# ULTRACAPACITOR BASED STORAGE SYSTEM FOR LEAD-ACID POWERED LIGHT ELECTRIC VEHICLE RETROFIT

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**Abstract.** The paper presents the concept of a supercapacitor based plug-in retrofit kit that can be easily installed on the electric vehicle powered by lead-acid batteries without the intervention in the control system to store regenerative braking energy, improve battery lifetime and efficiency. The installation of the retrofit can be done in a simple manner by connecting of only two wires to the DC bus and by installing a contactless current sensor on the battery wire. Many control strategies can be implemented to control such system. The paper is focused on the efficiency optimization. This purpose is achieved through regulation of supercapacitor based energy storage current proportionally to the battery current in the discharge process. Theoretical equations, Matlab simulation results and experimental results on the test bench are presented in the paper and show the validity of the approach.

**Keywords:** low speed electric vehicles, lead-acid batteries, supercapacitors.

## Introduction

The fossil fuel resources in the world are consumed at a very fast rate and could be emptied in near future. Increasing of transportation efficiency is the best place to start efforts to reduce internal combustion engines emissions. Light electric vehicles (LEV) are the only commercially available alternative to the conventional internal combustion engine cars, which in terms of low cost and performance still are the best option. Therefore, systems that can significantly improve the performance and cost of the pure electric vehicles should be investigated.

DC motors are still used in drive system of the LEVs, especially, in small power range. These motors provide simple and cheap drive design necessary for low budget LEVs. The other DC motor advantage is direct and easy speed and torque control methods which could be provided by help of simple dedicated traction controllers [1]. Speed is proportional to armature voltage of the motor while the torque is proportional to the supplied current. However, DC motors have their drawbacks which include high maintenance cost due to the commutator and brushes, but due to rather simple DC brush motor traction drive solutions such cons are not significant at small power and low speed range for small passenger capacity LEV, small LEV trucks and forklifts. But even if the LEV is equipped with the AC motor from the energetic processes at power supply side point of view there are no big differences, therefore it is possible to use the DC motor as the object of analysis of the additional storage system by any electric drive system.

The performance of the LEV is limited by the traction accumulator battery, because of its high cost, maintenance needs and limited lifetime. For low cost and small power LEVs the lead-acid battery is only an economically efficient solution, but such battery lifetime is significantly reduced by high consumed current. The power demand profile for small LEV is practically close to the city driving cycle and is characterised by repeated acceleration and deceleration, which will deteriorate the battery, especially when the battery state of charge is low [2; 3].

During deceleration traction drive produces short time high current peaks which could not be stored in the traction battery due to the low battery charging current value in comparison to discharge current. From another hand high charging current could be easily absorbed by supercapacitors which are nowadays used in traction drive systems as well as in grid connected applications [4-9]. For reducing of battery discharge current and regenerative braking energy storage the LEV battery could be combined with the supercapacitor based Energy Storage System (ESS). Supercapacitors are well suited to handle a peak power load, because they have low losses, long lifetime and are maintenance free compared to the batteries [10]. Also high dynamic performance of supercapacitor ESS is best suited for a hybrid power system based on a combination of supercapacitors and batteries [11; 12].

The research presented in this paper is based on an approach that supercapacitor based ESS can be connected to any common commercial LEV (taking into account voltages and power of the battery) via 2 wires to the DC bus and DC current clamp on the battery positive cable in a way that no reprogramming or modification of the existing drive is required. Such ESS improves the battery lifetime, efficiency and stores regenerative braking energy.

**Materials and methods**

Light electric vehicles today are used everywhere: in the agricultural sector, tourism industry, warehouses, regular commercial service routes with very low passenger flow, etc. Mostly LEV use a series connection of standard 12 V lead-acid batteries to run an electric DC motor. The voltage of the battery bank can be equal to 36 volt, 48 volt or 72 volt. In the paper, as an example in the simulation model the golf cart with nominal voltage equal to 72 volts is selected for analysis. The mass of the LEV used in the simulation is approximately equal to 1300 kg, the gear ratio is equal to $k_{red} = 8$ and the wheel diameter is $D_{wheel} = 0.63$ m, maximum acceleration at nominal power is 2 $m \cdot s^{-2}$ [13].

During acceleration of the vehicle the required amount of energy from the capacitor and the battery pack is transferred to the traction drive. During the deceleration phase the energy from the traction motor in generation mode flows to the ultracapacitor or/and voltage limiter circuit. The energy transfer process is shown in Fig. 2. Charging current of the lead acid batteries is relatively small, therefore the ultracapacitor based ESS allows to store regenerative braking energy and decrease power spikes from the lead-acid battery. To utilize regenerative energy as much as possible, a good control strategy is required.

The system (Fig. 1) that will be analyzed in the paper contains a permanent magnet brush-type DC motor of the electric vehicle traction drive. The rated current of the motor is 150 A, the voltage constant of the motor is equal to 0.1 $V \cdot rpm^{-1}$, the torque constant is equal to 0.2, the rated speed is equal to 3000 rpm. The traction motor is connected to the hybrid system of energy storages that provides DC voltage through a DC/DC converter.

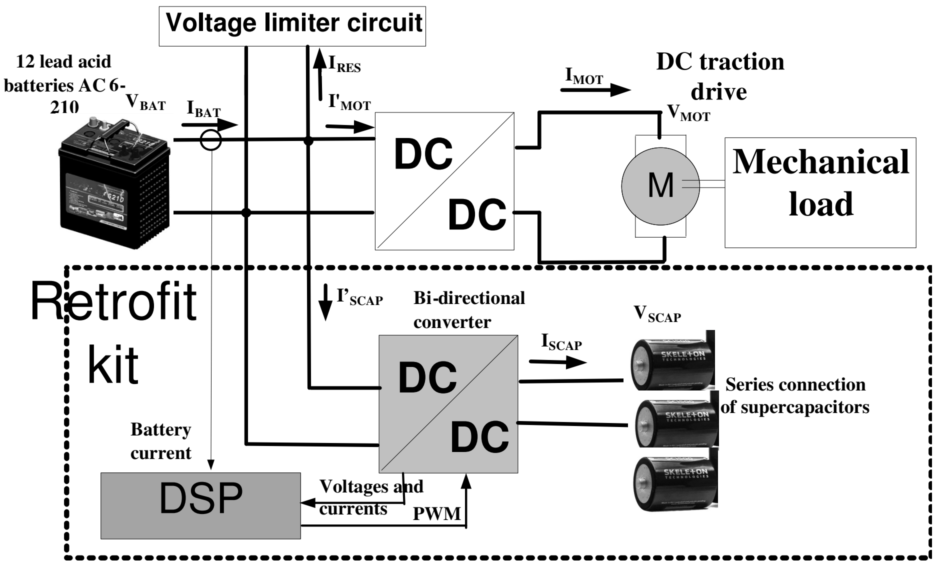


Fig. 1. **Block diagram of the system**

The LEV equipped with energy storage system retrofit kit shown in Figure 1 consists of the main battery, which has 12 lead-acid batteries with capacity 210 Ah in series, the series connection of the 33 Skelcap supercapacitors SC1500 with capacity 1500F, internal resistance 0.079 mΩ and bi-directional buck boost converter, which connects the supercapacitor based ESS to the DC bus. Voltage limiter circuit restricts the DC bus voltage less than 87 volts. Such a system will be simulated in Matlab software. Mechanical load can be replaced by the electrical machine that is controlled in such a way that it produces the same torque as real traction drive load.

During the movement of a vehicle the following forces act upon it (Fig. 2): the vehicle gravitational force that induces the force $F_R$ of reaction to the road, which determines the rolling resistance force $F_R$ on the wheels, the air resistance force $F_A$, grade resistance $F_G$ and the friction force of the mechanisms $F_f$. To obtain the equations describing the movement of a vehicle, a simplified dynamic model was adopted [14]. The model is based on the assumption that the vehicle has the mass

$m$ and equivalent moment of inertia $J_{eq}$ corresponding to those of the driving wheels and all rotating parts cinematically connected to them.

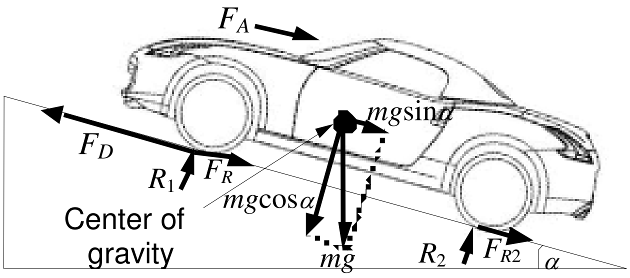


Fig. 2. **Forces acting on a vehicle**

An expression of the vehicle deceleration during coasting as a function of speed can be obtained [14]:

$$-a = \left(F_f + F_R + F_G + F_A\right) / m = C_0 + C_1 v + C_2 v^2 \approx Cv \tag{1}$$

Unknown constants C can be estimated using experimental methods or computer programs. The simplest way to determine them is the so-called coast-down test, which consists in launching a motor vehicle from a definite speed with the engine disengaged, and registering the current speed and distance during the free rolling until the vehicle stops. The test procedure is described in [14], this coefficient will be used further in a load simulator system to emulate a real vehicle.

As load simulator for the traction drive can be the DC machine [15], synchronous machine [16] or as in this case the induction machine. The induction machine is selected as load emulator because of availability for further practical experiments on the test bench. The simulator of the vehicle traction drive equivalent load is built by applying the induction motor with a field-oriented control frequency converter and a braking circuit containing a chopper-controlled braking resistor. The AC drive motor generates the opposite load torque $M_{ac}$, which produces the total drive torque.

The torque of the DC motor with permanent magnets can be written as:

$$M_{DC} = K_D I_{DC}\,, \tag{2}$$

where $K_D$ – a coefficient that depends on the motor construction;
$I_{DC}$ – the current of the DC motor.

The task for the control system of the load simulator is to control the frequency converter so that the AC motor acts like a rotating object with a very large moment of inertia $J_{eq}$ and with equivalent mechanical load torque $M_l$. The desirable behaviour of the mechanical system is described by the equation [17]:

$$\frac{d\omega}{dt} = \frac{K_D}{J_{eq}} I_{DC} - \frac{M_{eq}}{J_{eq}}\,, \tag{3}$$

where $M_{eq}$ is the equivalent momentum of resistance.

The expression for the reference angular speed of the frequency converter could be obtained by integration of equation 3:

$$\omega_{ref} = \int (A \cdot I_{DC} - C \cdot \omega) dt\,. \tag{4}$$

The coefficient A can be calculated as follows:

$$A = \frac{K_D}{J_{eq}} \tag{5}$$

and it can be determined from the acceleration data of the vehicle with rated current.

According to equation 4, the controller of the load simulator can be built as shown in Fig. 3. If the current of the DC drive is greater than zero ($I_{DC} > 0$) the system provides acceleration, while at $I_{DC} < 0$

the $\omega_{ref}$ value decreases and the system decelerates, thus imitating the braking mode. The more detailed description of the load simulator based on the induction machine is available in [17; 18]. The DC-DC converters are simulated by using the analytic simulation model described in [19]. The designed vehicle model is simulated over the part of the Urban Dynamometer Driving Cycle (UDDS). It has not used full UDDS in the graphs due to visibility.

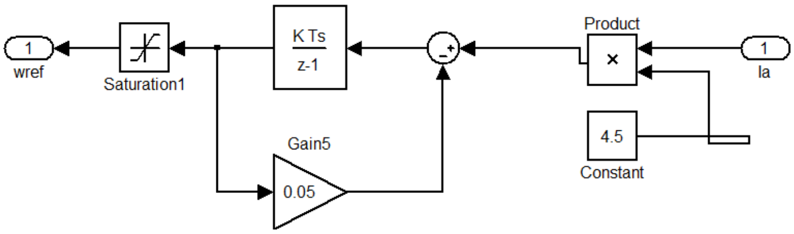


Fig. 3. **Controller of the load simulator**

## Results and discussion

This paper will examine series connection of the 33 supercapacitors with the summary capacitance of 45 F, maximum operating voltage equal to 90 volts. The minimum operating voltage of the supercapacitor bank is selected equal to 60 volts. The control algorithm must provide that all the energy of braking is stored in the ultracapacitor or in the lead-acid battery otherwise this energy is wasted in the brake resistor.

To accumulate all regenerative energy the supercapacitor based ESS control system in charge mode can use the control algorithm that keeps stable voltage on the DC bus equal to 80 V because the threshold of brake resistor operation is 85 V. The internal resistance of the lead-acid battery is 20 mΩ but of the ultracapacitor bank – only 2.6 mΩ. To establish the ratio at which the loss in both resistances is equal the following equation must be solved:

$$(1-x)^2 \cdot R_{AKB} = x^2 \cdot R_{SCAP}\,, \qquad (6)$$

where $x$ – used to represent the unknown proportion.

The result shows that from the point of view of power loss it is profitable to take 7 percent of current from the accumulator and 93 percent from the ultracapacitor. This control strategy would be best to reduce losses. Additionally, there are losses in the DC-DC converter and the energy of the supercapacitor based ESS is less than the lead-acid battery so such proportion leads to fast discharge of the ESS.

Figure 4 shows the results of the LEV simulation at the ESS converter proportional control algorithm mode. In the simulation shown in Fig. 4 the proportion between both currents is shared almost equally but anyway in one period the supercapacitor based ESS is discharged to minimum voltage and all of the current is taken from the lead-acid battery thus decreasing the efficiency. Of course, if the acceleration time is very long – driving up the hill the ESS will be discharged to the lowest threshold anyway.

The commonly used minimum supercapacitor voltage is $V_{Cmin} = 0.5V_{Cmax}$ and it is recommended by the manufacturers of supercapacitors. In this case 75 % of its energy capacity is utilised at the power capability $V_{Cmin}I_{Cref}$ varying from $0.5P_{max}$ to $P_{max}$. However, the braking power is maximal at the beginning of vehicle braking when the ESS has its minimum power capability. Therefore, a narrower voltage range was chosen – $V_{Cmin} \approx 0.7V_{Cmax}$, which gives 55 % utilisation of the supercapacitor energy capacity at power capability $0.67P_{max}$ at the beginning of LEV braking. Narrower ESS voltage range restricts the peak power shaving.

The following two voltages and two currents were measured for the ESS control purposes: filter capacitor voltage $V_f$, supercapacitor voltage $V_C$, supercapacitor current $I_C$, and battery output current $I_{BAT}$. Three of them were placed inside the ESS, and only the battery current sensor of a LEV has been installed in its power circuit. The battery current $I_{BAT}$ is measured and is used as a reference for the supercapacitor current controller.

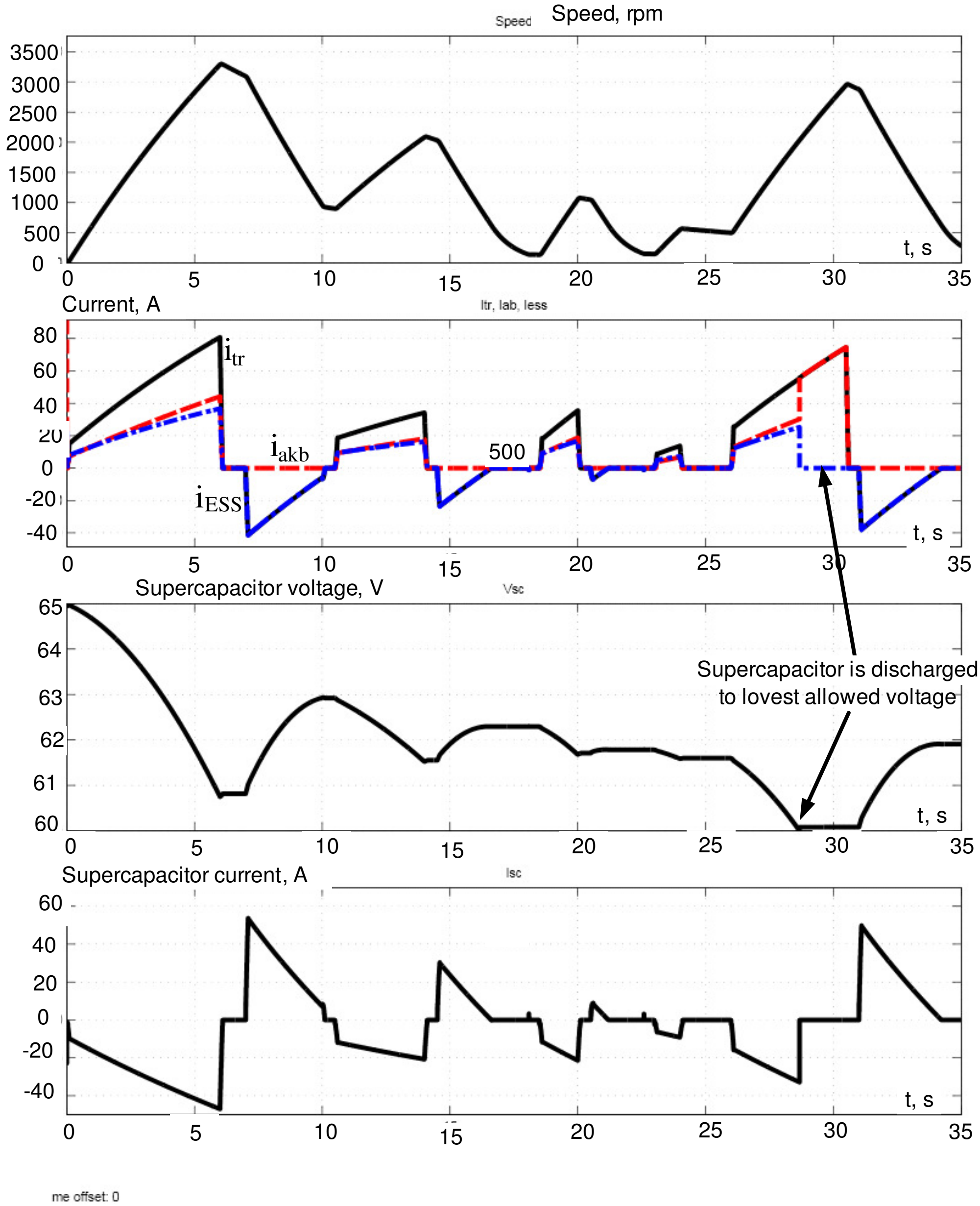


Fig. 4. **Current and voltages waveforms at the ESS converter proportional control algorithm**

The main task of the ESS controller is to store the whole braking energy of the LEV not allowing its dissipation in the braking rheostat, at the same time ESS must provide the discharge process as efficient as possible – it means that the time in which power is supplied only from the lead-acid battery must be as small as possible. As it can be seen in Figure 4, the variable that reports about to small or to large proportional coefficient is voltage of the supercapacitors. If the voltage of the supercapacitors stays equal to the maximum voltage level for some time, then more current must be taken from the supercapacitor ESS. If the voltage of the supercapacitor stays on the minimum allowed voltage, then more current from the battery must be taken. During the operation of the vehicle these times can be measured and a new proportional coefficient calculated.

For the possibility to implement such control algorithm on the real retrofit kit for LEV, the control algorithm was tested in the laboratory. The load simulator of the vehicle traction drive is built applying the induction motor with a field-oriented control frequency converter and a braking circuit containing a chopper-controlled braking resistor. The AC drive motor generates the opposite load torque. Figure 5 shows implementation of the digitally-controlled test bench (platform) for DC drive.

The frequency converter shown in Fig. 5 is connected to the 380V/50Hz network. When the DC motor is operating in the drive mode, the AC drive operates in the braking mode as load, with the braking energy produced by the load simulator transferred to the braking resistor. In the braking mode of the traction drive model, the load simulator works in the motor mode. The control system of the load simulator is designed to work in the speed control mode. The DC motor used in the test bench has the following parameters: $P_{nom}$ = 3.7 kW is the rated power of the motor; $r_a$ =0.46 Ω is the resistance of armature circuit; $n_{nom}$ = 1370 rpm is the rated speed of the motor; $C_E$ = 0.6366 is the electromagnetic constant of the motor. The AC motor is connected to the output of VLT5022 type Danfoss frequency converter. In order to control the DC-DC converter and to send the reference value to the frequency converter the STM32F407VGT6 microcontroller (MCU) is used. Also this MCU is used to control the DC-DC converter of the supercapacitor based ESS. To measure the signals, a YOKOGAVA digital oscilloscope was employed.

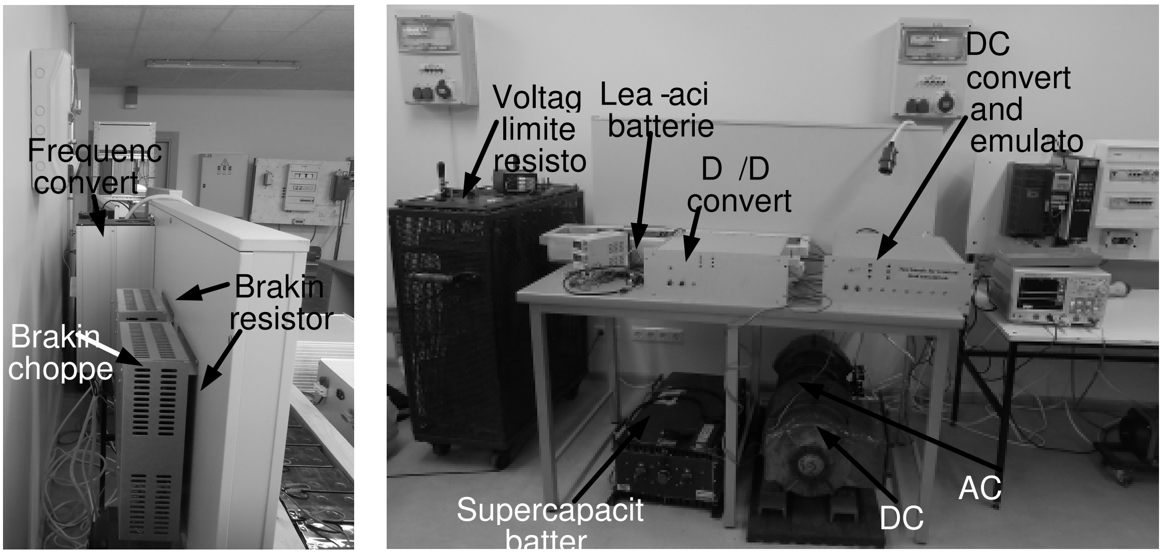


Fig. 5. **Test bench used for proportional control algorithm examination**

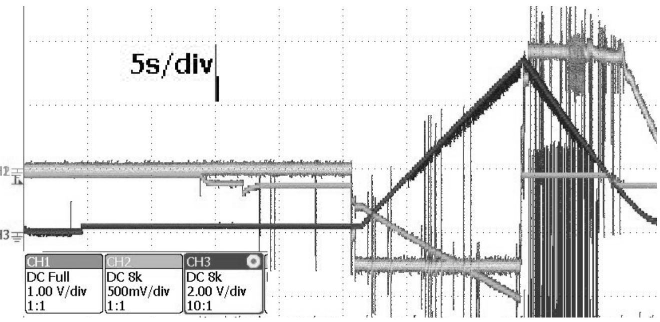


Fig. 6. **Emulation of the real LEV on the test bench:** CH1 – motor current 100 mV = 1 A (inverse); CH2 – battery current 100 mV = 1 A (inverse); CH3 – signal proportional to the speed

Figure 6 shows an example of waveforms on the test bench that emulates real LEV. The motor current can be adjusted via the potentiometer or the profile can be entered in the software. The test bench allows emulate inertia of the LEV during the braking process, so the energy storage system can be investigated on this test bench.

The difference between the calculated value $k_P I_{BAT} V_{SCAP}/V_{DC}$ is proportional to the battery current ($k_P$ is the proportion coefficient) and takes into account the difference between the supercapacitor voltage ($V_{SCAP}$) and DC bus voltage $V_{DC}$ and discharging current of the ultracapacitor $I_{SCAP}$ creates the error signal of the proportional-integrally-differential feedback system (Fig. 7). Reference values are corrected depending on the ultracapacitor voltage value. During acceleration, power partly is taken from the battery and ESS (Fig. 8).

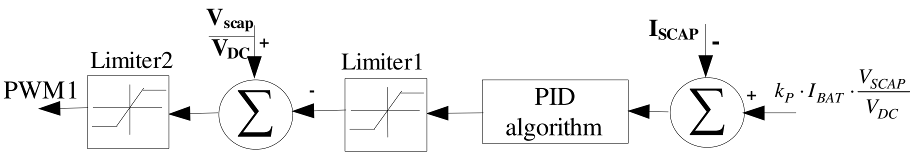


Fig. 7. **Control algorithm of the converter in boost (discharge) mode**

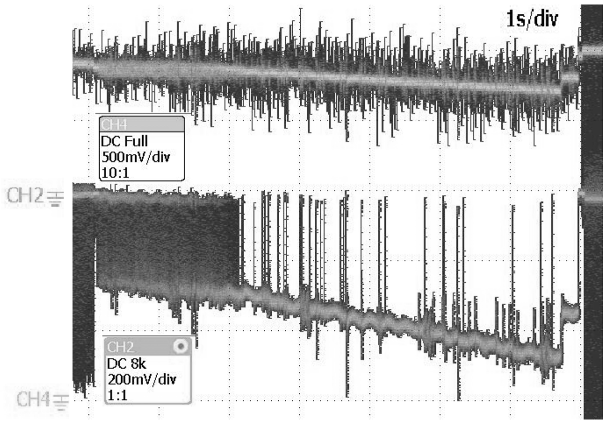


Fig. 8. **Control of the ESS current proportionally to the battery current in discharge mode:**
CH4 – voltage on current sensor proportional to the battery current (2.5 V = 0 A; 2 V = 10 A);
CH2 – supercapacitor ESS current (100 mV/A inverse)

During the braking mode of the vehicle the control algorithm must provide that all of the braking energy is stored in the supercapacitor based ESS, otherwise this energy is wasted in the brake resistor. To accumulate all regenerative energy the algorithm (Fig. 9) that keeps the voltage on the DC bus equal to 120 V is used because the threshold of the brake resistor operation is 125 V. Of course, the energy can be stored only in case if energy storage is not fully charged. If the duty cycle of a buck-boost converter is equal to division of input voltage by output voltage there is not the current flow. To work in the buck mode the duty cycle must be greater than this division, therefore (Fig. 10) to the value calculated by PI algorithm the division $V_{scap}/V_{DC}$ is added. Figure 8 shows the DC bus voltage during the braking phase. All of energy during braking is stored in the ultracapacitor and the voltage remains constant – equal to 120 volts.

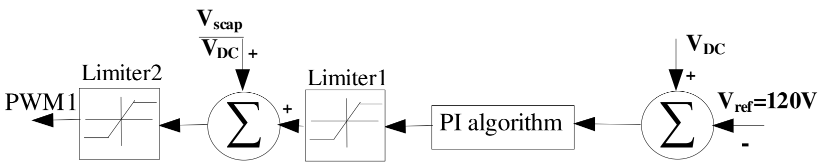


Fig. 9. **Control algorithm of the converter in buck (charge) mode**

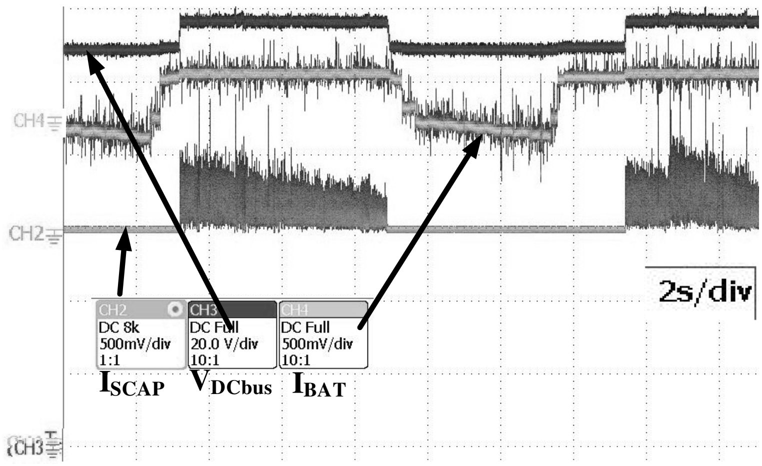


Fig. 10. **Control of the ESS in the braking mode: before PID control loop tuning and after tuning**

## Conclusions

The work presented in the paper shows that additional supercapacitor ESS with an independent control system could be used on LEV without any modification of the existing commercial drive. Only two wires and the current sensor must be connected and the system can work by itself improving the efficiency of the drive system. Future research is needed to develop the ESS system without the battery current sensor.

In the paper it is proposed to use the proportional current control strategy that controls the current of the ESS proportionally to the lead-acid battery traction drive supply current to improve the efficiency of the overall system. At first the LEV drive system and the supercapacitor based ESS with proportional control algorithm is simulated using Matlab/Simulink software. The simulation results show that the proportion relation factor between these currents can be corrected according to the supercapacitor average voltage.

The supercapacitor based ESS with power supply battery proportional control algorithm is implemented in the laboratory test bench that emulates the real electrical processes of the LEV. The experimental results show that the proposed control method can be implemented on the LEV drive system by using the microcontroller. Such ESS system allows storing regenerative breaking energy of the vehicle and the discharge process of the supercapacitors has good efficiency.

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