Kinetic Energy Storage in Hybrid Vehicles

The Mechanical Battery

The recovery of braking energy offers a significant potential for reducing energy consumption in vehicles. However, because of their properties, existing energy stores only allow limited use of this facility. Compact Dynamics is developing a new generation of kinetic stores, called Dynastore, that have been specially designed as electrical peak-load stores. The store will first be used in the Kinetic Energy Recovery System (KERS), a hybrid system for Formula One.

1 Introduction

Automotive manufacturers are making great efforts, not least due to the great political and social pressures, to reduce energy consumption and thus carbon dioxide (CO_2) emissions in their vehicles. On the other hand, one of the main potential ways of storing braking energy (recuperation) has hardly been used. The reason for this can be found in the poor quality of electrical storage systems currently available. Unlike stresses on previous vehicle electrical distribution systems, when a car is slowed down there are enormous power peaks. **Figure 1** shows different simulated driving cycles, showing the power and energy that are required to slow a car. The braking effect of the internal combustion engine (engine braking) has already been taken into account in the model. The evaluation simply shows the energy that is dissipated by the mechanical brake. If this is stored in the form of electrical energy, it can provide charging power of up to 30 kW for the battery. Standard batteries are unable to absorb these powers. Even in new types of batteries such as nickel-metal hydride batteries (NiMH), lithium-ion batteries (Li-Ion) or double-layer condensers, this load in association with high charging cycles leads to significant fluctuations in voltage and considerable thermal ageing. Thus, the storage systems in hybrid vehicles must be greatly over-dimensioned in order to achieve an acceptable lifespan. The replacement or final utilisation of these stores leads to an enormous amount of a wide range of different chemicals and heavy metals, whose disposal or recycling routes cannot be assured. A kinetic store, on the other hand, allows very high charging power with sufficient storage capacity, cycling stability and no indication of thermal ageing. A comparison between different storage technologies shows the advantages of a dynamic store as a peak-load store, **Figure 2**.

2 Function

Kinetic energy stores, also called flywheel stores, are used in many areas of technology. In order to store energy, an inert mass that turns around an axis is accelerated. The usable capacity [E] is defined by the moment of inertia [J] and the operating speed [ω], where the speed enters the energy balance quadratically: $E = J/2 \times \omega^2$. Mechanical flywheel stores are used principally to compensate for a lack of rotary balance and are used, for example, as flywheels and balancer shafts in internal combustion engines. By using high-performance materials and an engine control device with a high clock pulse, we are today able to produce electrical flywheel stores with high energy and power densities. In these systems, by accelerating a centrifugal mass using an electrical machine, the electrical energy is converted into kinetic energy. As air friction and bearing losses are very low compared to the stored energy, this can be stored over several hours with a very good memory effect. In generational operations, the flywheel is braked as it generates electrical power. The electrical energy generated in this way is fed back into the network. So far, these stores have mainly been used for voltage stabilisation in networks in stationary operation. Due to their weight and the costly technology involved, these stores are less suitable for use in cars. In addition, their centrifugal effect (gyro moment) can under certain circumstances affect the driving behaviour of the vehicle.

3 New Storage Concept for Use in Vehicles

The use of these systems in hybrid vehicles requires a completely new design of the flywheel store. The focus of development was on the short-term storage of limited energy with a high charging power, as is required for dynamic vehicle operation. This is why costly, magnetic bearings were not needed. Instead of a vacuum installation, reduced air pressure through a single evacuation of the store housing was sufficient to reduce air friction. The result of the development was a quadruple storage unit. The division into four small flywheels with a low mass leads to low forces that can be kept well under control in the housing in the case of an accident. The small units additionally allow simpler scaling and good integration into the vehicle. The integration of the flywheel into the engine generator function significantly

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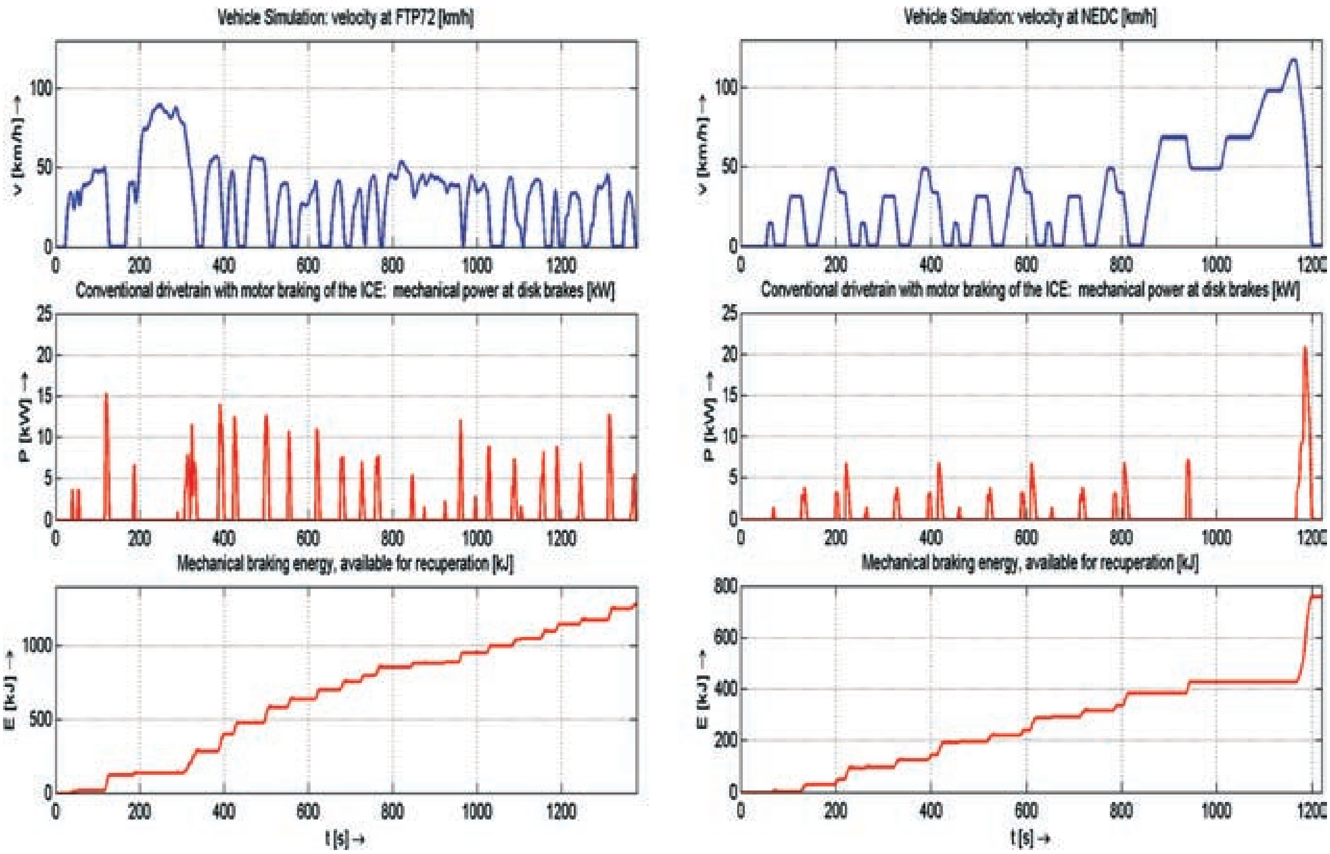

Figure 1: Simulation of power requirements and energy content when braking using standardised driving cycles [1]

reduces the complexity of the store. The drive was designed as a reluctance machine with an internal rotor, **Figure 3**. Its rotor is used simultaneously as an energy store (inert mass). An additional flywheel is therefore not required. Unlike in a permanently energised machine, a reluctance machine does not induce voltages in storage mode, that is at high rotational speeds (rpm). As there is therefore no core loss, the electrical machine works in storage operation with almost no losses. The structure of the rotor, which is made of thin sheets, is ideal from an electromagnetic point of view and additionally allows a high level of mass-specific energy, which is optimised by the arrangement of the teeth around the circumference. In the case of damage, unlike cast steel or carbon fibre reinforced plastic (CFRP) flywheels, the structure allows good failure behaviour. The stator, which lies on the outside, additionally contributes to the burst safety of the casing with its crumple zone. Due to the counter-rotation of the rotors, the store has no free gyro moment. Likewise, the engine moments produced during operation are also compensated for. As the bearings are the only component subject to wear, the lifetime of the store is based on their design. A pre-tensioned hybrid spindle bearing is used as the rotor bearing. The hardness and the low mass of the ceramic rolling elements allow an

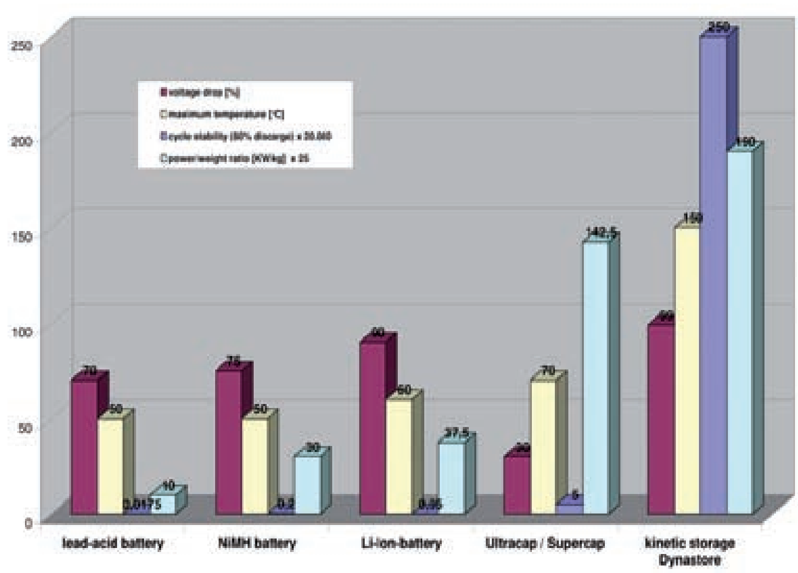

Figure 2: Comparison of storage systems based on characteristic properties; for ease of comparison, some of the values are shown using scaling factors [2, 3]

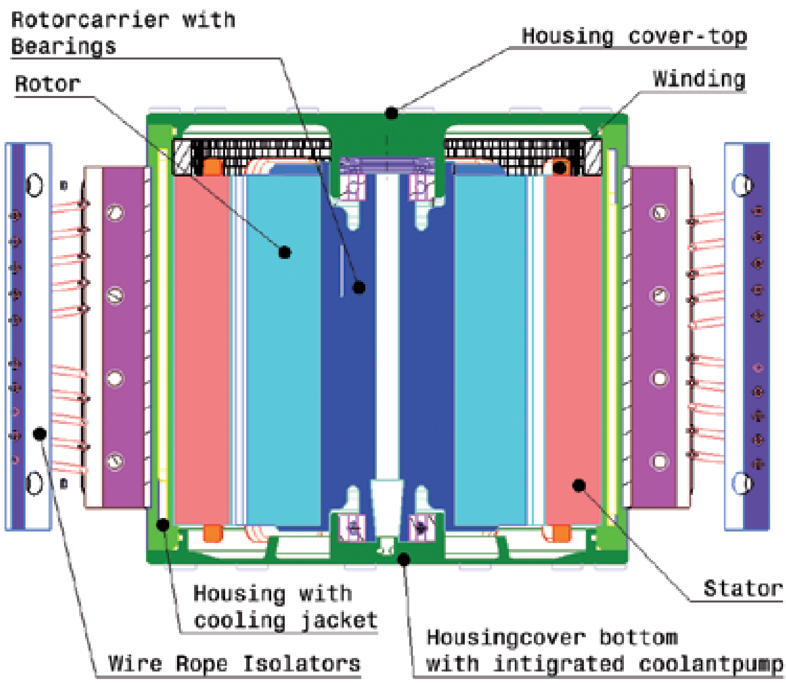

Figure 3: Cutaway image of an individual Dynastore storage system [4]

increase in speed of 25 % compared to standard bearings with a significant increase in running performance. However, it was worth finding an optimum balance between the speed and the rotor inertia. The shaping of the rotor as a ring significantly increases the moment of inertia ($J = m \times i^2$) of the rotor due to the increased radius of gyration. With a moderate increase in weight, it was possible to significantly lower the operating speed. For the optimal lubrication of the bearings, a lubricant is transported to the bearing from a sump on the floor of the store through a centrifugal pump integrated in the rotor carrier. Excess lubricant is additionally used for cooling the rotor, as convection cooling is seriously restricted due to the lower air pressure.

4 The Rotor as the Core of the Energy Store

As described above, the rotor of the electrical machine is additionally used as an inert mass for the storage system. In addition to good magnetically soft properties, it must also be very strong. As the speed enters the energy balance of the store quadratically, the loadability of the rotor material has the main influence on the energy content of the store, **Figure 4**. Typical rotor materials have a maximum yield point of 500 N/mm² and are therefore unsuitable for use in this case. One of the main tasks within the scope of development was therefore to find and verify very strong materials with sufficient magnetic properties. Due to the high material stresses in operation, changes to the magnetic properties under stress also had to be investigated. To do this, the hysteresis curves of high-strength materials under different stress conditions were determined, **Figure 5**. As expected, the magnetic properties of most materials decreased as the tensile stresses increased. At the same time, the total core loss increased significantly. Worthy of mention is a material that showed a new orientation of the structure through tensile stress, and the soft magnetic properties were significantly improved. As a result of the investigations, a suitable rotor material was found with a tensile strength of over 2100 N/mm² with good soft magnetic properties. As the values in the rolling direction and across the rolling direction were almost the same, the material has good isotropic properties. In the current design, only up to 70 % of this strength is used.

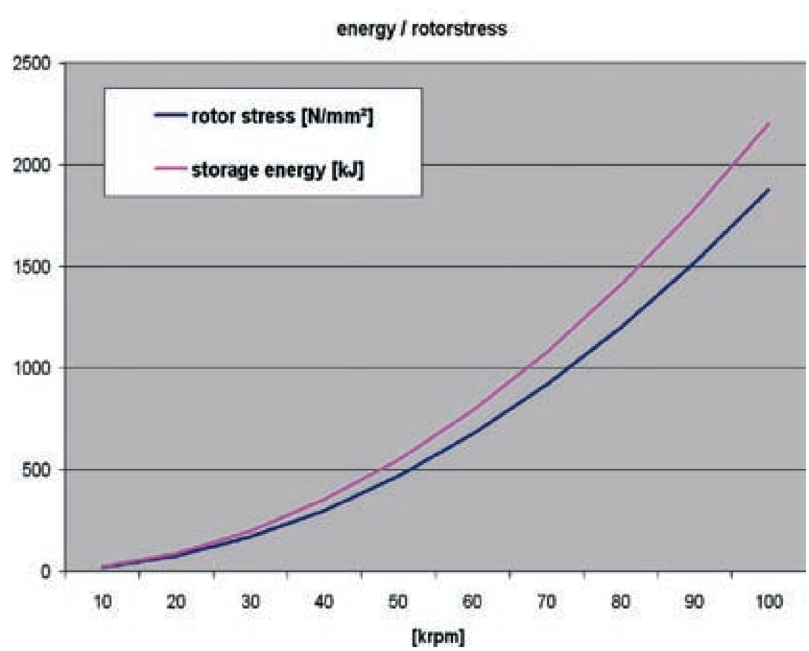

Figure 4: Dependency of the storage capacity and voltage stress at the rotor [4]

5 Functions of the Engine Control Device

The control device is linked to the car's intermediate circuit (vehicle electrical distribution system) and converts its direct current bi-directionally into the commutation current to control the electrical machine. The control device is adapted to the store housing. The direct

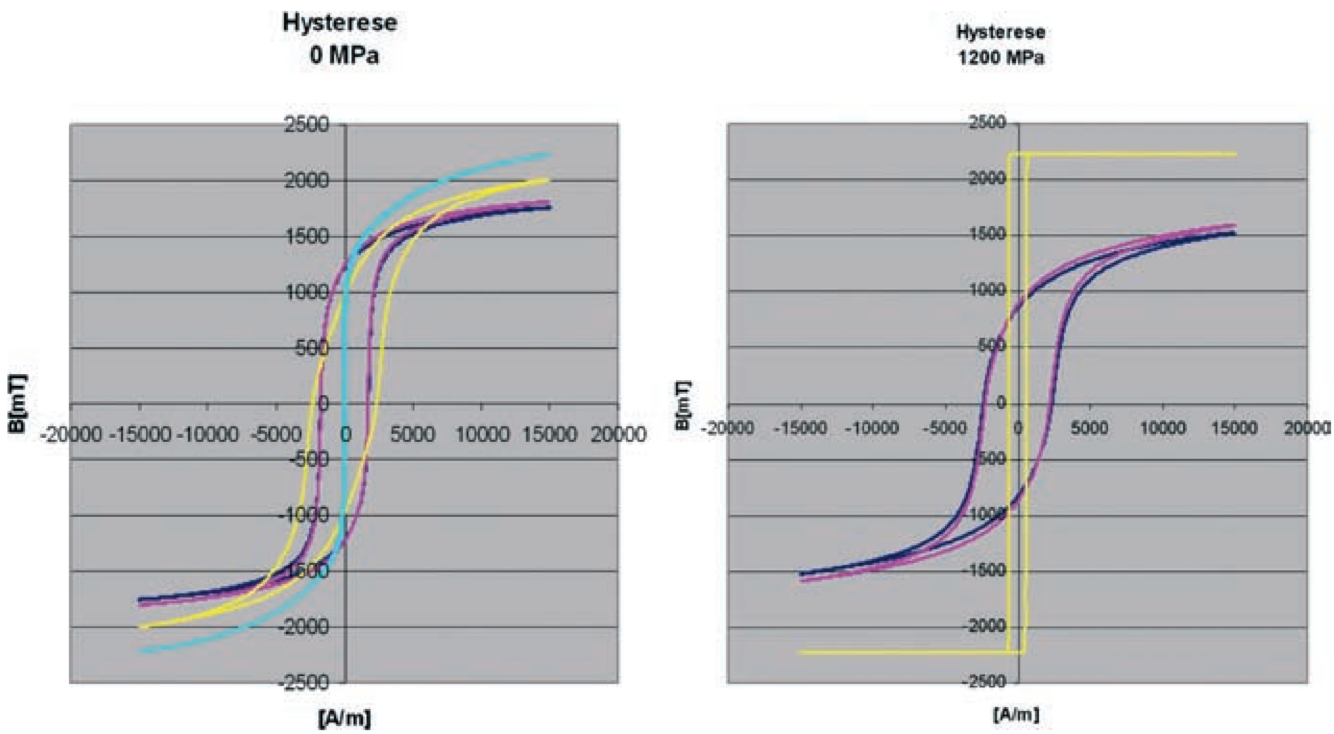

Figure 5: Hysteresis curves for different rotor materials under different stress conditions [5]

contacts to the engine windings eliminate the connection leads and also minimise electromagnetic compatibility (EMC) radiation. In addition, the control device takes over the charging management of the store, as well as the voltage stabilisation of the vehicle electrical distribution system. Unlike a battery, the direct current (DC) link voltage is monitored and stabilised as required by charging or discharging the store. This means there is no voltage dip even when large current loads are switched on. The reaction time of the store is less than 1 msec. Thus, even the smallest fluctuations can be compensated for. The charge state is calculated from the speed using the relationship: $E = J/2 \times \omega^2$. The speed information is determined using the electromagnetic effects of the electrical machine (sensor-free position recording). The controls are connected to the vehicle controller using a Controller Area Network (CAN) bus or Local Interconnect Network (LIN) bus and exchange any safety-relevant information. If required, for example in the case of a failure or a short-circuit in the vehicle electrical distribution system, the stores are discharged by converting the energy in the motor windings into heat. To prevent excessive overspeeds, the controls of the power semiconductor are interlocked with a hardware switch.

6 Summary

The properties of the Dynastore kinetic store allow braking energy to be utilised and large power loads to be supplied without the restrictions of batteries. Over-dimensioning of the stores based on a lack of cycle stability is no longer required. The reduction in weight achieved by this leads to further savings in energy. A division of the energy into several individual stores and the integration of active components into the safety concept allows maximum safety in the smallest space. Due to the exclusively physical energy storing processes, the store is not subject to ageing. The structure of the store corresponds to that of an electronically commutated motor. This results in a very compact and economical storage unit. The active charging management not only increases the efficiency of the vehicle electrical distribution system but also contributes to vehicle safety. As no chemical or capacitive stores are required, the use of heavy metals and chemicals is significantly reduced, particularly in hybrid vehicles. Special disposal and recycling measures are no longer required.

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