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Electric Power Control System for a Fuel Cell Vehicle Employing Electric Double-Layer Capacitor

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ABSTRACT

A fuel-cell-vehicle has been provided with an electric-double-layer-capacitor system (capacitor) to act as a back-up power source. The fuel cells and the capacitor have different voltages when the system is started, and for this reason the system could not be reconnected by relays.

A VCU (Voltage and current Control Unit) has been positioned in the path of electrical connection between the fuel cells and the capacitor as a method of dealing with this issue. The VCU enables the charging of the capacitor to be controlled in order to equalize the voltage of the two power sources and allow a connection.

INTRODUCTION

The motor in a fuel cell vehicle (FCV) employs the electrical energy produced when hydrogen and oxygen combine to form water.(1) The basic system of the Honda FCV was formulated on the basis of using a capacitor to enable the vehicle to provide a starting and running performance meeting normal automotive standards. This paper discusses the research conducted on methods of enabling the transfer of power from the fuel cells and capacitor, and the application of these methods when the capacitor is used in the vehicle system.

UTILIZATION OF A CAPACITOR

THE NECESSITY OF UTILIZING AN ENERGY BUFFER

The fuel cells in an FCV generate electricity in accordance with the power consumed by the equipment. The current produced by the cells is proportional to the amount of hydrogen and oxygen supplied to them. Therefore, when the equipment requires extra power, increased amounts of hydrogen and oxygen must be supplied to the fuel cells to enable the extra power to be generated. Because it takes time for the supply of hydrogen and oxygen to be increased, the response of the fuel cells to the demand for extra power is delayed.

In addition, fuel cells cannot store energy which is regenerated when the vehicle decelerates. This means that the kinetic energy of the vehicle during deceleration is lost as heat in the working of the mechanical brakes.

Energy is also required to supply hydrogen and oxygen to the fuel cells to enable them to generate electricity. When the vehicle is started, energy is required to enable the fuel cells to commence generating power. However, the fuel cells do not function before the vehicle is started, and therefore cannot supply energy.

These considerations indicate the necessity of employing an energy buffer in an FCV.

SELECTING AN ENERGY BUFFER

The primary requirement for the energy buffer in the system was the ability to compensate for the delay in fuel cell response by supplying the exact amount of energy required by the system. This made it necessary to select a buffer with a large electrical capacity, given that the power required by the FCV is around three times that required by usual hybrid vehicles. To enable a balance to be achieved between the provision of the required power and the achievement of weight savings, it was necessary to utilize an energy buffer with a high power density. Table 1 shows the power density of two types of battery and a capacitor. The Li-ion battery and the capacitor are clearly superior in terms of power density.

	Power density (W/kg)	System voltage (V)	Electromotive force (V)
Ni-MH	Over 500	400 ~210	320
Li-ion	Over 1000	400 ~285	340
Capacitor	Over 1000	400 ~0	-

Table 1 Comparison of power density of batteries and capacitor (2)

The secondary requirement of the energy buffer was controllability, to ensure that it neither over-charged nor over-discharged. Figure 1 shows the voltage-current characteristics of the fuel cells used in the FCV.

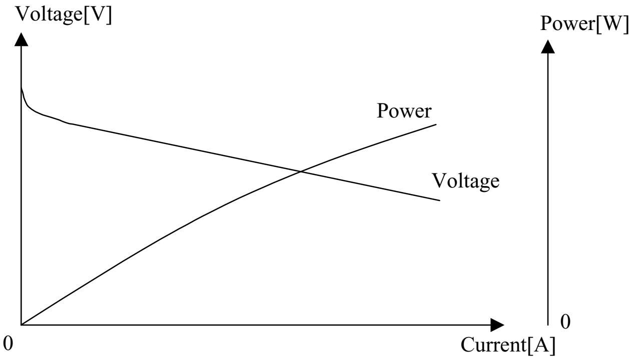
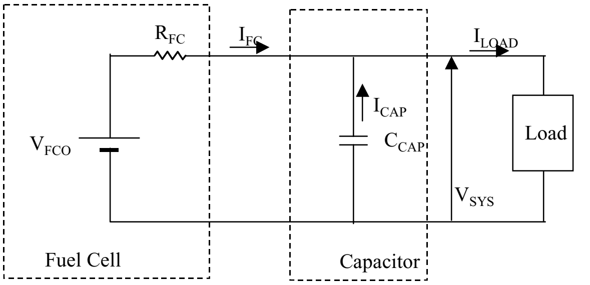


Fig.1 Fuel cell characteristic

Nickel metal-hydride and Li-ion batteries utilize chemical reactions to generate energy and their voltage is therefore stable. However, this fact makes it impossible to control charge and discharge if they are simply connected in parallel with fuel cells. By contrast, the voltage of a capacitor is proportional to its state of charge, and this characteristic makes it possible to directly connect capacitors in parallel with fuel cells.

Figure 2 shows a simple equivalent circuit for a parallel connection between fuel cells and a capacitor.



R_{FC}:Impedance of Fuel Cell
V_{FCO}:Electromotive force voltage of Fuel Cell
I_{FC}:Current of Fuel Cell
I_{CAP}:Current of Capacitor
C_{CAP}:Capasitance of Capacitor
V_{SYS}:System Voltage

Fig. 2 Schematic of fuel cell capacitor connection

The transfer function for transient response in this circuit is found using equation (1).

$$\frac{I_{FC}(S)}{I_{LOAD}(S)} = \frac{\frac{1}{R_{FC} \cdot C_{CAP}}}{S + \frac{1}{R_{FC} \cdot C_{CAP}}} \qquad \text{Eq. (1)}$$

This function is the primary delay function of I_{FC} against I_{LOAD}. For example, if the current drawn by the load varies in steps, the transient response shown in Fig. 3 is obtained.

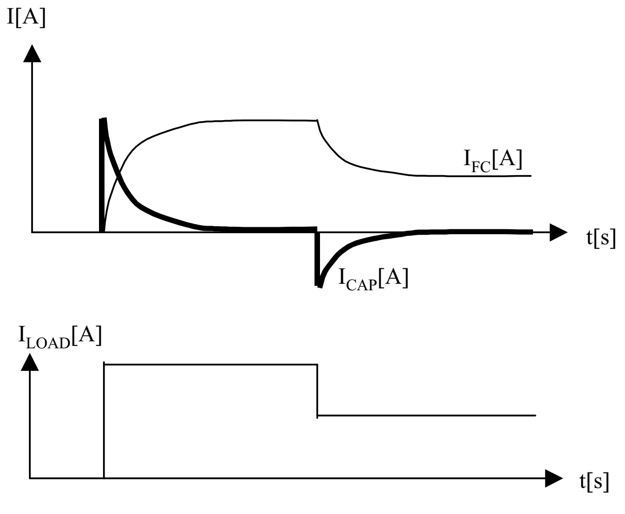


Fig. 3 Transient current characteristic of fuel cells and capacitor

This characteristic enables a capacitor to provide the required power in sudden, transient changes in load, enabling output from the fuel cells to be intentionally delayed. Utilizing such a delay gives the fuel cells time to generate the required extra power.

Another characteristic of capacitors is that the current converges on 0A after a fixed period of time has elapsed after they have been charged with current or have discharged current in response to changes in the load. At the same time, the fuel cell current increases to approach the current being drawn by the equipment, until they reach equilibrium at $I_{FC} = I_{LOAD}$. The use of a capacitor as an energy buffer therefore enables energy management without the requirement of utilizing any special electrical control devices.

The power density of capacitors and the ease with which their energy can be managed determined the selection of a capacitor system as an energy buffer for the FCV.

ISSUES ARISING FROM INSTALLATION OF A CAPACITOR SYSTEM

VOLTAGE DIFFERENCE WHEN THE SYSTEM IS STARTED

If the fuel cells, the capacitor and the equipment are constantly connected, the equipment draws dark current from the power sources when the system is stopped. This can cause the capacitor and fuel cells to over-discharge if the system is left off for an extended period, preventing it from being restarted. It was therefore necessary to design a system structure in which the power sources were isolated from the high-voltage equipment when the system was turned off. In the FCV, relays have been used to electrically separate the capacitor and fuel cells from the equipment.

However, the employment of this system configuration means that there is a voltage difference between the fuel cells and the capacitor when the system is next started. The capacitor voltage is varied by self-discharge. If they were to be connected by relays, the low impedance of both power sources would cause a high transient current flow, interfering with the normal functioning of the system.

CURRENT FROM THE FUEL CELLS DURING REGENERATION

In a system employing the fuel cell-capacitor connection shown in Fig. 2, fuel cell power responds to capacitor voltage (V_{SYS}). Current is supplied to the capacitor from the fuel cells, which have a starting voltage of V_{FC} and an internal resistance of R_{FC}. The equation for the current at this time is: $\dfrac{V_{FC} - V_{SYS}}{R_{FC}}$

Fuel cell power, P_{FC}, is therefore shown by equation (2):

$$P_{FC} = V_{SYS} \cdot \frac{V_{FC} - V_{SYS}}{R_{FC}} \qquad \text{Eq. (2)}$$

This relationship indicates that fuel cell power is determined solely by V_{SYS}, without consideration of the amount of power consumed by the vehicle. For this reason, when the motor is regenerating power during deceleration, power from the fuel cells charges the capacitor, and regenerated energy is lost, without being stored in the capacitor.

EMPLOYMENT OF VCU AS SOLUTION

CONSTRUCTION OF VCU SYSTEM

A VCU has been employed in the path of electrical connection between the fuel cells and the capacitor to provide a solution to the two issues outlined above. This VCU is a DC/DC converter which limits the power output of the fuel cells. The VCU circuit configuration is shown in Fig. 4.

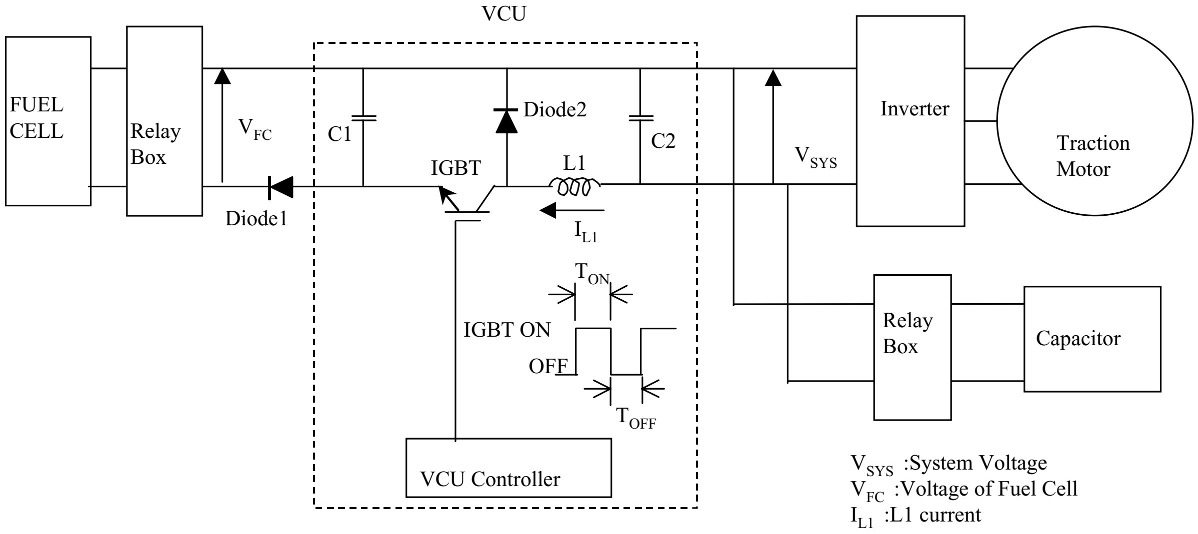


Fig. 4 VCU circuit

The VCU circuit provides control via a signal input to an IGBT. The IGBT has two states: ON and OFF. The VCU employs three modes, depending on the state of the IGBT switch.

	Mode	Status of IGBT
1	VCU OFF	OFF
2	Fuel Cell Power Control	Chopping
3	Connection	ON

Table2 VCU Mode

In VCU OFF mode, the IGBT is OFF, and no current flows from the fuel cells to the capacitor. In Fuel Cell Power Control mode, the IGBT switches ON and OFF at high speed, and the ratio of time between the ON and OFF states is regulated to enable control of fuel cell power. When the potentials of the fuel cells and the capacitor have been equalized by the Fuel Cell Power Control Mode, the IGBT remains ON, and the VCU switches to Connection mode.

In Fuel Cell Power Control mode, the IGBT switches between storing electromagnetic energy by L1 and releasing that energy.

When the IGBT is ON, V_{FC}-V_{SYS} is impressed in L1. The current from L1, I_{L1}, is therefore shown by equation (3):

$$I_{L1\_ON}(t)=\frac{1}{L}\cdot\int_{T_{ON}}\left(V_{FC}-V_{SYS}\right)\cdot dt \qquad \text{Eq. (3)}$$

When the IGBT is OFF, the energy stored in L1 when it was ON flows to Diode2. When the system is in this state, -V_{SYS} is impressed in L1.

I_{LI} is determined by the relationship shown in equation (4):

$$I_{L1\_OFF}(t)=\frac{1}{L}\cdot\int_{T_{OFF}}-V_{SYS}\cdot dt \qquad \text{Eq. (4)}$$
$$I_{L1\_OFF}(t)\geq 0$$

The relationships shown in equations (3) and (4) indicate that $\Delta I_{L1\_ON}=\Delta I_{L1\_OFF}$ is the condition at which the power output of the fuel cells becomes steady and constant. A solution on this basis produces the relationship shown in equation 5.

$$\frac{T_{ON}}{T_{ON}+T_{OFF}}=\frac{V_{SYS}}{V_{FC}} \qquad \text{Eq. (5)}$$

When the ratio of time that the IGBT is in its ON and OFF states is in the relationship shown in Eq. 5, I_{L1} is constant. If T_{ON} increases, I_{LI} also increases, and a reduction in T_{ON} produces a consequent reduction in I_{L1}.

This operating principle enables the VCU to actively control the output of the fuel cells by varying the ratio of time between the ON and OFF states of the IGBT.

RESPONDING TO VOLTAGE DIFFERENTIAL AT STARTUP

Figure 5[(3)] shows the voltage and current profiles of the fuel cells and capacitor and the operation of the VCU when the FCV is started.

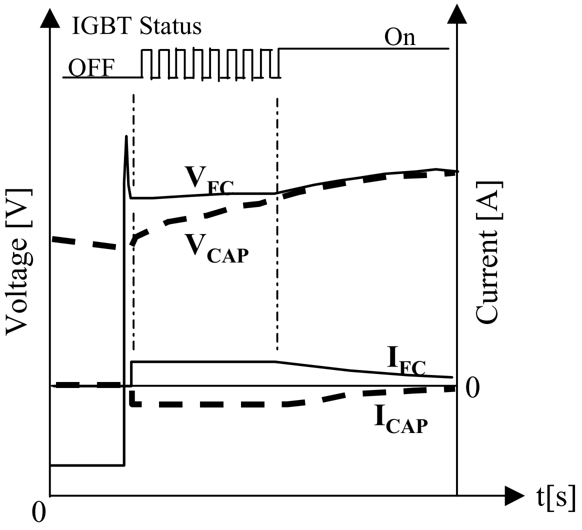


Fig.5 Voltage and current profiles of fuel cell and capacitor at starting up

At startup, there is a difference in potential between the fuel cells and the capacitor. At this time the IGBT is OFF and the VCU is on standby. Next, the capacitor and fuel cell relays are connected. The electrical paths are isolated by the VCU, and no current flows from the fuel cells to the capacitors. The VCU next limits the amount of power supplied from the fuel cells if the amount of power being generated makes it necessary, and gradually provides current to the capacitor. The voltage of the capacitor increases over time and the capacitors are charged, until its potential is equivalent to the potential of the fuel cells. The addition of the VCU to the system has provided an effective solution to the issue of the voltage differential between the fuel cells and enabled a connection to be established between the power sources.

The VCU limits I_{FC} in accordance with the I_{FC} control target (I_{CMD}) established on the basis of the amount of power generated by the fuel cells. If the VCU does not provide sufficient control and IFC exceeds I_{CMD}, the fuel cells will generate excess power. Because this increased power will simply be lost, the VCU must be capable, to the greatest extent feasible, of applying control to ensure that there is no overshoot of I_{CMD}. Figure 6 shows a control diagram of VCU control of I_{FC}. Originally, switching duty was calculated on the basis of the difference between I_{FC} and I_{CMD}. However, when I_{CMD} was given in steps at vehicle startup, I_{FC} would overshoot the command value.

The application of differential control can be expected to ensure that such overshoots do not occur, but this tends to make control unstable. It was difficult to maintain stable control while preventing overshoot. The control layout shown in Fig. 7 was therefore suggested as a solution. This system adds filters for I_{FC} to the original system, enabling the oscillating components of the I_{FC} frequencies to be amplified. The transfer function is as follows:

$$\frac{I_{FC}\,2(S)}{I_{FC}(S)} = LPF\ 2(S) + \{LPF\ 1(S) - LPF\ 2(S)\}\cdot G(S) \qquad \text{Eq. (6)}$$

Figure 8 shows the frequency response of this function.

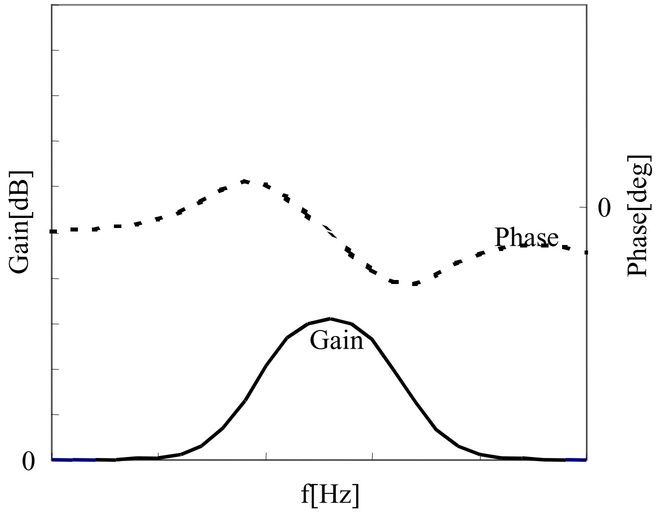


Fig. 8 Frequency response of I_{FC} filter

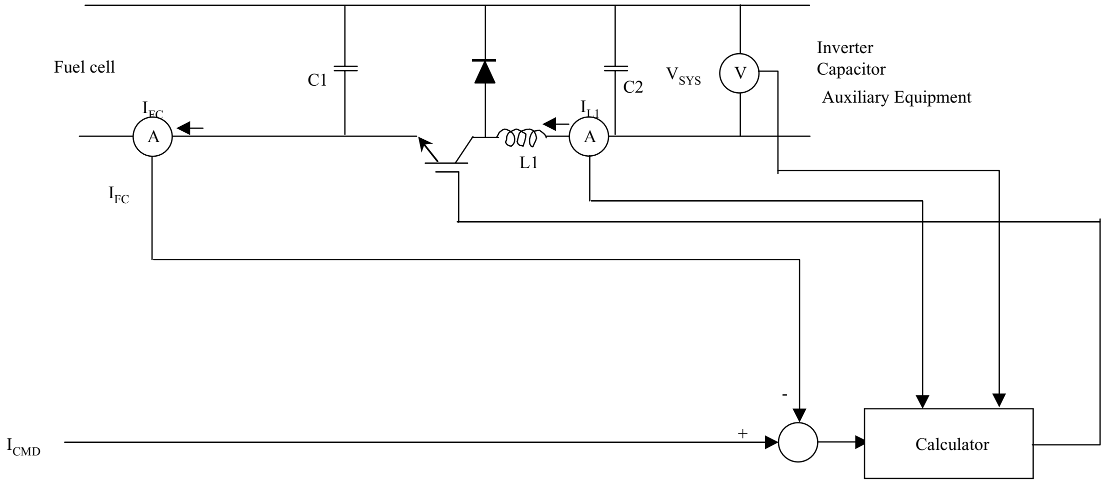


Fig. 6 Control of I_{FC} by VCU

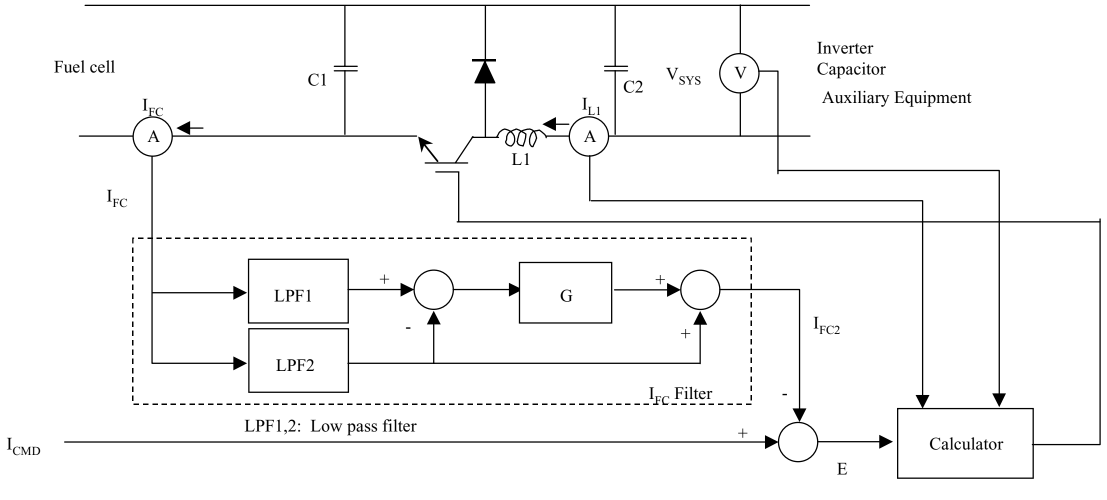


Fig. 7 Control of oscillation of I_{FC}

The cutoff frequencies of LPF1 and LPF2 are set to cause the oscillating frequencies (overshoots) to become gain peaks. In addition, even if the oscillating frequencies are fluctuating, the cutoff frequencies for LPF1 and LPF2 can be adjusted to provide gain across a broad range.

This enables the oscillating frequencies causing overshoot to be amplified and added to I_{FC}. This is extremely effective in controlling overshoot, because the oscillating frequencies causing overshoot are highlighted and fed back to the deviation. The original stability of control of frequencies of I_{FC} other than the oscillating component has been maintained, enabling complete control of oscillation in I_{FC}. Figure 9 shows the difference in current waveforms when the I_{CMD} command is given in steps with and without the filter in the system.

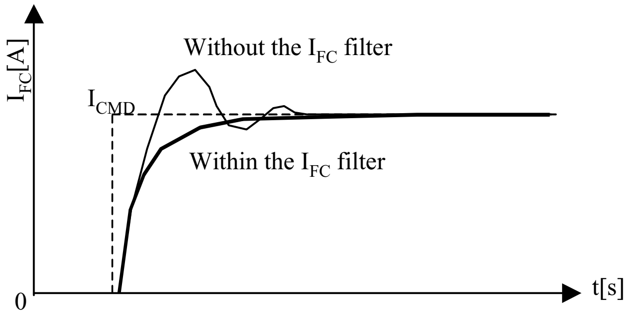


Fig. 9 I_{FC} transient response

LIMITATION OF CURRENT FROM FUEL CELLS DURING REGENERATION

The voltage and current profiles of the fuel cells and capacitor in regeneration mode are shown in Fig. 10$^{(3)}$.

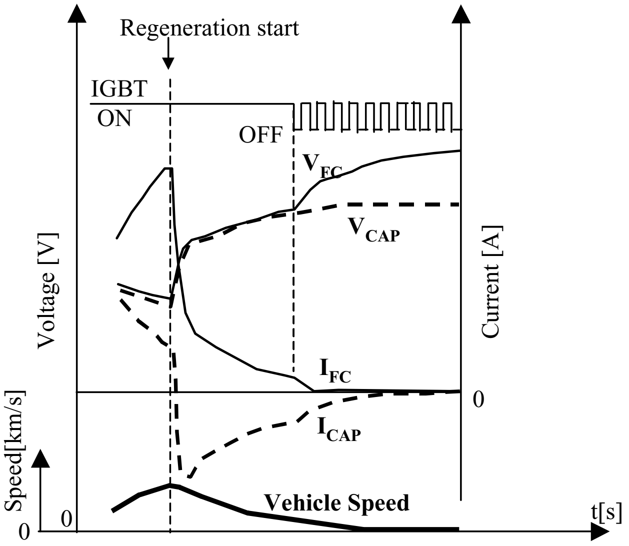


Fig.10 Voltage and current profiles of fuel cell and capacitor at regeneration mode

When the vehicle decelerates and the motor commences regeneration, the capacitor receives both regenerated power and power from the fuel cells, meaning that V_{FC} and V_{CAP} increase in unison. In this mode of operation, the amount of power coming from the fuel cells reduces the regenerated power taken in by the capacitor by the same amount. Control is therefore applied to restrict the power from the fuel cells when V_{CAP} reaches a predetermined level. This causes V_{FC} to increase independently of V_{CAP}, and ensures that the capacitors receive only regenerated power. This enables the capacitor to be charged only with regenerated power from the predetermined voltage by the VCU to its rated voltage.

ADDITIONAL EFFECT OF VCU

The employment of a VCU in the system was not only effective in providing a solution to the two issues involved in utilizing a capacitor in the system, as discussed above, but also contributed to enabling the equipment to be reduced in size.

As Fig. 1 shows, as the output of the fuel cells decreases, their voltage increases. Therefore, the voltage of the fuel cells rises when the equipment is not drawing much power and when the system is regenerating power. At these times, the VCU functions to limit the power from the fuel cells in order to prevent V_{SYS} from increasing. This resulted in a reduction of the rated voltage required from the traction motor inverter, the equipment and the capacitor by more than 100V, enabling the equipment connected to V_{SYS} to be made approximately 20% smaller.

CONCLUSION

A VCU has been employed to control the power from the fuel cells in a fuel cell vehicle utilizing an electric double-layer capacitor, with the following results:

(1) The limitation of power from the fuel cells by the VCU ensures optimum charging of the capacitor, eliminating the voltage differential between the fuel cells and the capacitor and enabling the two power sources to be connected.

(2) Electrical separation of the fuel cells and the capacitor by the VCU when the system is regenerating braking energy limits the amount of energy provided by the fuel cells to the capacitor, enabling a greater quantity of regenerated energy to be used in charging the capacitor.

(3) The step-down function of the VCU has reduced the rated voltage required from the traction motor inverter, the equipment and the capacitor by more than 100V, enabling the equipment to be reduced in size by approximately 20%.

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