EXAMINING THE BRAKING ENERGY RECOVERY IN A VEHICLE WITH A HYBRID DRIVE SYSTEM

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Summary

Results of examining the braking energy recovery in a passenger car with a hybrid system driving the front wheels have been presented. The tests were carried out on a vehicle with a series-parallel system, which combined an internal combustion engine with an electric motor. Such a system makes it possible to change the electric motor operation mode so that it becomes a generator, which charges a high-voltage battery with the use of the vehicle braking energy. The battery charging current was measured at braking with various vehicle deceleration values. The algorithm of controlling the battery charging current, the share of the energy recovered in the total braking energy, and the power of the regenerative braking in relation to the total braking power demand were analysed. The instantaneous power demand at braking on a horizontal road with a low rolling resistance coefficient was determined. The share of the electric power in the energy balance of the braking process as well as the demand and recovery of energy during this process were examined.

Keywords: vehicle with a hybrid drive system, regenerative braking, braking energy, braking power

1. Introduction

In connection with increasingly stringent exhaust gas emission requirements and limitations on the emission of carbon dioxide to the atmosphere, vehicle manufacturers seek for possibilities of reducing the fuel consumption and, in consequence, the carbon dioxide emission by motor vehicles. This objective is pursued in different ways, e.g. by using hybrid electric-petroleum drive systems. At present, fast development can be observed in the field of motor vehicles, both passenger cars and buses, provided with powertrains of this kind. In comparison with the internal combustion engine vehicles (ICEV), they are characterized by considerably lower consumption of petroleum-derivative fuels and a possibility of being driven by an electric motor only, with zero exhaust emissions, which is particularly important in the urban traffic.

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One of the methods of reducing the fuel consumption and extending the distance travelled by a vehicle with the use of its electric drive system is the possibility of recovery (recuperation) of the braking energy [1, 2, 6].

In the hybrid vehicles, the braking energy can be recovered in two ways:

- by charging a high-voltage battery from a generator directly driven by the vehicle wheels;
- by using of supercapacitors.

The battery recharging by regenerative braking (i.e. "regenerative charging") makes it possible to accumulate a vast amount of energy in comparison with what is offered by capacitors; however, this requires the braking time to be long enough, while the capacitor charging time needed for the energy accumulation is much shorter. Hence, these two electricity "stores" can complement each other.

To estimate the possibility of recovering the braking energy in normal vehicle operation conditions, road tests were carried out on a hybrid passenger car with a series-parallel powertrain and a regenerative charging system.

2. Object of testing

The test specimen was a passenger car with a series-parallel hybrid powertrain provided with a power split system (Fig. 1). Thanks to the use of an epicyclic gear, which connected together the internal combustion (IC) engine, generator, and electric motor, and a power flow control system, the power supplied by the two power sources, i.e. the IC engine and the electric motor, could be summed in any proportion. Such a system enabled the vehicle wheels to be driven by the electric motor, IC engine, or both, and the high-voltage battery to be recharged during individual system operation phases, with electrodynamic braking of the front wheels being also possible thanks to switching over the electric machine MG2 from the motor to generator operation mode. The service brake system, acting on all the vehicle wheels, was an electrohydraulic system with brake pedal displacement sensor, brake pedal force simulator, high pressure pump, and pressure accumulator. During the braking phase, the brake controller received a signal from the brake pedal displacement sensor and the pressure sensor, with a "feeling function" of the system being thus accomplished.

Such a signal provided the basic information on the braking deceleration intended by the driver. Based on this, a program in the brake controller computed the braking forces required to obtain the intended vehicle deceleration and actuated the hydraulic brakes of all the vehicle wheels with simultaneously operating the system of electrodynamic braking of the front wheels and controlling the voltage and intensity of the high-voltage battery recharging current. The pressure in the brake callipers was continuously measured and adapted to the required vehicle deceleration and tyre slip, with the electrical braking being taken into account. The IC engine also participated in the braking process, but the engine braking effect was minimized by applying variable valve timing to reduce the compression pressure (according to the Atkinson cycle) in order to enhance the recovery of electric energy.

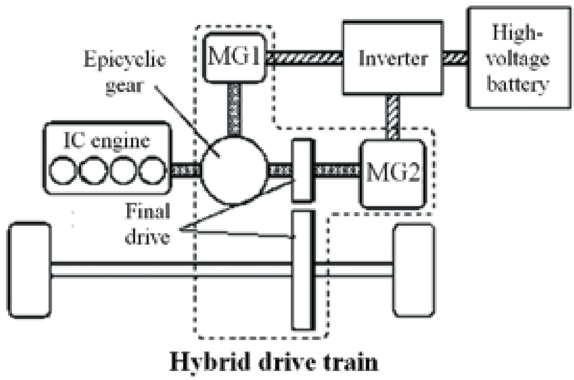

Fig. 1. Schematic diagram of the powertrain of the hybrid vehicle under test: MG1 – generator; MG2 – electric motor [9]

3. Examining the energy recovery

The energy recovery tests were carried out on a straight road section with flat and dry concrete surface. The car was accelerated to speeds of 50 km/h, 70 km/h, and 90 km/h and then braked to a halt by pressing the brake pedal with a constant force, such that the car was braked gently (with an acceleration of about 2 m/s^2), moderately (about 4 m/s^2), and hard (over 6 m/s^2). The state of charge of the NiMH high-voltage battery (nominal voltage 201.6 V, capacity 6 Ah [9]) before the braking was kept constant an equal to about 30 %. For every initial speed, the measurements were repeated n times, with the vehicle speed, brake pedal force, and battery charging current value being recorded during the vehicle braking. The battery charging voltage was measured as well. Example measurement results have been presented in Figs. 2 and 3.

In all the cases of regenerative braking, the battery charging current was so controlled that its maximum value was 90–100 A (a nickel-metal hydride battery). The charging voltage was dictated by a limitation on the maximum acceptable power of charging batteries of this type and by the algorithm of controlling the battery charging process. The maximum current value was kept for the short period of braking and afterwards the charging current was gradually reduced to reach the zero level at a vehicle speed of about 10–15 km/h. At several braking tests, the maximum current value was limited because of an excessive increase in the battery temperature. When the vehicle speed dropped to about 10 km/h, the electrodynamic braking faded away. An interesting finding is the fact that a current "peak" of the order of 50–80 A appeared when the driving phase turned into the phase of IC engine braking, which was followed by a drop in the charging current to about 15 A and the car slowed down with an average deceleration of about 0.5 m/s^2. The selection of the charging current in that period was connected with the requirement to obtain a deceleration of motion of the hybrid vehicle such as that occurring in normal vehicle operation conditions when the accelerator pedal is released and the vehicle is braked by the IC engine. In this phase of motion of the hybrid vehicle, the effect of braking the car by

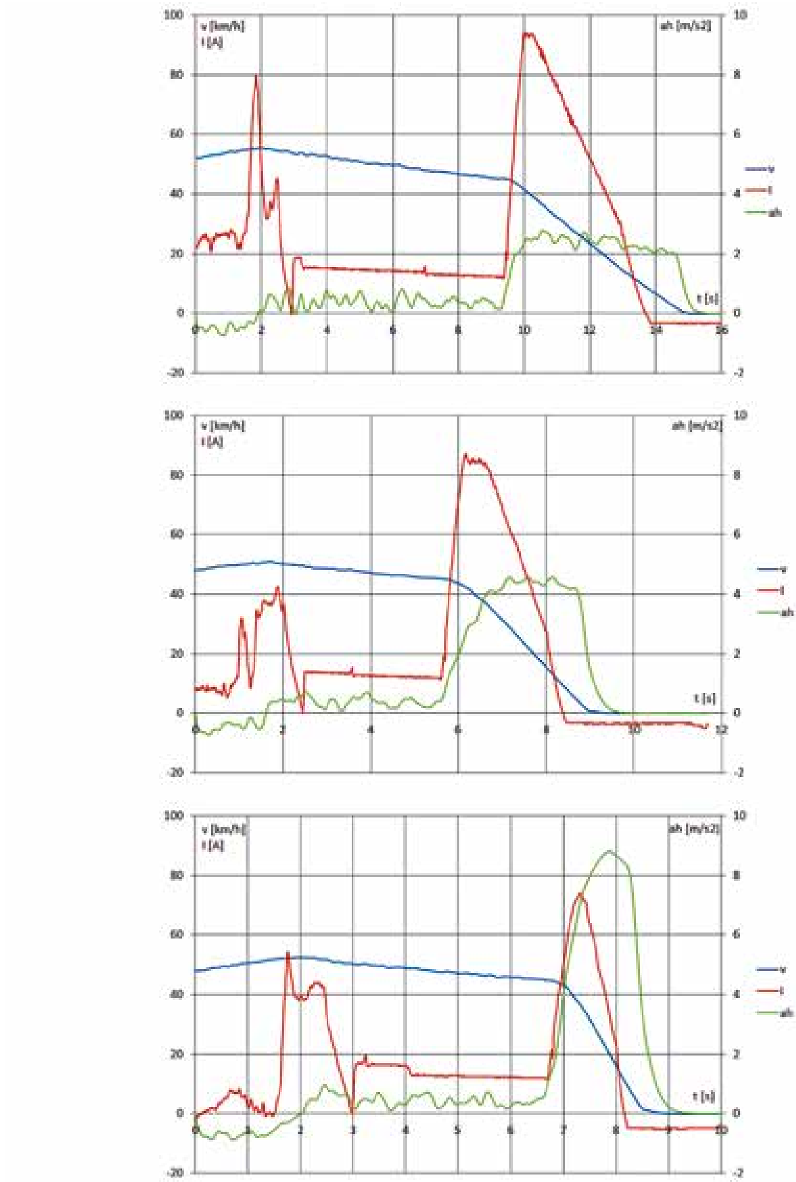

Fig. 2. Regenerative charging current at different braking deceleration values from an initial speed of 50 km/h

its IC engine took place as well, but it was limited by a change in the valve timing, which resulted in a significant reduction of the engine compression pressure.

Field tests of the energy recovery at normal vehicle operation in urban traffic conditions were also carried out. As an example, the energy recuperation system made it possible to recover 375 Wh of energy (determined with an accuracy of ± 5 %) during a 40 min. urban driving cycle in real traffic conditions (the changes in the vehicle speed have been presented in Fig. 4).

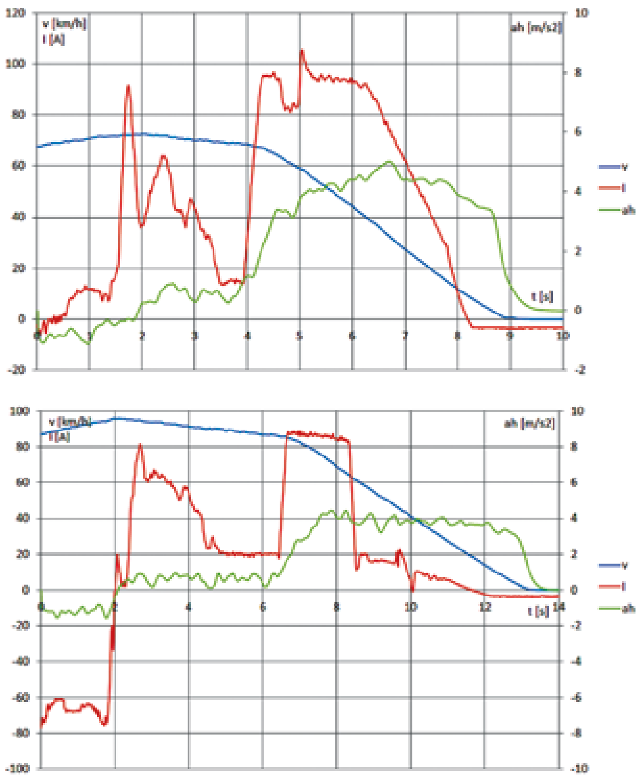

Fig. 3. Regenerative charging current at braking with a deceleration of about 4–4.5 m/s² from an initial speed of 70 km/h (top) and 90 km/h (bottom)

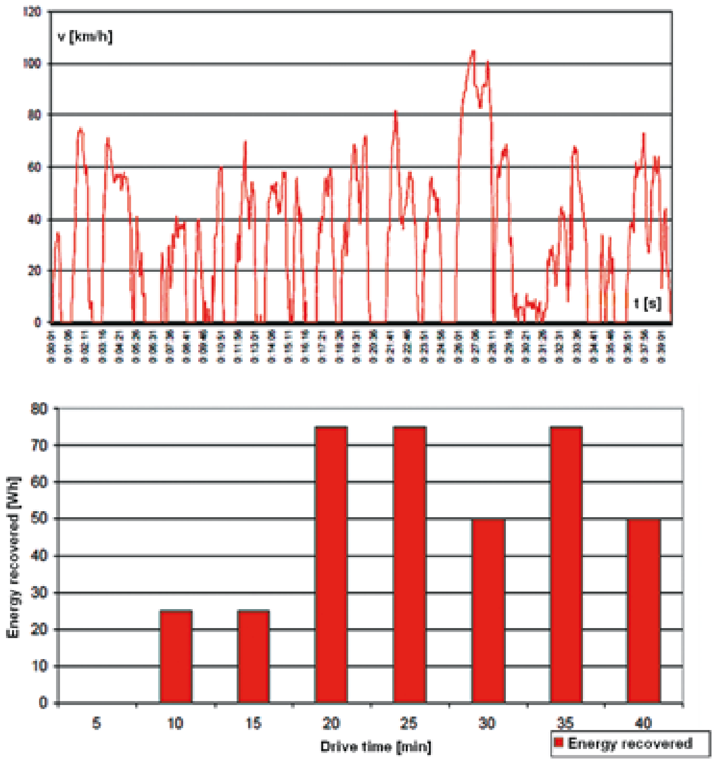

Fig. 4. Vehicle speed and energy recovered during the test drive performed in the urban driving cycle conditions [7]

4. Analysis of the test results

The possibilities of braking energy recovery were analysed for the following energy balance:

$$E = E_{\mathrm{h}} + E_{\mathrm{a}} + E_{\mathrm{t}} \tag{1}$$

where:

$$E = \int_0^t m a_h v(t) dt + \sum_1^4 \int_0^t I_k \varepsilon_k(t) \omega_k(t) dt$$

E_{h} – energy taken away by the vehicle's braking system and the engine's resistance to motion

E_{a} – energy taken away by aerodynamic drag forces

$$E_a = \int_0^t c_x A v(t)^2 \frac{\rho}{2} v(t)dt$$

E_t – energy taken away by the rolling resistance forces

$$E_t = \int_0^t mgfv(t)dt$$

m – vehicle mass

I_k – moment of inertia of rotating elements (vehicle wheels)

v, ω – linear and angular braking speeds (of the vehicle and its wheels), respectively

a_h, ε_k – vehicle and wheel decelerations

c_x – aerodynamic drag coefficient

A – frontal area of the vehicle

ρ – air density

f – rolling resistance coefficient

If the energy E_t is ignored as insignificant, the following equation may be formulated:

$$E_h = \int_0^t m a_h v dt + \sum_1^4 \int_0^t I_k \varepsilon_k \omega_k dt - \int_0^t c_x A v^2 \frac{\rho}{2} v dt \tag{2}$$

The value of the energy E_h required to stop the vehicle and generated by the braking system of the vehicle under test was calculated for a vehicle with a mass of 1 475 kg, aerodynamic drag coefficient of 0.25, and frontal area of 2.2 m^2. The amount of the energy stored in the high-voltage battery during braking was calculated from an equation:

$$E_{reg} = \int_{t1}^{t2} U(t)I(t)dt \tag{3}$$

where:

U –battery charging voltage

I –battery charging voltage

$t_2 - t_1$ –time of the regenerative charging during the vehicle slowing-down phase

Example results of calculations of the energy consumed for the vehicle to be slowed down to a halt and the energy recovered vs. the braking time for different values of the initial braking speed have been presented in Fig. 5.

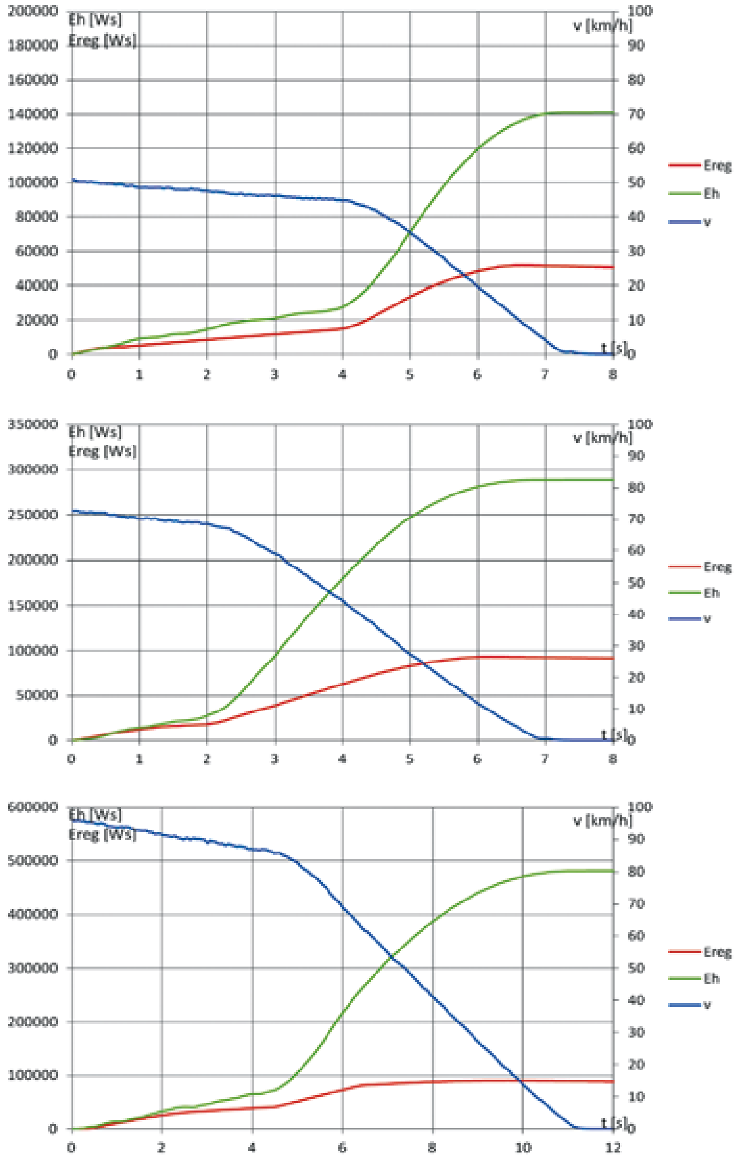

Fig. 5. Energy E_h taken away ("consumed") during the vehicle braking process and electric energy E_{reg} recovered ("regenerated") vs. the braking time, at a braking deceleration of 4–4.5 m/s²

The braking energy recovery ratio was calculated as follows:

$$k_{reg} = \frac{E_{reg}}{E_h} \cdot 100[\%] \tag{4}$$

The test results have shown that when the car slowed down without any pressure being applied to its brake pedal, which corresponded to the engine braking in a conventional motor vehicle, then the value of the energy recovery ratio was about 32–45 %. The remaining part of the vehicle braking energy was absorbed by the engine braking, resistance to motion in the powertrain, and air drag. In the case of braking forced by the use of the braking system, for the initial braking speed and deceleration values ranging from 50–90 km/h and from 2–4 m/s^2, respectively, the energy recovery ratio fell within a wide range from about 16% to 45%. The value of the energy recovered during single braking cycles did not exceed a level of about 100 000 Ws.

The demand for braking power P_h and regenerative braking power P_{reg} was also analysed, with the power demand values being calculated from the following equations:

$$P_h = (ma_h - c_x A v^2 \rho / 2) v(t) \tag{5}$$

$$P_{reg} = U(t) I(t) \tag{6}$$

Example results of this analysis have been presented in Fig. 6.

The test results revealed that the power of regenerative (electrical) braking was 2 to 6 times lower than the maximum demand for braking power. This may be chiefly explained by limitation on the power of charging a high-voltage battery (for the vehicle under test with an NiMH battery, the power limit was about 25 kW) and by the maximum power capacity of the vehicle's generator in relation to the instantaneous braking power. As an example: at an initial vehicle speed of 70 km/h and deceleration of 2–3 m/s^2, the initial braking power of the vehicle under test was 60.5–90.5 kW, as against the maximum power capacity of the generator of 50 kW. At an initial speed of 50 km/h and deceleration within a range of 2–3 m/s^2, the initial braking power was 43–65 kW. At such a speed, the value of the braking energy recovery ratio calculated from equation (4) was higher than the values calculated for the initial braking speeds of 70 km/h and 90 km/h. The amount of the energy recovered also depends on the state of charge of the battery before start of the braking and on the thermal state of the battery.

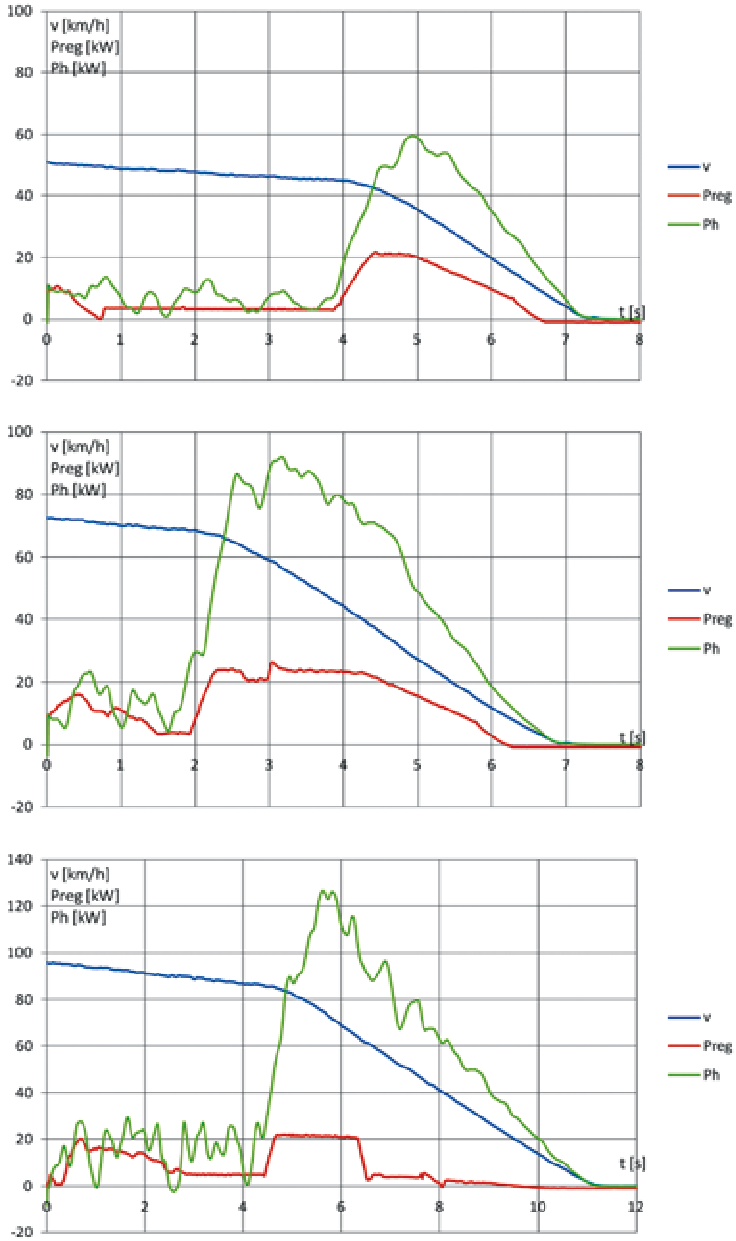

Fig. 6. Demand for braking power and regenerative braking power at various initial vehicle braking speeds

5. Recapitulation

The tests have shown that the existing braking energy recovery solutions are incapable of exploiting the full potential of such a process. Therefore, further theoretical and practical work on this issue is necessary. For the energy recovery to be high enough, the mechanical braking energy must be collected from both the front and rear vehicle wheels. The adequate transformation of mechanical braking energy into electricity in passenger cars requires that generators with power capacity of the order of 100 kW or even higher must be used. In the development of the technology of energy recovery with the use of electrical methods, the problem of energy collection rate and of the amount of the energy to be accumulated should be taken into account. The capacities of the batteries being in use at present make it possible to accumulate the energy recovered during single brake applications but they are insufficient for this energy to be taken away within a short braking time. The latter task can be performed by combined systems of supercapacitors and a high-voltage battery with a system controlling the braking energy recovery from both the front and rear vehicle wheels.

Supercapacitors make it possible to collect energy within a short time. They are characterized by high power density (expressed in [W/kg]) and adequate energy recovery power but rather low capability of energy accumulation. Conversely, batteries make it possible to accumulate much larger energy amounts but the energy collection time is considerably longer. Their energy density (expressed in [Wh/kg]) is about 10 times as high as that of supercapacitors [4]. The energy amount accumulated determines the vehicle range between battery charging and the power capacity of a source of electric energy is essential for vehicle dynamics and energy recovery rate. The combined use of supercapacitors and a battery for energy recovery raises the yield of this process but significantly complicates the system of electronic processing of electric energy.

To date, the use of supercapacitors for energy recovery has been implemented in practice by Mazda, where a system named i ELOOP (*Intelligent Energy Loop*) has been developed [8, 10]. In that system, the energy recovery is accomplished by charging a supercapacitor by an alternator operating at a voltage level raised to 25 V. The electric charge accumulated in the capacitor, flowing through a voltage-reducing DC converter, charges a 12 V battery and supplies system receivers with power. The alternator operation in the raised voltage mode takes place during engine braking and normal vehicle braking.

References

[1] Burnham K. J., Gajek A., Oleksowicz S.: *Regenerative Braking Mode, Legal, Safety and Control Consideration.* Technical Transactions. Mechanics. Cracow University of Technology 2012, 5/M.

[2] Burnham K. J, Oleksowicz S.: *Assessment of Hybrid Vehicle Braking Technologies*. Technical Transactions. Mechanics. Cracow University of Technology 2012, 3/M.

[3] Chłopek Z.: *Badanie zużycia energii przez samochód elektryczny* (*Research on energy consumption by an electric automotive vehicle*). The Archives of Automotive Engineering. PIMOT, vol. 57, No. 3, 2012, ISSN 1234-754X.

[4] Information materials of Toyota Motor Corporation, Prius 2010.

[5] Juda Z.: *Zastosowanie superkondensatorów w układzie odzysku energii pojazdu z napędem elektrycznym* (*Supercapacitors applied to the energy recovery system in an electric drive vehicle*). Technical Transactions. Mechanics. Cracow University of Technology 2008, 6/M.

[6] Juda Z.: *Zastosowanie zaawansowanych źródeł energii w miejskich pojazdach elektrycznych z funkcją odzysku energii* (*Application of advanced energy sources in electric vehicles with recovery of braking energy*). Technical Transactions. Mechanics. Cracow University of Technology 2012, 5/M.

[7] Pawełek M.: *Badania sterowania układem napędowym pojazdu hybrydowego w warunkach ruchu miejskiego* (*Testing of the system controlling the powertrain of a hybrid vehicle in urban traffic conditions*). Master's graduation work, supervised by A. Gajek.

[8] Service information about Mazda 6, 2013.

[9] Wei L: *Hybrid Vehicle System Modeling and Control*. Published by J. Wiley & Sons – USA, 2013.

[10] http://motoryzacja.wnp.pl/i-eloop: *Patent Mazdy na odzyskiwanie energii podczas hamowania* (*Mazda's patent for energy recovery during braking*). Visited on 24 March 2015.