# Regenerative braking as a way to recover lost energy in hybrid vehicles

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**Abstract**
The very rapid development of the automotive industry forces designers to implement new solutions. One of them is the construction of braking systems, which can enable the recovery of part of the energy lost during the braking process in hybrid vehicles. The article presents the basic types of hybrid drives currently used in motor vehicles. The principle of operation of the mechanical and electrical energy recovery system had been discussed, and the vehicles in which such solutions had been applied were indicated.

**Keywords:** braking system, regenerative braking, hybrid vehicles

## Introduction

Vehicular movement, especially in urban areas, forces the vehicle to stop or slow down quite often, which is associated with a reduction in speed and thus with braking. Due to the fact that the braking process involves a rapid reduction of kinetic energy, a lot of heat is released. Energy losses during braking are not so noticeable in the case of conventional vehicles, in which the drive unit is an internal combustion engine, however, in the case of hybrid vehicles any loss of energy is a big problem. Vehicle manufacturers are wondering how to reduce energy losses in braking. The solution is the hybrid and electric vehicles in which it is possible to use kinetic energy to accumulate some of itself and use it in the acceleration process or by converting kinetic energy into electricity for charging batteries.

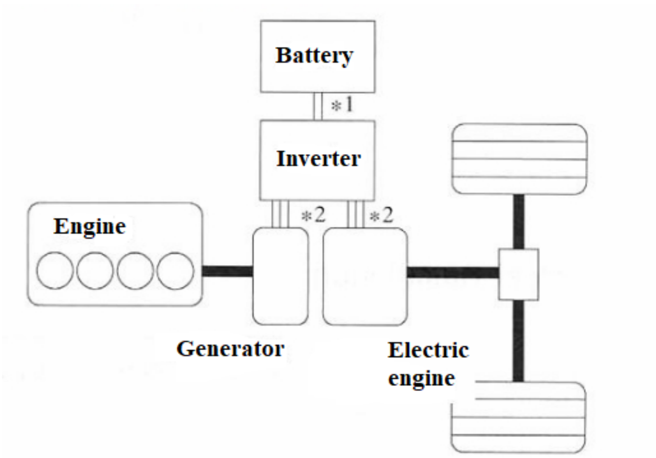


**Figure 1.** Series hybrid vehicle propulsion system [3]

## Hybrid constructions

The hybrid drive is a combination of two types of drives. Currently, hybrid vehicles use a combination of an internal combustion engine and an electric motor. Hybrid cars are divided into two categories. The first of which is divided due to the construction of the hybrid propulsion system. We distinguish the following: serial, parallel, mixed, and branched. Figures 1 and 2 show the serial and parallel drive systems of hybrid vehicles [7, 8].

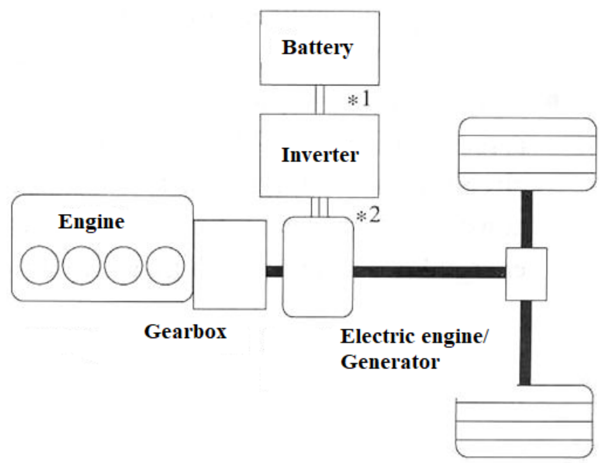


**Figure 2.** Parallel hybrid vehicle propulsion system [3]

The second division is the classification according to the degree of electrification of the vehicle, in which we distinguish:

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Micro Hybrid, Mild Hybrid, and Full Hybrid. Vehicles called Micro Hybrid are unique due to their system of energy recovery during braking as well as the automation of the start-stop system. Unfortunately, they cannot be classified as typical hybrid cars. However, they are able not only to reduce fuel consumption but also to reduce emissions of the harmful exhaust. In the next version, referred to as "the incomplete hybrid drive" – Mild Hybrid, the car cannot be moved solely by the means of an electric motor. It is designed to support the internal combustion engine, as well as to gather energy from the braking process. The final version is the Full Hybrid, in which the vehicle can be driven by an electric motor only on certain sections of the road. A serial or mixed hybrid drive is used in this type of vehicle. An example of this type of solution is the Audi A1 e-tron car, which is powered by an electric motor with a maximum torque of 240 Nm. The vehicle uses a battery with a capacity of 12-kilowatt hours, weighing 150 kg. After it is depleted, the car is powered by a small internal combustion engine. A single-stage gearbox was used for power transmission [7–9].

**Table 1.** Vehicle technical data: Audi A1 e-tron [17]

| | |
|---|---|
| Range extender engine capacity | 354cm³ |
| Range extender engine power | 25 kW (34 HP) |
| Torque of the range extender engine | 300 Nm |
| Electric motor power | maximum 85 kW |
| Electric motor torque | maximum 300 Nm |
| Battery capacity | 13.3 kWh |
| Range in electric driving mode | 50 km |
| Total coverage | 250 km |
| 0–100 km / h | 9.8 p |
| Maximum speed | 130 km/h * |
| Wheelbase | 2 469 mm |
| Own weight | 1 407 kg |

## Braking energy recovery systems

Electrodynamic braking with energy recovery (KERS) is a system that is used to recover kinetic energy lost during braking and to accumulate it in the flywheel or batteries. This energy is used for the subsequent acceleration process. The KERS system prevents energy losses that currently arise during the braking process in motor vehicles equipped with an internal combustion engine, where the friction energy in the combination of a brake disc-brake pad or drum brake-brake shoe is converted into heat and dissipated to the environment. The situation is different in the case of hybrid and electric vehicles, where it is possible to recover energy during braking. This process helps to improve the energy efficiency of the vehicle. Kinetic energy recovery systems have also been used in Formula 1 outputs [1, 2]. Table 2 presents selected models and makes of the vehicles in which hybrid drives with energy recovery systems during braking were installed [13].

**Table 2.** Brands and models of vehicles in which energy recovery systems during braking have been installed [13]

| Manufacturer | Model |
|---|---|
| Citroën | XsaraDynactive |
| Honda | Civic Hybrid, Insight |
| Nissan | Leaf |
| Toyota | Auris Hybrid, Prius |
| Volvo | V60 Plug-In Hybrid |
| Fiat | Multipla Hybrid Power |
| Ford | Escape Hybrid SUV |

Depending on the energy storage method, regenerative braking systems can be divided into mechanical and electrical. In the case of a mechanical system, the energy of a moving vehicle is converted into energy of the rotary motion of the flywheel. During the braking process, the continuously variable transmission, which is mounted in the differential transmits kinetic energy to the flywheel. The whole process is reversed when the driver presses the accelerator pedal, and then the flywheel transfers energy to the wheels using a CVT transmission. The use of a regenerative mechanical braking system prevents the conversion of kinetic energy into electrical energy. An additional advantage of using a mechanical system is that the flywheels are smaller, cheaper, and more efficient. Figure 3 shows the elements of a system of mechanical energy recovery during braking [4, 10, 11].

In an electric energy recovery system, it is the electric motor that draws its power from the battery and drives the wheels of the vehicle, thus producing kinetic energy that is necessary to move the vehicle. The whole process is reversed when the driver depresses the brake pedal. The kinetic energy that was initially used to drive the wheels of the vehicle initiates the rotation of the electric motor, which in this case acts as a generator. The generated electricity supply is collected in vehicle batteries or supercapacitors. Most of the elements that make up the entire energy recovery system during braking are part of the propulsion system, so this does not significantly affect the weight of the vehicle. The disadvantages of this solution that could be pointed out are the possibility of applying recuperative braking only on the drive wheels, as well as insufficient efficiency of energy recovery at low speeds. Figure 4 shows a diagram of the energy flow in the propulsion system during vehicle acceleration (green) and during braking (red) [2, 6, 10].

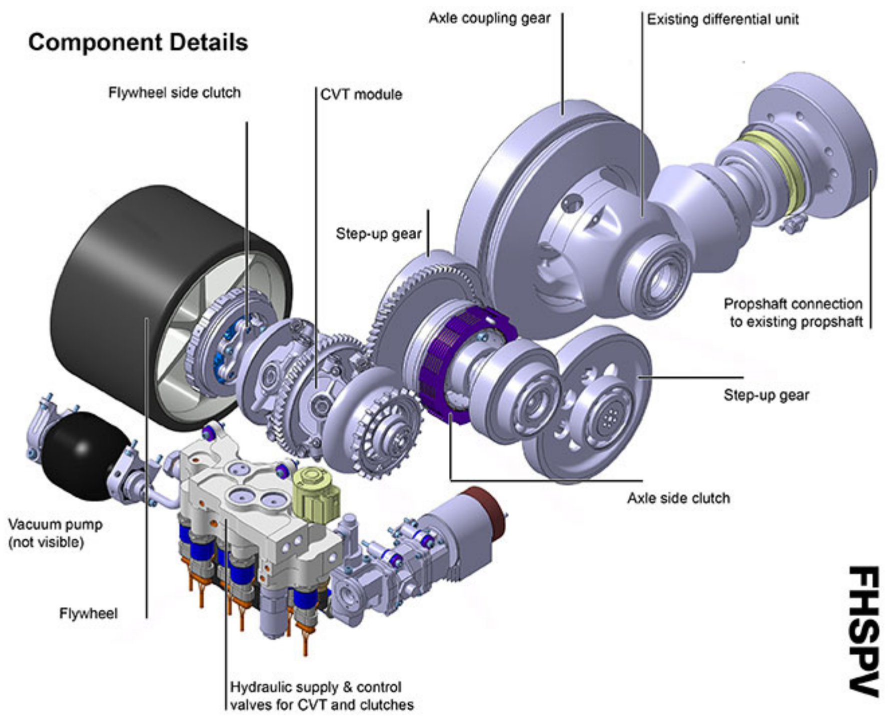


**Figure 3.** Elements of the mechanical energy recovery system during braking [4]

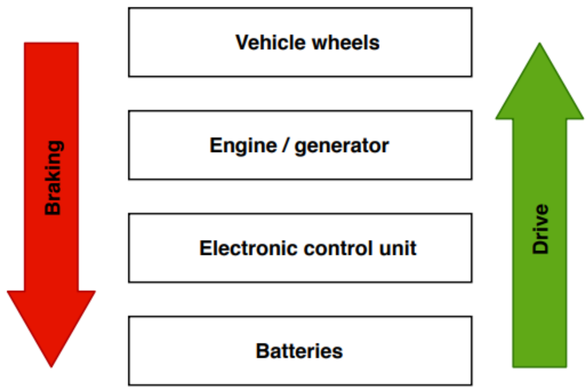


**Figure 4.** Schema of energy flow in the propulsion system during vehicle acceleration (green) and during braking (red) [own study]

There are many examples of the practical application of this type of solution. One of them is a hybrid car – Toyota Prius. An ECB (Electronic Control Brake) system that was installed in the vehicle calculates the braking moment based on the intensity of the force exerted by the driver on the brake pedal and the pressure value stored in the braking system. Based on this data, the controller calculates what force can be obtained, through the use of a generator, from a given regenerative braking process, as well as what force should be supplied through the hydraulic braking system to stop the vehicle [5].

The second example of energy recovery during braking is a system called "i-ELOOP," constructed by Mazda Motor Corporation. This system is intended for use in passenger vehicles in which a capacitor has been used. Compared to batteries, capacitors can be quickly charged and discharged, and at the same time, they are very resistant to long-term use. The whole system consists of fairly light elements that do not take up much space under the hood of the car. These include a new type of alternator with a voltage of 12 to 25V, a DC converter, and an EDLC supercapacitor (Electric Double Layer Capacitor). The "i-ELOOP" system enables an efficient conversion of kinetic energy created during braking into electrical energy, which can be used to power the air conditioning system, audio system, or other electrical receivers present in the car. Energy recovery begins when the driver takes his foot off the accelerator pedal. Then, the alternator, assisting braking, generates a current at a voltage of up to 25V, which goes directly to the capacitor. The increased voltage,

**Figure 5.** EDLC - the electric two-layer capacitor used in the "i-ELOOP" system [12]

due to the efficiency of the charging system, is then reduced to 12V by the converter. This is required because the voltage in the car's electrical system is equal to 12V [12, 15].

Particularly noteworthy is the fact that during research on increasing the car's energy efficiency by optimizing the energy recuperation system, it was found that with limited alternator power, the recuperation system is not able to recover all braking energy. This is very accurately reflected in the graph (Fig. 6), which shows the relationship between the share of recovered energy and the energy that is possible to recover in the range of alternator operation.

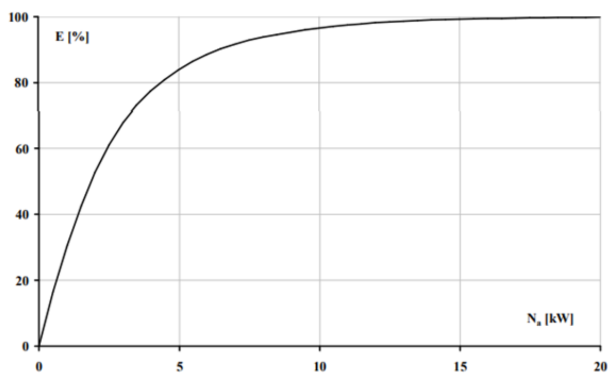


**Figure 6.** Share of recovered energy relative to the energy possible to recover in the alternator power range [16]

The course of the curve is related to the instantaneous power values, which can reach up to several kilowatts. And any power greater than the power of the alternator that will be generated during the braking process, cannot be used by it [16].

The voltage stability for various KERS systems, which is shown in Figure 7, is also a particularly important parameter. Compared to other energy storage systems, flywheels offer a maximum constant power level, which is independent of the load, temperature, and battery charge status, which is undoubtedly their large advantage. In the second place, there is the lithium-ion (Li-ion) battery, followed by the nickel-metal hydride NiMH and lead-acid batteries. Last come supercapacitors with 30% stability [14].

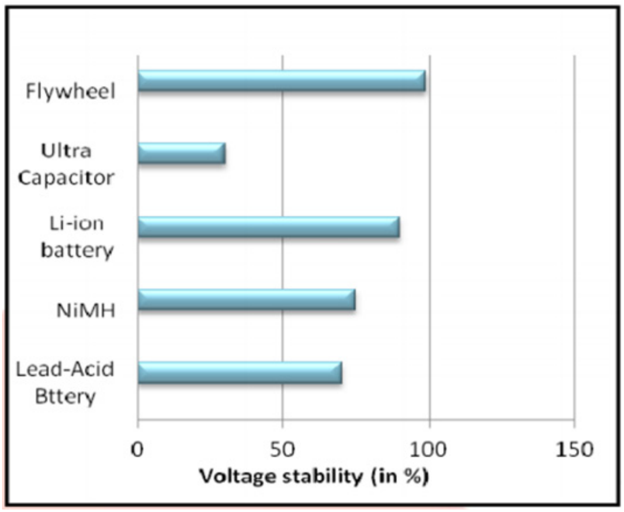


**Figure 7.** Voltage stability for various KERS systems [14]

## Conclusions

The use of a kinetic energy recovery system during braking, regardless of whether the car uses a mechanical or electrical system, has many benefits. The use of KERS allows to significantly reduce the operating costs of the vehicle, including the braking system, e.g. by extending the period per replacement of brake pads and discs, which can increase their lifetime due to partial absorption of kinetic energy by the flywheel or the generator. These systems allow not only to recover some of the lost energy but also to increase the range of the vehicle. In addition, thanks to the use of regenerative braking, we reduce environmental pollution, which is burdensome for the residents of larger cities. The KERS system is a solution that should also be implemented in public transport vehicles equipped with hybrid drives, e.g. in buses. The current development directions of hybrid and electric vehicles set the way in which the efficient use of lost energy still challenges vehicle manufacturers.

## Author Contributions

Conceptualization, Soliński M.; resources, Soliński M.; data curation, Soliński M.; writing – original draft preparation, Soliński M.; writing – review and editing, Soliński M.; visualization, Soliński M.

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