Ultra Capacitors Charging by Regenerative Braking in Electric Vehicles

Nikolay Lyuboslavov Hinov, Dimitar Nikolov Penev, Gergana Ilieva Vacheva
Department of Power Electronics, Faculty of Electronic Engineering and Technologies
Technical University of Sofia
8 Kliment Ohridski blvd., 1000 Sofia, Bulgaria
hinov@tu-sofia.bg, dim_penev@tu-sofia.bg, gergana_vacheva@tu-sofia.bg

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).

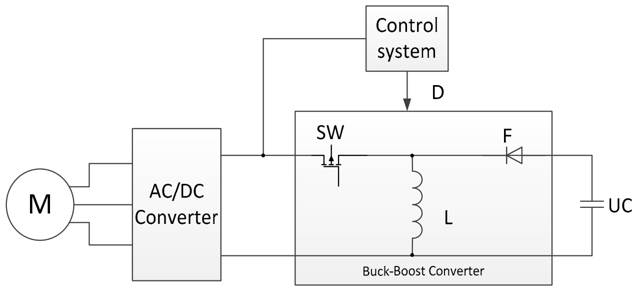

Fig.1.Block scheme

The control system consists of several levels due to the specifics of its components and systems of the electric vehicle and also due to the significant difference in time constants of the individual tracts [2, 6]. The structural diagram of the control system is shown in Fig. 2.

The control system is implemented as a cascade composed of two loops - internal and external. The external uses a signal from the change in motor rotational speed and compares it with a setpoint *(dV / dt) ref*, and the regulator *R1* feeds a reference for the motor current. The internal loop controls the DC converter for obtaining a constant and compliant to the reference motor current, by varying the duty cycle *D* of the electronic switch.

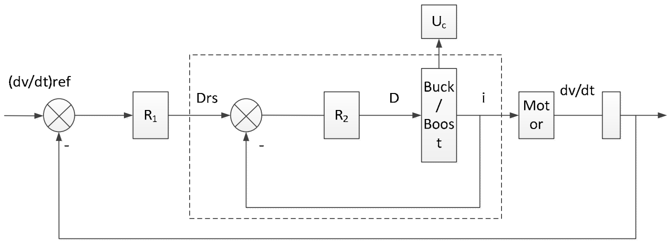

Fig.2. Control scheme

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

978-1-5090-2883-2 /16/$31.00 ©2016 IEEE

its internal resistance R_I, 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_F; UC ultracapacitors with capacity C_{UC} and internal series resistance R_{UC};

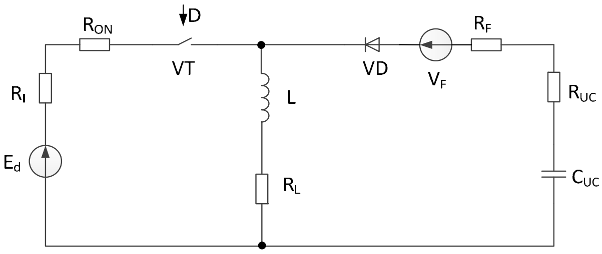

Fig.3. DC/DC Converter

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

For the conducting state of the transistor -

$$L(i_L,\theta)\frac{di_L}{dt} = E_d - (R_L + R_{ON} + R_I)i_L \qquad (1)$$
$$C_{UC}\frac{dU_{UC}}{dt} = 0$$

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

And when the switch is turned off:

$$L(i_L,\theta)\frac{di_L}{dt} + (R_L + R_F + R_{UC})i_L + U_{UC} = 0 \qquad (2)$$
$$C_{UC}\frac{dU_{UC}}{dt} = i_L$$

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 $\frac{dV}{dt} = const$, E_d is a linear function of time $E_d = E_{d\max} - kt$.

Assuming that $L = const$, 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

$$i_L((n+D)t_p) = i_L(nt_p)e^{-a/LDt_p} + \left(1 - e^{-a/LDt_p}\right)b$$
$$U_{UC}((n+D)t_p) = U_{UC}(nt_p) \qquad (3)$$
$$a = R_L + R_I + R_{ON}$$
$$b = E_d / a$$

where D is the duty cycle.

And when the switch is turned off:

$$i_L((n+1)t_p) = i_L((n+D)t_p)e^{-a/LDt_p} + \left(1 - e^{-a/LDt_p}\right)$$
$$U_{UC}((n+D)t_p) = U_{UC}((n+1)t_p) \qquad (4)$$
$$a = R_L + R_{UC} + R_F$$
$$b = E_d / a$$

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

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_{max} is $E = \frac{mV_{\max}^2}{2\eta}$, where η is the efficiency of the energy conversion from the storage element to the wheels.

Assuming, that the energy of the ultracapacitor is $E_{UCS} = kE,\ k \in [0,1]$. The repartition of energy from the two sources by departure is determined by the coefficient k. Assuming that $U_{UC\max} = E_{d\max}$ for the capacity of the ultracapacitor it's obtained $C_{uc} > \frac{2kE}{U_{UC\max}^2}$. The energy charged into the ultracapacitors at constant speed will be $E_{IN} = E_{UCS} - E_{UCRB}$, 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 $U_{UCIN} = \sqrt{\frac{2E_{IN}}{C_{UC}}}$.

IV. RESULTS

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

Mass of electric vehicle $m = 700kg$;

Acceleration by departure $\frac{dV}{dt} = 2ms^{-2}$;

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 table1,2,3. An IGBT transistor of type AN4544 is used, Schottky diode SBR40U300CT and 120 ultracapacitors of type BCAP035 connected in series with capacity 350F, voltage 2.5V, and internal resistance 3.2mΩ. The following anotations are used:

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

$$\eta = \frac{E_{UC}}{E_{UC} + E_{VT} + E_{R_l} + E_{RL} + E_{VD} + E_{RUC}}$$

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.

- ΔI_{Lmax}- maximum value of ripple current through the inductor

TABLE 1

f=300 KHz, D_{max}=0.85

L [μH]	30	40	50	80	100	110
EUCRB,[J]	50310	50310	50310	50310	50310	50310
η	0.896	0.896	0.8965	0.896	0.896	0.896
ΔILmax [A]	15.19	12.76	9.06	5.81	4.5	4.11

TABLE 2

f=200 KHz, D_{max}=0.85

L [μH]	30	40	50	80	100	110
EUCRB,[J]	50312	50310	50310	50309	50310	50310
η	0.896	0.896	0.896	0.896	0.896	0.896
ΔILmax [A]	23	16.95	13.42	8.35	6.78	6.15

TABLE 3

f=100 KHz, D_{max}=0.85

L [μH]	45	50	80	100	110
EUCRB,[J]	50312	50311	50309	50308	50308
η	0.897	0.897	0.897	0.897	0.897
ΔILmax [A]	30.18	27	16.9	13.1	12.35

In Fig. 4., Fig. 5., Fig. 6. and Fig. 7. are shown the graphical results as following:

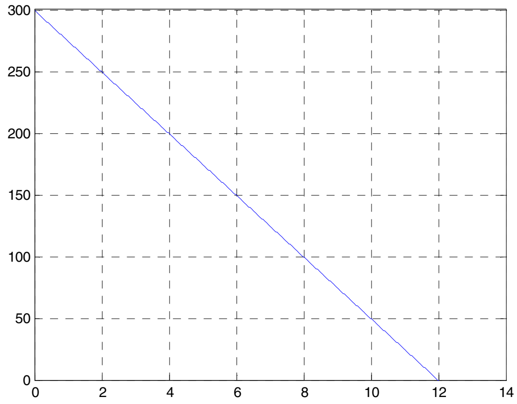

Fig.4. Input voltage of DC/DC converter

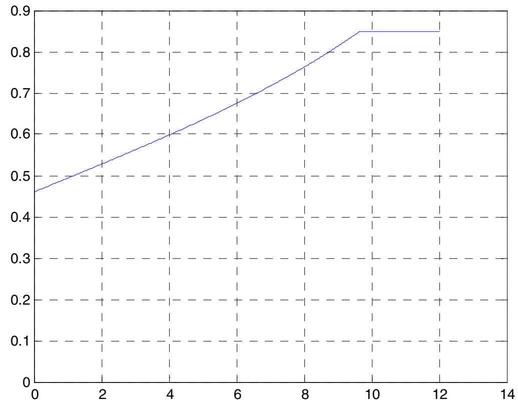

Fig.5. The change of the coefficient in the duty cycle in DC/DC converter

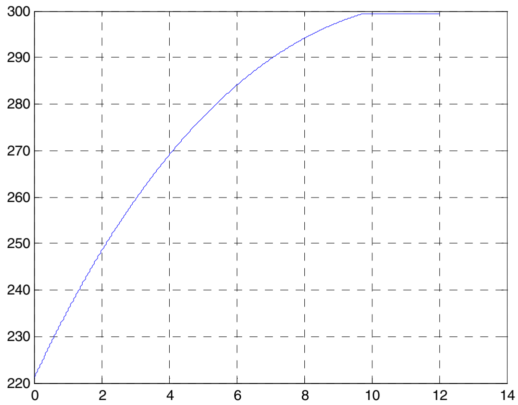

Fig.6. The voltage of the ultracapacitor

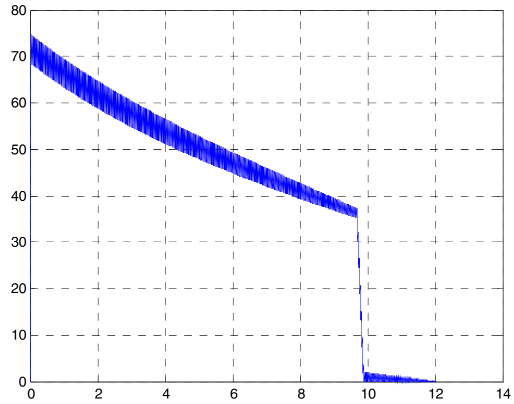

Fig.7. The current through the filter inductance of the DC/DC converter at operating frequency f=200kHz and the value of inductance L=110μH.

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.

Acknowledgments

The authors acknowledge the Internal Contest of Technical University of Sofia for funding this research work under project with number: 162ПД0006-03. The authors would like to thank all the reviewers for their advices and suggestions on improving this paper.

References

[1] Amar Patil, Grzegorz Maliga, “Using ultracapacitors for saving energy in regenerative braking in hybrid vehicles”, Electrical and Computer Engineering Department, Faculty of Engineering University of Tehran, Tehran, Iran

[2] Vivek Kumar Yadav, Navjot Bhardwaj, “Regenerative braking for an electric vehicle using hybrid energy storage system”, International Journal of Electrical and Electronics Engineering Research (IJEEER) ISSN 2250-155X Vol. 3, Issue 4, Oct 2013,pp. 35-42

[3] Yogesh Abhale, Prateek Nigam, ”Review on Regenerative Braking Methodology in Electric Vehicle”, International Journal of Advanced Research in Electrical, Electronics and Instrumentation Engineering, Vol. 4, Issue 7, July 2015

[4] Sagar Maliye, Sudeendra kumar, Ayaskanta Swain, K.K. Mahapatra, “A Novel Regenerative and Anti-Lock Braking Technique for Electric Vehicles”, International Science Press, Proceedings of XII – Control Instrumentation System Conference, 2nd -4 th Nov 2015

[5] M. Rajabzadeh, S. M. T. Bathaee, M. A. Golkar, “Dynamic modeling and control of hybrid electric vehicle with batteries, ultracapacitors and fuel cell”, Toosi University of Technology, Sci.Int.(Lahore),27(2),1079-1084, 2015 ISSN 1013-5316; CODEN: SINTE 8

[6] Jin-uk Jeong, Hyeoun-dong Lee, Chul-soo Kim, Hang-Seok Choi, Bo-Hyung Cho, “A Development of an Energy Storage System for Hybrid Electric Vehicles Using Supercapacitor”, 2002 EVS19, pp.1379-1389

[7] Mohammad Ashar, “Integration of Ultra Capacitor with Battery using DC-DC Bidirectional Buck Boost Converter in an Electric Vehicle”, International Research Journal of Engineering and Technology (IRJET), Volume: 03 Issue: 02 | Feb-2016, e-ISSN: 2395 -0056

[8] K. Erhan, E. Özdemir, A. Aktaş, “Design and Analysis of Ultra-Capacitor Regenerative Braking Energy Storage System for Hybrid and Electrical Vehicles”, Department of Energy Systems Engineering, Kocaeli University, Kocaeli, Turkey, , Erhan et al. / 8th International Ege Energy Symposium and Exhibition - 2016

[9] Jarrad Cody, Özdemir Göl, Zorica Nedic, Andrew Nafalski, Aaron Mohtar, “Regenerative braking in an electric vehicle”, University of South Australia, Zeszyty Problemowe – Maszyny Elektryczne Nr 81/2009, pp.113-118

[10] Manoj.E, Dino Isa, Roselina Arelhi, “Supercapacitor/Battery hybrid Powered Electric Bicycle via a Smart Boost Converter”, World Electric Vehicle Journal Vol. 4 - ISSN 2032-6653 - © 2010 WEVA, pp.280-286

[11] Marian K. Kazimierczuk, Pulse width Modulated Converters, Wright State University Dayton, Ohio, USA 2008.