Using ultracapacitors for saving energy in regenerative braking in hybrid vehicles

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Abstract: An ultracapacitor bank control system for an Electric Vehicle has been simulated. The purpose of this device is to allow higher accelerations and decelerations of the vehicle with minimal loss of energy, and minimal degradation of the main battery pack. The control of the system measures the battery voltage, the battery state-of-charge, the car speed, the instantaneous currents in both the terminals (load and ultracapacitor), and the actual voltage of the ultracapacitor. This last indication allows knowing the amount of energy stored in the ultracapacitor. When the car runs at high speeds, the control keeps the capacitor discharged. If the car is not running, the capacitor bank remains charged at full voltage. Medium speeds keep the ultracapacitors at medium voltages, to allow future accelerations or decelerations. The battery voltage is an indication of the car instantaneous situation. When the vehicle is accelerating, the battery voltage goes down, which is an indication for the control to take energy from the ultracapacitor. In the opposite situation (regenerative braking), the battery voltage goes up, and then the control needs to store the kinetic energy of the vehicle inside the ultracapacitor. The measurement of the currents in both sides allows keeping the current levels inside maximum ratings. The battery state-of-charge is used to change the voltage level of the ultracapacitor at particular values. If the battery is fully charged, the voltage level of the capacitors is kept at lower levels than when the battery is partially discharged.
Keywords: Hybrid vehicles, Ultracapacitor, Regenerative braking, energy modelling, Battery pack.

1 INTRODUCTION

Ultracapacitors are a new technology that allows to store 20 times more energy than conventional electrolytic capacitors. Despite this important advance in energy storage, they are still far from being compared with electrochemical batteries. Even Lead-acid batteries can store at least ten times more energy than ultracapacitors. However, they present a lot better performance in specific power than any battery, and can be charged and discharged thousand of times without performance deterioration. These very good characteristics can be used in combination with normal electrochemical batteries, to improve the transient performance of an electric vehicle, and to increase the useful life of the batteries. Fast and sudden battery discharge during acceleration, or fast charge during regenerative braking can be avoided with the help of ultracapacitors. Besides, ultracapacitors allow regenerative braking even with the batteries fully charged. In this paper, an auxiliary ultracapacitor bank, using a Buck-Boost converter, has been simulated. The ultracapacitor has a capacity of 7 Farads, a nominal voltage of 300 Vdc, and a maximum voltage of 360 Vdc. It comprises 144 units in series, each one with 1,000 Farads, and 2.5 volts dc nominal (2.7 volts maximum). The maximum current is 400 amps, and the weight of the capacitor bank is 45 kg. The total weight of the equipment is estimated in 70 kg.

2 THE SYSTEM PROPOSED

The Figure 1 shows a diagram of the ultracapacitor system proposed. The power circuit has two main components: the converter, and the ultracapacitor bank. The equipment is connected in parallel to the main battery, which has 26 batteries in series (312 Vdc nominal). The capacitor voltage is allowed to discharge until one third of its maximum voltage (around 120 Vdc), allowing to store an amount of 112 Wh of useful energy. This apparently poor amount of energy allows having more than 40 kW of power during 10 seconds, which is more than enough time for a good acceleration (or deceleration) without detriment in the battery life. The nominal power of the traction motor is 32 kW, and the peak power is 53 kW. During acceleration, transfer energy from the capacitor to the main battery. During regenerative braking, move energy in the opposite direction. Because of the topology of converter, the ultracapacitor never reaches voltages higher than the battery pack (self-protection).

To do all the duties during acceleration and deceleration correctly, a good control strategy is required. The control strategy strongly depends on the size of the ultracapacitor. With a large capacity, the vehicle can run taking an almost constant battery current (the average current). Under these conditions, the capacitor gives all the positive and negative variations around this average current and its voltage can indicate when is required to increase or decrease the average current given by the battery pack. However, this solution is costly because ultracapacitors are quite expensive right now. This reason forces to install an ultracapacitor as small as possible, but large enough to avoid battery voltages too low or too high, and battery currents (negative or positive) too high. Under these economical reasons, many variables need to be measured, each one with a different priority.

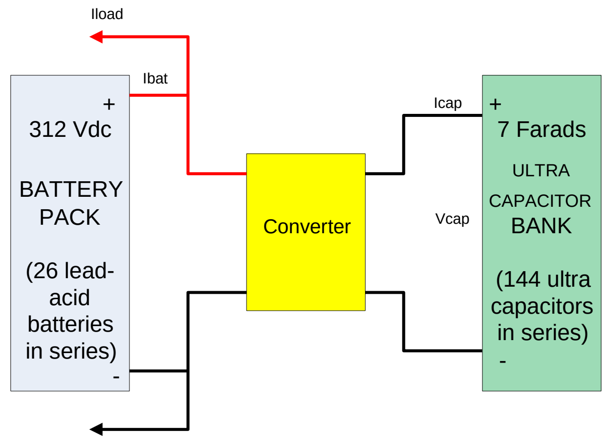

Figure1, Ultracapacitor system

3 CONTROL STRATEGY

Considering the high cost of the ultracapacitors, the total capacity in Farads has to be minimized. Then, a more complicated control strategy is required, because the energy stored is in this case limited. Every variable, such as instantaneous battery voltage, battery state of charge, instantaneous battery current, ultracapacitor initial conditions, capacitor current, and so, need to be sensed. The speed of the vehicle also needs to be taken in account because when the vehicle is going to start, all the capacitor energy will be required. By contrast, when the vehicle run at high speeds (more than 80 km/h), the ultracapacitors need to be empty, to be able to receive the energy coming from a sudden emergency stop. At medium speeds, the ultracapacitor should have in-between charge inside. The state of charge has to be considered because full charged batteries do not accept any current, and hence, under this condition, the ultracapacitor has to be discharged (that means no more than 15-20 % of its full capacity). Only if the car goes to a total detention, some amount of energy could be required. By contrast, if the battery state of charge is poor, the ultracapacitor should keep an amount of energy higher than under normal conditions. The state of charge 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. As the energy stored in the ultracapacitor is proportional to $V_{CAP}2$, this voltage gives a good indication of its remained charge. The capacitor voltage is being controlled, through the interaction of the other aforementioned variables, such as the vehicle speed, and the state of charge of the battery. The measurement of the instantaneous battery voltage, and the sign of the load current (positive or negative), If the battery voltage goes up rapidly, the controller activates, and a given amount of energy is transferred to the ultracapacitor. This situation happens when the vehicle is running and the brake is activated. Under this condition, the previous state of the overall system should have kept the ultracapacitor voltage at low levels. By contrast, in acceleration the control operation will be activated when the battery voltage goes down (acceleration), and when the vehicle is going to move, or accelerating from low speeds (positive current from the batteries). Under these conditions, and if the battery is not fully charged, the ultracapacitors should be at high levels of stored energy. All the operation described above, has to be controlled by a microprocessor, which discriminates and takes the appropriate decisions for each particular situation. The best way to give each variable a right significance, is by using a combined control. This combined control has two levels: a Primary Control, and a Secondary Control. The Primary Control establishes the current reference(I_{REF}) to be given to the ultracapacitor for each operation condition, and the Secondary Control generates the PWM signals for Converter. The Figure 2 shows the Primary Control.

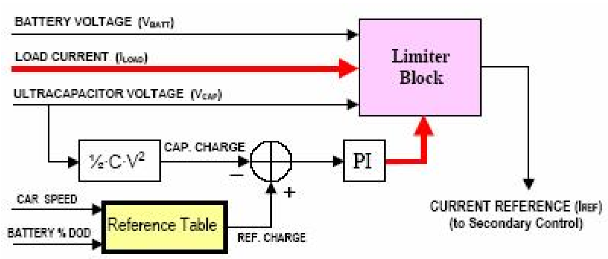

Figure 2, Primary Control

The first duty of the Primary Control is to keep an adequate level of energy into the ultracapacitor. This level of energy, or charge (REF. CHARGE in Figure 2), is calculated through the EV speed (CAR SPEED), and the battery state of charge (BATTERY % DOD). The block named Reference Table in Figure 2 makes this calculation, following a criterion shown in Figure 3. The higher the speed, the lower the charge, and the higher the battery state-of-charge, the lower the charge too. The shape of these curves was estimated taking in account the time the control takes to reach the desired ultracapacitor charge.

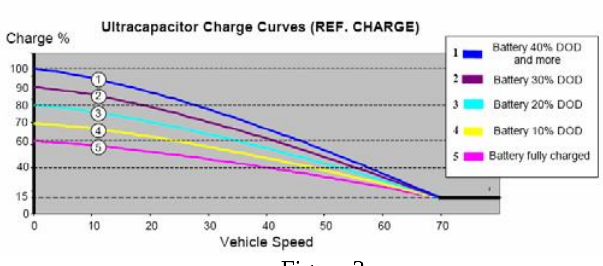

Figure 3,
Family plots of the Reference Table, to evaluate the reference charge.

At the same time, the ultracapacitor voltage V_{CAP} is measured, and the actual charge is calculated. The error signal, between the reference charge and the actual charge is passed through a PI control, which evaluates the amount of current reference (I_{REF}), necessary to maintain the ultracapacitor bank with the desired amount of energy.

All the process explained in the previous paragraph, to maintain an adequate charge into the ultracapacitor, is followed accordingly. However, if the battery voltage (V_{BATT}) exceeds their minimum and maximum settings, IREF is modified. A similar action is performed when the ultracapacitor voltage V_{CAP} is too low or too high. The load current (I_{LOAD}) is also an important reference inside the Primary Control. When this current exceeds the maximum absolute values set on the battery pack (I_{BATT}), the current reference (I_{REF}) is also modified. Then, to take in account all these situations, some logical rules have been implemented. These rules are programmed inside the Limiter Block shown in Figure 2.

4 SIMULATION RESULTS

The next oscillograms show the results obtained with the simulation. Many different situations were simulated. To make the results more real, use the conclusions of some experiments with the electric vehicle were performed on the streets. These experiments allowed evaluating the time the vehicle needs, and the current and voltage variations during acceleration, and regenerative braking. These experiments showed that the vehicle can accelerate from 40 to 60 [km/h] in a little more than 4 seconds, and that the maximum current taken from the battery reaches 200 amps. When the vehicle reaches steady-state at 60 [km/h], the battery current goes down at a constant value of around 20 [A]. With these informations, the system proposed was simulated. The result of this simulation (from 40 to 60 [km/h]) is shown in Figure 4. This figure displays the battery voltage V_{BATT}, the ultracapacitor voltage V_{CAP}, the load current to accelerate the car I_{LOAD}, the battery current I_{BATT}, and the compensation current I_{COMP} that comes from the energy stored in the ultracapacitor. The settings for the battery into the control were: V_{min}=300 V_{dc}, and V_{max}=360 Vdc; I_{min}=-70 A_{dc}, and I_{max}=70$_{Adc}$.

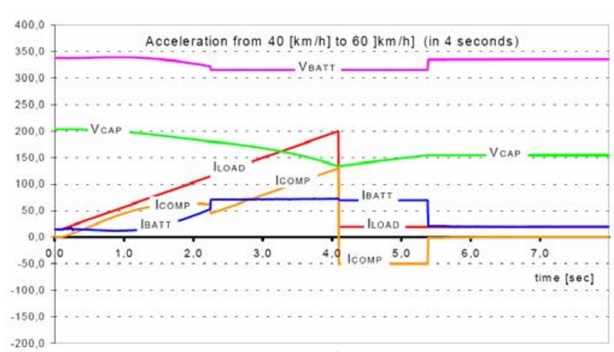

Figure 4, Acceleration from 40 to 60 [km/h]

When the load current begins to increase, most of the current is taken from I_{COMP}, which comes from energy stored into the ultracapacitor. As the capacitor voltage V_{CAP} decreases (energy is going down), more current begin to be taken from the battery, but when the battery reaches its limit (70 amps.), the capacitor is forced to give all the current in excess of 70 [A]. This action produces a faster decrease in the ultracapacitor voltage. If the capacitor voltage reaches its minimum setting (120 Vdc with a maximum of 360 Vdc), then the vehicle should not be able to continue accelerating, because at this point, 90% of the capacitor energy would have been used. If the capacitor is large enough (as in this case), this situation will not happens, and the capacitor will be able to end its duty. Later on, the capacitor will be able to recover energy, once the vehicle reaches constant speed. This case is also shown in the Figure 4. When the EV reaches constant speed (60 km/h), the compensating current I_{COMP} becomes negative, charging the capacitor. As the car is not braking, this energy is being taken from the battery, but at a maximum value given by the limit set by the controller (70 Adc). Once the capacitor recovers its energy, the battery current goes down, as shown in the final seconds of simulations in Figure 4. Finally, when the ultracapacitor recovers the energy, which corresponds to the value given by the Reference Table of Figure 2, the load current takes power only from the battery pack. A second simulation, displayed in Figure 5, shows a deceleration from 40 [km/h] to stop. This regenerative action takes 2.1 seconds. The regenerative current goes from 200 Adc to zero in the time indicated above. Both, the battery and the ultracapacitor, through I_{BATT} and I_{COMP}' receive this current respectively. The simulation shows that the battery receives a current smaller than the limit of 70 Adc. This happens because the maximum voltage allowable by the battery (360 Vdc) is reached first. This means that the battery is almost fully charged, and then cannot receive more than 30 Adc approximately. For this reason, most of the current is taken by the ultracapacitor. Once the vehicle stops, the battery continues charging the capacitor until it reaches its final charge (the Reference Table of Figure 2 gives the required amount of charge). In this case the amount of energy stored in the ultracapacitor corresponds to a voltage of around 260 Vdc.

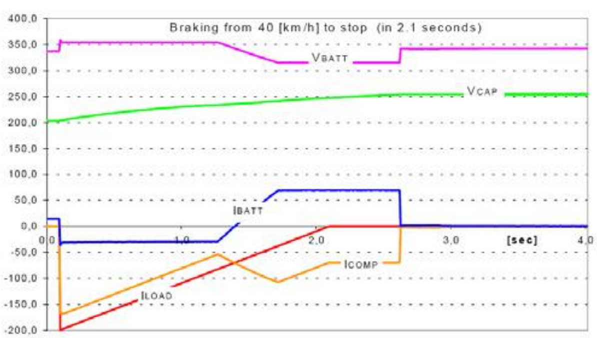

Figure 5, braking from 40 [km/h] to zero

It can be noted that the battery current begins to be positive before the vehicle reaches zero speed. This is because the capacitor needs to have more energy at that particular speed, and then the control begins to charge the capacitor in advance.

5 CONCLUSIONS

An ultracapacitor bank for an Electric Vehicle has been simulated. The purpose of this device is to allow higher accelerations and decelerations of the vehicle with minimal loss of energy, and minimal degradation of the main battery pack. The control of the system measures the battery voltage, the battery state-of-charge, the car speed, the instantaneous currents in both the terminals (load and ultracapacitor), and the actual voltage of the ultracapacitor. The simulations showed that the control system can work properly, taking in account all the aforementioned variables.. It is interesting to mention that, if ultracapacitor reaches in the future, a specific energy of at least 20 Wh/kg (at this moment some laboratory samples reach 10 Wh/kg), it will be possible to implement EVs with ultracapacitors only. They could give a range of 100 kms with a 500 kgs capacitor bank, with very short charging time and excellent life expectancy. The EV will be able to be fully charged in few minutes. Besides, the ultracapacitor could last all the vehicle useful life.

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