Ultra Capacitors Charging by Regenerative Braking in Electric Vehicles

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Abstract – The process of regenerative braking of an electric vehicle with source of energy - battery and ultracapacitor is subject of this work. The studied system is composed of a brushless DC motor, buck-boost DC converter and ultracapacitors. An optimization of the control system for storing maximum energy in the ultracapacitors is performed. The results are useful for the aim of improving the control of energy flows in electric vehicle and achieving maximum range with a single charge.

Keywords – electric vehicles, buck-boost converters, regenerative energy, control of energy flows, ultracapacitors

I. INTRODUCTION

One of the main advantages of electric traction vehicles are the reversible energy flows in the electric machine. Thus, energy created from regenerative braking of the vehicle can be stored. Most often it is reused for supporting acceleration at vehicle departure [5, 9, 10]. Due to its advantages, regenerative braking is widely used in transport: electric and hybrid vehicles, electric bicycles, railways etc. [1, 6, 7].

The system that stores electric energy is in most cases composed of ultracapacitor and battery. This reduces the working stress on the battery and increases its lifetime [8, 9]. The most important property of ultracapacitors is that they store and deliver energy rapidly. This justifies their use to improve the vehicle dynamics, despite their relatively high price at the moment. Due to the specifics and differences between the characteristics of the above two energy storage elements, the use of power electronic converters is necessary, a DC-DC buck/boost converter is used in the studied system. The process of storing energy in ultracapacitors by regenerative braking is examined in the current work.

II. REALIZATION

The block diagram of the studied system is shown on Fig. 1. It consists of the following elements: a brushless DC motor (M), AC / DC converter, buck-boost DC converter and ultracapacitors (UC).

The object of this study is to analyse the operation and setting of the system internal control loop (contoured by a dashed line in Fig. 2).

III. MATHEMATICAL MODELS

A mathematical model of the system is implemented for the simulations. The equivalent circuit of the system is presented at Fig.3. It comprises of a voltage source $E_d$ with...
its internal resistance $R_a$, a switching transistor $VT$ with its internal resistance in the “ON” state $R_{ON}$; a filter inductance $L$ and its active resistance $R_L$; diode $VD$, a forward voltage $V_F$ and dynamic resistance $R_d$; UC ultracapacitors with capacity $C_{UC}$ and internal series resistance $R_{UC}$.

The different stages the converter operation are described mathematically with the following system of equations:

For the conducting state of the transistor -

$$L(i_L, \theta)\frac{di_L}{dt} = E_d - (R_L + R_{ON} + R_f)i_L$$

$$C_{UC} \frac{dU_{UC}}{dt} = 0$$

(1)

where, $i_L$ is the current through the inductance and $U_{UC}$ is the voltage of the ultracapacitor.

And when the switch is turned off:

$$L(i_L, \theta)\frac{di_L}{dt} + (R_L + R_F + R_{UC})i_L + U_{UC} = 0$$

$$C_{UC} \frac{dU_{UC}}{dt} = i_L$$

(2)

In generator mode the motor voltage at the output of the rectifier is proportional to the speed $V$ of the electric vehicle, i.e. $E_d = kV$. When braking with constant force $\frac{dV}{dt} = \text{const}$, $E_d$ is a linear function of time $E_d = E_{d\text{ max}} - kt$.

Assuming that $L = \text{const}$, i.e. the inductance of the inductor is independent from the current or the temperature, the system equations (1) have the following solution:

When the switch is on

$$i_L((n + D)t_p) = i_L(nt_p)e^{-a/Ld_{tp}} + \left(1 - e^{-a/Ld_{tp}}\right)b$$

$$U_{UC}(n + D)t_p) = U_{UC}(nt_p)$$

$$a = R_L + R_i + R_{ON}$$

$$b = E_d/a$$

(3)

where $D$ is the duty cycle.

And when the switch is turned off:

$$i_L((n + 1)t_p) = i_L((n + D)t_p)e^{-a/Ld_{tp}} + \left(1 - e^{-a/Ld_{tp}}\right)b$$

$$U_{UC}((n + D)t_p) = U_{UC}((n + 1)t_p)$$

$$a = R_L + R_{UC} + R_F$$

$$b = E_d/a$$

(4)

The following consideration is taken into account for simplification and easier solution: $L \ll C$, so $U_{UC} = \text{const}$ for $nt_p < t \leq n(t_p + D)$.

The capacity of the ultracapacitors, inductance of the inductor and the operating frequency of the converter are determined.

The ultracapacitors have two functions: to assist the departure and to collect energy when braking.

The necessary power in starting mode of an electric vehicle with mass $m$ and final speed $V_{\text{max}}$ is $E = \frac{m V_{\text{max}}^2}{2\eta}$, where $\eta$ is the efficiency of the energy conversion from the storage element to the wheels.

Assuming, that the energy of the ultracapacitor is $E_{UC} = kE$, $k \in [0, 1]$. The repartition of energy from the two sources by departure is determined by the coefficient $k$. Assuming that $U_{UC\text{ max}} = E_{d\text{ max}}$ for the capacity of the ultracapacitor it’s obtained $C_{uc} > \frac{2kE}{U_{UC\text{ max}}^2}$.

The energy charged into the ultracapacitors at constant speed will be $E_{IN} = E_{UC\text{ max}} - E_{UCRB}$, where $E_{UCRB}$ is the energy that will be stored in the ultracapacitor by the vehicle regenerative braking.

The ultracapacitors should be partially charged before the braking, so that after the process of regenerative braking they can be charged up to their maximum operating voltage. From where the initial voltage of charging in regenerative braking is determined

$$U_{UC\text{ IN}} = \sqrt{\frac{2E_{IN}}{C_{UC}}}$$

IV. RESULTS

A numerical experiment – simulation of an electric vehicle with the following characteristics is performed:

Mass of electric vehicle $m = 700$ kg;

Acceleration by departure $\frac{dV}{dt} = 2$ m/s$^2$;

By assumption the energies drawn from the battery and the ultracapacitor by vehicle departure are equal.

A proportional-integral regulator is used for controlling the motor current. The experiment is carried out under the following assumptions:

- Zero magnetic losses in the inductor;
- The inductor is linear;
- For operating frequency of the DC-DC converter is chosen the maximum possible according to the frequency limits of the circuit components;
- The lower limit of the operating frequency is determined from the requirement for continuous current through the inductor;
- Description of losses in the individual circuit elements is performed according to the methodology shown in [11].
The results of the experiment are presented in table 1, 2, 3. An IGBT transistor of type AN4544 is used, Schottky diode SBR40U300CT and 120 ultracapacitors of type BCAP035 connected in series with capacity 350 F, voltage 2.5 V, and internal resistance 3.2 mΩ. The following annotations are used:

- $E_c$ is the energy in the ultracapacitor at the end of the regenerative braking process

$$\eta = \frac{E_{uc}}{E_{uc} + E_{VT} + E_{R_t} + E_{RL} + E_{VD} + E_{RUC}}$$

Is the efficiency of energy conversion in regenerative braking. The energies in the denominator are respectively: the losses in the transistor, the losses in inductor, diodes and in the ultracapacitor.

- $\Delta I_{L_{max}}$ maximum value of ripple current through the inductor

<table>
<thead>
<tr>
<th>TABLE 1</th>
<th>$f=300$ KHz, $D_{max}=0.85$</th>
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<tbody>
<tr>
<td>$L$ [µH]</td>
<td>30  40  50  80  100  110</td>
</tr>
<tr>
<td>$E_{UCRB}$ [J]</td>
<td>50310 50310 50310 50310 50310 50310</td>
</tr>
<tr>
<td>$\eta$</td>
<td>0.896 0.896 0.8965 0.896 0.896 0.896</td>
</tr>
<tr>
<td>$\Delta I_{L_{max}}$ [A]</td>
<td>15.19 12.76 9.06 5.81 4.5 4.11</td>
</tr>
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<tr>
<th>TABLE 2</th>
<th>$f=200$ KHz, $D_{max}=0.85$</th>
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<tbody>
<tr>
<td>$L$ [µH]</td>
<td>30  40  50  80  100  110</td>
</tr>
<tr>
<td>$E_{UCRB}$ [J]</td>
<td>50312 50310 50310 50309 50310 50310</td>
</tr>
<tr>
<td>$\eta$</td>
<td>0.896 0.896 0.896 0.896 0.896 0.896</td>
</tr>
<tr>
<td>$\Delta I_{L_{max}}$ [A]</td>
<td>23 16.95 13.42 8.35 6.78 6.15</td>
</tr>
</tbody>
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<tr>
<th>TABLE 3</th>
<th>$f=100$ KHz, $D_{max}=0.85$</th>
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</thead>
<tbody>
<tr>
<td>$L$ [µH]</td>
<td>45  50  80  100  110</td>
</tr>
<tr>
<td>$E_{UCRB}$ [J]</td>
<td>50312 50311 50309 50308 50308</td>
</tr>
<tr>
<td>$\eta$</td>
<td>0.897 0.897 0.897 0.897 0.897</td>
</tr>
<tr>
<td>$\Delta I_{L_{max}}$ [A]</td>
<td>30.18 27 16.9 13.1 12.35</td>
</tr>
</tbody>
</table>

In Fig. 4., Fig. 5., Fig. 6. and Fig. 7. are shown the graphical results as following:
Fig. 7. The current through the filter inductance of the DC/DC converter at operating frequency $f=200\,\text{kHz}$ and the value of inductance $L=110\mu\text{H}$.

V. CONCLUSION

Regenerative braking is an efficient way for improving electric vehicles dynamics and extension of the battery life. As a result from the present research, the following conclusions are made:

- The amount of energy stored in the ultracapacitors depends slightly on the switching frequency of the DC converter;
- Losses in the converter are proportional to the switching frequency;
- The ripple of the motor current is practically independent from the filter inductance $L$;
- The control system is invariant from the amount of energy recovered and the converter parameters. The influence of the regulator settings on overall system efficiency is weak. The majority of losses in the system are in the ultracapacitors.

A natural extension of this research is a study of the outer control loop of the system.

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