

Electric Vehicle Using a Combination of Ultracapacitors and ZEBRA Battery

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Abstract—The sodium–nickel chloride battery, commonly known as ZEBRA, has been used for an experimental electric vehicle (EV). These batteries are cheaper than Li-ion cells and have a comparable specific energy (in watt–hours per kilogram), but one important limitation is their poor specific power (in watts per kilogram). The main objective of this paper is to demonstrate experimentally that the combination of ZEBRA batteries and ultracapacitors (UCAPs) can solve the lack of specific power, allowing an excellent performance in both acceleration and regenerative braking in an EV. The UCAP system was connected to the ZEBRA battery and to the traction inverter through a buck–boost-type dc–dc converter, which manages the energy flow with the help of DSP controllers. The vehicle uses a brushless dc motor with a nominal power of 32 kW and a peak power of 53 kW. The control system measures and stores the following parameters: battery voltage, car speed to adjust the energy stored in the UCAPs, instantaneous currents in both terminals (battery and UCAPs), and present voltage of the UCAP. The increase in range with UCAPs results in more than 16% in city tests, where the application of this type of vehicle is being oriented. The results also show that this alternative is cheaper than Li-ion powered electric cars.

Index Terms—Energy management, energy storage, road vehicle electric propulsion.

I. INTRODUCTION

SODIUM–NICKEL chloride batteries (ZEBRA) are a good choice for electric vehicles (EVs) [1], [2]. They are safe and low cost and can endure more than 1000 cycles without significant degradation [3]. Moreover, they can be discharged almost to 100% of its total capacity without degradation in its cycle life. Its specific energy (in watt–hours per kilogram) is comparable with high-quality batteries, like Li-ion (120 Wh/kg). However, specific power (in watts per kilogram) of ZEBRA batteries is rather low when compared with other batteries as shown in Fig. 1 [4].

For example, Li-ion batteries have almost three times more specific power than ZEBRA (around 400 W/kg), but its price in terms of dollars per kilowatt hour is around three times higher.

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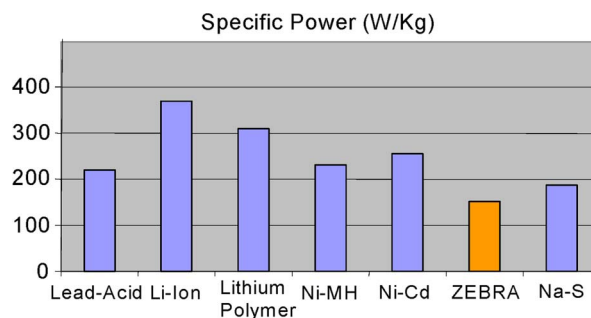


Fig. 1. Specific power of the most common secondary batteries for EVs.

Today, it is quite difficult to get a Li-ion battery at an affordable price. The cheapest Li-ion batteries available today in the market are the small-cell-type 18650 (3.6 V, 2.4 Ah), from which a battery car, using around 4000 units, can be implemented [5]. However, the lowest market price per unit, buying more than 1000 of these cells, is US\$4.75 per unit [6], which means that for 4000 units, the cost is US\$19 000. This value does not consider the large amount of electronic circuits for voltage balancing, temperature control, and current balancing, which may increase the total cost to more than US\$40 000. Besides, this battery pack will need the container, reinforcements, mechanical protections and time to construct, which will increase the cost of the battery, probably to more than US\$50 000. The maker of electric cars, AC Propulsion Systems, sells the “TZero” EV, made with 6800-cell-type 18650, at a cost of US\$220 000. They also sell the same EV with lead-acid batteries at US\$80 000 [7], [8]. This difference in price means that this battery with 6800 cells, with all the electronic support for safe operation, costs more than US\$140 000. Then, for 4000 cells, the cost is higher than US\$82 000 (around US\$2400/kWh). AC propulsion decided to make the car with those small units because this solution demonstrated to be cheaper than a large Li-ion module (which is not easily available today). Another example is the Chevrolet “Volt” from GM. This hybrid plug-in EV (also defined as range-extended EV) is going to be commercialized by the end of 2009. It uses a Li-ion battery pack of 16 kWh and GM estimates that the battery alone will cost around 20 000 (US\$800/kWh). However, this is a very unreal estimation because, at present, the price of Li-ion batteries for EVs is more than US\$2000/kWh [9]. The price of “TZero,” from AC Propulsion Systems, is a good example of cost of Li-ion batteries today. The experimental vehicle under study uses a ZEBRA battery of 28.2 kWh with a cost on the order of US\$19 000 [10] (real cost in March 2009), which includes auxiliary control circuits (US\$680/kWh). The ZEBRA



Fig. 2. ZEBRA-type Z36-371-ML3X-76.

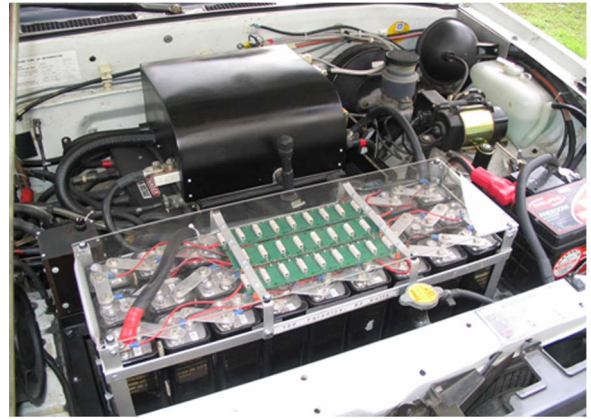


Fig. 4. UCAP bank in front of the vehicle.



Fig. 3. EV prototype.

being used in the experimental EV comes from factory in only one pack, easy to install, which weights only 245 kg. It stores 28 kWh of useful energy, which gives a specific energy of 115 Wh/kg (the specific energy of the battery used by the Chevrolet “Volt” is only 90 Wh/kg).

Fig. 2 shows the ZEBRA battery (type Z36-371-ML3X-76) that is being used in the experimental EV [2]. This EV is shown in Fig. 3 and was implemented at the Department of Electrical Engineering of the Pontificia Universidad Católica de Chile [11]. The car is powered by a 53-kW brushless-dc traction motor and has a gross weight of 1700 kg [12].

To solve the lack of power problem, an ultracapacitor (UCAP) bank was installed [13]–[15]. This bank, with a total capacity of 20 F and 300 Vdc, stores a practical amount of 200 Wh of energy. However, with this small amount of energy, but with the big amount of specific power (more than 1000 W/kg), the UCAP can easily deliver 40 kW of power during 20 s (more than enough to solve the lack of power of the ZEBRA during the acceleration). In a similar way, during regenerative braking, the UCAPs can receive, in a short period of time, a high amount of energy. This is quite important because sudden peaks of negative power can increase the ZEBRA battery voltage dangerously [16]–[18]. The actual cost of the UCAP bank installed on the vehicle is around US\$9000. However, road tests have demonstrated that a small capacitor bank

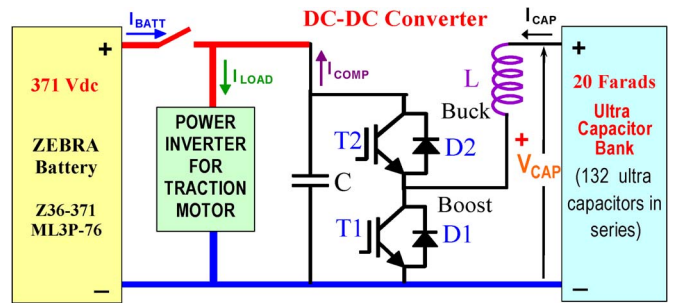


Fig. 5. Block diagram of the power system to manage the energy flow into the vehicle.

(80 Wh), with a cost of US\$3000, is adequate for the acceleration and regenerative braking (the weight of this small bank is around 30 kg with frame included). Fig. 4 shows one of the packs of UCAPs installed in front of the vehicle. The combination of ZEBRA (high amount of energy but low specific power) with UCAPs (low amount of energy but high specific power) allows making an electric car [19], with better range, good acceleration, and full regenerative braking capability [20].

II. POWER CIRCUIT

Fig. 5 shows the block diagram of the power circuit used in the EV to manage the energy flow between ZEBRA, UCAPs, and the traction system [21]. The battery feeds the power inverter, and when the battery voltage goes low, the UCAPs inject energy to both ZEBRA and inverter through the dc–dc converter. This process keeps the battery voltage at normal values and helps the EV during acceleration. During regenerative braking, the UCAPs recover the energy to avoid overvoltages at the battery terminals. The dc–dc converter is water cooled and weighs only 15 kg. It was designed and implemented at the Department of Electrical Engineering, and the cost of implementation was less than US\$2000. Taking into account the prices of ZEBRA (US\$19 000), UCAPs (US\$3000), and dc–dc converter (US\$2000), the total cost of this system is US\$851/kWh, which is far lower than Li-ion price (today around US\$2000/kWh).

Special control algorithms keep the capacitor voltage at the required level, according to particular driving conditions (mainly speed, battery state of charge (SOC), and UCAP voltage).

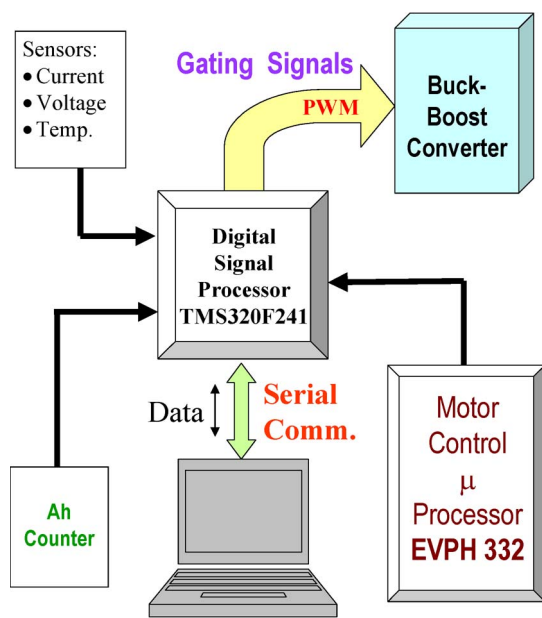


Fig. 6. Control scheme of the system.

III. CONTROL SCHEME AND CONTROL CIRCUIT

Fig. 6 shows the control circuit in block diagrams, and Fig. 7 shows the control board implemented for the ZEBRA–UCAP system. This control scheme was implemented in a TMS320F241 DSP from Texas Instruments. In addition, a monitoring feature was implemented in the DSP, which communicates with a portable PC. The monitoring program at the PC allows real-time plotting and storing of all valuable data. In addition, the control program at the DSP can be commanded from the PC to work in slave (user-controlled currents) or automated mode.

The signals required to perform calculations are the following: ZEBRA battery voltage, battery current, drive current, UCAP voltage, input and output currents of the dc–dc converter, UCAP current, battery SOC, and also vehicle speed. Some of these signals are taken from the main microprocessor that controls the power inverter. The rest of the signals are acquired from specially installed sensors and an ampere–hour counter installed in the vehicle. The control system outputs are two pulsewidth-modulation (PWM) signals, which commutate the two insulated-gate bipolar transistors in the buck–boost dc–dc converter. The PWM is calculated as part of a closed-loop PI control, comparing a preset current reference and the measured current from the dc–dc converter. The power transfer algorithm calculates the preset current value for the current control, considering the battery SOC, the battery voltage, the UCAP charge, the vehicle speed, and the power drive system current.

The transfer algorithm adjusts the amount of energy stored in the UCAPs according to car speed and battery SOC. The lower the speed, the higher the UCAP charge. The speed information is necessary because, at low speeds, more energy is required for acceleration, and for high speeds, more space for storing regenerative energy is needed. Similarly, if the batteries are fully charged, only a small amount of energy stored in the

UCAPs is needed. In this way, all the energy recovered from regenerative braking will go to the UCAPs. By contrast, if the battery SOC is poor, the UCAP should keep an amount of energy higher than under normal conditions. The charge curves of the UCAP for those operating conditions are shown in Fig. 8. These curves were estimated, taking in account the time needed by the control to store the right amount of energy into the UCAP. This control, using the same TMS320F241, was also implemented using neural networks strategy [22], [23].

The SOC is estimated by time integration of the battery current (positive or negative). The system also recognizes a fully charged battery when its voltage goes up rapidly under a regenerative braking condition.

IV. SIMULATION RESULTS

Fig. 9 shows a simulation of the ZEBRA battery at 80% depth of discharge (DOD) during acceleration of the vehicle from 40 to 60 km/h in 4 s. The UCAPs are not connected, and it can be seen that the battery voltage is strongly affected by the current variations. A serious problem arises when battery has to supply more than 150 A, because, in this case, the voltage at the ZEBRA terminals drops to values smaller than 250 Vdc. Under these conditions, the control of the traction motor reset the PWM signals of the inverter due to undervoltage operation, and the current cannot go higher. The simulation shows, in dot lines, the unreachable current when voltage goes below 250 V, because, in fact, the vehicle cannot work under these conditions.

The deep variation of the ZEBRA voltage is due to the poor specific power of this kind of battery. The only way to avoid this problem without power assistance is to keep a very low acceleration value.

Fig. 10 shows the ZEBRA battery at the same 80% DOD, but with UCAPs, accelerating the vehicle from 40 to 60 km/h in 4 s. In this case, the battery voltage is not seriously affected by the current variations because UCAPs are injecting power to the system to keep the ZEBRA current limited to 70 A. Under this condition, the voltage cannot go lower than 320 Vdc unless UCAPs become fully discharged. After acceleration comes to an end, the control adjusts the UCAP voltage according to car speed and battery SOC. During constant speed, the battery voltage recovers its normal operating value (around 370 V, depending on current released by the ZEBRA battery at that speed). As was already mentioned, at higher speeds, UCAPs are fully discharged (at factory limits). When a vehicle travels at medium speeds, the UCAPs keep some charge to have energy for future acceleration. Similarly, the UCAPs must have some room to receive energy during regenerative braking. When the car is not moving, UCAPs are fully charged for good acceleration, with minimum support from the battery.

The simulation in Fig. 11 shows the ZEBRA during regenerative braking from 40 to 0 km/h in 2 s. UCAPs are not connected, and it can be seen that the battery voltage goes higher than 400 Vdc when the current reaches around -40 Adc.

However, under real conditions, the control of the inverter would disrupt the PWM signals to avoid overvoltage conditions. This operation is necessary to avoid a permanent damage



Fig. 7. DSP control circuit.

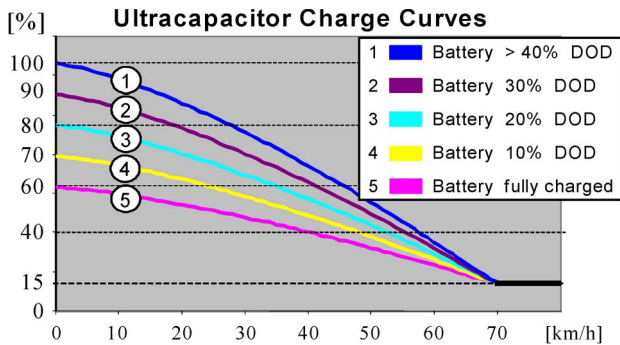


Fig. 8. Transfer algorithm charging curves for UCAP as a function of speed and battery charge.

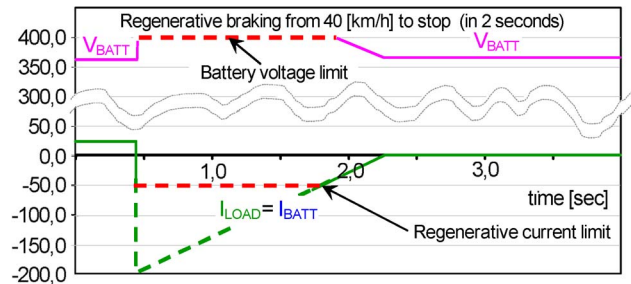


Fig. 11. Regenerative braking simulation from 40 km/h to stop in 2 s, without UCAPs.

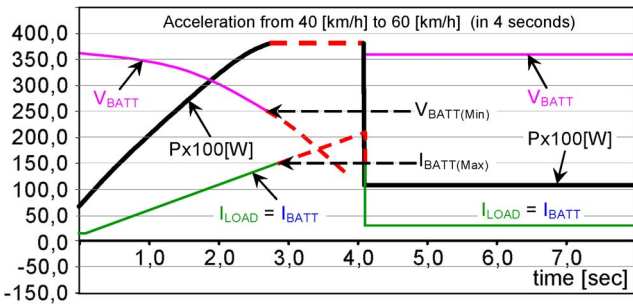


Fig. 9. Acceleration simulation from 40 to 60 km/h in 4 s, without UCAPs.

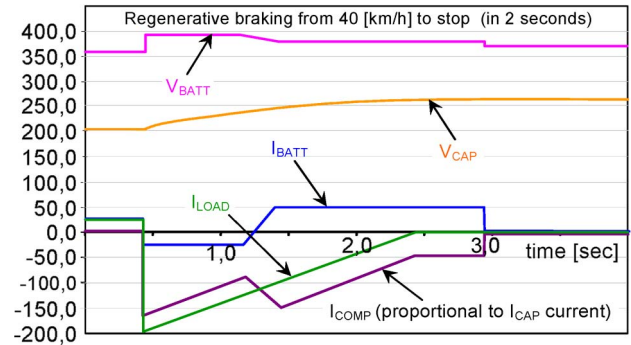


Fig. 12. Regenerative braking simulation from 40 km/h to stop in 2 s, with UCAPs.

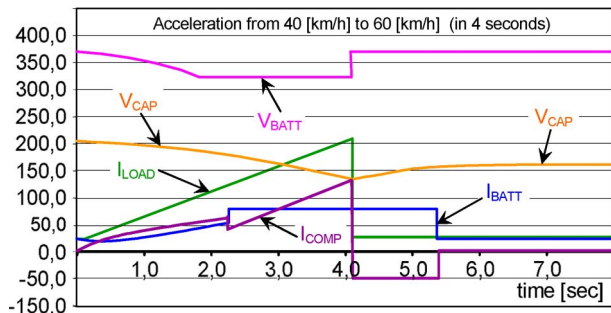


Fig. 10. Acceleration simulation from 40 to 60 km/h in 4 s, with UCAPs.

on the power inverter. The car will be unable to recover an important part of kinetic energy, and the life of mechanical brakes will be reduced.

Finally, the simulation in Fig. 12 shows again the ZEBRA during regenerative braking from 40 to 0 km/h in 2 s. UCAPs are now connected, and it can be seen that the battery voltage

never goes higher than 400 Vdc because most of the current is now absorbed by the UCAPs. The UCAP current I_{CAP} is proportional to I_{COMP} (they are related through the modulation index of the dc-dc converter). In this case, the regenerative braking works well because UCAPs take care of the currents, avoiding battery voltage to go higher than 400 Vdc. It is important to mention that the control system can be programmed according to the characteristics of the system. In this case, two important limits have to be respected: the undervoltage of 250 Vdc and the overvoltage of 400 Vdc. It is also worth to mention that regenerative braking with only UCAPs does not work in large downhill, because they finally will reach their maximum voltage, being unable to receive more energy. Under these conditions, the regenerative braking has to be limited to the capacity of the ZEBRA to receive power without reaching the voltage limit (400 Vdc). Other solution is to add power resistors for downhill operation, but this option is very inefficient because the braking energy is not recovered.

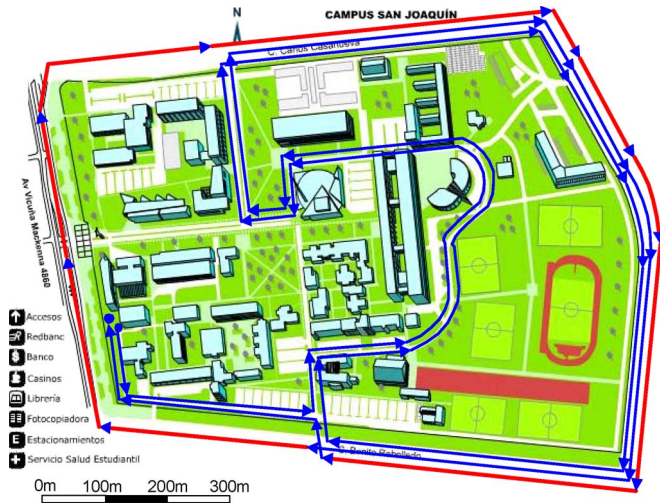


Fig. 13. Urban circuit test course. In red: fast track. In blue: slow track.

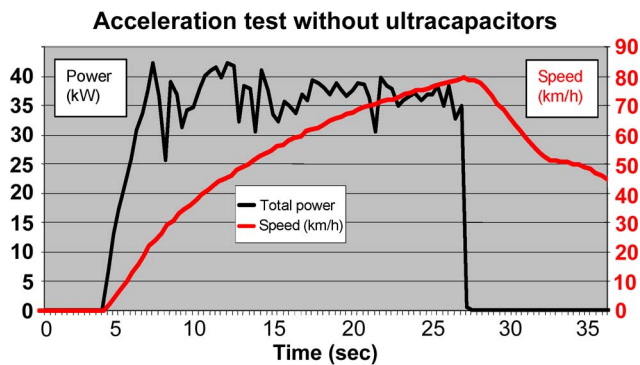


Fig. 14. Acceleration tests without UCAPs.

V. EXPERIMENTAL RESULTS

The following oscillograms and tables show the performance of the EV with the ZEBRA battery, when it operates without and with the help of UCAPs. All the experiments were performed with the full equipment installed (UCAPs are disconnected electronically). Tests road where made in a circuit around the university campus, as shown in Fig. 13. The approximate average speed was of 18 km/h, with maximum speeds of 80 km/h in the fast track showed in the external (red) rows.

A. Acceleration Tests

The oscillograms in Figs. 14 and 15 show the acceleration tests without the UCAP bank and with the UCAP bank, respectively. In Fig. 14, the EV needs around 25 s to reach the 80 km/h at full battery power capability ($P_{MAX} = 43$ kW). When P_{MAX} is reached, the battery voltage drops to 250 Vdc. Under this situation, the control circuit disconnects the power inverter due to undervoltage protection. However, when the inverter is disconnected, the ZEBRA voltage goes up, and the power inverter is connected again. A cyclical off-on operation is created that can destroy the power inverter (very dangerous repetitive operation).

When UCAPs are connected, the total power needed by the power inverter is shared between the ZEBRA ($P_{MAX} = 29$ kW now) and the UCAPs ($P_{MAX} = 45$ kW), as shown in Fig. 15.

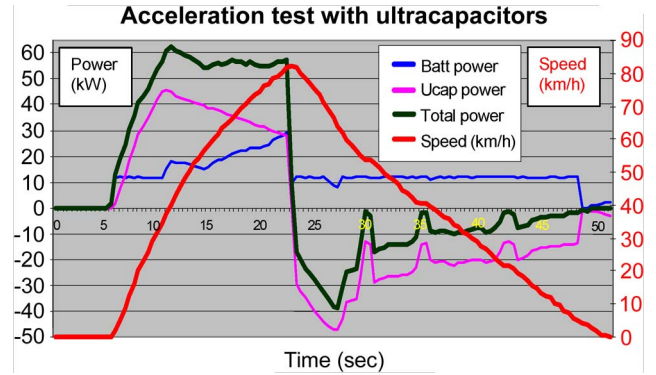


Fig. 15. Acceleration tests with UCAPs.

TABLE I
ACCELERATION WITH AND WITHOUT UCAPs

	Acceleration time (seg.)		
	0-40 km/h	0-60 km/h	0-80 km/h
Tests without ultracapacitors	7,8	14,4	24,9
Test with ultracapacitors	6,5	9,9	15,3
Improvement with ultracapacitors	16,1%	31,3%	38,5%

In this case, the power disruptions are eliminated because the voltage never drops below 250 V. Moreover, as the traction power has increased from 43 to 64 kW (29 kW + 45 kW), the time to reach 80 km/h has been reduced from almost 25 s to a little more than 15 s. The total energy delivered by the UCAP is around 160 Wh, but the stored energy can be restricted to reduce the size of the UCAPs, because 29 kW delivered by the ZEBRA is smaller than its P_{MAX} (43 kW). Moreover, if the acceleration time is increased a little more (20 s), then the necessary energy stored into the UCAPs will be around 70 Wh. This value is around 33% of the total energy stored in the actual capacitor bank (200 Wh). This reduction permits having an UCAP bank that weighs only 30 kg (frame included) and with a cost of around US\$3000.

The regenerative power is now safer and more efficient because overvoltages (over 400 Vdc) are avoided with the UCAP system. During the regenerative braking, the UCAPs recover part of the kinetic energy. In the cyclic process (stop-start-stop), some energy is lost and has to be supplied by the battery to recover the full charge into UCAPs. It is important to say that the UCAPs do not supply energy during an acceleration-deceleration cycle (this average energy is zero). They only flatten the energy delivered by the battery pack.

Table I shows the acceleration time, from zero to different final speeds (0-40, 0-60, and 0-80 km/h). It can be noticed that the acceleration time is reduced and UCAP assistance becomes more significant for higher final speeds.

The information about acceleration shown in Table I was obtained with the ZEBRA battery almost fully charged (95% SOC). When the ZEBRA SOC is low, results without UCAPs become less effective, because battery voltage goes down more

TABLE II
RANGE TESTS WITH AND WITHOUT UCAPS

	Range (km)	
	Fast track	Slow track
Tests without ultracapacitors	99,4	106,8
Test with ultracapacitors	110,1	124,6
Improvement with ultracapacitors	10,76%	16,67%

TABLE III
EFFICIENCY IN KILOMETERS PER KILOWATT-HOUR,
WITH AND WITHOUT UCAPS

	Efficiency (km/kWh)		
	Lead-acid Batteries (Fast Track)	ZEBRA Battery	
		Fast track	Slow track
Tests without ultracapacitors	3,1	3,6	3,8
Test with ultracapacitors	3,25	3,9	4,5
Improvement with ultracapacitors	4,8%	8,3%	18.4%

rapidly. However, with UCAPs connected, these results do not depend too much on SOC, because acceleration depends mainly on UCAPs.

Regarding regenerative braking without UCAPs, it becomes very poor when the ZEBRA SOC is near 100%. The battery cannot receive too much energy under full charge, and its voltage goes up very rapidly during charge, reaching the limit of 400 Vdc. However, this problem disappears when UCAPs are connected.

B. Range and Efficiency Tests

Table II shows that the EV range increases when the UCAP bank is activated. It can also be noted from Table II that the range increases more in a slow track (see Fig. 13) because it represents a way with more starts and stops than the fast track, and the average speed is slower. This range was obtained by discharging the ZEBRA battery up to 90% DOD. It is important to mention that ZEBRA batteries allow almost 100% DOD without damage.

Finally, Table III shows the improvement in efficiency in terms of kilometers per kilowatt-hour. As can be seen, the efficiency improves more than 18% for the slow-track case (the efficiency of 3.8 km/kWh without UCAPs goes up to 4.5 km/kWh with UCAPs). A comparison with lead-acid batteries (fast track) is also displayed in Table III.

VI. CONCLUSION

This paper has analyzed the combination of a ZEBRA battery (high specific energy but low specific power) with UCAPs (low

specific energy but high specific power). This arrangement increases range, efficiency, acceleration, and regenerative braking capability in an EV. When this battery works with the help of UCAPs, the electric car behaves as good as a car with Li-ion batteries. However, the cost of the ZEBRA system is almost three times lower, including the cost of UCAPs and dc-dc converter. The endurance of ZEBRA batteries is also higher than that of Li-ion batteries, because they can survive more than 1000 cycles at almost 100% DOD. The only drawback of this system is the lack of regenerative braking capability during downhill. The UCAPs can only store a limited amount of energy, and hence, they only can cover a limited distance when the car goes downhill. For downhill, a braking resistor may be required. The same happens when the car goes up for a long time, because the UCAPs will discharge completely and the car will lose power after some meters going up the hill. In this case, the only solution for the problem is going up slowly. The tests have shown very good behavior in horizontal highways. The EV was able to keep a constant speed of 120 km/h (the maximum speed permitted at highways in Chile), without the help of UCAPs.

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