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ОБЗОР РАСЧЕТА ЭНЕРГИИ РЕКУПЕРАТИВНОГО ТОРМОЖЕНИЯ ЭЛЕКТРИЧЕСКИХ АВТОМОБИЛЕЙ

AN OVERVIEW OF EVS REGENERATIVE BRAKING ENERGY CALCULATION

Ле Тхань Нань[1], **Ле Нуе Тай Минь**[1], **Дам Хоанг Фук**[1],
Нгуен Тхань Тунг[1], **Харитончик С. В.**[2], д-р техн. наук., доц.,
Кусяк В. А.[2], канд. техн. наук, доц.,
[1]Группа «Автомобили», Институт Механики,
Университет Ханоя Техники и Науки, г. Ханой, Вьетнам
[2]Белорусский Национальный Технический Университет,
г. Минск, Республика Беларусь
Le Thanh Nhan[1], Le Hue Tai Minh[1], Dam Hoang Phuc[1],
Nguyen Thanh Tung[1],
S. Kharitonchik[2], Doctor of technical Sciences, Associate Professor,
V. Kusyak[2], Ph.D. in Engineering, Associate Professor,
[1]Automotive Engineering Group, School of Mechanical Engineering,
[1]Hanoi University of Science and Technology, Hanoi, Vietnam
[2]Belarusian National Technical University, Minsk, Belarus

В работе приводится обзор существующих систем рекуперативного торможения электромобилей. Описано устройство системы рекуперации энергии, принцип ее работы, преимущества и методы определения полученной энергии от системы рекуперации. В статье также представлен коэффициент рекуперативного торможения, который является важнейшим параметром при определении регенерируемой энергии, и метод его расчета.

This paper presents an overview of the regenerative braking system on electric vehicles. The definition, working principle, and advantages of the regenerative braking system are shown in this study. Moreover, the regenerative braking coefficient, which is a characteristic parameter in defining recuperate energy rate, and its calculation method will be introduced in this paper.

Ключевые слова: *электромобиль, расчет энергии рекуперативного торможения, коэффициент рекуперативного торможения.*

Keywords: *electric vehicle, regenerative braking energy calculation, regenerative braking coefficient.*

INTRODUCTION

The demand for vehicles using low energy levels has increased in recent years due to the general public's drive for the sustainability of products and processes. Electric vehicles (EVs) emerge as an excellent solution for sustainable development and energy-saving. However, the relatively small driving range on a single traction battery charge is a constraining factor in the launch of large-scale EV production. A regenerative braking system (RBS) in EV is the ideal solution to this problem because this process allows converting the vehicle's kinetic energy into electrical energy for recharging the batteries during braking, forced deceleration, or downhill movement [1]. This paper aims to provide an overview of RBS in terms of definition, working principle, advantages, and calculation method for evaluating its energy efficiency in the given driving cycles. Many methods for calculating the regenerative braking energy efficiency are given.

DEFINITION

Regenerative braking system (RBS) in electric vehicles (EVs), which is also called the kinetic energy recovery system (KERS), is an automotive system that recuperates a moving vehicle's kinetic energy under braking or decelerating [2]. The recovered energy is stored in a battery for later vehicle motion or used for auxiliary systems.

The principle behind regenerative braking is that when an electric motor runs in one direction, it converts electrical energy into mechanical energy that can be used to perform work such as turning the wheel. When the motor runs in the opposite direction, a properly designed motor becomes an electric generator. When the wheels spin without acceleration, the rotation induces a reverse energy flow, producing a generator effect. A back electromotive force (back EMF, BEMF) is induced in the motor, which is a voltage that appears in the opposite direction to current flow due to the motor´s coils moving relative to a magnetic field. This voltage serves as the principle of operation for a generator. The back EMF is directly related to the speed of the motor, so knowing the value of the back EMF allows us to calculate the speed of that motor. Its primary function is to convert mechanical energy into electrical energy. This electrical energy can then be fed into a charging system for the car's batteries as a backup.

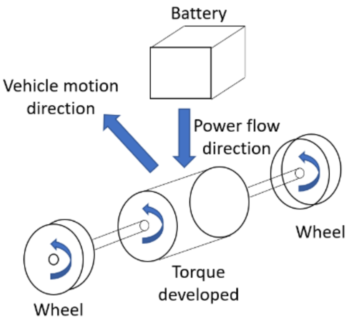

Figure 1 – Forward driving condition

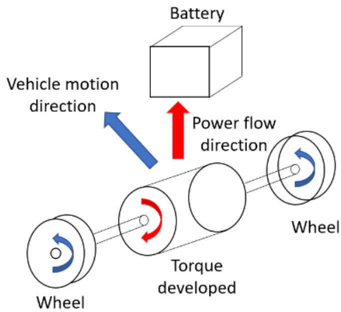

Figure 2 – Regenerative braking condition

Fig. 1 shows the normal forward driving condition in which the motor rotates forward; thus, torque acts in the wheel-spinning direction. The back EMF produced opposes the motion of the vehicles according to Lenz law. In this, the strength of the magnetic field is increasing, thus increasing the vehicle's speed profile. Fig. 2 shows the regeneration during braking in which the motor acts as a generator; thus, the strength of the magnetic field is reduced and thus reducing the speed. In the motor, torque acts in the opposite direction to the wheel spinning direction. Also, it shows that the energy is transferred back to the battery, whereas the above diagram shows that the battery supplies energy.

RBS provides many merits for EV development:

1. Better control on braking [1].

2. RBS can provide most of the total braking force during stop-and-go traffic, mainly in urban regions [3], vastly improving the energy economy.

3. Prevents wear and tear on mechanical braking.

4. Fully EVs benefit from increased range from a single charge of the batteries. Regenerative braking increases the EV range by about 16,3 % while reducing the total time of the braking process [4].

CALCULATION METHOD

The regenerative braking coefficient (RBC) usually characterizes RBS; however, each study brings up a different method to calculate this coefficient. RBC can be defined as the function of vehicle speed, deceleration or initial braking speed, as demonstrated below. Most useful parameter for evaluating the RBS energy efficiency of is the regenerative braking coefficient, the calculation methods of which will be described below.

Hamza et al. [5] introduce the calculation of the instantaneous regenerative braking based on experimental measurements of regenerative braking power values using curve fitting and concatenation of two deceleration modes: with or without acting on the braking pedal. The instantaneous regenerative braking efficiency as a function of deceleration level was found to be approximated using a two-term exponential decay function, as shown in equation (1):

$$\eta = k_7 \cdot e^{k_8 \cdot a} + k_9 \cdot e^{k_{10} \cdot a} \quad (1)$$

In the above equation, a nonlinear least squares method was adopted using a trust-region algorithm, where the maximum number of iterations and the tolerance function were set, respectively, to 600 and 1.0×10^{-6}. η refers to the regenerative braking efficiency. a is the instantaneous acceleration (m/s^2), which is negative in this case, and k_7, k_8, k_9, and k_{10} are coefficients whose values are given in Table 1, which also shows the performance of the proposed curve fitting in terms of R^2 and the root-mean-square error (RMSE). Fig. 3 illustrates the variation in the instantaneous regenerative braking efficiency as a function of the deceleration level.

Table 1 – Coefficients and performance of instantaneous regenerative braking efficiency as a function of the deceleration level

Coefficients (with 95 % Confidence Bounds)	*R-Square*	*RMSE*, %
k_7 = 0.9645 (0.8555, 1.073)	0,9785	0,0548
k_8 = – 0,009234 (–0,05018, 0,03171)		
k_9 = –1,036 (–1,149,–0,9221)		
k_{10} = 2,848 (2,006, 3,69)		

FASTSim (Future Automotive Systems Technology Simulator) calculates the regenerative braking coefficient as a function of vehicle speed, as seen in Fig. 4 [6]. The value of η_{regen} in FASTSim is calculated using equation (2):

$$\eta_{regen} = \frac{\%regen_{max}}{(1 + RA \cdot e^{(-RB.(v\cdot(mile/h)+1})}, \quad RA = 500, \quad RB = 0{,}99. \tag{2}$$

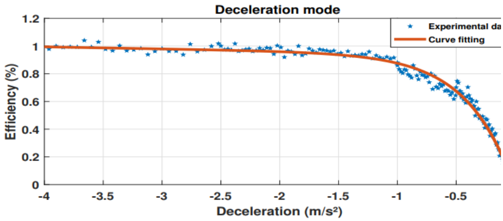

Figure 3 – Deceleration-dependent regeneration efficiency

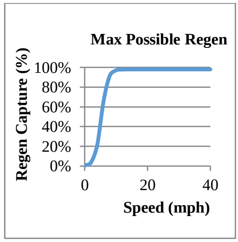

Figure 4 – Speed-dependent regeneration efficiency

In which: $\%regen_{max}$ is the percentage of maximum attainable regenerative energy, v is the vehicle velocity (measured in mile/h), and *RA* and *RB* are experimentally determined constants.

Mauricio et al. [7] present the braking energy recovery efficiency, η_b, is the relation between recovered energy E_m and the total energy lost during braking E_b, as shown in equation (3):

$$\eta_b = \frac{E_m}{E_b} = \frac{\int U_b \cdot I_b \cdot dt}{\frac{1}{2} \cdot m \cdot (V_0^2 - V_f^2)} \cdot 100\ \%, \tag{3}$$

where, U_b is the voltage at the motor controller while recovering braking energy, I_b is the motor controller current present in the braking action, *t* is the time of motor braking, m is the mass of the vehicle, V_0 is the initial velocity of braking, V_f is the final velocity of braking. The study indicates that the initial braking speeds, brake usage, and the vehicle's weight are the most significant influence factors on RBS efficiency, with 23 % average RBS efficiency in different routes and approximately 77 % RBS efficiency at high initial braking velocity (above 44 km/h).

Zhongyue Zou et al. [8] present a more profound calculation of regenerative energy based on the concept of recycling energy in EVs using supercapacitors. The consuming energy distribution of the supercapacitor vehicle during regenerative braking can be illustrated in fig. 5.

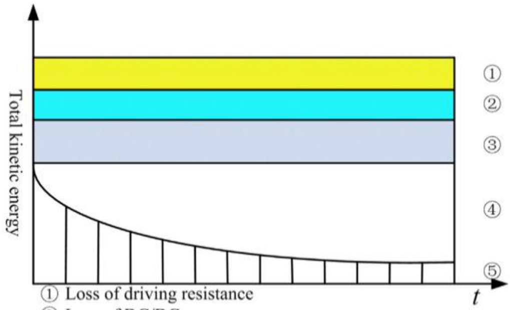

Figure 5 – Distribution of vehicle kinetic energy [8]

RBC (η) in this study is defined as the ratio of recycling energy to kinetic energy, as shown in equation (4):

$$\eta = \frac{(1-\eta_r)\cdot\left(\int U_0 \cdot I_0 \cdot dt - \int I_0^2 \cdot R \cdot dt\right)}{\frac{1}{2}\cdot m \cdot v^2}, \tag{4}$$

where U_0 is the voltage of the battery (V), I_0 is the current of the energy source (A), R is the equivalent internal resistance of the supercapacitor pack, v is the vehicle's speed before braking (m/s). η_r is the ratio of charging energy losses to generating electrical energy from vehicle kinetic energy can be given by

$$\eta_r = e^{1/(R\cdot C)}, \tag{5}$$

where C is the capacitance of the supercapacitor pack. From that calculation, the study shows that an electric truck (10,000 kg) using a supercapacitor has 65 % and 14 % regenerative efficiency over total kinetic energy with and without a high load, respectively. This result is derived from the heavy load increasing the total energy consumption and can not improve regenerative efficiency.

There are many methods for calculating RBS recovered energy with different assumptions, using arear and operational conditions. The results of the given methods show the roles of RBS in increasing the vehicle energy economy [9].

CONCLUSION

This paper has provided a basic understanding of RBS and its energy estimation based on RBC calculation. Regenerative braking is one of the best ways to increase the vehicle's energy economy. There are many methods for energy calculating the characteristic parameter of the RBS. Its results show the effectiveness of the regenerative braking system on vehicle energy consumption when moving on given driving cycles.

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