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# Development of Experimental Equipment for Regenerative Braking Energy with PEMFC Application

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## 1 Introduction

Electric and fuel cell vehicles are operated by electric control among the components such as battery, supercapacitor, motor or generator and fuel cell. Fuel cell system by using hydrogen can produce electricity to drive the fuel cell vehicle which can be controlled by the power from battery and supercapacitor together. The kinetic energy of moving vehicle is dissipated to environment as thermal energy when brake system is operated. Regenerative braking energy can be used to save total energy consumption of vehicle driving. Especially it is effective for the city driving because the vehicle repeats stop and start frequently.

An experimental equipment for educational purpose, which consists of battery, BLDC motor, supercapacitor and flywheel with a PEMFC (Polymer Electrolyte Membrane Fuel Cell) stack, shows the way to use the regenerative braking energy. The flywheel is originated from the idea of a fast moving vehicle. A generator linked with the flywheel converts mechanical kinetic energy of the flywheel to electric energy during braking period and works as a motor which consumes the electric energy to produce kinetic energy during driving period. The electric energy is stored into the supercapacitor and the battery, and is used for accelerating the flywheel speed later. The electric energy from the fuel cell stack is used for normal driving of the flywheel and sometimes for charging the battery.

Increasing regeneration energy from braking system affects regeneration current and SoC(State of Charge) of supercapacitor. The equipment represents a good simulator to understand how the energy consumption of a hybrid vehicle can be saved by calculating theoretical kinetic energy of the flywheel and conversion efficiencies from kinetic energy to electric energy, and measuring electric current and SoC of supercapacitor.

## 2 Theoretical Background and Experiment

Mechanical kinetic energy of a rotating flywheel system is used as the kinetic energy of moving vehicle. The flywheel is made to calculate and to check various kinetic energy by attaching additional disks to a basic disk. The theory is given with the following equations.

$$\Delta E = E_2 - E_1 = (1/2)J(\omega_2^2 - \omega_1^2)$$

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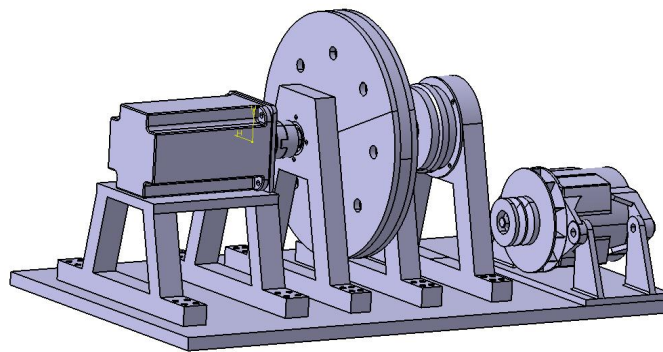
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$$J = \int r^2 dm = \pi t \rho (1/2) R^4$$

J is the polar moment of inertia and  $\omega$  is the angular velocity. By using the information data of the flywheel disks the kinetic energy can be calculated by the equations. The basic flywheel disk has the radius (R) of 185 mm, the thickness (t) of 30 mm and the density( $\rho$ ) of 7,870 kg/m<sup>3</sup>.

When there is no load, the flywheel continues rotating until the kinetic energy of the rotating flywheel is absorbed by mechanical friction and air friction. When regenerative energy is produced in the generator, the flywheel continues rotating until the kinetic energy of it is absorbed by generator and brake.

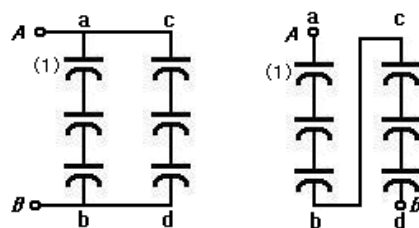
Experimental regenerative braking system is shown as follows. Motor and generator are used to check the conversion efficiencies of motor and generator between kinetic energy of flywheel and electric energy.



**Figure 1: Regenerative braking system.**

A BLDC motor with the power of 1.5 kW at 4.78 Nm, 24V, 66.3A and 3000 min<sup>-1</sup> is used to turn the flywheel. Usually motor needs motor controller because motor has 3-phase current input and output but supercapacitor and battery have direct current input and output. Fuel cell stack produces direct current output electricity. Motor controller can support various experimental conditions by control of revolution speed (min<sup>-1</sup>) and current.

Supercapacitor is a physical electric energy storage with large power density which charges and discharges quickly. It is used in UPS (uninterrupted power supply), hybrid electric vehicles and fuel cell vehicles.



(a) Parallel circuit (b) Serial circuit

**Figure 2: Parallel-serial connecting of capacitor.**

Supercapacitor is used by serial or parallel circuit connection as illustrated by the following figure to get electric energy or to release the electric energy from or to the total system.

An electrical character of supercapacitor is like a general character of capacitor. Each of following numerical equations shows serial connection, parallel connection and stored energy of capacitor respectively.

$$\text{(Serial): } 1/C = 1/C_1 + 1/C_2 + \dots + 1/C_n \text{ [F]}$$

$$\text{(Parallel): } C = C_1 + C_2 + \dots + C_n \text{ [F]}$$

$$\text{(Energy): } E = (1/2)CV^2 \text{ [J]}$$

The supercapacitor has the characteristic of a condenser and a battery. The state of stored energy is expressed by SoC as following numerical formula.

$$\text{SoC(\%)} = (V_o)^2 / (V_{\max})^2 \times 100$$

The hybrid system with supercapacitor extends the life time of battery and is used to support peak power as auxiliary power source. The benefits of the system are to reduce the voltage drop of main power and to support for the starting power as auxiliary power.

Ni-MH battery is used to save electric energy from fuel cell or generator and to release it to the motor. The characteristics of the battery are 1.2 V, capacity of 100 Ah at 20°C, nominal energy of 120 Wh, energy density of 155.9 Wh/L, specific energy of 66.7 Wh/kg and air cooling. The temperature range of battery-use is between -40°C to 55°C. It is very much safe because there is no electrolyte liquid which might be spilled out by vibration and impact.

Automobile companies are developing compact fuel cell system to apply for the power system of automobile with hydrogen fuel which can replace the internal combustion engine and oil based fuel. Because the price of fuel cell stack is too much expensive the hybrid system with battery and supercapacitor is useful for the fuel cell vehicles. A fuel cell stack made by Ballard is used to supply electric energy to experimental equipment.

### 3 Conclusions

An educational and experimental device for regenerative braking energy with motor, generator, supercapacitor, battery and fuel cell is developed to explain how to get, save and use the regenerative energy. It is possible how to calculate the conversion efficiency from the mechanical kinetic energy of flywheel to electric energy which is saved in battery and supercapacitor. The device can be used to demonstrate for the regenerative energy of various vehicles and trains. Students can know how to save the discarding energy of vehicles by brakes.

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