

DSP Based Ultracapacitor System for Hybrid-Electric Vehicles

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Abstract

A DSP based ultracapacitor system for hybrid-electric vehicles has been implemented and tested successfully. The system can work with different primary power sources like fuel-cells, microturbines, zinc-air batteries or other supply unable to recover energy from regenerative braking, or with scarce power capacity for fast acceleration. The ratings of the ultracapacitor bank are: nominal voltage: 300 Vdc; nominal current: 200 Adc; capacitance: 20 Farads. The amount of energy stored allows delivering 40 kW of power during 20 seconds, which is enough to accelerate the vehicle with minimum help of the primary power source. The vehicle uses a brushless dc motor with a nominal power of 32 kW, and a peak power of 53 kW. The control system, based on a DSP, measures and stores the following parameters: primary source voltage, car speed to adjust the energy stored in the ultracapacitors, instantaneous currents in both terminals (primary source and ultracapacitor), and actual voltage of the ultracapacitor. The increase in range with ultracapacitors has been estimated in 16% in city tests, but the difference looks almost negligible in highway tests. However, tests are still under way. The car used for this experiment is a Chevrolet LUV truck, similar in shape and size to a Chevrolet S-10, which was converted to an electric vehicle at the Universidad Católica de Chile. These results will lead to conclusions about the overall economical and technical advantage of the use of ultracapacitors in combination with other kind of primary source in hybrid-electric vehicles. The efficiency gain is being monitored at the ultracapacitor level, at the primary source level, and at the vehicle level. In the experimental work, a lead-acid battery pack is being used, and the DSP control is adjusted in such a way that it does not allow regenerative currents flowing back to the batteries. When the system is compared without ultracapacitors, regenerative braking is disconnected from the main computer of the traction drive system, and the battery currents are limited to a maximum of 100 A (normal maximum is 250 A). Related with the design of the ultracapacitor system, this has been optimized in weight and size, by using a water-cooled IGBT power converter, and an aluminum inductor with air core.

Keywords: “HEV”, “Ultra Capacitor”, “Control System”, “Efficiency”, “Regenerative Braking”.

1. Introduction

Throughout the years hybrid vehicles have proofed themselves the shorter path to efficient, non-contaminating transportation. While new and conventional technology batteries are still on their way to achieve a reasonable energy density, which could make pure electric transportation a competitive option, the combination of high-energy-density primary sources and high-power-density auxiliary sources have already reached the automotive market in the form of attractive, low-operational-cost hybrid models. This trend has encouraged technology developers and researchers within the electric traction field to explore new auxiliary energy systems, which combine optimal energy management and high-power-density storage devices (Flywheels, Ultracapacitors, high-power batteries, etc.).

In the context of developing a series topology hybrid vehicle, an Ultracapacitor-based Auxiliary Energy System (AES) has been implemented and tested. This paper presents the results of experimental drive tests using the AES in combination with lead-acid batteries as a primary source. The purpose of these tests is to assess the increase of the overall efficiency in the use of energy, using a primary source that is clearly inefficient at high power regimes. The results will lead to conclusions about the adequacy of this particular AES (Ultracapacitors and a Buck-Boost converter) for use in hybrid vehicles in combination with other primary sources; and will also serve as a yardstick to evaluate a new optimal algorithm that is being developed to be implemented in the same vehicle configuration.

A control and monitoring system, based on a TMS320F241 DSP from Texas Instruments, has also been implemented in the AES. It controls the DC-DC converter (executing the algorithm in use), acquires and stores data, and is capable of monitoring and sending all relevant data to a Personal Computer on a real time basis. A PC software was developed to display and store data, tune algorithm parameters and set different functioning modes. The DSP can work on automated mode, according to the pre-established algorithm, or supervised mode in which it accepts commands from the PC.

2. Power Topology

The power topology implemented is a series configuration [1] (one mechanical power source only, the electric motor). This configuration allows an easy change of the primary source, because the only liaisons are the electrical conductors; therefore no mechanical modification is needed to change between different primary sources. This practical advantage makes it possible to test the auxiliary energy system with different primary energy sources and draw conclusions about the overall efficiency gain.

In this case the primary energy source used is a Lead-Acid battery pack, which can be compared (within certain limits) with a fuel cell or a diesel-powered generator.

Figure 1 show the power topology implemented in the Electric Vehicle.

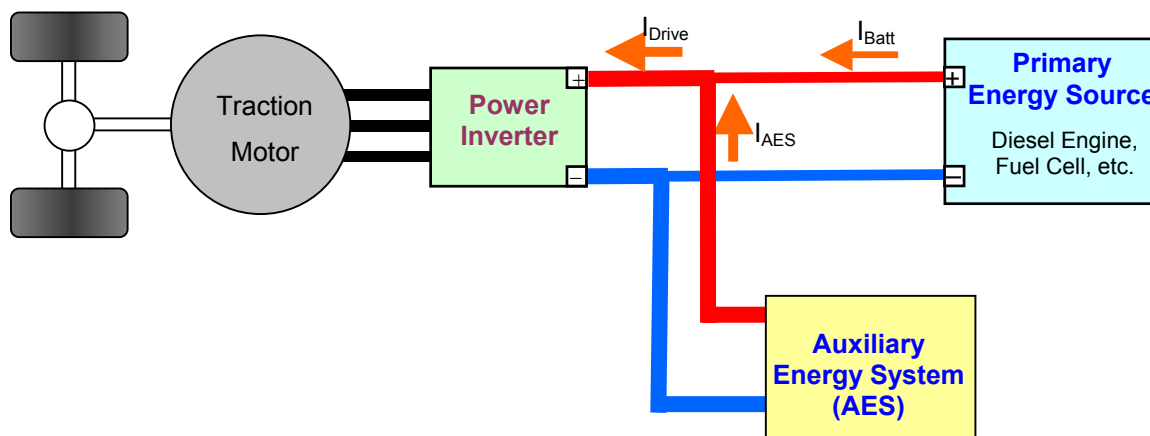


Figure 1: Power Topology.

The Primary Energy Source shown in the figure is composed of 26 Lead Acid batteries connected in series. This battery pack has a capacity of 50 Ah @ 356V, nominal; from which an 80% can be used without battery deterioration, therefore a total 14.2 kWh are available. This is much less energy than that contained in most primary sources used in Hybrid vehicles, but it is enough to ride a few tens of

kilometers and test the efficiency gain using the auxiliary energy system. The battery pack can also simulate a non-regenerative power source by disabling the regenerative feature while driving on primary-source-only mode; and by manipulating the Auxiliary Energy System software while driving on both-sources mode (this can be made by absorbing all regenerative currents at the Auxiliary System).

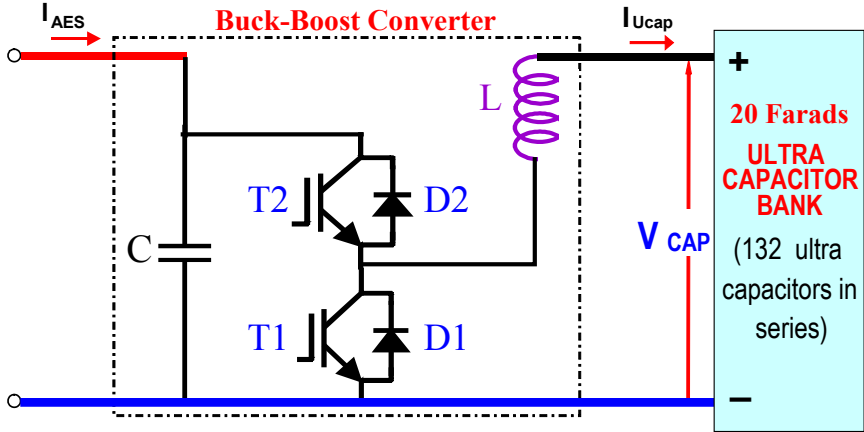


Figure 2: Auxiliary Energy System (AES).

The Auxiliary Energy System (AES), shown in fig 2, is composed of an Ultracapacitor bank (132 capacitors in series, 2700F, 2.3V each) and a Buck-Boost converter, which controls the transfer of energy. The Ultracapacitor bank's nominal voltage is 303V and its capacitance is 20F, making it possible to store up to 255 Wh; this amount of energy allows to have 40 kW for more than 20 seconds, enough to accelerate the electric vehicle to an acceptable cruise speed of more than 80 kph (without accounting for losses).

A Buck Boost topology was chosen because it can transfer energy both ways while one side of the converter has a lower voltage than the other. In this case the battery-pack's nominal voltage is 356V, which is always higher than the Ultracapacitor-bank's voltage.

The electric vehicle in which the system was implemented, is shown in figure 3 [2]. It is similar in shape and size to a Chevrolet S10 light truck.



Figure 3: Electric vehicle, Chevrolet LUV.

3. Control Scheme

The Auxiliary-Energy-System's main objective is to support the battery (or other primary source) during acceleration and regenerative braking. But the control system also has to predict the need for energy (before accelerating) or for energy storage space (before braking) and create the necessary conditions for the Auxiliary system to work properly (namely, have enough energy or space for storing it in the Ultracapacitors). Therefore the control system has to monitor and limit the Battery's current; and control the Ultracapacitor's state of charge.

As batteries are passive elements, currents through them can be controlled by monitoring the Drive currents and imposing a complementary current from the AES (as shown in fig. 1). Also the Ultracapacitors SOC can be controlled with a simple closed loop that manipulates the Ultracapacitors current. But the Ultracapacitor's current and the AES current are directly related by equation 1 (not accounting for losses), therefore these two tasks seem to conflict with each other; but on the contrary they are complementary, because when the vehicle accelerates a lower SOC is desirable (to have space for regenerative braking energy) and a positive complementary current from the AES is desirable to support batteries during acceleration, hence both actions pull the same way.

$$I_{AES} = I_{Ucap} \cdot \left(\frac{V_{Ucap}}{V_{Batt}} \right) \quad (\text{Eq. 1})$$

Nevertheless a priority has to be established to determine which task will rule over the other. This is easily done by over imposing two control modules, one that controls the Ultracapacitors SOC and another one that limits currents through the batteries. The result of this control scheme (shown in fig. 4) will be the AES current reference.

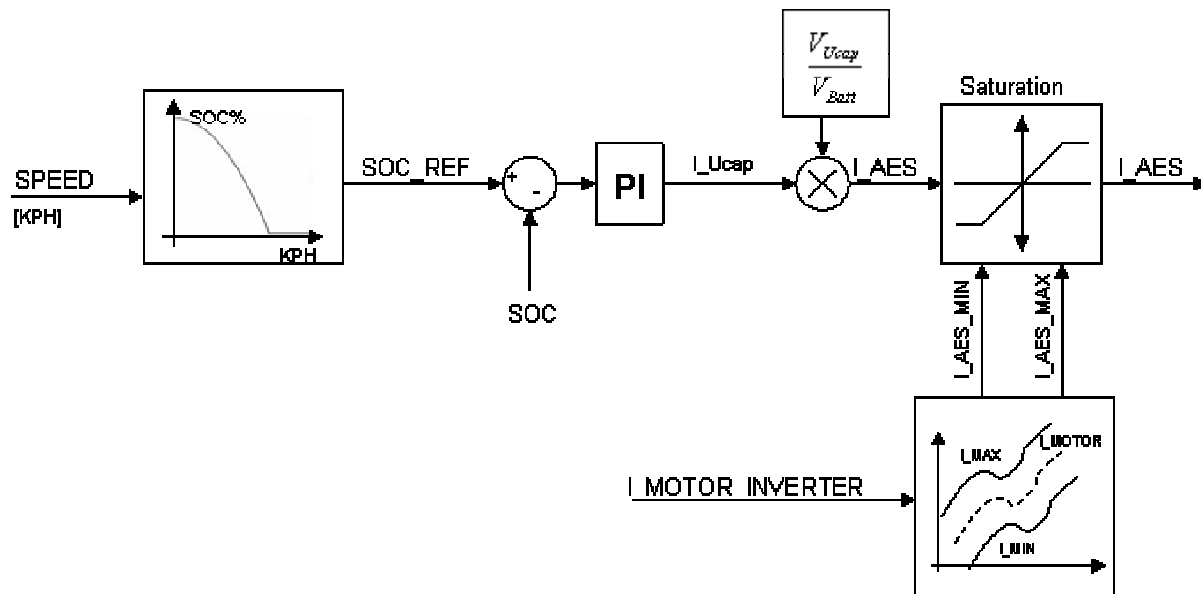


Figure 4: Control Scheme.

This control scheme was implemented in a TMS320F241 DSP from Texas Instruments. Also 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 all valuable data; also the Control program at the DSP can be commanded from the PC to work in slave mode (user controlled currents) or automated mode.

Figure 5 shows the control system communication layout.

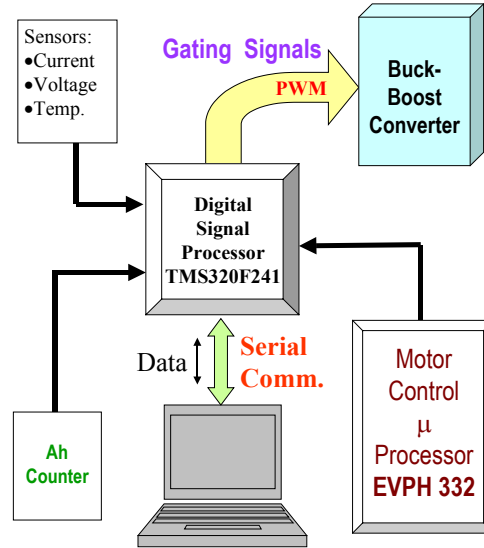


Figure 5: Control system communication layout.

4. Road Test Results Using the Auxiliary Energy System

For the road test a regular-city-traffic circuit of 28 Km was used. The test was performed under three conditions: without-regeneration, without-AES; with-regeneration, without-AES; and with-Regeneration, with-AES. Each test was performed several times to obtain a mean value for each condition's yield. For the operation with the AES the limits on the battery currents were set at [+30A,-3A].

Table 1 shows the results for each option tested.

Table 1: Road tests results.

	Without Regeneration, and Without AES (*)	With Regeneration	
		Without AES	With AES
<i>Km</i>	28.1	28.1	28.1
<i>Yield Km/KWh</i>	3.27	3.82	4.22
<i>Yield increase compared to (*)</i>		16.85%	30.4%

From table 1 it can be deduced that an extra 10.47% yield increase was accomplished using the AES for regeneration support with respect to the same experiment using batteries for storing regeneration energy. It can also be seen that this AES would increase the yield of a hybrid vehicle in about 30.4% (under the same conditions) if the primary source has a loss characteristic comparable to that of lead-acid batteries (comparable internal resistance).

Also a considerable increase in life span and reduction of rated power of the primary source is expected using this type of Auxiliary Energy System. In this case the primary source's maximum delivered power is reduced from more than 54kW to 10,7kW.

Figure 6 shows a fragment of the power currents and speed during one of the road tests in which the AES was used. It can be seen that the battery currents are limited at 30A on the positive side and almost 0A on the negative side.

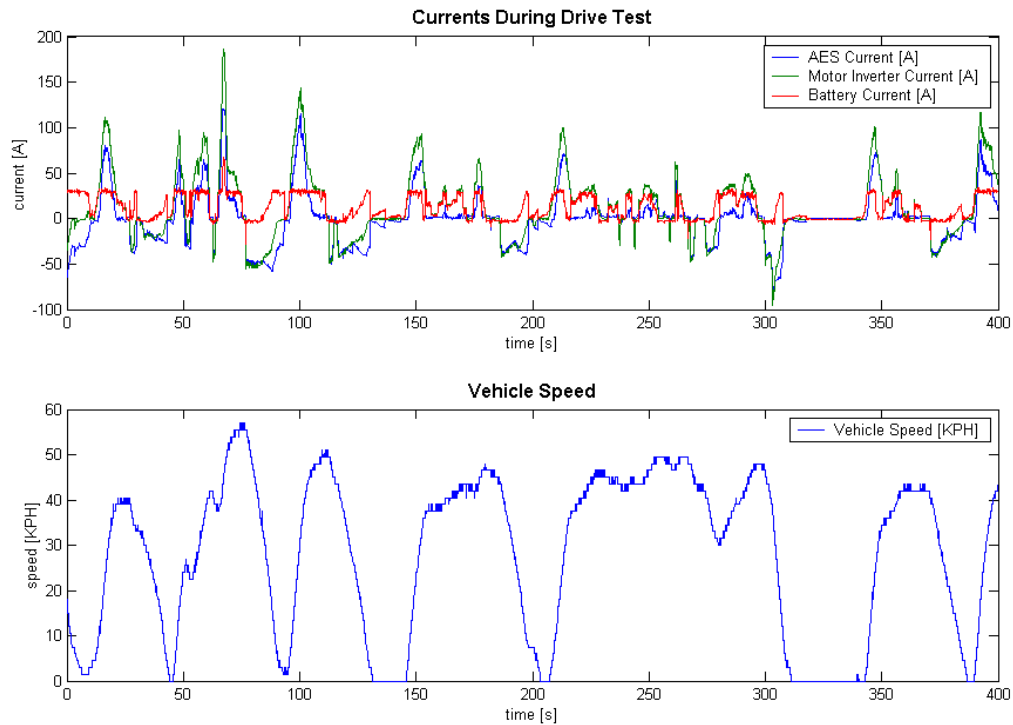


Figure 6: Fragment of drive test currents and speed (W-reg, W-AES).

It can be noticed the intense strain the batteries are spared of by absorbing regenerative currents from the AES. Currents of up to 100A and more are prevented from being injected to the batteries, which otherwise would cause great battery-life derating.

5. Future Algorithm Developments

The AES system and control algorithm implemented has proved useful as a power support and efficiency enhancing device during high demand periods. This has been demonstrated by the results obtained during road tests and the current plots extracted from them. The energy management strategy is based on an instantaneous Ultracapacitor SOC control and a battery current limiter. But this algorithm implemented, elaborated by a rather intuitive procedure, may not be (and probably isn't) the most efficient way of administrating the AES's capacity for power delivery.

Therefore the next step in the AES improvement process is the development of a control strategy that makes optimal use of the energy flow, in such a way that all systems operate within a maximum efficiency region for a given set of conditions. For this task an optimal-dynamic systems control method will be used [4,5].

The power distribution is adjusted by controlling the power delivered by the Ultracapacitors through the Buck-Boost converter. This can be seen in equation 2.

$$P_{Batt} = P_{Load} - P_{UC} \quad (\text{Eq. 2})$$

The variable chosen to control the power delivered by the Ultracapacitors will be the current through them. The following are the dynamic equations ruling the system.

$$SOC_{Batt}(t+1) = SOC_{Batt}(t) + (P_{UC}(t) - P_{Load}(t)) \cdot \eta_{Batt}(V_{Batt}(t), I_{Batt}(t)) \cdot T_e \quad (\text{Eq. 3})$$

$$SOC_{UC}(t+1) = SOC_{UC}(t) - P_{UC}(t) \cdot \eta_{UC}(V_{Batt}(t), V_{UC}(t), I_{UC}(t)) \cdot T_e \quad (\text{Eq. 4})$$

Where:

$SOC_{Batt}(t)$:	Batteries State Of Charge at instant t.
$SOC_{uc}(t)$:	Ultracapacitors State Of charge at instant t.
$P_{uc}(t)$:	Net power produced by the Ultracapacitors at instant t.
$\eta_{Batt}(V_{Batt}(t), I_{Batt}(t))$:	Batteries energy conversion efficiency.
$\eta_{uc}(V_{Batt}(t), V_{uc}(t), I_{uc}(t))$:	AES energy conversion efficiency.
T_e :	Sample time.

The cost function to be minimized is the one shown in equation 5.

$$J = \sum_{t=0}^{N-1} \dot{SOC}_{Batt}(V_{Batt}(t), I_{Batt}(t)) \cdot T_e \quad (\text{Eq. 5})$$

Where \dot{SOC} represents the instantaneous rate at which batteries are discharged ((-) charged).

The method consists in resolving this system for a set of different city circuits, in such a way that the system behavior will be known for a wide variety of particular cases.

To implement the strategy in real time, an expert system could be trained based on the results obtained from the previous stage. A particular possible procedure would be to train a neural network in order that it learns of every solution of the optimization function for each case studied.

6. Conclusions

An Ultracapacitor-based Auxiliary Energy System has been successfully implemented and tested. The system, intended to be used on a hybrid vehicle, was installed on a battery-powered vehicle to test power improvement and overall efficiency gain. The results showed that the main energy source's delivered power diminished from more than 54kW to 10,7kW. The yield increased in 30,41% compared to the vehicle's yield without using regenerative braking; and it increased in 10,47% compared to the vehicle's yield using only batteries to capture regenerative energy. These results are considered a very good first approach.

The next step will be to implement an optimal strategy, such that for a set of different drive patterns will operate the system in the most efficient region possible. This is intended to be done using dynamic optimal control techniques. Basic state equations and cost function have been established.

7. References

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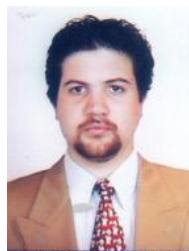
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