Effectiveness of Supercapacitors as Power-Assist in Pure EV Using a Sodium-Nickel Chloride Battery as Main Energy Storage

Giuseppe Guidi[1], Tore M. Undeland[1], Yoichi Hori[2]

[1]*Norwegian University of Science and Technology, Dept. of Electric Power Engineering*
O.S. Bragstads plass 2E, 4etg., 7491 Trondheim, Norway
giuseppe.guidi@elkraft.ntnu.no
[2]*The University of Tokyo, Institute of Industrial Science, hori@iis.u-tokyo.ac.jp*

Abstract

The use of hybrid energy source on board of electric vehicles has been proposed and analyzed extensively in the literature. This paper focuses on the simultaneous use of energy-dense Sodium-Nickel Chloride (ZEBRA) battery and power-dense Supercapacitors on board of a small pure electric vehicle intended for city use, like the Norwegian Th!nk EV. The behavior of the vehicle has been simulated according to several standard drive cycles, highlighting the effect of the hybridization of the energy source. It is shown that the main effect of hybridization is a considerable reduction of losses within the battery with consequent lifetime extension of the expensive and normally short-lived battery. On the other hand, driving range extension does not appear as a good reason for hybridization.

Keywords: Electric Vehicle, Sodium-nickel-chloride battery, EDLC, Energy source.

1 Introduction

In a pure EV, the ideal energy tank should satisfy the following basic operational requirements:
- Sufficient amount of energy storage capability, in order to achieve a satisfactory driving range between recharges;
- Sufficient power capabilities, so that the necessary power required for propulsion can be supplied to the motor in any reasonable driving condition;
- Quick charging time, in order to increase vehicle availability;
- Sufficient lifetime, both in terms of calendar life and number of charge/discharge cycles.

In addition, there are a number of other requirements which are not directly related to the performance of the EV, but still are of utmost importance:
- Safety, both during normal operation and in case of accidents;
- Cost.

Unfortunately, there is no single available battery on the market that satisfies all the criteria stated above. One way to fulfill most of the requirements is to hybridize the power source by combining an energy-dense battery with a power-dense Supercapacitor bank. The use of hybridization would allow for independent optimization of the two concurrent sources for highest specific energy and highest specific power, respectively.
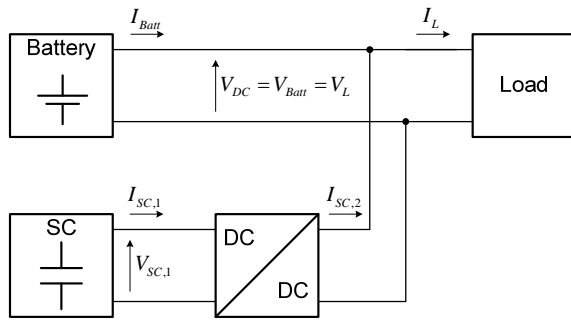
Figure 1: Battery-SC hybrid system with direct battery connection.

In the literature, it is often claimed that in electric vehicles the combination of power-dense supercapacitors (SC) with energy-dense batteries leads to a hybridized energy source having superior performance in terms of driving range, acceleration and lifetime, compared to a classical battery-only design [1]-[4]. However, whether a hybrid energy source is really advantageous and - if it is - to what extent, is still very controversial, due to the many variables involved in the evaluation of those systems. This paper aims at answering those basic questions in the particular case-study of a purely electric city vehicle. The performance of the vehicle, originally equipped with a high temperature Sodium-Nickel Chloride (ZEBRA) battery [5] is analyzed, with and without the addition of a SC-based power buffer according to the configuration in Fig.1.

2   Power Flow Management

One key aspect for successful operation of the hybridized system is the management of power flow. The algorithm used to decide what share of the power required (or given back) by the load at any instant should be supplied (or absorbed) by the battery and by the Supercapacitor buffer, respectively, must be designed with the aim of getting the best out of each individual source. A proper strategy should be able to achieve one or more of the following objectives:

– Maximized driving range (can also be stated as maximized overall efficiency);
– Minimum component stress, resulting in extended system life-time.

Stated in simple terms, the operating principle of hybrid energy source is expressed by the following paradigms:

– The primary energy source (battery) is the one with the highest energy content and should therefore supply the average power needed by the load; Steady power flow ensures minimum losses and reduced stress.

Since the battery cycle-life is currently the most critical factor for the overall system life-time, the latter aspect is particularly important.

– The secondary energy source (supercapacitor) should assist the battery by handling the momentary load power peaks. Due to relatively low internal resistance, supercapacitors can efficiently handle large power bursts; moreover, their life-time will not be significantly affected by this intermittent operation, provided their thermal limits are not exceeded.

Although apparently straightforward, those principles are not easy to implement in practice. In fact, the load requirement is not known a-priori, making the concept of ideal power sharing a non-deterministic one. In addition, optimal power sharing will depend on the state of the individual energy sources (state of charge, internal resistance, etc.), introducing several additional variables and constraints to the optimization problem. Moreover, while efficiency and achievable driving range are relatively easy to measure, effects on system life-time are not as apparent.

To date, there is no standard solution to the problem of optimal power sharing described above. There is however plenty of publications on the subject, mainly divided in three categories according to the kind of algorithm used:

– Heuristic algorithms, based on simple practical assumptions reflecting the basic principles reported above [6-8]. Main advantage of those algorithms is that they do not need a-priori information about the particular driving pattern; only some general specifications of the system components are needed, making the strategy easy to implement.

– Deterministic algorithms based on analytical minimization of losses [9-12]. Typically, information about the driving pattern is needed for proper optimization, along with detailed information about the system structure and electrical specifications of each component. The optimization process is complicated by the physical constraints (limited energy available in the SC-buffer, maximum current in and out of the battery, etc.) present in the system.

– Non-deterministic algorithms, utilizing stochastic methods, fuzzy logic and/or neural networks trying to achieve a real time solution of the optimization problem [13-16]. These methods are very popular for solving complex optimization problems that are not easy to express in closed mathematical form; performance can be very dependent on the particular implementation and training and, in

any case, optimality cannot be guaranteed for every particular driving pattern.

2.1 Model-based algorithm for power management

In order to illustrate the operating principle and to highlight the main advantages and drawbacks of a hybrid system, an algorithm belonging to the first category above is developed. The algorithm, whose block diagram is shown in Fig. 2, evaluates the share of the load power that must be handled by the SC-based power buffer $P_{SC,ref}$, using as input for the calculation the vehicle speed v, the SOC of the traction battery and the power required by the load P_{Load}.

Assuming the DC-DC converter in Fig. 1 to be ideal, the following power balance must hold:

$$P_{Load} = P_{SC} + P_{Batt} \qquad (1)$$

The load power requirements consist of the following components [17]:

1. Base load (on-board electrical loads, including air conditioning), P_{base};

2. Rolling resistance P_{roll};

3. Aerodynamic drag, P_{drag};

4. Gravitational load during uphill/downhill driving, P_g;

5. Inertial load during acceleration/braking, P_{acc}.

The first 4 components are "steady components", meaning that they can remain nearly constant for long time. Due to this characteristic, they should be supplied by the battery, in order not to deplete the power buffer. On the other hand, power for acceleration and braking, due to its quick transient nature, should come from (or be sunk by) the power buffer. With this strategy in mind, the first step is to estimate the "steady loads":

$$P_{Load,steady} = P_{base} + P_{roll} + P_{drag} + P_g$$
$$= P_{base} + k_{roll} \cdot |v| \cdot Mg\cos\psi + k_{drag} \cdot |v|^3 + Mg\sin\psi \qquad (2)$$

In the equation above, M, v are the total vehicle mass and speed, respectively; ψ is the inclination of the road surface. The coefficients k_{roll}, k_{drag} are known from vehicle geometry and weight, and can be considered constant for the degree of accuracy that is here required.

Total steady power in (2) can be either positive (load requires power) or negative (load is giving power back to the sources), with the latter being possible only in the case of downhill driving. In principle, the amount of power defined by (2) is the one that should be supplied by the battery; however, it is first necessary to check for absolute power limitations given by the battery manufacturer that are normally a function of the SOC.

The set-point for the battery power is finally determined by multiplying the value obtained above by a coefficient k_{mar} slightly bigger than unity, in order to leave some margin for SOC control of the SC bank and for unavoidable parameter mismatch in the evaluation of (2); the reference is also smoothed by a simple first order low pass filter, to avoid fast gradients that may have adverse effect on battery lifetime:

$$P_{Batt,ref}{}^* = \frac{k_{mar}}{1+\tau s} \cdot P_{Load,steady} \qquad (3)$$

As a consequence, the SC bank will have to supply the rest, in order to satisfy (1).

The problem with this algorithm is that it does not take into any account the limitation of the energy content in the SC-based power buffer. It is then
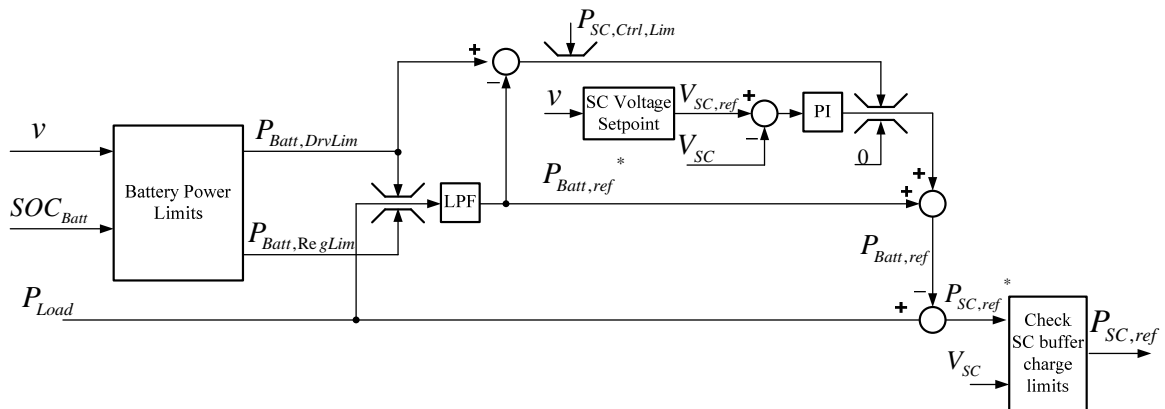

Figure 2: Heuristic power sharing algorithm between a battery and a supercapacitor bank.

possible that during operation, due to unavoidable parameter mismatch, the SC buffer becomes either completely depleted or completely filled. When that happens, its contribution to the load power requirement disappears, leaving the battery as the only available source.

Ideally, the SC buffer should be operated so that in any given instant, it is able to accept energy from the load if sudden braking occurs or, conversely, it is able to supply acceleration power to the load as required by the driver.

Braking energy that can be expected from the load at any given instant is at most equal to the kinetic energy of the vehicle:

$$E_{\mathrm{Re}g,Max} = \frac{1}{2}M \cdot v^2 \tag{4}$$

On the other hand, the energy that can be accepted by the SC-based power buffer for a given SOC is expressed as:

$$\Delta E_{SC} = \frac{1}{2}C_{SC} \cdot \left(V_{SC,Max}^{2} - V_{SC}^{2}\right) \tag{5}$$

For the buffer to be able to accept all the energy that could be possibly sent back from the load, its terminal voltage should be controlled to:

$$V_{SC}\left(v\right) \le \sqrt{V_{SC,Max}^{2} - \frac{M}{C_{SC}}v^2} \tag{6}$$

It is beneficial to apply (6) with the sign of equality so that, at the same time, the amount of energy already present in the power buffer is maximized. Such energy can be used for acceleration.

Once the desired SC voltage has been calculated by (6), a standard P-I controller is used to force the actual SC voltage to track its reference. Obviously, the energy necessary for such a tracking process must come from the battery and it is therefore necessary to decide how much effort should be put into this process. This is done by properly shaping the upper and lower limits of the P-I controller generating the additional term of the battery power needed for SC voltage tracking, as shown in Fig. 2. The idea is to operate the voltage tracking as a low priority process, using as little battery energy as possible. In addition, the lower output limit of the voltage regulator is set to zero, meaning that no energy can be sent back directly from the SC bank to the battery; this is done in order to avoid unnecessary power loops within the system and their associated losses.

3 Simulation of a city EV with hybrid energy source.

In order to highlight the advantages of a battery-supercapacitor energy source against a battery-only system, Matlab-Simulink® simulations are performed, representing a particular case study of a small, pure electric, city vehicle.

Main modelling assumptions are as follows:

− Electric power required by the vehicle is calculated by imposing a given speed profile, taking into account a simplified vehicle dynamics, including rolling resistance, aerodynamic drag, grading and electric base load. When the SC-based power buffer is used, its weight is added to the vehicle mass;

− Electric drive train (electric motor, inverter, transmission system) is assumed to have an overall efficiency of 80%, constant over the whole operating range;

− Battery is modeled with a Thevenin equivalent circuit with both open circuit voltage and internal resistance variable according to the SOC.

− Supercapacitors are modeled with a simple R-C network. Their losses are evaluated assuming an ideal boost DC-DC converter as interface; capacitance and internal resistance are assumed constant; power control is assumed to be ideal, meaning that the SC buffer will deliver (or absorb) the amount of power calculated by the power sharing algorithm.

− Power sharing algorithm is the one described in the previous section.

Simulation parameters are given in Table 1; they are derived from basic mechanical and electrical specifications of the Norwegian Th!nk City EV [18] equipped with a ZEBRA battery. Supercapacitor electrical specifications are based on commercially available Maxwell's MC-type cells [19].

Two different standard drive cycles are used to illustrate the behaviour of the hybrid energy source system (see Table 2):

− European standard ECE-EUDC combined drive cycle;

− American standard FUDS urban drive cycle.

The former is a rather simple pattern consisting of periods of constant acceleration and periods of constant velocity. It is presented here, since it is the standard with which all the European car manufacturer (including Th!nk EV) have to refer when stating their vehicle's performance in terms of achievable range and emissions; however, due to the smoothness of the speed profile, such a

pattern is not closely resembling actual city driving and is obviously not very well suited to highlight the advantages of the hybrid energy source, that aims at lowering the battery losses by peak-power shaving.

On the other hand, the FUDS cycle is derived from actual urban driving data, and exhibits continuously variable speed over the whole cycle, making the effect of the hybrid energy source much more evident.

As an example, simulation results related to a single FUDS cycle with and without the SC-based power buffer are shown in Fig. 3 and Fig. 4, respectively. Most noticeable effect of the addition of the power buffer is the smoothing of the power flow related to the battery. As a consequence the battery terminal voltage does not experience excessive reduction during peak load absorption, meaning that internal losses are sensibly reduced.

Results related to several driving conditions are summarized in Table 3, where the effect of hybridization in terms of loss reduction and driving range extension are quantified.

4   Impact of hybridization of the energy source on performance of a city EV.

In this section, simulation results presented in the previous chapter are critically analyzed, trying to draw some conclusions about the actual impact of the use of an expensive SC-based power buffer on some key performance indexes of the EV.

Table 1: Parameters of the simulated hybrid electric energy source system for city EV.

Vehicle	Mass	$M_{EV} = 920\,kg$
	Rolling constant	$k_{rr} = 0.11\,W/\left(kg \cdot m^2/s^3\right)$
	Dragging constant	$k_{drag} = 0.75\,W/\left(m^3/s^3\right)$
Battery	Open Circuit Voltage	$OCV = \begin{cases} 278V\ @\,100\%\ SOC \\ 254V\ @\,20\%\ SOC \end{cases}$
	Internal resistance	$R_{Batt} = \begin{cases} 486\,m\Omega\ @\,100\%\ SOC \\ 702\,m\Omega\ @\,20\%\ SOC \end{cases}$
	Mass	$M_{Batt} = 180\,kg$
Supercapacitor bank	Capacitance	$C_{SC} = 23.9\,F$
	Internal resistance	$R_{SC} = 38\,m\Omega$
	Voltage limits	$V_{SC,Max} = 240V$ $V_{SC,Min} = 120V$
	Mass	$M_{SC} = 50\,kg$
Control parameters	SC voltage regulator	$k_P = 0.3;\quad k_I = 0.1$
	Smoothing filter for $P_{b,ref}$	1st order LPF, $\tau = 2\,s$

Table 2: Main characteristics of the two standard drive cycles used in simulation.

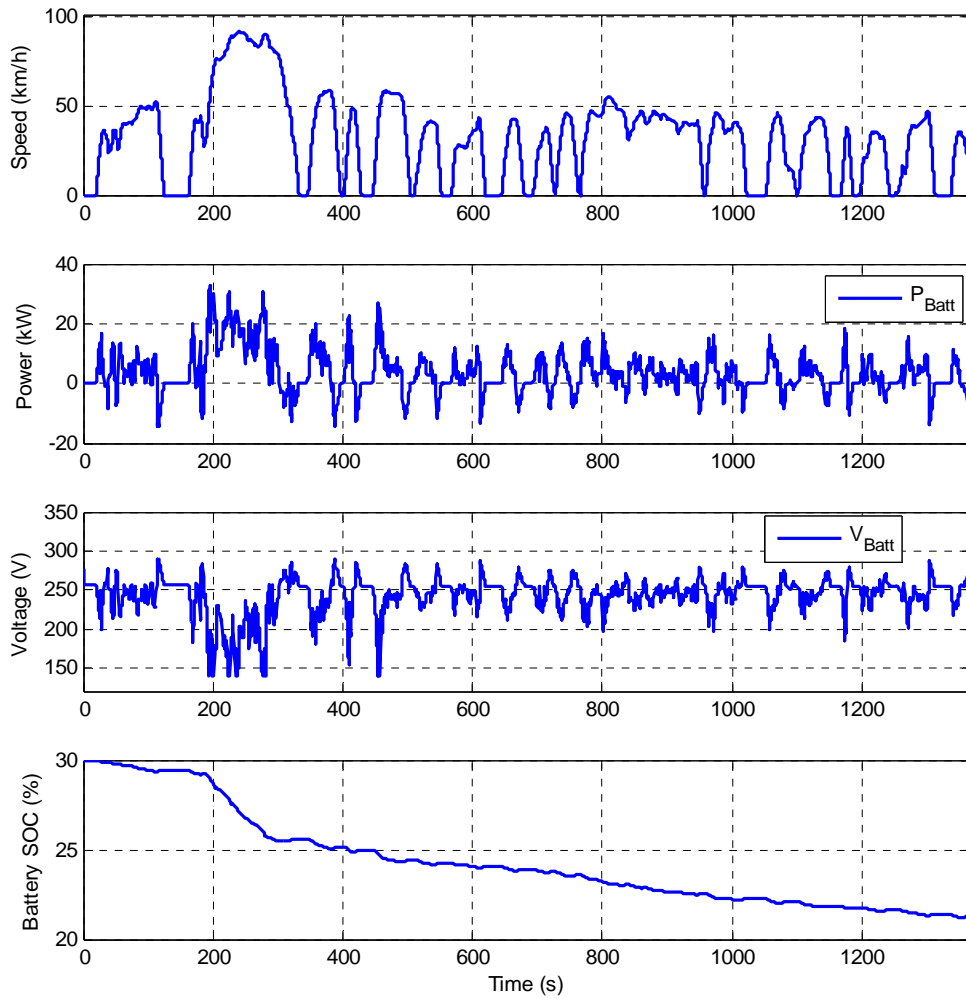| Cycle name	Duration (s)	Distance (km)	Avg. speed (km/h)	Max speed (km/h)	% of time @ zero speed	Max. accel.	Max braking
ECE-EUDC	1224	10.6	31.1	90.0	26.6	0.15g	-0.15g
FUDS	1369	12.0	31.5	91.2	17.7	0.11g	-0.14g

Figure 3: Simulation of a complete FUDS cycle, battery only, initial SOC = 30%.

4.1 Extension of driving range

Driving range is recognized as a serious limitation of pure EV; as a consequence, range extension is one of the most claimed advantages of a hybrid energy source. According to the simulations, the improved efficiency resulting from the use of the power buffer yields a range extension in the order of 5% for realistic city driving. Admittedly, this figure can be slightly improved by the use of more sophisticated power sharing algorithms; however, the numbers in Table 3 show that even if we were able to eliminate completely the losses in the energy source (that is the limit case of a perfect power buffer), the improvement in driving range would be below 20%. This improvement is not likely to be a sufficient motivation for the deployment of such an expensive solution; Indeed, utilizing the extra money, volume and weight necessary for the power buffer to install a slightly bigger battery would lead to a better gain in driving range. In this specific case, according to data in Table 3, if the battery is enhanced with a mass equal to that of the SC buffer, and assuming unchanged energy density, the available energy would be increased by about 27%, which is certainly beyond any reasonable figure for the range extension achievable by using an SC-buffer.
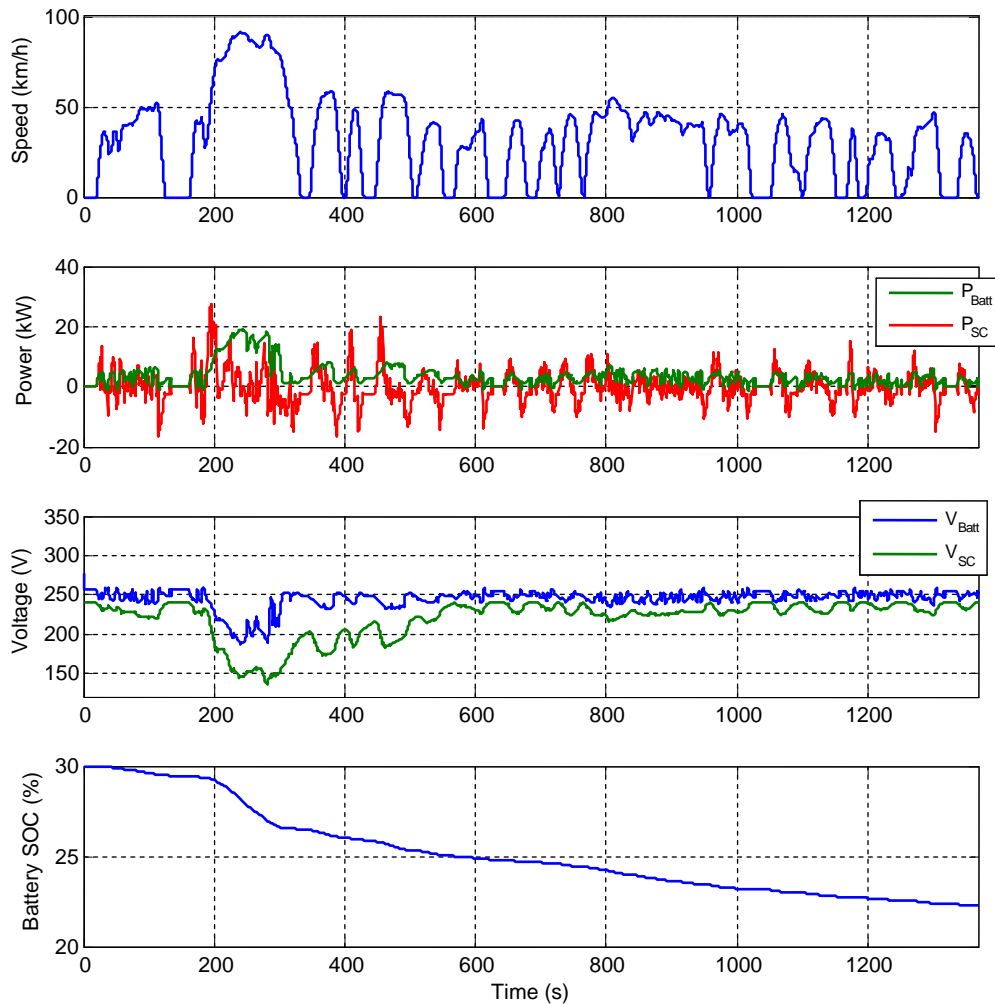
Figure 4: Simulation of a complete FUDS cycle, battery plus SCs, initial SOC = 30%.

4.2 Improved vehicle performance

The use of the power buffer has the potential to make the acceleration performance of the EV virtually independent of the battery SOC; on the other hand, a battery-only vehicle may experience some loss of power capabilities towards the very end of the battery discharge. In principle, the use of SCs in combination with oversized power electronics converters can substantially improve the short-term acceleration performance and the regenerative braking capabilities of the EV. However, steady state performance like maximum speed, or maximum sustained gradeability cannot be improved. It is hereby noticed that the power limitation of the battery is not likely to be a major problem in pure EV, due to the fact that a relatively large (and therefore quite powerful) battery is anyway needed in order to ensure reasonable driving range and maximum speed. For instance, in the Think EV, the battery is specified to be able to supply the peak power of the motor all the way down to 10% SOC, even though the simulation in Fig. 3 shows that the voltage of a depleted battery may decrease to unacceptable levels during hard acceleration (excessively low battery voltage may limit the achievable speed; this aspect is not modelled in the simulation). The picture can be quite different in the case of ICE-electric hybrids, where battery size is considerably smaller; however, this kind on vehicles is not discussed here.

4.3 Improved system lifetime

The most remarkable effect of the SC-buffer is the drastic reduction of the losses in the battery.

Table 3: Simulation results.

Simulated conditions	Average power Loss in Energy Source (W)		Used battery energy (pu)		Projected range extension due to hybridization	Loss reduction in the battery due to hybridization
	Hybrid Source	Battery only	Hybrid Source	Battery only		
ECE-EUDC, SOC(0)=100%	Batt: 334 SC: 9.8	463	0.068	0.070	2.9%	27.9%
ECE-EUDC, SOC(0)=30%	Batt: 707 SC: 9.4	1019	0.081	0.086	5.8%	30.6%
FUDS, SOC(0)=100%	Batt: 203 SC: 22.0	473	0.068	0.071	4.2%	57.1%
FUDS, SOC(0)=30%	Batt: 398 SC: 21.7	1031	0.078	0.087	10.3%	61.4%

For the realistic FUDS cycle, such a reduction ranges from a minimum of 57.1% (battery initially full) to a maximum of 61.4% (battery towards the end of discharge). Arguably, augmenting the battery mass by the amount corresponding to the weight of the SC buffer would decrease the losses, for the same power requirements. However, such a reduction is much less than what is achieved by the deployment of the supercapacitors. Reducing the stress on the battery can have significant effect on the lifetime of this component, which happens to be the most critical element of a pure electric EV, and arguably the one that most of all has hindered the commercialization of electric cars. It is very difficult to establish a precise relationship between the average losses in the battery and its lifetime, and more data should be gathered on the matter; however, if the natural correlation between the two aspects is confirmed, the resulting extension of the battery life could be a very convincing argument for the use of a SC-based power buffer in pure electric vehicles.

5 Conclusion

The impact of the addition of a power buffer based on supercapacitors to a pure electric city vehicle equipped with an energy dense Sodium-Nickel Chloride (ZEBRA) battery has been investigated.
Main effect of the hybridization of the energy source is the remarkable reduction of losses in the battery during normal city driving. This is believed to result in longer battery life, even though the life extension effect is difficult to quantify. Ad-hoc experiments should be performed to clarify this aspect.

On the other hand, deployment of supercapacitors is shown to have negligible effect on driving range extension.
Acceleration performance can be improved by using the SC-based power buffer, but that would require proper inverter-motor design to handle the high power bursts.

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Authors

Giuseppe Guidi got his MSc. from the University of L'Aquila, Italy, in 1995, and his PhD from NTNU, Norway, in 2009. From 1998 to 2001 he was with Fuji Electric R&D Ltd, Tokyo, Japan, as R&D engineer; he then joined SIEI Spa, Gerenzano, Italy, where he worked until 2004. In April 2009, he joined Yokohama National University, Japan, where he is currently a Research Associate, working on Power Electronics applied to Automotive

Tore M. Undeland has been Professor at NTNU, Trondheim, Norway since 1984. IEEE Power Electronics Society board member in 6 years, and Past president of EPE – European Power Electronics Association. His research interests are: Design of converters and Conversion and control in Renewable Energy. He has published about 100 papers, and is coauthor of the much used textbook: Mohan, Undeland, Robbins: Power Electronics, John Wiley & Sons, 3rd Ed 2003

Yoichi Hori joined the University of Tokyo in 1983, where he is now a Professor. He was the Treasurer of IEEE Japan Council and Tokyo Section during 2001-2002. He is now an AdCom member of IEEE-IES. He was the Vice President of IEE-Japan IAS in 2004-2005. He has been the chairman of ECaSS Forum since 2005. His research fields are control theory and its industrial application to motion control, mechatronics, robotics, electric vehicle, etc. He is an IEEE Fellow. He is the recipient of the Best Transaction Paper Awards in IEEE Trans. on Industrial Electronics in 1993 and 2001.