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Implementation of a Fuel Cell Dynamic Simulator

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ABSTRACT

This paper presents the development of a fuel cell dynamic simulator using a programmable DC power supply and LabVIEW graphical user interface. The developed simulator closely describes the static and dynamic characteristics of an actual proton exchange membrance fuel cell (PEMFC). The experimental results are provided to verify the operation of the simulator. The developed simulator can be used as a convenient and economic alternative to an actual fuel cell for developing and testing a fuel cell power conditioning system.

Keywords: Fuel cell, simulator, graphical user interface, power conditioning system

1. Introduction

A fuel cell is a device capable of converting chemical energy into heat and dc electrical energy by means of the oxidation of a fuel, usually hydrogen. Because a fuel cell makes energy electrochemically, and does not burn fuel, it is fundamentally more efficient than combustion systems. And it is clean energy, putting little toxic chemicals into the air. Therefore, the fuel cell is regarded as an important solution to the problems of depleting fossil fuel resources and global warming and is expected to be a major source of power generation in the near future [1], [2].

A fuel cell system is composed of many components for operating it such as the fuel cell stack, reformer and complex controller. Therefore, there are many difficulties in developing fuel cell application systems. As a simple alternative to an actual fuel cell system, a fuel cell simulator describing electrically the output characteristics of the actual fuel cell can be considered. Several studies on this topic have been reported [3],[4]. However, these systems only replicated the static V-I characteristics of a fuel cell.

Since a fuel cell system has slow dynamic characteristics in response to load and hydrogen concentration changes, the consideration of fuel cell dynamics is very important in developing a fuel cell power conditioning system. Therefore, this paper proposes a fuel cell dynamic simulator which can replicate the dynamic characteristics as well as the static V-I characteristics of a fuel cell. The proposed fuel cell simulator consists of a programmable DC power supply and a LabView based instrumentation and control system. The static and dynamic characteristics of an actual proton exchange membrace fuel cell (PEMFC) are modeled and implemented in the LabView software package with a

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graphic user interface (GUI). Hence, fuel cell application systems such as the fuel cell inverter can be easily developed using the proposed simulator. The implementation method and experimental results of the proposed simulator are presented in this paper.

2. Fuel Cell Characteristics

2.1 Static V-I characteristics

The most common way to characterize the performances of a fuel cell is a static V-I curve. Fig. 1 shows the simplified static V-I curve of a typical PEMFC stack [6], which describes the steady-state voltages for the given output current.

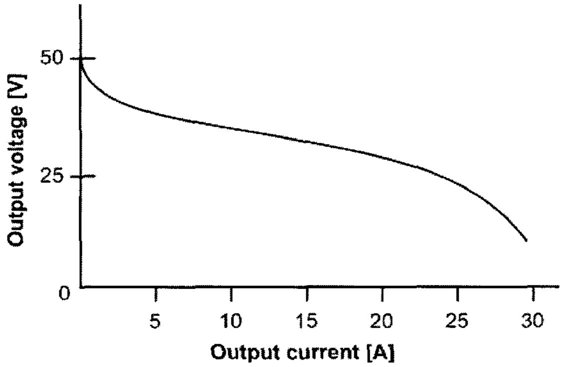


Fig. 1 Static V-I characteristics of a single fuel cell

The static V-I curve can be obtained by measuring the steady-state voltage responses at several current points and fitting a curve to the measured data. This curve is generally represented as a third-order polynomial given as

$$V = f(I) = \alpha_3 I^3 + \alpha_2 I^2 + \alpha_1 I + \alpha_0 \tag{1}$$

where V is the fuel cell terminal voltage and I is the fuel cell output current.

2.2 Dynamic characteristics for load changes

The voltage responses to the load changes can be represented by using the AC output impedance of the fuel cell at the given DC operating point. A simple AC equivalent circuit of a fuel cell is given as shown in Fig. 2. The circuit parameters can be determined by the impedance measurement. The AC output impedance can be measured using an impedance analyzer for the output terminal of the fuel cell. Fig. 3 shows a typical Bode plot for the AC output impedance of the PEMFC.

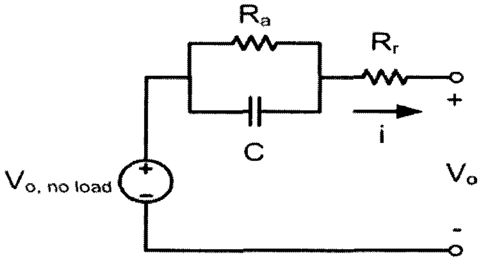


Fig. 2 AC equivalent circuit model of fuel cell

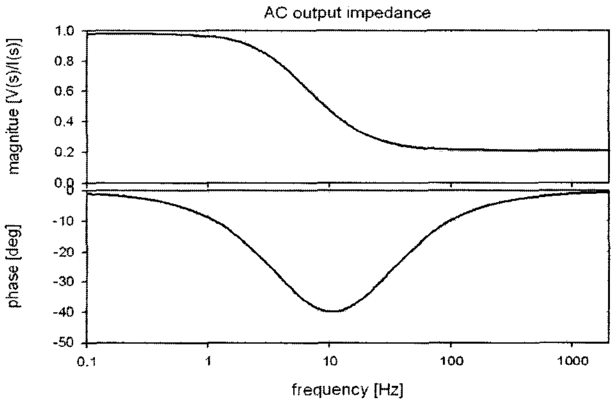


Fig. 3 Bode plot for the AC output impedance of PEMFC

From this figure, the AC output impedance can be given as

$$\frac{V(s)}{I(s)} = KH_d(s) \tag{2}$$

where K is the DC output impedance which can be obtained from the static V-I curve and also defined in the equivalent circuit as

$$K = R_a + R_r \tag{3}$$

$H_d(s)$ is the normalized AC output impedance represented as

$$H_d(s) = K_n \frac{(s+z)}{(s+p)} \tag{4}$$

where

$$K_n = \frac{R_r}{R_a + R_r}, \quad p = \frac{1}{R_a C}, \quad z = \frac{R_a + R_r}{R_a R_r C}$$

The pole and zero of $H_d(s)$ can be obtained from the Bode plot for the AC output impedance.

2.3 Dynamic characteristics for changes in hydrogen concentration

The static and dynamic characteristics are changed when the hydrogen concentration is changed by the fuel cell control system. Fig. 4 shows changes in the static V-I characteristics and operating points caused by hydrogen concentration changes[4].

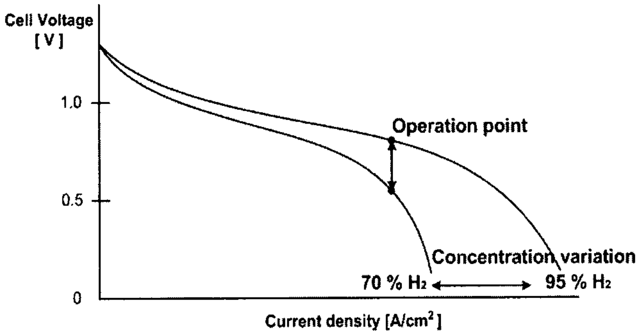


Fig. 4 Change of the operating point due to the hydrogen concentration change

This change is accompanied by a long delay as shown in Fig. 5 [1], which can be measured by a frequency analysis of the relationship between the hydrogen concentration command and the fuel cell output voltage. This time delay generally appears with a first order behavior, which can be represented as

$$H_c(s) = \frac{\alpha}{s + \alpha} \tag{5}$$

where

$$\alpha = \frac{2\pi}{\tau_{delay}}$$

where τ_{delay} denotes the time constant of the first order delay element due to the hydrogen concentration change.

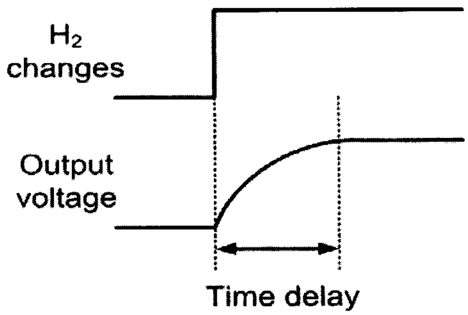


Fig. 5 Time delay of out voltage due to the hydrogen concentration changes

3. Implementation of Fuel Cell Simulator

3.1 Hardware configuration

Fig. 6 shows the hardware configuration of the proposed fuel cell simulator, which consists of the programmable DC power supply and the LabView environment including the GUI software, data acquisition (DAQ) card and signal conditioning module. The output current of the programmable DC power supply flowing to the equipment under test (EUT) is measured and the voltage command to control the power supply is produced by the LabView software on the Pentium PC. The variable load condition is produced by the programmable electronic load connected to the EUT. The hydrogen flow rate is changed by the control command generated from the fuel cell control system.

The programmable DC power supply used in the proposed simulator has a power rating of 2kW (100V/20A). The response time at the transient state is 2ms for 30% load change. The output voltage of the power supply can be adjusted by the remote analog control port. The DAQ card and signal conditioning module used are the National Instruments PCI-6036E and BNC-2120, respectively. The maximum sampling rate of this system is 200kS/sec.

3.2 Implementation of fuel cell characteristics

Fig. 7 shows the control block diagram of the proposed fuel cell simulator. The operation of this system is explained as follows.

The hydrogen concentration is set by the control input from the fuel cell control system and the matched static V-I curve is selected. The delay from the control input to the output voltage is considered in the transfer function $H_c(s)$. The load current is measured and fed to the analog input port and the voltage command is generated using the static V-I curve. The output voltage of the programmable DC power supply is controlled by the generated voltage command. When a load change occurs, the transient response can be realized by the transfer function $H_d(s)$.

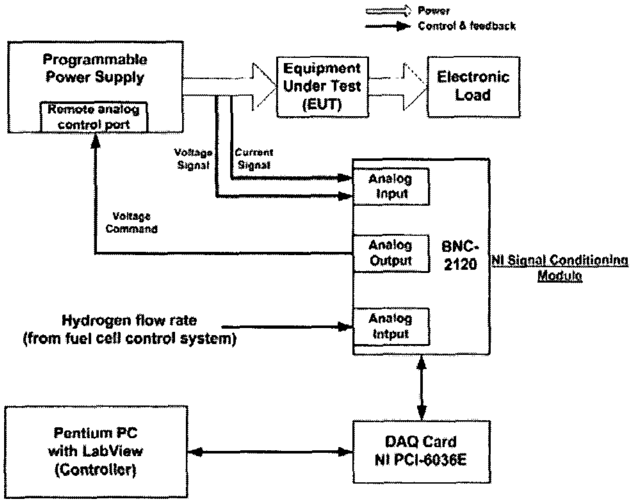


Fig. 6 Hardware configuration of the proposed fuel cell simulator

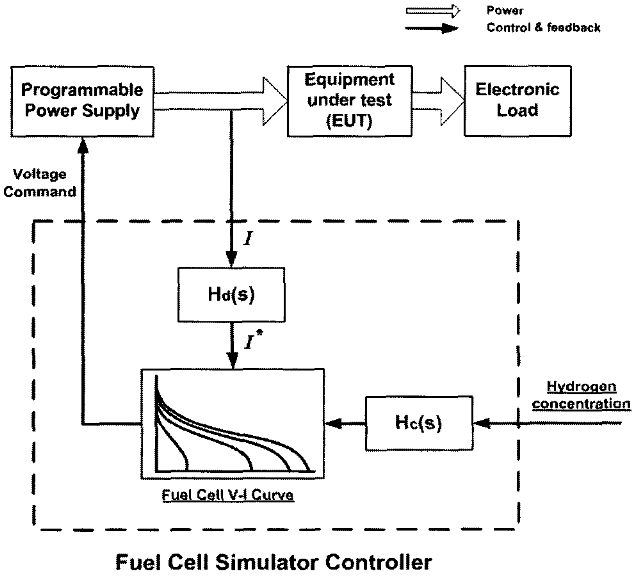
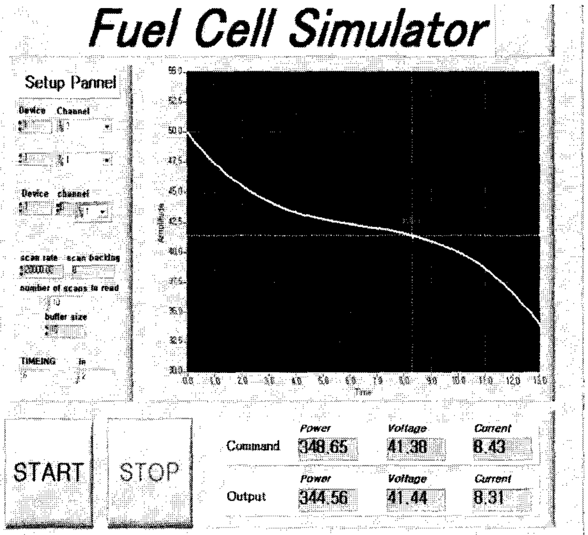


Fig. 7 Control block diagram of the proposed fuel cell simulator

The control panel of the proposed fuel cell simulator implemented in LabView is shown in Fig. 8. The operating point of the fuel cell simulator is displayed in this GUI. Fig. 9 shows the implemented fuel cell simulator which consists of the programmable DC power supply, the LabView based controller and GUI, and the electronic load.

4. Experimental Results

To verify the operation of the proposed simulator, the experiment is carried out for the various load conditions. The coefficients of the static V-I curves for various hydrogen concentrations used in the experiment are given in Table 1.



	Power	Voltage	Current
Command	348.65	41.38	8.43
Output	344.56	41.44	8.31

Fig. 8 Control panel of the proposed fuel cell simulator

Table 1 Coefficients of static V-I curves for various H_2 concentration

Concentration Coefficient	95%	75%	55%	35%	15%
α_3	-0.022	-0.023	-0.024	-0.098	-0.597
α_2	0.407	0.406	0.398	0.817	0.649
α_1	-2.951	-2.941	-2.912	-3.511	-3.021
α_0	50.00	49.27	49.910	49.602	48.705

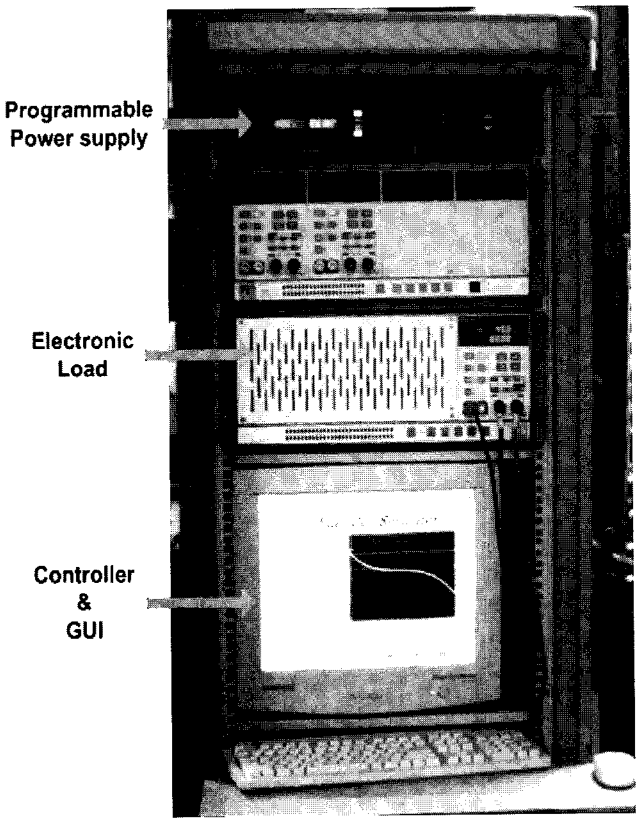


Fig. 9 Photograph of implement fuel cell simulator

The pole and zero of the normalized output impedance $H_d(s)$ are given as $p=2\pi\cdot 13$ rad/sec and $z=2\pi\cdot 22$ rad/sec, respectively. The first-order time delay is considered for the hydrogen concentration change and the transfer function $H_c(s)$ is given as

$$H_c(s)=\frac{2\pi\cdot 0.1}{s+2\pi\cdot 0.1} \tag{5}$$

The experimental results for the proposed fuel cell simulator are given in Figs. 10 through 14.

Fig. 10 shows the transient response of the proposed simulator under the step load changes. When the output current is abruptly changed from 5A to 1A, the output voltage slowly increased from 42V to 47V with the dynamic characteristics given in $H_d(s)$. Fig. 11 shows the transient response of the proposed simulator under the hydrogen concentration changes. When the hydrogen concentration is changed from 95% to 55% at 10A load current, the output voltage is slowly decreased from 40V to 35V with the dynamic characteristics given in $H_c(s)$.

Figs. 12 through 14 show the transient response of the proposed fuel cell simulator under the periodic load changes, where the load current varies sinusodally with the amplitude of 4A and frequencies of 1Hz, 5Hz and 20Hz, respectively. Since the pole and zero of the output impedance $H_c(s)$ are located at 13 and 22Hz, respectively, the load changes at the low frequency (below 10Hz) dominantly affect the voltage output. It is shown that the load current change directly affects the shape of the output voltage waveform.

It is shown from the experimental results that the proposed fuel cell simulator replicates the static and dynamic characteristics of the PEMFC well.

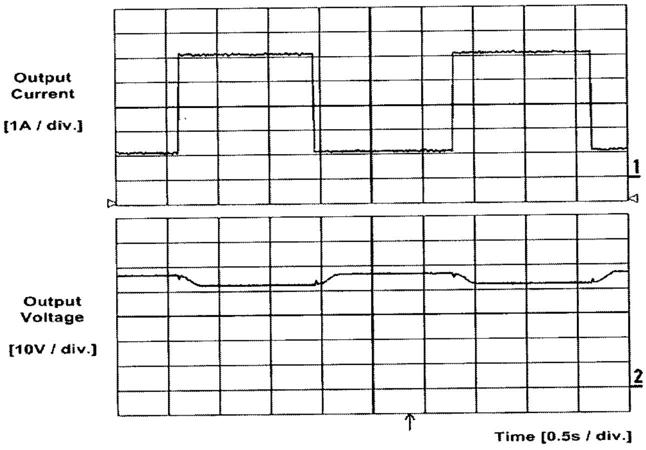


Fig. 10 Transient response of the proposed simulator under the load changes

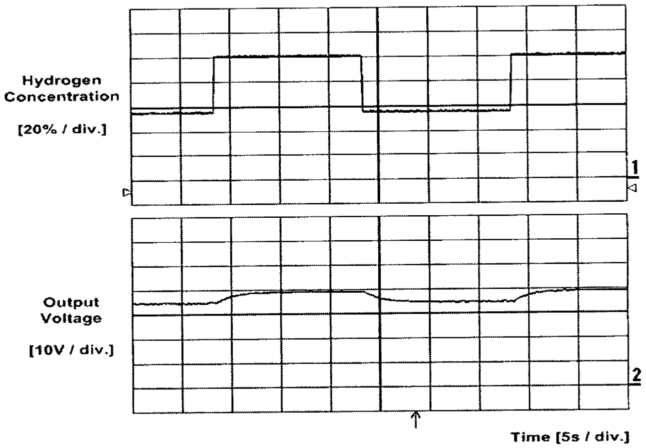


Fig. 11 Transient response of the proposed simulator under the hydrogen concentration changes

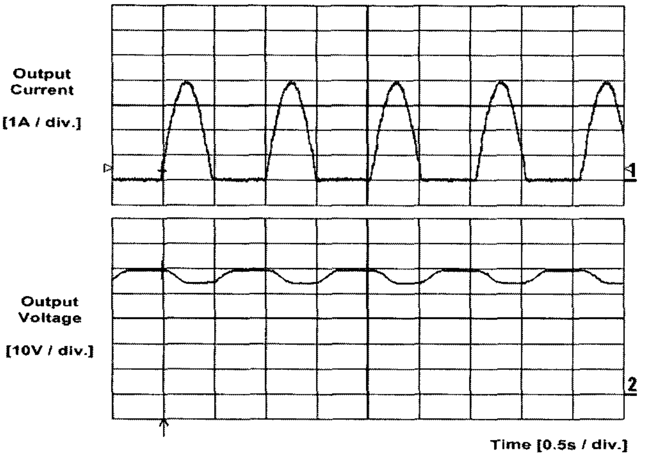


Fig. 12 Transient response under 1Hz sinusoidal load change

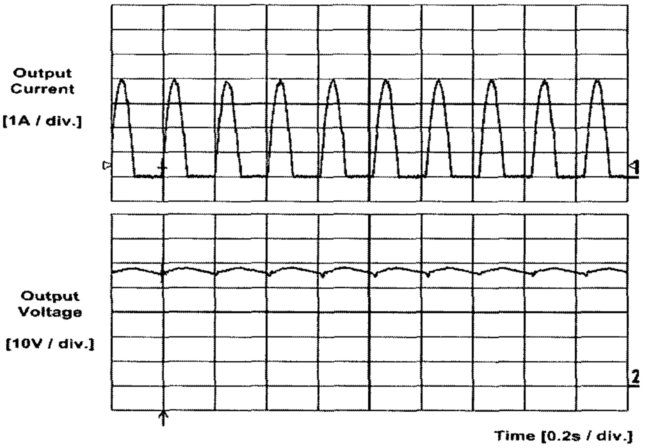


Fig. 13 Transient response under 5Hz sinusoidal load change

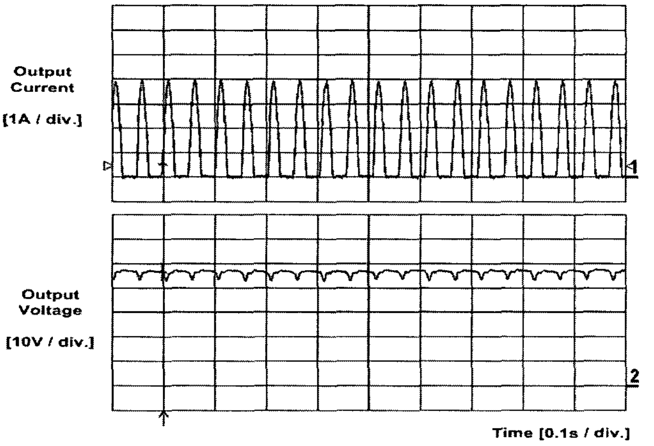


Fig. 14 Transient response under 20Hz sinusoidal load change

5. Conclusions

In this paper, a fuel cell dynamic simulator, which replicates static and dynamic characteristics, has been developed using a programmable DC power supply and LabView GUI software. The proposed fuel cell simulator provides more accurate representation of the fuel cell characteristics by considering the dynamic characteristics of the load and hydrogen concentration changes. Since the developed fuel cell simulator is implemented by LabView GUI software, the characteristics of various types of fuel cells can be easily customized by inputting the fuel cell data. Therefore, the proposed fuel cell simulator can be used as a convenient alternative to an actual fuel cell system in developing and testing fuel cell power conversion systems.

Acknowledgment

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