Fundamental Study on a Hybrid Power System of Passive-type Polymer Electrolyte Fuel Cells and Capacitors

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Abstract

A simple hybrid power system of fuel cells and capacitors suitable for lightweight electric vehicles was studied in order to achieve long distance run without charging from outside. Passive-type polymer electrolyte fuel cells and electric double-layer capacitors were used in this system. In order to simplify the control of the power system, the authors attempted to adapt a series hybrid power control, and proposed an original control sequence for the power devices in this system. A fixed experimental apparatus made as a model of a lightweight electric vehicle with a series hybrid power system was used in this study. The operating characteristics of the system using this control sequence along with the control scheme to drive the vehicle were measured under various running conditions including deceleration with electricity regeneration. The experimental results were described to show the suitability of the control sequence.

Keywords

passive- type polymer electrolyte fuel cell, electric double-layer capacitor, hybrid system, lightweight electric vehicle, control sequence

1. INTRODUCTION

Some of serious problems in the highly-industrialized societies of the 21st century are environment contamination and shortage of energy resources. Therefore, urban air pollution and global greenhouse effect caused by automobiles have to be prevented and also their fuel consumption has to be reduced to the utmost. As a power source of an automobile or a small vehicle, polymer electrolyte fuel cells (PEFCs) fuelled with hydrogen are believed to be one of the best solutions to date, because their emission is only water and their energy conversion efficiency is very high [Takehara, 2000].

In an aging society to come, the need of lightweight electric vehicles (motor-driven bicycle, scooter, wheelchair, etc.) increases more and more. But it is not convenient to use them, because the running distance per one charge of batteries is short and it takes long time to charge them. Under the above-mentioned situation, a motor driven hybrid power system with storage devices (batteries or capacitors) and fuel cells is desirable for a lightweight electric vehicle in order to achieve long distance run without charging from outside. In the case of electric automobiles powered by fuel cells (FCEV) which have been put into practical use recently, their power system is mainly a parallel hybrid system composed of fuel cells, storage devices and an electric motor. In their parallel

Table 1 Symbols

Symbol		Unit
C	Capacitor capacity	F
D_m	Motor duty ratio	-
D_f	Fuel cell duty ratio	-
I_c	Capacity current	A
I_m	Motor current	A
I_f	Fuel cell current	A
I_{fl}	Upper limit of I_f	A
J	Moment of inertia	kgm^2
K_e	Motor voltage constant	V·s
K_t	Motor torque constant	Nm/A
L_m	Motor inductance	H
n_m	Motor revolution speed	s^{-1}
R	Wheel radius	m
R_c	Capacitor reluctance	Ω
R_m	Motor reluctance	Ω
R_f	Fuel cell internal resistance	Ω
R_w	Gear ratio	-
s	Laplace operator	s^{-1}
T_m	Motor torque	Nm
T_l	Load torque	Nm
t	Time	s
t_{all}	Time per one control cycle	s
$t_{f(on)}$	Fuel cell ON time per one cycle	s
$t_{f(off)}$	Fuel cell OFF time per one cycle	s
$t_{m(on)}$	Motor ON time per one cycle	s
$t_{m(off)}$	Motor OFF time per one cycle	s
v	Vehicle speed	km/h
V_c	Capacitor voltage	V
V_m	Motor voltage	V
V_f	Fuel cell voltage	V
V_{fl}	Lower limit of V_f	V

hybrid system, the control of power distribution is very complicated, so such a system is not suitable for lightweight electric vehicles.

In this paper, a simple hybrid power system of fuel cells and storage devices, which is suitable for lightweight electric vehicles, is studied in order to achieve long distance run without charging from outside.

As a storage device, electric double-layer capacitors having high power density, high efficiency and long life are used. As fuel cells, passive-type PEFCs (any air pumps, humidifiers and temperature controllers are not employed, so the cell module is very simple) are used.

In order to simplify the control of the power system, the authors attempt to adapt a series hybrid power control in which the transfer of electric energy between power devices (namely fuel cells, capacitors and a motor) is executed in series. In this system, the complicated control of power distribution is not necessary, so the system is suitable for lightweight electric vehicles.

For making a fundamental study, a fixed experimental apparatus, which is made as a model of a lightweight electric vehicle with a series hybrid power system, is used in this study. The authors propose an original control sequence of the power devices in this system. The operating characteristics of the system using this control sequence are measured under various running conditions including deceleration with electricity regeneration. The experimental results are described to show the suitability of the control sequence.

2. MODEL OF A FUEL CELL HYBRID ELECTRIC VEHICLE

2.1 Experimental apparatus

Figure 1 shows the experimental apparatus used in this study. It is mainly composed of passive-type PEFCs, electric double-layer capacitors, a permanent magnet synchronous motor, an inverter /converter and a flywheel. In this apparatus, the fuel cells, the capacitors and the motor are connected parallel in the electric circuit. The capacitors are charged by the PEFCs and the electricity of the capacitors is supplied to the motor. The flywheel driven by the motor has an inertia moment ($J = 3.52 \times 10^{-3}$ kgm^2) corresponding to a lightweight electric vehicle (its total mass is set at 80 kg, the wheel radius is set at 330 mm and the ratio of the motor rotation to the wheel rotation is set at 49 : 1). A torque meter is used only when the motor torque constant (K_t) is measured before an experiment in running state. In this experiment, the actual road load for any lightweight electric vehicles is not added but only the frictional load peculiar to the experimental apparatus is imposed because the generation power of the PEFCs used here is low. Its load is linearly increased with the vehicle speed as shown in Fig. 2.

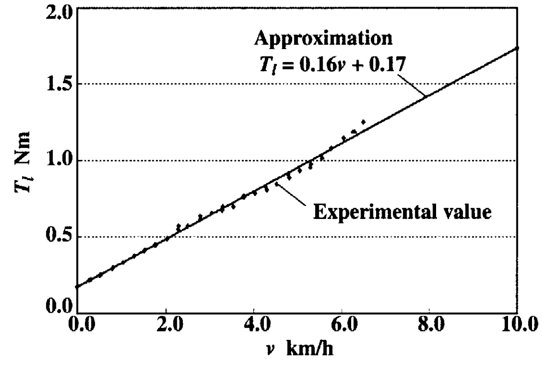


Fig. 2 Frictional load of the experimental apparatus

2.2 PEFC

In the authors' laboratory, the research and development of PEFCs are being carried out, but those PEFCs are only small power single cells [Nishioka et al., 2002].

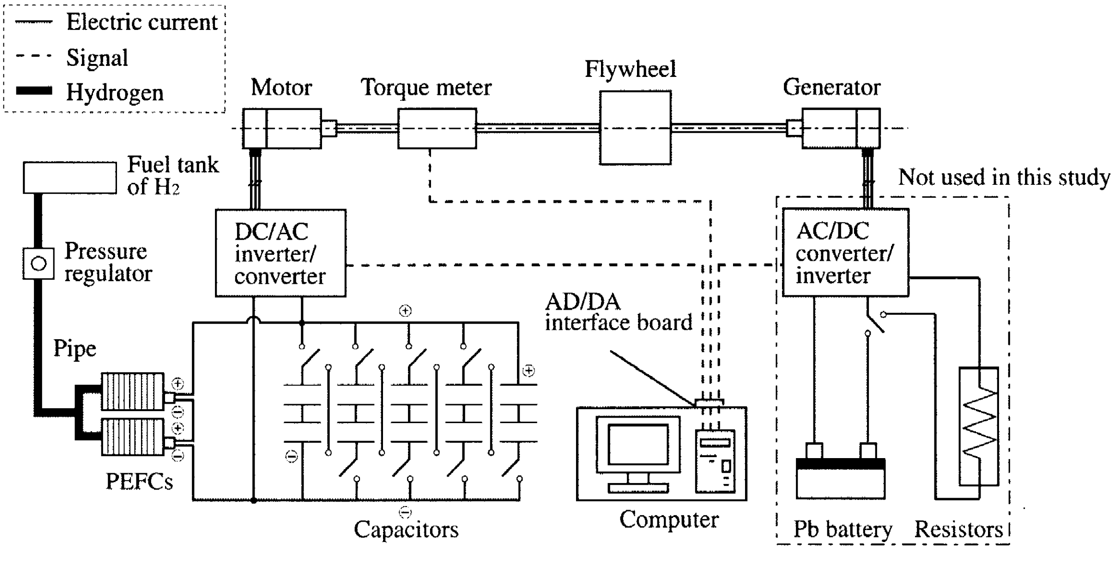


Fig. 1 Experimental apparatus

Therefore, commercial passive-type PEFC units (PFC 1212C) manufactured by Daido Metal Co.,Ltd. are used in this study. The specifications of the PEFC unit are shown in Table 2. In the experimental apparatus, two PEFC units connected in series are installed and the total nominal voltage of the PEFC module is 24 V. In order to storage hydrogen, a small tank containing hydrogen absorption alloy is used. Its specifications are shown in Table 3. The hydrogen ejection gauge pressure is 0.5 MPa and its pressure is reduced by a regulator down to the gauge pressure 0.07 MPa for supplying to the PEFC units.

Table 2 Specifications of the PEFC unit

Nominal power	12W
Continuous nominal power	8W
Nominal voltage	12V
H_2 supply pressure	0.07Mpa
Size	ϕ70 × 160mm
Mass	800g

Table 3 Specifications of the H_2 tank

H_2 absorption material and mass	Zirconium alloy, 400 g
H_2 absorption quantity	75 normal L
H_2 ejection pressure	0.5 MPa
Size	ϕ50 × 135 mm
Tank mass	950 g

Figure 3 shows the structure of a single cell of the passive-type PEFC unit. Electro chemical reaction occurs between hydrogen going through the center of the cell and oxygen going from outside of the cell without any air pumps. The MEA (Membrane Electrode Assembly) is composed of an electrolyte membrane and two sheets of carbon cloth coated with platinum catalyst. The one unit of the PEFC has twenty cells connected in series.

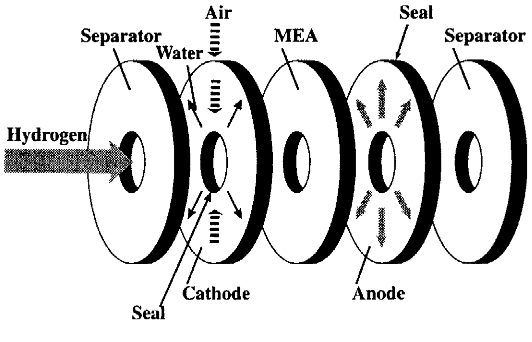


Fig. 3 Structure of a single cell of the passive-type PEFC uunit

In order to prevent the damage to the electrolyte membrane, a protection circuit is installed in the PEFC unit. When the PEFC voltage becomes lower than 8.5 V, the protection circuit cuts off the PEFC output. Figure 4 shows the voltage-current characteristic of the PEFC unit.

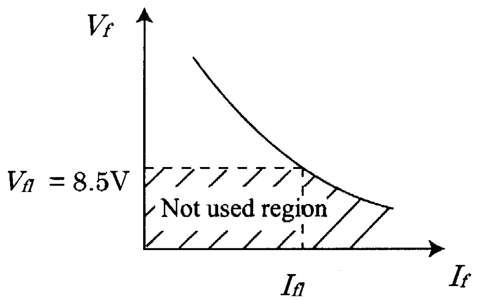


Fig. 4 V_f - I_f characteristic of the PEFC unit

2.3 Capacitor

The specifications of the electric double-layer capacitors (UP-Cap UPA manufactured by Matsushita Electric Components Co.,Ltd.) used in this study are shown in Table 4. They have good efficiency and long life for repeating use [Okamura, 2001]. Therefore they are suitable for vehicles, because the driving mode changes frequently. In order to work the capacitors effectively, the authors devise the following method and apply it in this experiment:

Ten units of the capacitors are connected in series (nominal voltage is 23 V) when they supply electricity to the motor, and the connection of the capacitors is changed to parallel connection of the five sets of two units connected in series (nominal voltage is 4.6 V) by means of relays when electricity is regenerated to the capacitors in decelerating the vehicle. Such lowering of the capacitor total voltage without using any voltage converter makes it possible to store electricity generated by the motor (the motor is substituted as a generator) at lower speed efficiently. This means that the kinetic energy of the vehicle is recovered more efficiently. When the connection of the capacitors is changed, the electric current to/from the capacitors is cut by setting the PWM duty ratio at zero for suppressing the spark in the relays.

Table 4 Specifications of the capacitor

Nominal voltage	2.3 V
Nominal capacity	2000 F
Power density	1000 W/L
Energy density	4.5 Wh/L
Internal resistance	3 mΩ
Size	ϕ51 × 126 mm
Mass	460 g

2.4 Motor

The specifications of the permanent magnet synchronous motor (EC45 manufactured by Maxon Motor AG.) used in this study are shown in Table 5. Magnetic field of this motor is made by permanent magnet, not coil. Not using coil for magnetic field achieves high efficiency

Table 5 Specifications of the motor

Rated power	250 W
Nominal voltage	24 V
Maximum revolution	200 s^{-1}
Maximum continuous torque	283×10^{-3} Nm
Maximum continuous electric current	7.1 A
Size	$\phi 45 \times 101.5$mm
Mass	1.15 kg

and small size. This motor is controlled by an inverter based on PWM (Pulse Width Modulation) control [Sugimoto, 1990].

2.5 Control of capacitor charge by the PEFCs

The power devices in the experimental apparatus are connected parallel in the electric circuit. But the fuel cells cannot charge the capacitors while the capacitors supply electricity to the motor. Therefore, charging and discharging of the capacitors have to be executed alternately. As a problem concerning the charging by the fuel cells, the charging current depends on both of the capacitor voltage which is determined by the capacitor SOC (State of Charge) and the fuel cell voltage which falls with an increase of output current as a characteristic of fuel cells. Furthermore, the fuel cells cannot charge the capacitors with large current, because the output voltage is limited to a certain value (lower limit voltage V_{fl}) due to the protection circuit as shown in Fig. 4.

As the control sequence of the charge and discharge of the capacitors, the authors contrive an original one based on a time splitting technique, and its technique is applied in this study as follows:

The electricity supply from the capacitors to the motor is executed for the ON periods in the PWM signal, and the electricity supply from the PEFCs to the capacitors is executed for the OFF periods in the above-mentioned PWM signal for the motor control. Figure 5 shows the concept of electric current control from the PEFCs to the capacitors.

The time of one cycle in the PWM signal is denoted by t_{all}, and the electricity supply time from the capacitors to the motor per one cycle is denoted by $t_{m(on)}$ (Fig. 5(a)). The motor duty ratio D_m designates the ratio of $t_{m(on)}$ to t_{all} as follows:

$$D_m = \frac{t_{m(on)}}{t_{all}} \qquad (1)$$

During the OFF time $t_{m(off)}$ in the PWM signal, namely during the ON time in the INVERSE signal (Fig. 5(b)), the PEFCs can charge the capacitors while the charging current is smaller than the upper limit current. For the decelerating period of the vehicle, the connection of the capacitors is changed from series to parallel as described in Section 2.3, and the capacitor total voltage is made one-fifth. This makes the charging current from the PEFCs considerably large in the deceleration period. Consequently, in this period the charging current has to be controlled within the upper limit current by breaking the charging current during the ON time in the INVERSE signal (Fig. 5(b), (c)) so that the protection circuit may not work. The electricity charge time from the PEFCs to the capacitors is denoted by $t_{f(on)}$ (Fig. 5(d)), and the time t_{all}-$t_{f(on)}$ is denoted by $t_{f(off)}$. As a measure of the utilization of ON time in the INVERSE signal for charging the capacitors by the fuel cells, the charging time ratio α_f is defined as follows:

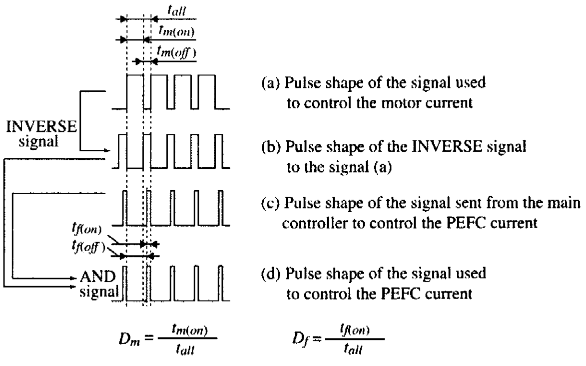


Fig. 5 Control of electric current from the PEFCs to the capacitors

$$\alpha_f = \frac{t_{f(on)}}{t_{m(off)}} \qquad (2)$$

$$(\ 0 \le \alpha_f \le 1\ )$$

The value of α_f is limited by the fuel cell upper limit current I_{fr}.

The fuel cell duty ratio D_f is defined by Eq. 3. From this equation, it is shown that the value of D_f is determined by D_m and α_f.

$$D_f = \frac{t_{f(on)}}{t_{all}} = \alpha_f \frac{t_{m(off)}}{t_{all}} = \alpha_f (1 - D_m) \qquad (3)$$

In order to examine the transient response of the fuel cells used in this study, the charging electric current from the fuel cells to the capacitors is measured with a voltage drop method by inserting a resistor of 5 Ω to the capacitor circuit in series. Figure 6 shows a measured result of the charging current to the capacitors followed by the discharging current from them under the condition t_{all} = 84 μ s, D_m = D_f = 0.5, v = 4 km/h and initial value of V_c = 20 V.

It is found that the passive-type PEFCs can charge the capacitors with quick response although a resistor having large resistance is inserted temporarily.

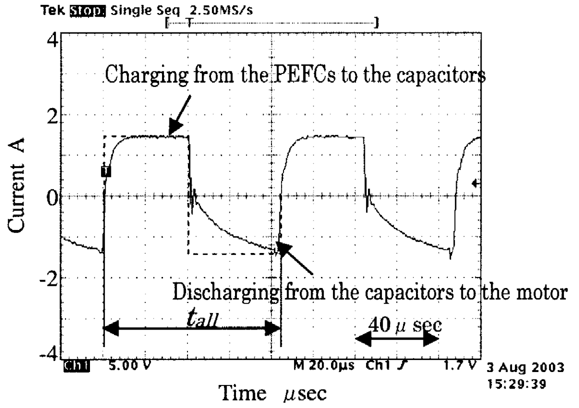


Fig. 6 Measured result of the transient response of charging and discharging current

3. DRIVING MODE

Electric energy transfer in this hybrid power system in each driving mode is described below:

Figure 7 illustrates the electric energy transfer in this system. The amount of transferred electric energy is determined by the motor duty ratio D_m and the fuel cell duty ratio D_f.

3.1 In the case that the vehicle runs fast

In this case, the motor needs much energy for driving, therefore the motor duty ratio D_m is large, whereas the fuel cell duty ratio D_f is small. The relationship between D_m and D_f is as follows:

$$D_m \geq D_f \tag{4}$$

Accordingly the amount of energy consumption in the capacitors is large (Fig. 7(a)).

3.2 In the case that the vehicle runs slowly

In this case, the motor does not need much energy for driving, therefore the motor duty ratio D_m is small, whereas the fuel cell duty ratio D_f is large. The relationship between D_m and D_f is as follows:

$$D_m < D_f \tag{5}$$

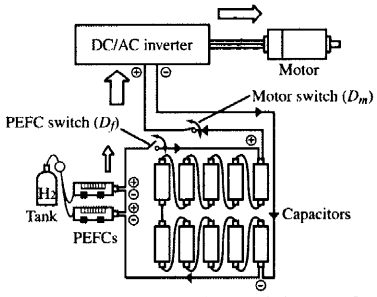
Accordingly the amount of energy consumption in the capacitors is small (Fig. 7(b)).

3.3 In the case that the vehicle slows down

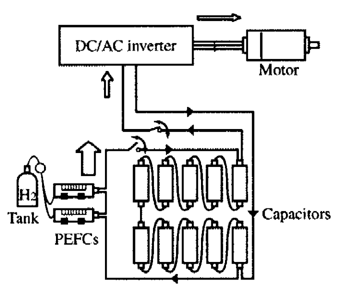
In this case, the regeneration electric energy is stored in the capacitors effectively by changing the series connection of them to the parallel connection, and also the fuel cells charge the capacitors by means of the time splitting technique (Fig. 7(c)).

3.4 In the case that the vehicle stops

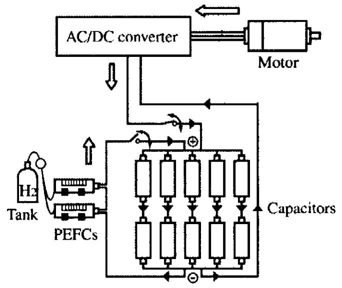
In this case, the motor does not rotate, so the electric energy path between the capacitors and the motor is intercepted. Namely, $D_m = 0$. On the other hand, the fuel cells charge the capacitors based on the fuel cell duty ratio D_f (Fig. 7(d)).



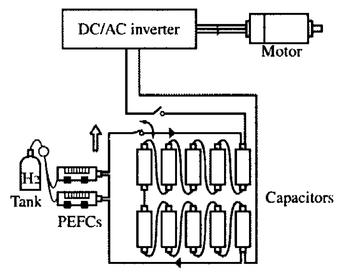
(a) In the case that the vehicle runs fast



(b) In the case that the vehicle runs slowly



(c) In the case that the vehicle slows down

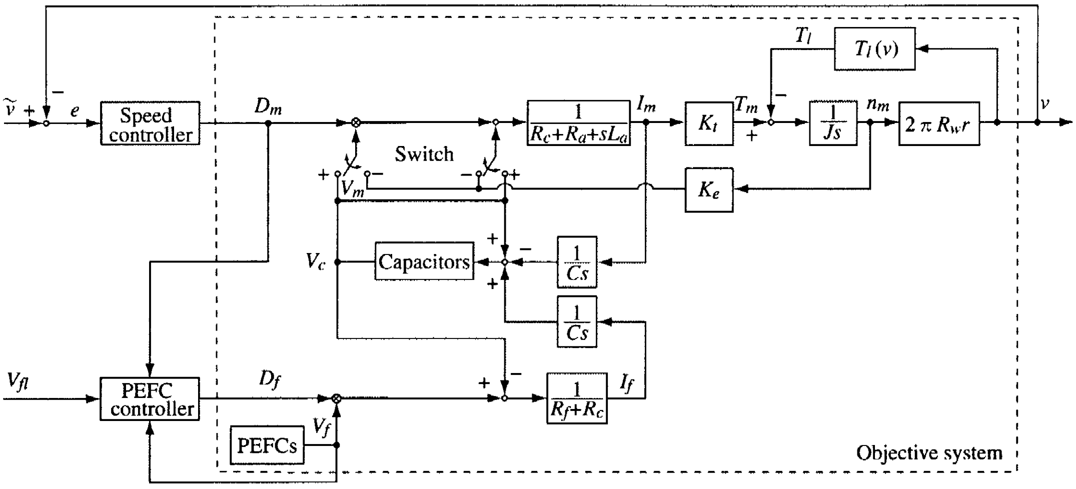


(d) In the case that the vehicle stops

Fig. 7 Illustration of the electric energy transfer in the hybrid power system

4. CONTROL SCHEME TO DRIVE THE VEHICLE

A control scheme to drive the vehicle in an acceleration and deceleration mode is contrived. The block diagram of the drive train system is shown in Fig. 8, where J is the equivalent moment of inertia of the lightweight electric vehicle. As a load in this experiment, only the frictional load peculiar to the experimental apparatus is



Driving mode	Switch
Power run	Left
Regeneration	Right

Fig. 8 Block diagram of the drive train system

imposed as described in Section 2.1.

The motor duty ratio D_m is calculated by the speed controller of PI control based on the deviation e of present speed v from target speed $\tilde{v}$ [Imanishi et al., 2002]. The fuel cell duty ratio D_f is calculated by the PEFC controller based on the motor duty ratio D_m, the fuel cell voltage V_f and the fuel cell lower limit voltage V_{fl}.

5. EXPERIMENTAL RESULTS

The control sequence of the hybrid power system along with the control scheme to drive the vehicle is examined using the experimental apparatus in long run tests and also in acceleration and deceleration tests. In every test, the initial total voltage of the capacitors is set at 23 V.

5.1 Long run tests

In order to examine the effect of electricity supply by the PEFCs on the vehicle motion, long run tests are executed in two cases without and with the PEFCs. The experimental condition is as follows: the initial vehicle speed is 8 km/h, and the duty ratios D_m and D_f are set constant (D_m = 0.88, D_f = 0.12).

The experimental results are shown in Figs. 9 and 10. In the case that only capacitors are used as an electricity supply source, the motor stops after a lapse of 8475 sec. In the case that both of the capacitors and the PEFCs are used, constant speed run (v = 4 km/h) is achieved at an equilibrium state of charging and discharging to/from the capacitors, and the motor continues to run until hydrogen fuel is exhausted. It is found that this hybrid power system has capability for long distance run without charging from outside.

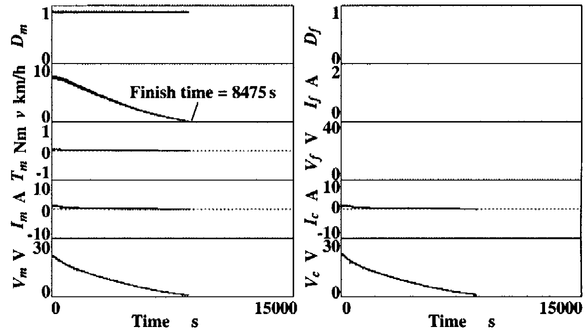


Fig. 9 Long run test without PEFCs

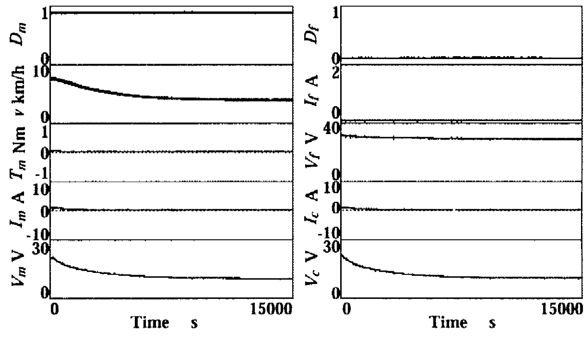


Fig. 10 Long run test with PEFCs

5.2 Acceleration and deceleration tests

The pattern of the vehicle speed change in this test is trapezoidal, namely the driving mode is composed of acceleration, constant speed and deceleration. The experimental condition is as follows: the vehicle stops from t = 0 to 5 sec, and then it starts and speeds up at constant acceleration up to $\tilde{v}$ = 8 km/h from t = 5 to 20 sec. After then it runs at constant speed ($\tilde{v}$ = 8 km/h) from t

= 20 to 35 sec, and then it slows down at constant deceleration to $\tilde{v}$ = 0 km/h from t = 35 to 50 sec. In order to examine the effect of electricity supply from the PEFCs and that of electricity regeneration during deceleration on the vehicle motion, above-mentioned mode tests are executed in three cases shown in Table 6.

Table 6 Experimental conditions

Case	Regeneration	PEFCs
A	None	None
B	Adapted	None
C	Adapted	Adapted

The experimental results are shown in Figs. 11, 12 and 13. In the acceleration and constant speed periods for all cases, it is found that the vehicle speed v follows the target speed $\tilde{v}$ very well. In the deceleration period for Case A, however, the vehicle speed v does not follow the target speed $\tilde{v}$ because the regeneration braking is not adapted in this case. Furthermore, in the deceleration period for Cases B and C, the vehicle speed v does not follow the target speed $\tilde{v}$ after v becomes lower than a speed because the regeneration braking does not work due to the lowering of regeneration voltage below the capacitor voltage. In a practical vehicle, however, a mechanical brake helps braking, so it is not a problem. In Figs. 12 and 13, the capacitor current I_c becomes minus quantity during deceleration, therefore the capacitors are charged by regeneration for Case B or by the PEFCs and regeneration for Case C (D_f = 1-D_m in the acceleration and constant speed periods, and D_f = 0.09 in the deceleration period).

The amounts of electric energy stored in the capacitors before and after driving for Cases A, B and C are evaluated from the experimental results, and are shown in Fig. 14. It is shown that the electricity charge to the capacitors by regeneration during deceleration for Case B recovers 7% of the consumed electric energy in the test run for Case A. Furthermore, the electricity charge to the capacitors by the PEFCs and regeneration for Case C recovers 60% of the consumed electric energy in the driving test for Case A. It is found that the PEFCs work successfully in this driving mode. For practical use, however, it is necessary to increase the fuel cell power much more.

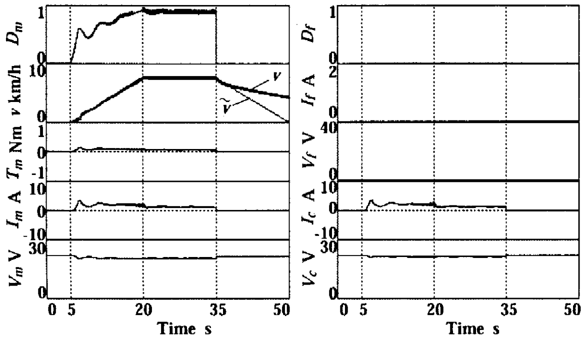


Fig. 11 Acceleration and deceleration test for Case A

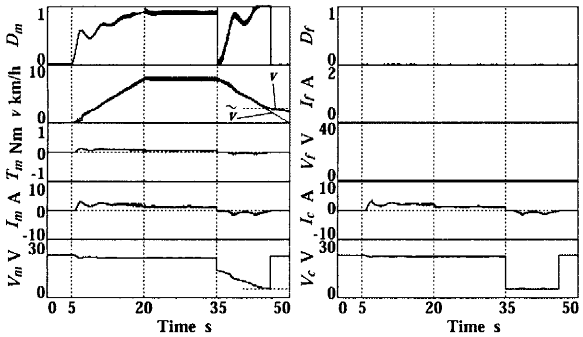


Fig. 12 Acceleration and deceleration test for Case B

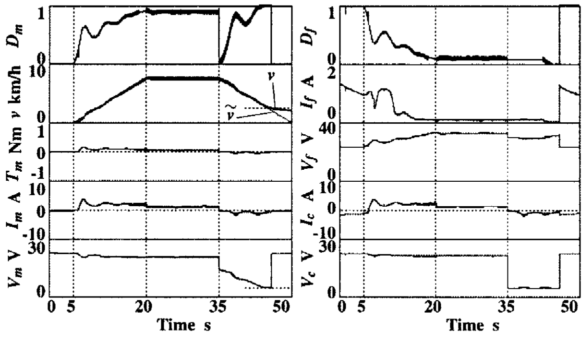


Fig. 13 Acceleration and deceleration test for Case C

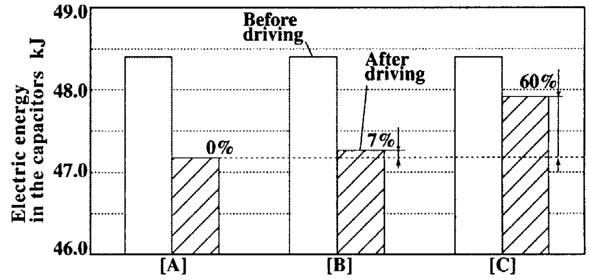


Fig. 14 Differences of electric energy stored in the capacitors before and after driving

6. CONCLUSIONS

As a hybrid power system of fuel cells and capacitors for a lightweight electric vehicle, the following simple series hybrid system has been tested:

Passive-type polymer electrolyte fuel cells, electric double-layer capacitors and a permanent magnet synchronous motor were connected parallel in the electric circuit but the electric energy transfer between them was executed in series by means of an original control sequence of the authors based on a time splitting technique.

A control sequence for the electric energy transfer, namely the electricity charge from the fuel cells to the capacitors and the electricity supply to (and regeneration from) the motor has been proposed, and its effectiveness has been confirmed experimentally by long run and acceleration/deceleration tests.

When electricity was regenerated in a deceleration period, the connection of the capacitors was changed from series to parallel in order to lower the total voltage of the capacitors. This has made it possible to store the regeneration electricity into the capacitors effectively.

A control scheme to drive the vehicle in an acceleration and deceleration mode has been contrived, and it has been shown experimentally that the vehicle speed followed the target speed successfully during the test runs.

Lastly, as a subject hereafter, the optimization of the power devices and control algorithm of the system will be studied to achieve high efficiency and easy handling for practical use of the lightweight electric vehicle. Furthermore, the influence of road load on the vehicle motion will be investigated.

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