

Development of Electric Double-layer Capacitor System for Fuel Cell Vehicle

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ABSTRACT

An electric double-layer capacitor system has been developed for the Honda FCX fuel cell vehicle. This high-power capacitor system offers more than 30% higher output power and more than twice the power density of the nickel-metal hydride batteries used in hybrid electric vehicles (HEV) at an equivalent system voltage, and satisfies automotive power requirements. The new system is equipped with a capacitor cell protection system, which monitors capacitor voltage and provides equalization and malfunction detection functions. Heat insulation and a cooling system control increases in temperature both when the vehicle is parked and when it is moving. The effectiveness of these systems has enabled the new capacitor to satisfy durability and reliability requirements in unit tests and running tests.

1. Introduction

Increasing concern about environmental impact and global warming have made efforts to reduce emissions of exhaust gases, including CO₂, an important aspect of the research agendas of automotive manufacturers. As one solution, Honda has marketed a hybrid car fitted with its proprietary IMA system. In a new innovation aimed at achieving further reductions in emission levels, Honda has developed the FCX, a fuel cell passenger vehicle that releases no pollutants. A capacitor system assists the fuel cells, which form the main power source, by storing energy recovered during deceleration as electricity. This energy is provided when power is required during acceleration. Unlike conventional secondary batteries, the capacitor system contains no heavy metals, and is therefore an environmentally friendlier energy storage system, which, with the fuel cells (FC) also employed in the FCX, is a clean energy technology with considerable future potential. This paper will discuss the concept behind the new energy storage system and the technologies applied in the capacitors it employs.

2. Comparison of Energy Storage

The energy storage system to be used in the FCX was required to compensate for the poor instantaneous response performance of the FC. The assist power required in the FCX is approximately three times that demanded in the CIVIC Hybrid, and it was therefore necessary to achieve a high specific power density from a lightweight unit. As Table 1 shows, Li-ion batteries and capacitors display superior specific power density. At the same mass, the nickel metal-hydride battery utilized in the CIVIC Hybrid provides about half the assist power of a capacitor system. Both nickel metal-hydride and Li-ion batteries utilize chemical reactions to produce electricity, and therefore generate a stable voltage. Capacitors do not employ a chemical reaction, and voltage varies with the status of energy in the units. Because this characteristic enables the capacitor system to synchronize with the voltage of the FC, it is possible to connect it in parallel with the FC without passing the current through a voltage regulator unit, thereby increasing fuel economy.

Capacitors also have lower internal resistance than nickel metal-hydride batteries, and therefore not only display a

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Table 1 Power density and voltage of secondary batteries

	Power density (W/kg)	System voltage* (V)	OCV (V)
Ni-MH	Over 500	400 ~210	320
Li-ion	Over 1 000	400 ~285	340
Capacitor	Over 1 000	400 ~0	—

* Upper voltage fixed 400V

better charge and discharge efficiency across the entire power range, but also demonstrate very little energy loss when charging and discharging (Fig. 1).

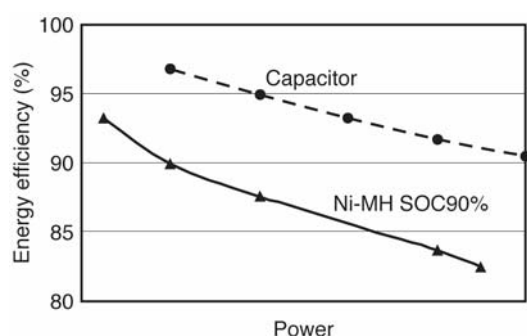


Fig. 1 Energy efficiency

In addition, because capacitors show little decline in performance with repeated charge and discharge, they are able to provide a stable source of power and energy for the life of the FC. There is no memory effect and the state of charge can be determined from voltage, enabling the control system to be simplified. Extremely reliable high-power capacitors are therefore the most suitable energy storage system for use with FC.

3. Development Goals

This development represented the first time in the world that a capacitor system had been utilized in a passenger car, making it necessary to reduce the space required by the unit as much as possible. Development was conducted with a strong focus on the following points, established as necessary prerequisites for achieving compactness and a high level of reliability:

- (1) Direct connection to ensure stable mounting of the capacitor units and guarantee the required voltage, while making the system more compact
- (2) Minimum space requirements for the heat insulation and cooling systems
- (3) Capacitor protection and control systems that increase system reliability in addition to contributing to stable performance

4. Study of Capacitor Module and Vehicle Installation

4.1. Structure of Capacitor Module

As Fig. 2 shows, the capacitor module is made up of 80 capacitors, a protection circuit to monitor their status, and a cooling structure. The newly developed series connection enables the positive and negative electrodes to be positioned on the same side, and the connection structure between the high-voltage capacitors and the protection circuit unit can be compactly organized in an 11.5 mm thick plastic plate, which also serves an electrical insulation function. Module support stays have been positioned at the top and bottom of the central section where functions are concentrated, increasing the strength of the support of the front section of the module, and enabling the capacitor box, which protects the capacitors and ensures cooling air flow, to be constructed from 0.8 mm thick aluminum.

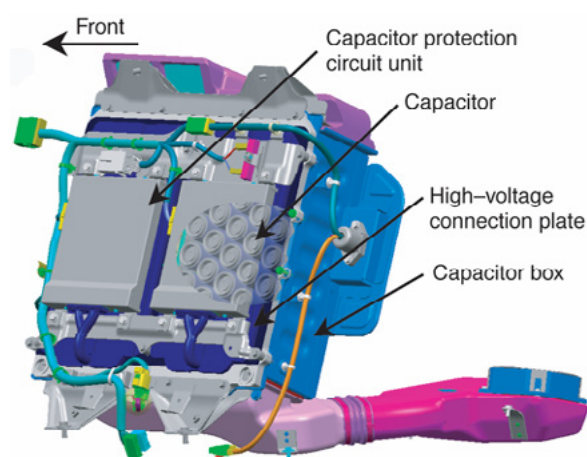


Fig. 2 Structure of capacitor module

4.2. Connection Structure

Welding is standard for conventional battery connections, and was employed for the connection in the CIVIC Hybrid. YAG laser welding must be employed when welding is used to connect capacitors, and control of component tolerances in the welded section is extremely important when utilizing YAG laser welding. The necessity of ensuring weld quality with consideration of the dimensional tolerances of the capacitor cells and possible deviations in assembly makes the technique impractical when connecting multiple capacitors. A low-resistance, lightweight and compact connection that would enable regular and accurate assembly and series connection of multiple capacitors was therefore studied.

Figure 3 shows the new series connection structure. The distinctive characteristic of this connection is that it balances support provided by screws with the achievement of low resistance conductivity through the use of contact washers. In addition, the connection structure has been concentrated at one side to simplify the monitoring of the voltage of individual capacitor cells.

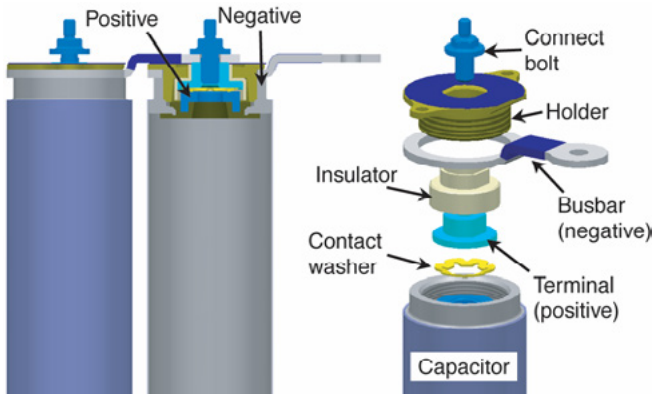


Fig. 3 Structure of capacitor series connection

The torque method was studied for tightening. It was confirmed that at a specified torque resistance stabilizes, enabling the target value for resistance to be achieved (Fig. 4).

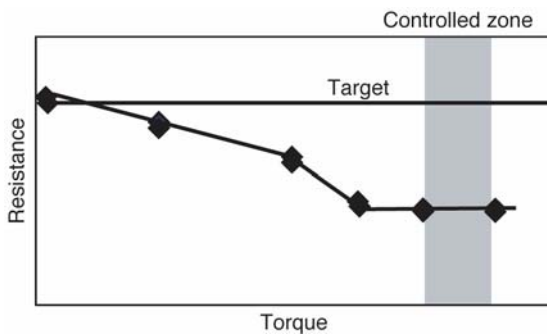


Fig. 4 Torque and electrical resistance

4.3. Controlling Temperature Increase when the Vehicle is Exposed to the Sun

The vertical positioning of the capacitor box behind the rear seat, as shown in Fig. 2, raised concerns that the capacitors in the upper part of the box might become overheated due to exposure to the sun on hot days. The following points were a significant focus during the development of the system of installation in the FCX. Because there is almost no natural ventilation when a vehicle is left exposed on a summer day, the internal temperature rises to more than 100 °C in the sections directly exposed to sunlight, and to more than 80 °C in the sections in the shade. There is no difficulty in protecting the capacitor at even 80 °C if its voltage is zero; the status of the unit's voltage determines the progress of performance decline. If the temperature of the capacitor is maintained at around 60 °C, there is no need to consider the effect of voltage on performance decline, and this was therefore established as a target for temperature control, after which study focused on methods of thermal insulation. The polypropylene foam proven in the CIVIC Hybrid was utilized in the upper duct to provide insulation, while a rubber flap was attached to the inlet of the same duct; the flap blocks the inlet when it is not being used for cooling (Fig. 5). Insulating materials have also been packed around the capacitor module to further contribute to thermal insulation.

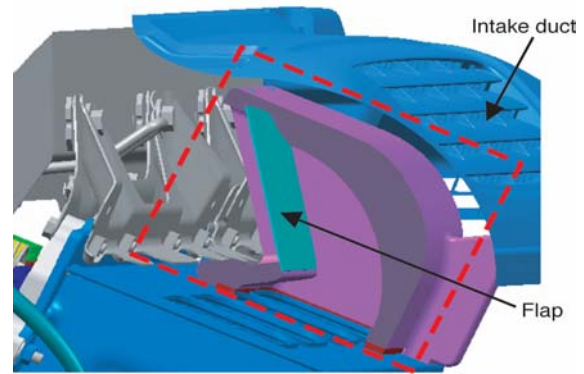


Fig. 5 Structure of upper capacitor box

Figure 6 shows the results of measurements of temperature of an installed module employing the insulating materials and flap described above. The results indicate that the new insulation layout has ensured that the temperature of the capacitors does not exceed 60 °C even if the vehicle is left exposed on a hot day, and functions efficiently to prevent overheating.

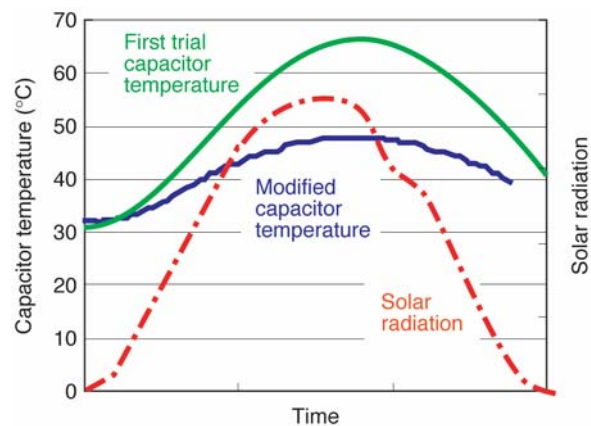


Fig. 6 Effect of heat insulator

4.4. Control of Temperature Increases during Vehicle Operation

The increase in temperature occurring during operation of the vehicle is dependent on the square of current multiplied by resistance during discharge and regeneration. Reduction of the current is effective in controlling temperature increase, but because this is dependent on the driving mode, it cannot be effected on the energy storage system side. The next most effective measures are the reduction of internal resistance and connection resistance. An aluminum case was adopted for the capacitor system in place of the SUS case utilized for the nickel metal-hydride batteries employed in the HEV, and the high heat conductivity of the material has increased cooling efficiency. In addition, as discussed above, the cell connection structure has reduced the level of heat generated by the system. In combination with the increased cooling efficiency provided by the aluminum case, this has enabled the capacitor system to generate half the heat of a Ni-MH battery at an identical system voltage (Fig. 7). The reduction of the heat generated by the system has also enabled the fan to be made more compact, consequently reducing noise.

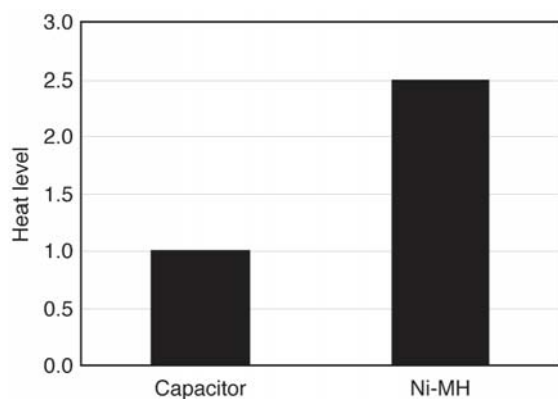


Fig. 7 Heat balance of energy storage

Figure 8 shows the cooling air flow. Cooling air is driven from the top of the module through the duct in the bottom by an axial-flow fan.

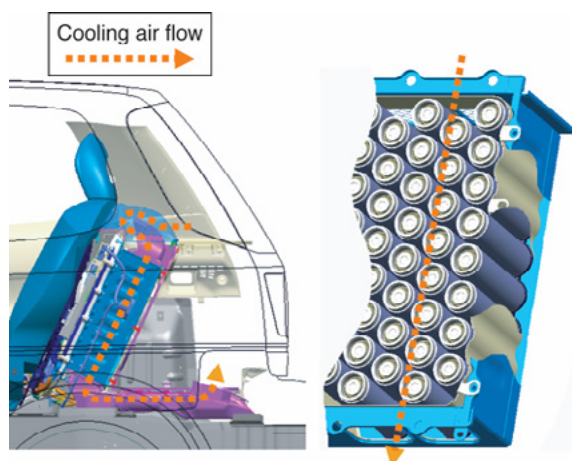


Fig. 8 Cooling air flow

To design the cooling structure for the capacitor box, the driving mode generating the greatest increase in heat value was selected from actual driving data, and the highest increase in heat value occurring in one continuous operation of the vehicle was abstracted from this mode. This was made the test mode (Fig. 9).

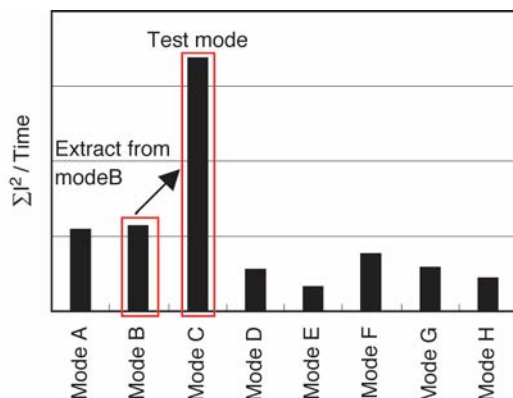


Fig. 9 Heating value in various modes

The temperature of the capacitors during operation of the FCX was measured, and a thermal analysis was conducted on the data. The results are shown in Fig. 10. The measurements were commenced with the temperature of the capacitor and the surrounding ambient temperature at 35 °C. Even in continuous operation in evaluation mode, 45 °C represented the upper limit for temperature increase. This is a result of the balance between the low level of heat generated by the capacitors and the efficiency of the cooling system.

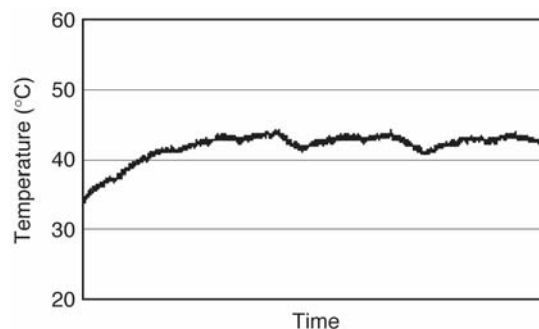


Fig. 10 Temperature transition in continuous mode C

5. Capacitor Protection Circuit

5.1. Configuration of Capacitor Protection Circuit

The electrical system of the capacitor system is made up of the high-voltage capacitors and a 12 V system, which controls them, with an insulating section positioned between them. The capacitor control circuit is composed of a voltage detection circuit and a circuit, which equalizes voltage variations between individual cells. The control circuit processes signals detected in the high-voltage circuit and communicates with the electronic control unit (ECU).

Figure 11 shows a schematic of the system.

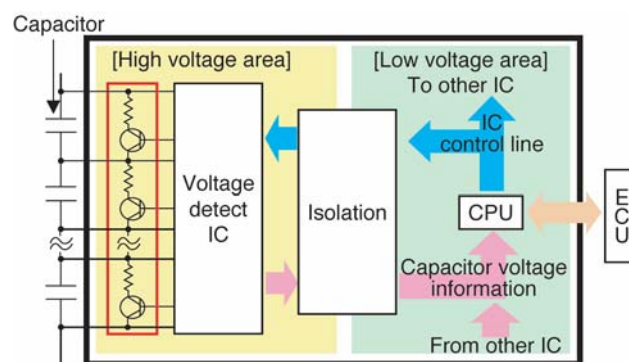


Fig. 11 Capacitor voltage detect system schematic

The functions that have the greatest effect on improving capacitor performance are:

- Capacitor voltage detection
- Equalization of capacitor voltage variations
- Capacitor malfunction detection.

The importance of each of these functions will be discussed below.

5.2. Voltage Detection

The energy of the capacitors reaches its maximum in use at a system voltage close to the upper limit. For this reason it was essential to increase the accuracy of the detection of the voltage of individual cells, leading to the use of integrated circuit (IC) in the voltage detection system. This has enabled the achievement of high-accuracy voltage detection of $\pm 1.5\%$ ($0^\circ\text{C} - +80^\circ\text{C}$).

Three criteria were established for detected voltage:

- 1) Upper limit detected voltage = Maximum absolute rated voltage for capacitor
- 2) Voltage for commencement of equalization $\equiv$ Rated voltage for capacitor
- 3) Malfunction detection voltage = 0.7 V

The employment of IC has the added advantage of lowering the current consumed by the circuit when the vehicle is stationary (ignition OFF) to approximately $1\ \mu\text{A}$, enabling capacitor voltage to be maintained at more than 98% over periods of disuse of up to a month.

5.3. Equalization of Voltage Variations

Preventing variations in voltage between multiple capacitors is essential to reducing energy loss and a decline in performance. Figure 12 shows an image of the convergent capacitor voltage achieved by the voltage equalization circuit connected in parallel to the capacitors.

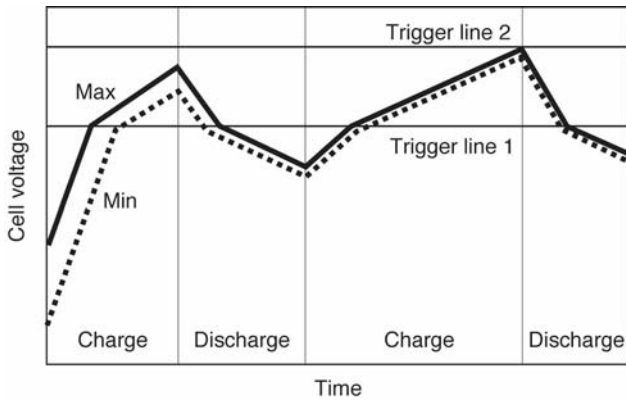


Fig. 12 Image of convergent capacitor voltage

The voltage equalization circuit operates between the voltage established for commencement of equalization and the upper limit detected voltage. When capacitor voltage reaches the level established for commencement of equalization, the equalization circuit connected in parallel operates to render capacitor voltage uniform by allowing part of the current to bypass the circuit. The development of the equalization circuit and the high-accuracy voltage detection circuit discussed above has enabled voltage variations between the capacitors to be controlled to less than 0.1 V , reducing the level of energy loss.

5.4. Malfunction Detection

The total voltage of the series-connected capacitors is considered as source voltage by the new voltage detection IC. If for any reason the voltage of the capacitor system connected to the IC falls below a lower limit, the circuit detects a system malfunction. The malfunction detection

circuit can also detect internal shorts in the capacitor, shorts in the connection structures, and disconnections.

6. Verification of Durability

6.1. Changes in Durability towards Voltage and Temperature

By contrast with batteries, because no chemical reaction is involved in the charging and discharging of capacitors, they demonstrate little physical change and show superior durability. However, temperature and voltage affect the durability of capacitors, making the above-mentioned insulating and cooling systems and voltage control essential to the achievement of a stable performance. Figure 13 shows the rate of change of energy retention under different temperature and voltage conditions. It is clear that the level of durability changes as temperature and voltage increase.

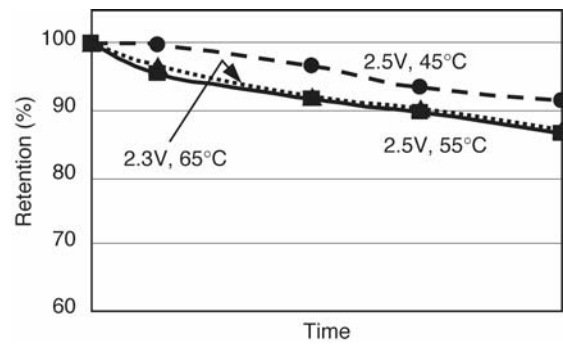


Fig. 13 Energy retention in relation to temperature and voltage

6.2. Establishing a Durability Test Mode

Voltage and temperature were distinguished as factors affecting the performance of capacitor cells. The higher the impressed voltage or the temperature, the more rapid the decline in the performance of the cells. Driving data from prescribed modes and actual modes were therefore focused on, and Mode A in Fig. 14 was abstracted as the durability test mode, because the average voltage in the capacitors and the heat generated by charge and discharge were at their maximum in this mode. By adding an idling time reflecting market data to the durability test mode, it was possible to establish a mode providing a sufficiently accurate representation of the actual conditions of use of the FCX (Fig. 14).

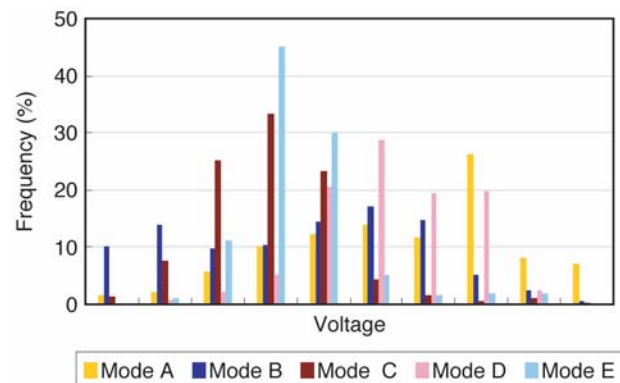


Fig. 14 Voltage frequency

Figures 15 and 16 show changes in performance during durability tests. Although the durability test mode was established on the basis of the most severe use conditions for the capacitors in the FCX, no sharp decline in performance occurred during tests, and the capacitors showed an energy retention rate of more than 90% and an assist time retention rate of more than 80% after tests.

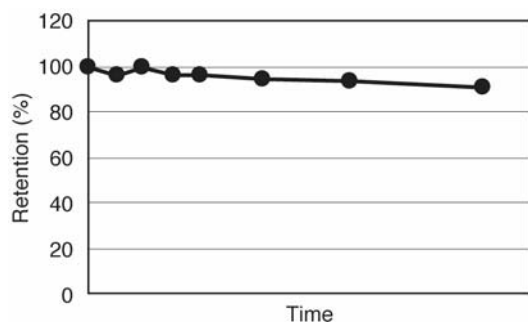


Fig. 15 Energy retention

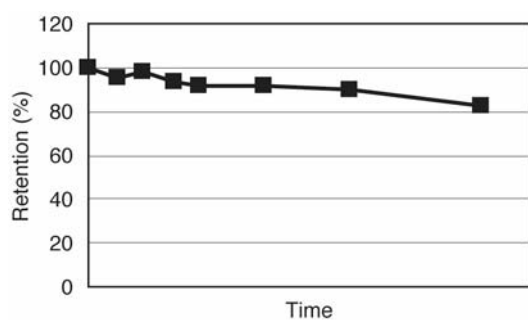


Fig. 16 Assist time retention

7. Current and Voltage Behavior when Installed

Because it is not generated by a chemical reaction, the voltage of a capacitor is not stable, but changes with the status of energy in the cell. For this reason a parallel connection was adopted in the FCX, to enable the changes in voltage in the capacitor cells to synchronize with changes in FC voltage during vehicle operation.

Figure 17 shows changes in FC and capacitor power.

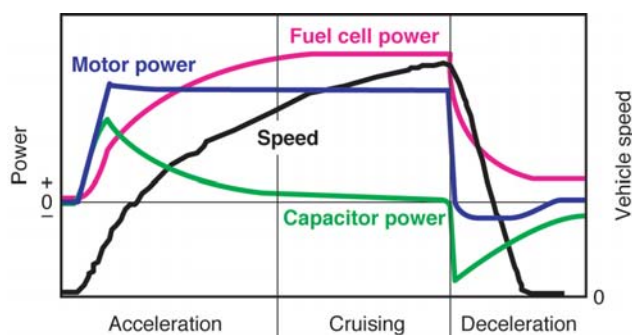


Fig. 17 Fuel cell and capacitor power characteristics

- During acceleration
The capacitor cells compensate for the poor instantaneous power response of the FC, and provide the vehicle with power according to demand.

- During regeneration
Part of the energy utilized in deceleration is regenerated in the capacitor system, which instantaneously recharges during deceleration.

8. Summary

An electric double-layer capacitor system has been employed as the energy storage system in the Honda FCX fuel cell passenger vehicle, the first time in the world that this type of system has been utilized in a passenger car. Development focused on the capacitor type most suited to the demands of FC. Series connection was adopted to enable stable mounting and to achieve low resistance, increasing the voltage of the system. In addition, the system has been provided with heat insulation and a cooling structure, to control temperature increases when the vehicle is in operation or is left exposed to the sun. A capacitor protection circuit has also been developed to ensure the reliability of the energy storage system.

Combining these innovations, the system provides power from the capacitors to compensate for the poor instantaneous power response of the FC, contributing to the excellent takeoff and acceleration performance of the FCX.

The capacitor system is not only superior to batteries in terms of power and efficiency, but generates half the heat of the nickel metal-hydride battery employed in Honda's HEV at the same state of charge, confirming that from this perspective too it represents the optimum energy storage system for automotive applications in use today.

Acknowledgments

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Reference

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