Analysis of the Opportunities for Energy Efficiency Improvement of Electric Vehicle Regenerative Braking

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Abstract – **In current paper we made an analysis of the energy efficiency regenerative braking process.**

It was applied a method of series connected high efficiency DC-DC converters to the electric drive machine. More over in the paper is analyzed system behavior, controlled by proportional-integration regulator. Finally is suggest an algorithm for realizing of all process with single chip microcontroller and defined the limitation of regenerative braking efficiency.

Keywords – **Regenerative braking, Efficiency, DC-DC converter, Regulator.**

I. Introduction

A regenerative brake is an energy recovery mechanism which slows a vehicle by converting its kinetic energy into another form, which can be either used immediately or stored until needed. This contrasts with conventional braking systems, where the excess kinetic energy is converted to heat by friction in the brake linings and therefore wasted.

In the speed range in which the braking energy is most dissipated, the operating efficiency of the electric motor, functioning as a generator, may be of most concern.

The braking energy dissipated in the low-speed range, such as below 15 km/h in all the typical driving cycles, is insignificant. This result indicates that we need not attempt to obtain high operating efficiency at low speeds in the design and control of regenerative braking. In fact, it is difficult to regenerate at low speeds, because of the low motor electromotive force (voltage) generated at low motor rotational speeds. Thus, the operation of the hybrid brake system must be at speeds higher than a minimum threshold value. Electric regenerative braking should be applied primarily to recapture as much braking energy as possible. At speeds lower than this threshold, mechanical braking should be primarily applied to ensure the vehicle's braking performance [1].

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II. Formulation of the Problem

One of the main problems in the implementation of electronic circuits for managing the process of regenerative braking is a practical impossibility to realize DC-DC converter operated without loss. This leads to restriction of the returned energy in to the battery in the process of recovery.

In general, regenerative braking depends on the initial speed, from which start the braking, the mass of the car, the resistance forces and slope of the road. It is important to note that this examination is done only in terms of energy balance.

$$E_r = \eta_g \eta_t \eta_B \left\{ \left[\int_{t0}^{t1} V_0 . \sum \overrightarrow{F_S}\, dt \right] \pm E_P - E_K \right\} \quad (1)$$

where E_r - regenerative braking energy, m - mass of the vehicle, V_0 - initial speed of the vehicle, $\sum \overrightarrow{F_S}$ - the sum of resistance forces affecting the vehicle, E_P - potential energy of the vehicle, E_K - kinetic energy of the vehicle, η_g - efficiency of the machine (in generator motor mode), η_t - efficiency of the DC-DC converter, η_B - efficiency of battery charging.

From the analysis made here shows that a significant contribution to energy loss is DC converter. This problem is especially relevant at relatively low speed of the car the car and consequently a small amount of energy they could recuperate. Practical in this case regenerative process is ineffective and inappropriate.

In general, losses in the DC converter can be divided into two groups – permanent loss and losses, depending on the converted power. Assuming that the power loss increases linearly in terms of power conversion, it can be written the following expression:

$$P_Z = P_C + k_Z . P_{in} \quad (2)$$

Consideration is simplified in terms of that interest in this analysis is the process in a small amount of regenerated power.

$$\eta_t = \frac{P_{in} - P_C - k_Z . P_{in}}{P_{in}} \quad (3)$$

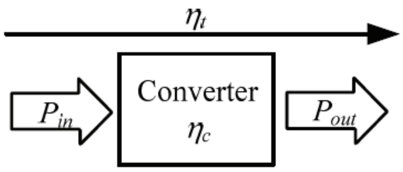
The main idea is published in [2]. The total efficiency is obtained by including the DC-DC converter in part of the input power. It can be calculated by the expression:

$$\eta_t = \frac{P_1 + P_2 . \eta_c}{P_1 + P_2} \tag{4}$$

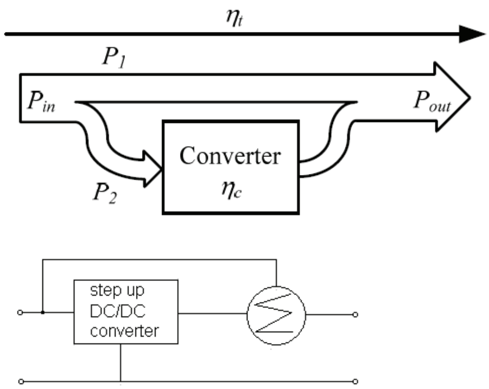
$$\eta_c > \frac{P_1 + P_2 .}{P_2} \eta - \frac{P_1}{P_2} \tag{5}$$

The total efficiency of the proposed converter is obtained by Eq. (4) if the loss of the direct mode power P_1 can be neglected. Therefore, the total efficiency obtained by using the proposed concept is improved, as shown by Eq. (5).

The basic idea is shown in Fig. 1.



(a) Conventional concept.



(b) Proposed concept.

Fig. 1. Power flow diagrams.

It can be seen that the resulting efficiency is higher then the same of DC-DC converter.

III. Functional Scheme of Converter with PI Controler

For aims of current work it is used proportional integration regulator. The derivate component of regulator is not included because the reference is constant. It is important to be noted that the maximal energy have to be regenerated in the battery and the ultracapacitor. For this reason the regulator reference is always in maximal value. Thus the schematic diagram is shown in Fig. 2.

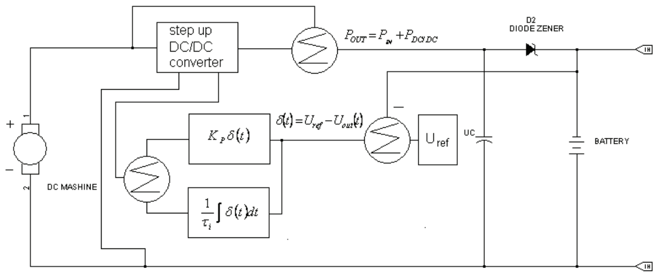


Fig. 2. Functional diagram of regeneration.

A. Expression of output energy.

In general case the regenerated energy can be expressed as:

$$E_r = E_{in} + E_{DC/DC} \tag{6}$$

E_r - energy of regenerative braking, E_{in} - input energy

$E_{DC/DC}$ - output energy from DC/DC converter

It can be written following expressions:

$$P_{out} = U_{out} . I_{out} \tag{7}$$

P_{out} - output power

were:

$$I_{out} = I_{bat} + I_{UC} \tag{8}$$

I_{out} - output current, I_{batt} - battery charging current, I_{UC} - ultracapacitor current

and

$$U_{out} = U_{UC} = U_{batt} + U_D \tag{9}$$

U_{out} - output voltage, U_{batt} - battery voltage, U_{UC} - ultracapacitor voltage, U_D - diode voltage

The output signal of regulator will be:

$$U_M = K.\delta(t) + K_i \int \delta(t) dt \tag{10}$$

U_M - managing voltage, output signal of PI regulator,

K - proportional value of regulator

K_i - integration value, $\delta(t)$ - output error versus time

where:

$$\delta(t) = U_{out}(t) - U_{ref} \tag{11}$$

After substituting Eq. (11) in Eq. (10) the total output voltage of DC-DC converter became:

$$U_{DC/DC} = k_1.k_{tr}.\left\{ \begin{array}{l} K\left[U_{out}(t) - U_{ref}\right] + \\ K_i \int \left[U_{out}(t) - U_{ref}\right] dt \end{array} \right\} \qquad (12)$$

Where:

k_{tr} - coefficient of step up transformation of DC/DC converter, k_1 - coefficient of transformation of U_M related to the coefficient of Pulse Wide Modulation

Finally the expression of output energy becomes:

$$E_{out} = \int_{t0}^{t1} \left\{ k_1.k_{tr}.\left\{ \begin{array}{l} K\left[U_{out}(t) - U_{tef}\right] + \\ K_i \int \left[U_{out}(t) - U_{ref}\right] dt \end{array} \right\} \right\}.(I_{batt} + I_{UC})dt + E_r \qquad (13)$$

Where:

t_0 - start moment of regeneration, t_1 - final moment of regeneration

Of Eq. (13) it can be seen that the regenerative braking is possible until recovered energy becomes equal of DC-DC converter losses, e.j.:

$$P_C + k_Z.P_{in} = \left\{ k_1.k_{tr}.\left\{ \begin{array}{l} K\left[U_{out}(t) - U_{tef}\right] \\ + K_i \int \left[U_{out}(t) - U_{ref}\right] dt \end{array} \right\} \right\}.(I_{batt} + I_{UC})dt + P_{in} \qquad (14)$$

B. Algorithm for realizing of proposed concept.

The proposed concept can be realized with single chip microcontroller. In this way the scheme will become more energy efficient and relatively cheaper then others decisions. In this case one of the basic problems is numerical integration. This mathematical operation needs of relatively large system resource. This is an important question for optimal practical realization. In [3] is represented a simplest algorithm for numerical integration, suitable for the goal of current work. Thus all mathematical operations of Eq (13) can be represented by sum and subtraction.

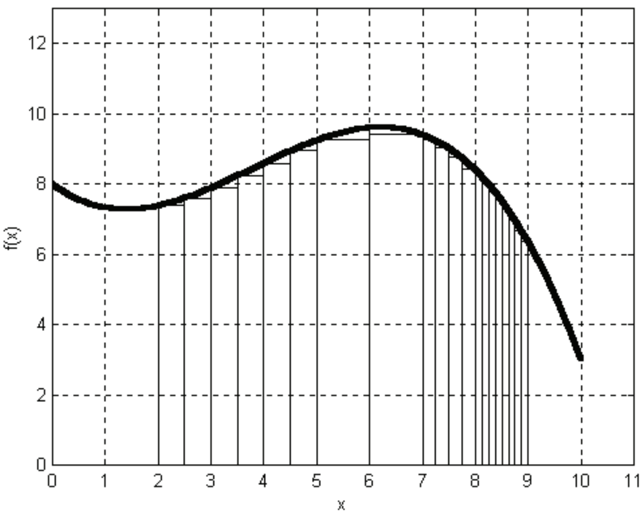


Fig. 3. Numerical integration by using a variable step discretization.

IV. Conclusion

In current paper it was made an analysis of possibilities for increasing energy efficiency of regenerative braking process. Then it was suggest a new circuit consisted proportional integration regulator and step up DC-DC converter. It was applied a method of separating input energy [2] and in this way the energy efficiency of the suggested system is higher then the DC-DC converter. Moreover the suggested scheme allows common work of ultracapacitor and battery. Then it was made an expression Eq. (14) witch define the limiting conditions for regenerative braking. Finally it was made recommendation for composing an algorithm for realizing suggested concept with single chip microcontroller.

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