period, how much supercapacitor cycles were done

$$t_{1SCcycle} = t_{n_{displ,SCfull}}$$

$$n_{SCcycles} = \frac{t}{t_{n_{displ,SCfull}}}$$

(must be < $n_{SCcycles,\max}$, see datasheets SC's)

As the lifespan of supercapacitors is in part determined by the number of cycles they do, the supercapacitor’s datasheets mentions a maximal number of cycles. The value of n_{SCcycles} should not be greater than this maximum. If it is bigger, the supercapacitor pack could be enlarged so $E_{\text{SCpack,tot}}$ increases and the supercapacitor pack will not be fully charged as quickly and consequently do less cycles.

3.2.4 After a given period, how much energy (kWh), and thus euro, can be saved

$$\mathrm{E}_{\text{tot,out}}(kWh) = \frac{n_{SCcycles}\cdot E_{SCpack,tot}(Wh)\cdot\eta_{converter}}{1000}$$

$$Earnings = \mathrm{E}_{\text{tot,out}}(kWh)\cdot \mathrm{E}cost\left(€/_{kWh}\right) - Cost$$

4 Results based on the example measurements

Figure 6 illustrates the results in case of intensive use of the elevator over three floors with zero load in the elevator cage (= much recuperation when the elevator goes up). In this case there were three levels of intensity defined (t_{idle}=):

- 15 seconds, corresponds to intensive usage, 12 hours a day
- 45 seconds, corresponds to intensive usage, 6 hours a day
- 185 seconds, corresponds to intensive usage, 1,8 hours a day

The total installation cost was roughly estimated as followed:

$$Cost = n_{cells} \cdot C_{cell} \cdot Cost/_{Farad} + Cost_{converter}$$

Assuming the cost per Farad at 0,01€ and the cost of the converter (and possibly other installation costs) at 1500€. Other default values used during the calculations are indicated in the abbreviations list. Ideally (and quite realistically) the elevator motor controller can be refitted to work also as supercapacitor pack converter (at minimal cost). So, the break-even point could be reached much faster.

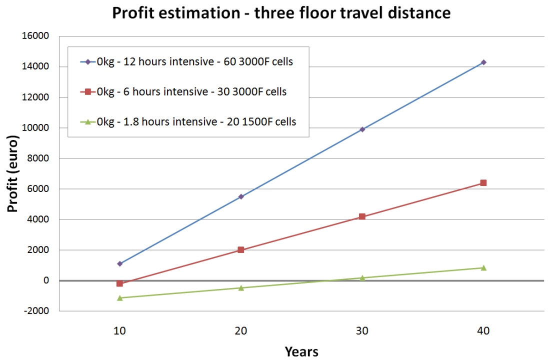

Figure 6 – Profit estimation for 0kg load at three intensity levels over three floors.

5 Provisional conclusion

The case studies, which were based on very simple assumptions and calculations, show that in certain cases there is a possibility to make financial profit by using supercapacitors. The only problem is whether the period after which the break-even point is reached, is acceptable or not.
Future work based on better data, such as data incorporating dynamic (realistic) elevator usage profiles and better calculation of the costs concerning installation, simulations of interest rate, maintenance costs, variations in energy cost, etc. should enable the creation of a more realistic model and should give a clearer view on the use of supercapacitors in elevator systems.

The case study also indicates the importance of the load cycle. The bigger the elevator movement, the bigger the recuperations and the bigger the profits get. But, on the other hand, this results in larger and more costly supercapacitor packs (to limit the number of cycles).
The use of one supercapacitor pack in an elevator system consisting of more than one elevator could also prove interesting. In such a case the pack will also be bigger and more expensive. Whether or not and for which load profiles such a setup is technically and economically interesting has to be examined.

Acknowledgments

Close cooperation with one elevator manufacturer, Coopman Liften, ensured realistic simulation results and a possible future practical implementation of a supercapacitor enhanced elevator system.

6 Abbreviations

In order of appearance (default values used during the calculations are indicated between [..]):

SC supercapacitor

$V_{SCpack,\max}$ maximal voltage of the SC packet (V)

$V_{SCpack,\min}$ minimal voltage of the SC pachet (V)

$\%_{high}$ maximal state of charge of a SC packet or cell [0.95]

$\%_{low}$ minimal state of charge of a SC packet or cell [0.5]

n_{cells} number of SC cells (in series) in a packet

$V_{cell,\max}$ nominal voltage of a SC cell (see datasheet cell) (V) [2.7V]

C_{cell} capacity of a SC cell (F)

C_{tot} total capacity of a SC packet (with the cells connected in series) (F)

$E_{SCpack,tot}$ total energy that can be stored in the SC packet (Joule or Wh, as indicated)

$n_{displ,SCfull}$ number of elevator displacements needed to fully charge the SC packet

$E_{\text{brake,measurement, at load x kg}}$ measured brake-energy at a certain load (sum of values up- and down movement) (Wh)

$\eta_{converter}$ efficiency of the SC converter [0.9]

$\mathrm{E}_{\text{tot,out}} / _{\text{SC cycle}}$ the total energy the SC packet and converter could deliver after one discharge (Wh)

$Cost$ cost of the installation (e.g. hardware, maintenance, etc.) (€)

$Earnings$ earnings based on the recovered energy (€)

$\mathrm{E}_{\text{tot,out,breakeven}}$ total energy derived from the SCs between start and break-even point (kWh)

$n_{SCcycles,breakeven}$ number of SC charge and discharge cycles between start and break-even point

E$cost$ Energycost (€/kWh)

$t_{n_{SCcycles,breakeven}}$ time needed to reach $n_{SCcycli,breakeven}$ (s)

$t_{1SCcycle}$ time needed to fully charge the SC packet, being one charge and discharge cycle (s)

$t_{n_{displ,SCfull}}$ time needed to reach $n_{verpl,SCvol}$ (s)

t_{1displ} calculated and adjusted time for one elevator displacement (across n pre-defined floors) (s)

$t_{\text{1displ,at load x kg,from measurements}}$ measured time for one elevator displacement (across n pre-defined floors) (s) [10s]

$\mathrm{t}_{\text{buffer, load- \& unloadtimes}}$ geschatte tijd nodig voor het in- en uitstappen of in- of ontladen van de lift (s) [5s]

t_{idle} estimated time an elevator (on average, e.g. on daily base) idles between two displacements (s)

t chosen time over which an analysis is desired (s)

$n_{SCcycles,\max}$ maximal number of SC cell of packet cycles, to be found in the datasheet

$\mathrm{E}_{\text{tot,out}}$ total energy derived from the SCs between start and chosen time t (kWh)

References

[1] R. Kötz, M. Carlen, *Principles and applications of electrochemical capacitors*, Electrochimica Acta, The Journal of the International Society of Electrochemistry, ISSN 0013-4686, Volume 45, Number 15, 3 May 2000, pp. 2483-2498(16).

[2] Faggioli E.; Rena P.; Danel V.; Andrieu X.; Mallant R.; Kahlen H., *Supercapacitors for the energy management of electric vehicles*, Journal of Power Sources, ISSN 0378-7753 ,Volume 84, Number 2, December 1999, pp. 261-269(9).

[3] 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, nr. 2, pp. 7, 2006, Impact factor: 2.770, impact year: 2005.

[4] J. Van Mierlo, Simulation software for comparison and design of electric, hybrid *and internal combustion vehicles with respect to energy, emissions and performances*, PhD thesis promoted by Gaston Maggetto, Vrije Universiteit Brussel, 2000

[5] A. Burke, *Comparisons of lithium-ion batteries and ultracapacitors in hybrid-electric vehicle applications*, EET-2007 European Ele-Drive Conference, Brussels, Belgium, 2007

[6] O. Bohlen, D. Uwe Sauer, *How to achieve the maximum lifetime for supercapacitors - A quantitative analysis of cell balancing systems and a proposal for improved cell protection concepts*, EVS-22 Yokohama, Japan, 2006

[7] A. Rufer, *A supercapacitor-based energy-storage system for elevators with soft commutated interface*, IEEE transactions on industry applications, vol. 38, no. 5, 2002

[8] P. Barrade, A. Rufer, *Supercapacitors as energy buffers : a solution for elevators and for electric busses supply*, PCC 2002 : Power Conversion Conference, Osaka, Japan, 2002

Authors

Frederik Van Mulders graduated in 2005 as a Mechanical Industrial Engineer at the Erasmus University College Brussels and was invited to be a PhD student at the ETEC-department for the Vrije Universiteit Brussel and the Erasmus University College Brussels. There, his main research covers supercapacitor based peak power units.

Noshin Omar was born in Kurdistan, in 1982. He obtained the M.S. degree in Electronics and Mechanics from Hogeschool Erasmus in Brussels. He is currently pursuing the PHD degree in the department of Electrical Engineering and Energy Technology ETEC, at the Vrije Universiteit Brussel, Belgium. His research interests include applications of supercapacitors and batteries in HEV's

Bavo Verbrugge received his Masters degree in industrial engineering in 2007. After which he started as a PhD. candidate at the free University of Brussels (VUB), where he's currently performing research on integrated modelling of batteries and EDLC's.

Joeri Van Mierlo obtained his PhD in Engineering Sciences from the Vrije Universiteit Brussel. Joeri is now a full-time lecturer at this university, where he leads the ETEC research team on transport technology. His research interests include vehicle and drive train simulation, as well as the environmental impact of transportation.

Peter Van den Bossche graduated as civil mechanical-electrotechnical engineer from the Vrije Universiteit Brussel, and got involved in the research activities on electric vehicles at that institution. Since its inception in 1990, he has been coordinating the international association CITELEC, more particularly in the field of electric and hybrid vehicle research and demonstration programmes. Furthermore, he has a particular research interest in electric vehicle standardization issues on which he finished a PhD work.