

Development of System Control for Rapid Warm-up Operation of Fuel Cell

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ABSTRACT

Cold weather operation has been a major issue for fuel cell hybrid vehicles (FCHV). To counteract the effects of low temperatures on FCHV operation, an approach for rapid warm-up operation based on concentration overvoltage increase and conversion efficiency decrease by limiting oxygen or hydrogen supply was adopted. In order to suppress increases in exhaust hydrogen concentration due to pumping hydrogen during rapid warm-up, dilution control using bypass air and reduction of concentration overvoltage by a minimum voltage guard were implemented. These approaches effectively control waste heat generation and suppress exhaust hydrogen concentrations during cold start and warm-up. These developments were incorporated into the 2008 Toyota FCHV-adv and it was confirmed that the rapid warm-up operation strategy allowed the FCHV-adv to be successfully and repeatedly started at -30°C .

CITATION: Naganuma, Y., Manabe, K., Imanishi, H. and Nonobe, Y., "Development of System Control for Rapid Warm-up Operation of Fuel Cell," *SAE Int. J. Alt. Power.* 1(1):2012, doi:10.4271/2012-01-1230.

1. INTRODUCTION

Over the course of the development of its Fuel Cell Hybrid Vehicle (FCHV), Toyota Motor Corporation has been working to identify real-world issues related to the following points: (1) driving range, (2) cold start capability, (3) stack durability, and (4) cost reduction. It is recognized that these must be resolved prior to the widespread acceptance of the FCHV in the market, and Toyota is making progress toward this aim by improving the performance of the fuel cell and its related systems and controls.

Released in 2008, the FCHV-adv (Fig. 1) shows significant advances in driving range, cold start capability, and stack durability, enabling the FCHV-adv to be driven practically as an ordinary vehicle. In particular, to resolve the issue of cold start capability, a rapid warm-up method that dramatically speeds up the increase in the fuel cell stack temperature was developed in addition to an impedance-based method of controlling the fuel cell water content. By adopting these methods in the vehicle system, the FCHV-adv is capable of starting in temperatures as low as -30°C .

The rapid warm-up operation increases the power generation losses of the fuel cell by controlling the air supply to cause an oxygen concentration overvoltage increase, thereby warming up the fuel cell using its own waste heat. The rapid warm-up operation has two purposes, increasing the fuel cell stack temperature above freezing point to enable the vehicle to be driven immediately after start up in cold

conditions (i.e., the cold start mode rapid warm-up), and warming up the fuel cell stack to between 60 and 70°C for the water content control, which allows the fuel cell to operate at high efficiency (i.e., the driving mode rapid warm-up). However, the cold start mode rapid warm-up control and the driving mode rapid warm-up control have different operational requirements. Increasing the concentration overvoltage, which is used to maintain a high amount of generated waste heat in the output recovery process, causes the generation of hydrogen from the cell cathode because there is locally insufficient oxygen for power generation (this is called "pumping hydrogen" below). Consequently, this increases the hydrogen concentration in exhaust air.

This paper describes the concept behind the optimum rapid warm-up control when the vehicle is started in cold conditions and afterwards while the vehicle is being driven. It also details how pumping hydrogen is generated by the rapid warm-up control, the control for suppressing increases in exhaust hydrogen concentration due to pumping hydrogen, and the results of applying this control to the vehicle system.



Fig.1. FCHV-adv under Cold Testing

2. RAPID WARM-UP OPERATION TO ENABLE COLD START

2.1. BASIC PRINCIPLE OF RAPID WARM-UP

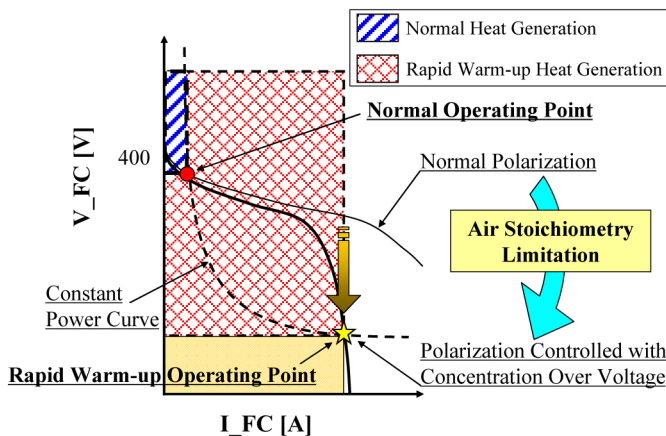


Fig.2. Rapid Warm-up Operation Point of Fuel Cell Stack

The key issue of fuel cell start-up and operation in sub-freezing environments is the treatment of the generated water during power generation. Figure 2 shows the voltage-current (IV) characteristics (referred to as the “polarization curve” below) of a fuel cell with 400 cell layers. In normal operation, the operating point is determined based on a normal polarization curve to achieve the fuel cell power demand (the “normal operating point” in Fig. 2). In contrast, the rapid warm-up operation uses the rapid warm-up operating point. At this operating point, the voltage on the constant power curve from the normal operating point is lowered to increase the amount of waste heat energy generated by the fuel cell while also achieving the power demand. The generated waste heat rapidly increases the fuel

cell stack temperature above freezing point in a short period of time.

2.2. CONCEPT OF RAPID WARM-UP OPERATING POINT

The three main objectives of increasing the fuel cell stack temperature using the rapid warm-up control are as follows: (1) to increase the fuel cell stack temperature above freezing point to prevent the freezing of water generated when the fuel cell operates in cold temperatures, (2) to increase the fuel cell stack temperature to secure sufficient power output to drive the vehicle, and (3) to increase the fuel cell stack temperature to an optimum level for the water content control that allows the fuel cell to operate at high efficiency. Points (1) and (2) are required functions during the cold start mode rapid warm-up control. The system must maximize the amount of generated waste heat to secure cold start capability and to shorten the time required to start the vehicle. Point (3) is a required function during the driving mode rapid warm-up control. The system must suppress to some extent the amount of waste heat generation to improve the total efficiency. However, since the system is already permitting the vehicle to be driven, the minimum voltage of the drive motor and an output response of several tens of kilowatts are required.

Therefore, the system operating voltage is reduced to several tens of volts during the cold start mode rapid warm-up control. In contrast, during the driving mode rapid warm-up control, the system gives priority to the fuel cell output response and controls the operating voltage basically to a fixed level. Although the amount of waste heat generation and the rate of temperature rise can be controlled freely by changing operating voltage during the cold start mode rapid warm-up control, they depend on the driving pattern during the driving mode rapid warm-up control. The power generation efficiency at these points are 10% or less when cold start is performed and approximately 30% during driving.

2.3. FUEL CELL OPERATING POINT DURING AIR STOICHIOMETRY LIMITATION

The factors that contribute to power generation efficiency include the gas supply, fuel cell stack temperature, and membrane electrode assembly (MEA) water content. Of these factors, the rapid warm-up operating point is controlled by identifying the polarization curve of the fuel cell with respect to temperature and the concentration overvoltage characteristics with respect to the air supply.

Figure 3 shows the polarization curve of the fuel cell at each temperature. The polarization curves under these conditions are referred to as the standard polarization curves.

Limiting air stoichiometry reduces voltage compared to the polarization curve shown in Fig. 3. It is thought that this voltage drop is caused by the concentration overvoltage in the

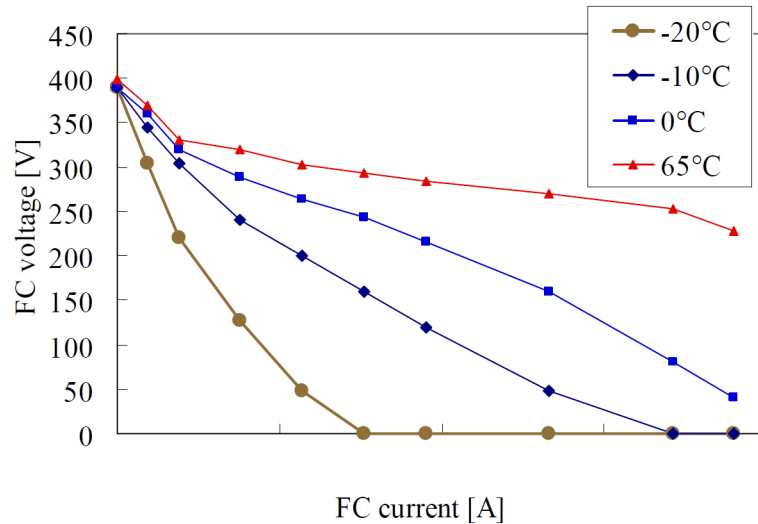


Fig. 3. Fuel Cell Standard Polarization Curve

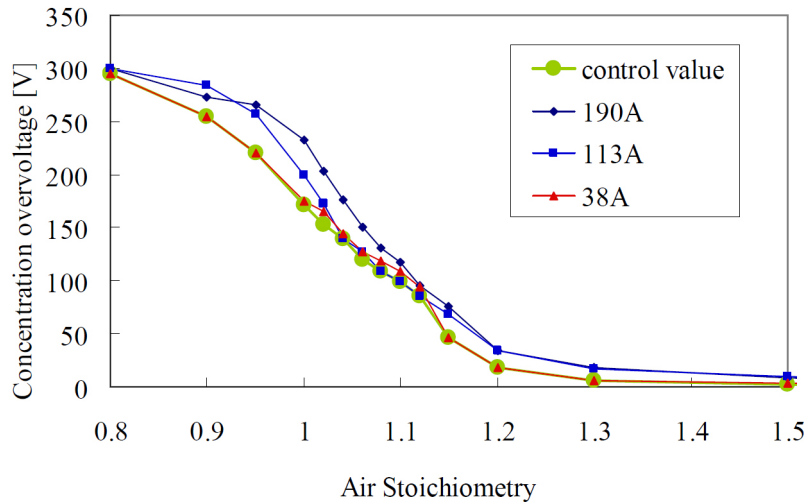


Fig. 4. Concentration Overvoltage to Air Stoichiometry Ratio

fuel cell reaction. A virtually constant value was calculated experimentally that did not depend on the current (Fig. 4). Considering the variation of over voltage for each current, the value with the lowest voltage to air stoichiometry is used for the system control.

Figure 5 shows a block diagram of the control that uses this polarization curve to derive the air stoichiometry for realizing the rapid warm-up operating point.

The fuel cell current demand I_{FC_ref} and the stack voltage demand V_{FC_ref} for a rapid warm-up operation point are obtained from the fuel cell power demand P_{FC} and the waste heat demand P_{LOSS} . The fuel cell stack temperature T_{FC} and I_{FC_ref} can be applied to the standard polarization curve map in Fig. 3 to obtain the standard stack voltage V_{FC_std} .

The air stoichiometry demand to achieve the required concentration overvoltage is calculated based on the

deviation between V_{FC_std} and V_{FC_ref} from Fig. 4. The fuel cell air demand is calculated as the product of the air stoichiometry and the theoretical air amount.

The rapid warm-up operating point control is performed by controlling the DC/DC converter that controls the stack voltage demand and the air compressor that controls the fuel cell air demand.

3. RAPID WARM-UP CONTROL AND PUMPING HYDROGEN

The system uses the characteristics of oxygen concentration overvoltage by restricting the air supply to perform the rapid warm-up operating point control. However, although limiting the air stoichiometry generates waste heat, hydrogen ions are simultaneously re-combine with electrons and hydrogen is generated from the cathode in cells with