DIGITALLY CONTROLLED SYNCHRONOUS BUCK-BOOST CONVERTER FOR ULTRACAPACITOR BASED ENERGY STORAGE APPLICATION

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Abstract. The paper presents a synchronous buck-boost DC-DC converter which connects the ultracapacitor pack and a DC bus of an electric vehicle. In order to control this kind of DC-DC converter the digital signal processor (DSP) is used. The proposed power converter charges the ultracapacitor pack to store the kinetic energy during the vehicle braking and regenerates this stored energy during the next speed up. In the paper the software algorithm of the control loop of the converter is presented. The experimental test of the DC-DC converter was performed using the test platform for DC electric motor of a traction vehicle. The presented switched converter can be used for electric vehicles with a low-power DC electric motor.

Keywords: DC-DC switching converter, digital control, ultracapacitors.

Introduction

The resources in the world are consumed at a very fast rate. Increasing the transportation efficiency is the best place to start efforts to reduce emissions of carbon dioxide (CO_2), which is a primary culprit in global warming because approximately one third of all CO_2 emissions come from transportation. Electric vehicles (EV) are the only commercially available alternative to the internal combustion engine cars, which in terms of cost and performance still are the best option. Therefore, systems that can improve the performance and cost of electric vehicles should be researched.

DC motors have a long history in EV use. DC motors provide simple and cheaper drive design that is also easier to manufacture. The other good thing about the DC motor is that it has a direct and easy way in controlling the speed and torque [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 due to the commutator and brushes which will wear in time.

A large limitation for the EVs is the battery, because of the cost, maintenance needs and limited lifetime. The power demand profile for city driving is characterised by repeated acceleration and deceleration, which will deteriorate the battery, especially when the battery charge is low. Supercapacitors are well suited to handle such a power load. They have low losses, long lifetime and are maintenance free compared to the batteries [2]. This makes it worthwhile to research a hybrid power system based on a combination of supercapacitors and batteries [3-5].

The proposed system

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. 1. Charging current of the lead acid batteries is relatively small, therefore, in order not to damage them the bi-directional power flow is disabled using series connection of the diode. To utilize as much as possible of regenerative energy, a good control strategy is required.

Fig. 1. **Energy and current flow a) during acceleration; b) during deceleration**

The experimental set-up (Fig. 2) contains a DC motor that simulates the electric vehicle traction drive and an AC induction motor controlled by the frequency converter that simulates the traction drive load. The principle of operation of the traction drive load is described in the previous publication [6]. The traction motor is connected to the hybrid system of energy storages that provides DC voltage through a two quadrant digitally controlled DC/DC converter which allows simulation of the traction and regeneration braking modes without reversing of the direction of rotation. The DC motor has P_{nom} = 3.7 kW rated power and rated rotation speed 1370 rpm.

The hybrid energy storage system consists of the main battery, which has 9 lead-acid batteries with capacity 12 Ah in series, the ultracapacitor bank BMOD0063 P125 with 63 F capacity and bi-directional buck-boost converter, which connects the ultracapacitor to the DC bus. Voltage limiter circuit regulates the DC bus voltage less than 130 volts.

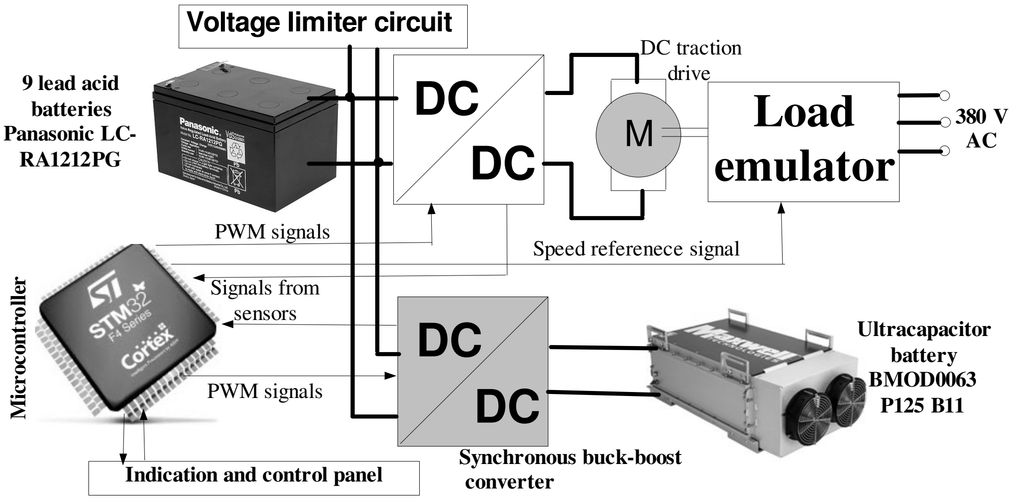

Fig. 2. **Block diagram of the experimental set-up**

In order to control the DC-DC converter and to send the reference value to the frequency converter the STM32F407VGT6 microcontroller (MCU) is used. This ARM Cortex-M4 32 bit MCU with a floating-point unit has 210 DMIPS, up to 1 MB Flash, 194 KB RAM, 17 timers (including the general purpose ones), 3 analogs to digital converters (ADC), 15 communication interfaces. The MCU maximal operating frequency is 168 MHz. It also includes a full set of the digital signal processor (DSP) [7]. To measure signals the YOKOGAVA digital oscilloscope was used. The buttons, potentiometers, LEDs and LCD display provide user interface.

Design of the converter

Figure 3 shows the structure of the DC-DC converter. It is bi-directional as it can work in both, buck and boost mode. For the direct power flow the buck configuration is activated. The transistor T1 is controlled by pulse width modulation and operates in the forward conduction mode but VT2 – by the complementary inverted signal with a small time delay (dead time) and operates in the reverse conducting mode. The opposite power flow is provided by activating the boost configuration. The switching frequency of the converter is selected to f_{SW} = 25 kHz.

Minimal voltage of the supercapacitor ($U_{SCAPmin}$) at which still all of regenerated energy can be accumulated can be calculated by dividing of the nominal power of the motor (P_{nom}) multiplied by the efficiency of the DC-DC converter of traction drive (η = 0.94) by maximum current of the converter ($I_{SCAPmax}$ = 40 A) that is limited by the construction of PCB :

$$U_{SCAP\min} = \frac{P_{nom} \cdot \eta}{I_{SCAP\max}} = \frac{3700 \cdot 0.94}{40} \approx 85 \text{ V}. \quad (1)$$

To commutate such a current two parallel connected IXFK120N25 MOSFETs were selected having the resultant R_{Dson} = 11 mΩ. The inductance of the inductor (L) can be calculated in order to ensure pulsations of current less than ΔI = 5 A:

$$L_{\min} = \frac{\left(U_{DC\max} - U_{SCAP\min}\right) \cdot U_{SCAP\min}}{U_{DC\max} \cdot f_{sw} \cdot \Delta I} = \frac{(120-85) \cdot 85}{120 \cdot 25 \cdot 10^{3} \cdot 5} = 200\ \mu\text{H}, \quad (2)$$

where U_{DCmax} is maximum voltage of the DC bus and $U_{SCAPmin}$ is the minimal voltage of the supercapacitor.

As the magnetic core for the choke a toroid core of iron powder T400A-26 was selected with the inductance constant (A_L = 260 nH), relative magnetic permeability (μ = 75), length of magnetic circuit (l = 0.249 m) and maximum saturation flow density (B_{max} = 1.5 T). The necessary count of the windings (w) for inductance at least 200 µH can be calculated by the following equation:

$$w = \sqrt{\frac{L_{\min}}{A_L}} = \sqrt{\frac{200 \cdot 10^{-6}}{260 \cdot 10^{-9}}} = 28 . \qquad (3)$$

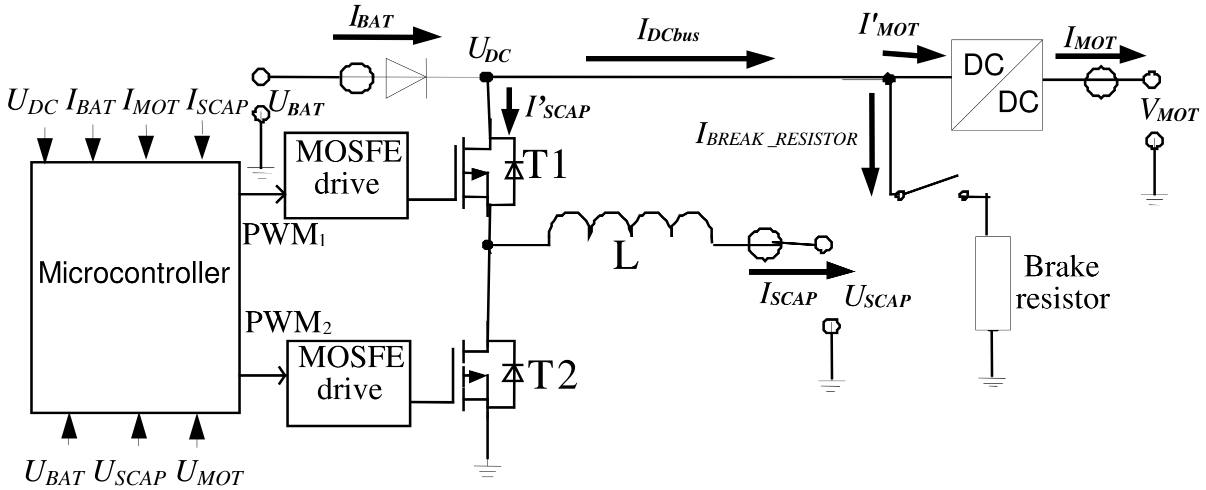

Fig. 3. **Schematic of the synchronous buck-boost converter**

Considering that the initial permeability depends on the magnetizing force (H) the winding count is increased to 40. The selected 6 mm^2 copper wire yields to around 8 W losses by current 40 A so further increasing the number of windings is not desirable. The magnetizing force (H) and magnetic flux density (B) can be calculated as follows:

$$H = \frac{I \cdot w}{l} = \frac{40 \cdot 40}{0.249} = 6426 \, \frac{\mathrm{A}}{\mathrm{m}} = 81 \, \mathrm{Oe} , \qquad (4)$$

$$B = \mu \mu_0 H = 4 \cdot 3.14 \cdot 10^{-7} \cdot 75 \cdot 6246 = 0.59 \, \mathrm{T} . \qquad (5)$$

The calculated magnetic flux density 0.59 T is less than the maximum saturation flow density (B_{max} = 1.5 T), the calculated magnetizing force leads to decreasing of real inductance proportional to the coefficient k_L that can be found in technical documentation of the magnetic core. Calculated by equation 6 inductance will cause 6 A current ripple.

$$L_{real} = A_L w^2 k_L = 260 \cdot 10^{-9} \cdot 40^2 \cdot 0.4 = 166 \, \mu\mathrm{H} \qquad (6)$$

Synchronous rectification is used in the DC/DC converter because of significantly lower conduction losses. Dead time was selected equal to 400 ns after analyzing oscillograms of voltage and the current commutation process of the power MOSFETs.

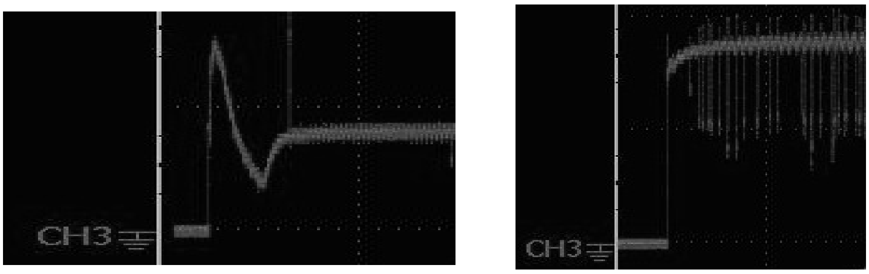

Fig. 4. **Step change response of current of the converter before and after tuning of control loop**

To select the initial parameters of the proportional – integral control loop the PSIM model of the converter was used. The obtained coefficients lead to significant oscillations (Fig. 4), therefore proportional and integral coefficients were adjusted experimentally – by changing the values proportionally to the analogue values of the potentiometers and analysing such a system response to the step function. The result is shown in Fig. 4.

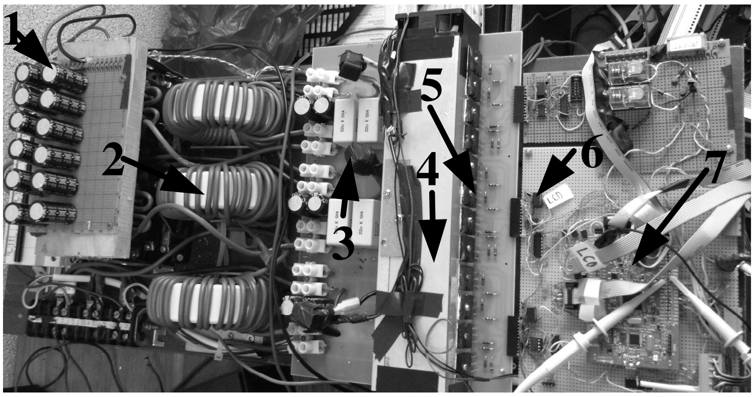

Fig. 5. **Hardware of DC-DC converter for ultracapacitor charging/discharging**

Figure 5 shows hardware implementation of a digitally controlled synchronous buck boost DC-DC converter. The power transistors (5) are placed on the radiator plate (4). The PWM signals from the microcontroller board (7) goe to the MOSFET drivers (6). Current is measured by LEM CASR15 current sensors (3), the inductor (2) is designed by using of the toroidal core.

Control algorithm and results

This paper will examine energy storage with a large installed capacity of the ultracapacitor. This means that the ultracapacitor can store all breaking energy of more than one deceleration cycle. The control algorithm must provide that all the energy of braking is stored in the ultracapacitor, otherwise this energy is wasted in the brake resistor. To accumulate all regenerative energy algorithm that is similar to [8] is proposed (Fig. 6) that keeps the voltage on the DC bus equal to 125 V because the threshold of the brake resistor operation is 130 V. Of course, the energy can be stored only in case if energy storage is not full, therefore correct discharge strategy is required.

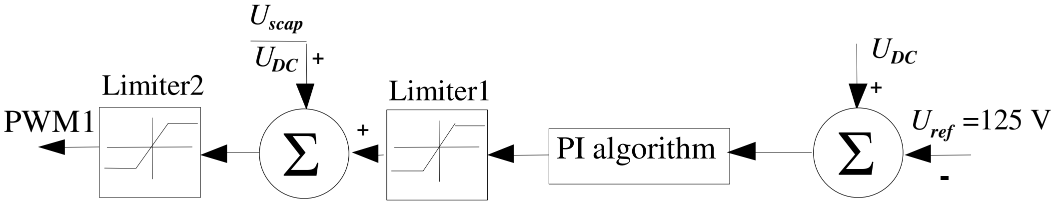

Fig. 6. **Control algorithm of the converter in buck mode**

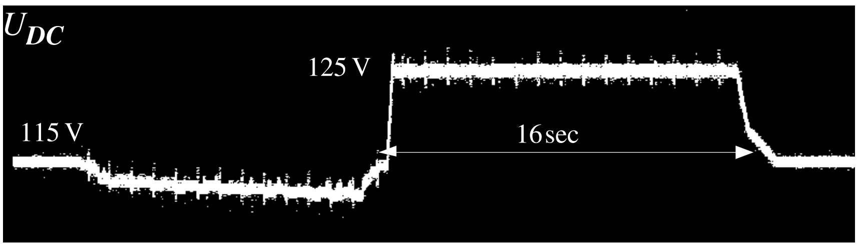

Fig. 7. **DC bus voltage**

If the duty cycle of a buck-boost converter is equal to the division of the input voltage by the output voltage there is not current flow. To work in the buck mode the duty cycle must be greater than this division, therefore (Fig. 6) to the value calculated by PI algorithm division U_{scap}/U_{DC} is added. To work in the boost mode from the value calculated by PI algorithm division U_{scap}/U_{DC} is subtracted. Figure 7 shows the DC bus voltage during accelerations and the braking phase. All of energy during braking is stored in the ultracapacitor and the voltage remains constant – equal to 125 volts.

An internal resistance of the lead-acid battery is 270 mΩ but of the ultracapacitor – only 18 mΩ. To establish the ratio at witch the loss in both resistances is equal equality 7 must be solved where x is used to represent the unknown proportion. The result shows that of point of view of power loss it is profitable to take 20 percent of current from the accumulator and 80 percent from the ultracapacitor. This control strategy would be best to reduce losses. As the current consumed from the accumulator is so small, this will lead to discharge of the ultracapacitor and in some periods of time big current from the accumulator must be consumed.

$$(1-x)^2 \cdot R_{AKB} = x^2 \cdot R_{SCAP}. \quad (7)$$

Such a mode of operation of the accumulator leads to big power losses in internal resistance and this will shorten the life of the battery. Therefore, another discharge strategy is proposed. The DC/DC converter for charging or discharging of the ultracapacitor can be controlled in such a way that it does not control the current of the ultracapacitor but indirectly controls the current of the lead-acid battery. It can be realized because from the measured currents (I_{MOT} – current of the DC motor) and voltages (U_{DC} – voltage of the DC bus; U_{MOT} – voltage of the DC motor) the necessary current of the ultracapacitor to maintain the current of the battery in the desired level can be calculated:

$$I_{ref} = \frac{U_{DC}}{U_{SCAP}} \cdot \left(I_{MOT} \frac{U_{MOT}}{U_{DC}} + I_{BATreference} \right). \quad (8)$$

Assuming that all of the regenerative energy is stored in the ultracapacitor, from the driving cycle statistical data by integrating the average current and relative length of braking time can be calculated. During the acceleration and idling phases the vehicle can run taking a constant battery current $I_{BATreference}$ equal to dividing of average current by relative non braking time. Under these conditions, the ultracapacitor gives all the positive and negative variations around this average current, and its voltage can indicate [9] when it is required to increase or decrease the average current given by the battery pack. During the operation of the vehicle the current I'_{MOT} can be integrated and a new more accurate value of average current calculated.

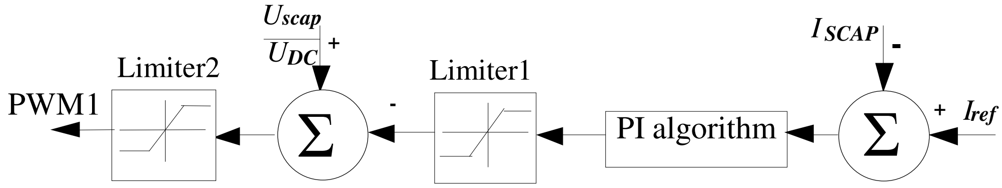

Fig. 8. **Control algorithm of the converter in boost mode**

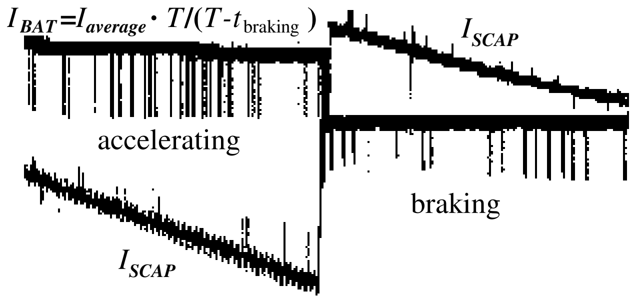

Fig. 9. **Currents during acceleration and braking modes**

The calculated value I_{ref} and boost current of the ultracapacitor I_{SCAP} create error signal of the proportional-integral feedback system (Fig. 8). Reference I_{ref} is averaged to improve the stability of the feedback system. During acceleration the current of the battery is constant and equal to the average current (Fig. 9), the current of the ultracapacitor is growing to ensure constant battery current. In the braking mode the ultracapacitor stores all of the regenerative energy and there is not a current flow to the lead-acid battery (it is disabled by series diode connection) and to the brake resistor because the voltage do not exceed 130 volts.

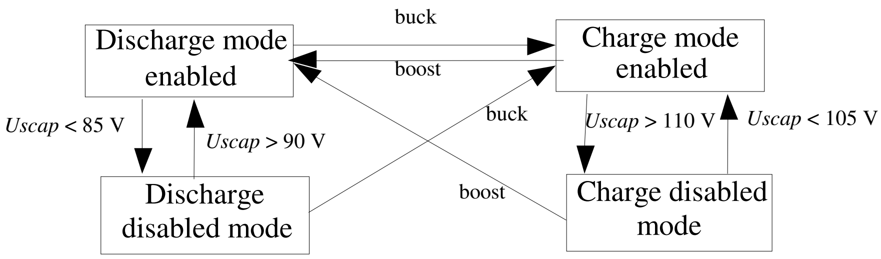

Fig. 10. **Transition between the states of the DC-DC converter**

In order to prevent the ultracapacitor from overcharging or to deep discharge the algorithm shown in Figure 10 is used. In this algorithm hysteresis is used to avoid unwanted rapid switching. The lower threshold of the ultracapacitor is chosen equal to 85 V because it is the minimal voltage at witch the ultracapacitor can be charged with maximum power.

Conclusions

A digitally controlled synchronous buck-boost converter for the ultracapacitor based energy storage system is designed. The converter has minimum number of elements and has a simple construction. The algorithm to accumulate all of regenerative braking energy and use it in the next acceleration cycle with minimal losses is offered. To implement this control algorithm for control of the converter DSP is used. Digital control allows driving transistors synchronously thus reducing losses, it allows realizing transition between acceleration and the braking mode in a simple way.

The test of the converter was successfully performed on the test bench, further it can be used for traction vehicles with DC traction drive to utilize energy of regenerative braking. The converter allows higher accelerations and decelerations of the vehicle with minimal loss of energy and minimal degradation of the main battery pack. If in the future the supercapacitor reaches specefic energy 20 $Wh \cdot kg^{-1}$, it will be possible to implement electric vehicles with ultracapacitors only.

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