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A Fuel Cell Generation System with a Fuel Cell Simulator

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ABSTRACT

A fuel cell (FC) system includes a fuel processor plus subsystems to manage air, water, and thermal energy, and electric power. The overall system is high-priced and needs peripheral devices. In this paper, a FC simulator is designed and constructed with the electrical characteristics of a fuel cell generation (FCG) system, using uses a simple buck converter to overcome these disadvantages. The characteristic voltage and current (V-I) curve for the FC simulator is controlled by a simplified linear function. In addition, to verify FCG system performance and operation, a full-bridge DC/DC converter and a single-phase DC/AC inverter were designed and constructed for FC applications. Close agreement between the simulation and experimental results confirms the validity and usefulness of the proposed FC simulator.

Keywords : Fuel Cell Simulator, Fuel Cell Generation System, PEMFC

1. Introduction

At the beginning of the 21st century, fuel cells are meeting the power needs of a variety of applications. A fuel cell generating(FCG) system is an electrochemical device that converts chemical energy directly into electrical and thermal energy.

A fuel cell(FC) system is composed of six basic subsystems: a FC stack, a fuel processor, air, water, and thermal management subsystems, and a power conditioner. A FC system provides a number of advantages, such as diversity of fuels(natural gas, LPG, methanol, etc.), high efficiency at full and partial-loads, comparability of a wide range of sizes, and independence of environmental pollution.

Because of the environmental problems associated with energy consumption, a FC system is regarded as a preferable power source due to its high-energy conversion efficiency. However, it is high-priced and needs peripheral devices[1]-[3].

In this paper, the FC simulator is designed and constructed using the electrical characteristics of a FCG system. It uses a simple buck converter to overcome the disadvantages of high price and need for peripheral devices. The characteristic voltage and current (V-I) curve for the fuel cell simulator is controlled by a simplified linear function. We designed the fuel cell simulator at the rating of a 3kW PEMFC. The system measures the output voltage(output voltage range: 39~60Vdc) and current. If the current exceeds a defined value, the fuel cell simulator is controlled in ohmic mode. If the current is less than a defined value, the simulator is controlled in activation mode. The proposed control system is implemented using a digital signal processor (DSP), TMS320C31, which uses function of floating-point arithmetic.

In addition, to verify fuel cell generation system

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performance and operation, a full-bridge DC/DC converter and single-phase DC/AC inverter are designed and manufactured for fuel cell applications. Because the output generated by the fuel cell stack (fuel cell simulator) has low voltage, therefore, it is necessary to boost the output voltage to effectively drive the other systems. The boosting voltage is the voltage of the DC link. To supply a DC voltage generated by the fuel cell simulator instead of by the fuel cell stack, it should be connected to the commercial load using the constructed 3kW inverter [4]-[7].

In this paper, we also present a test bench measurement procedure for experimental verification and compare the experimental results with the simulation results.

2. Fuel Cell Generation System

2.1 Fuel Cell Generation System

The configuration of the fuel cell generation system is shown in Fig. 1. Fuel cells are electrochemical devices that continuously convert chemical energy into electric and thermal energy as long as fuel (natural gas, LPG, methanol, etc.,) and oxidants are supplied. The voltage generated is from 39V to 72Vdc (ohmic region: 39~60 V) and needs to be boosted to 400Vdc for home appliances. The system converts dc output from the fuel cell into single-phase sinusoidal ac voltage and current which is suitable for domestic use [4].

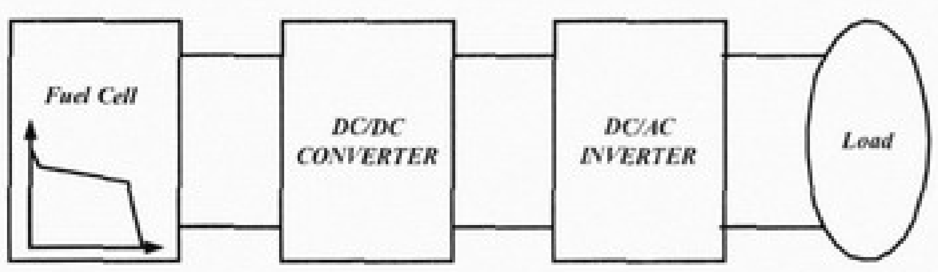


Fig. 1 Configuration for fuel cell generation system

The overall system for fuel cell generation including the fuel cell simulator is shown in Fig. 2. It consists of a full bridge DC/DC converter and a full bridge DC/AC inverter.

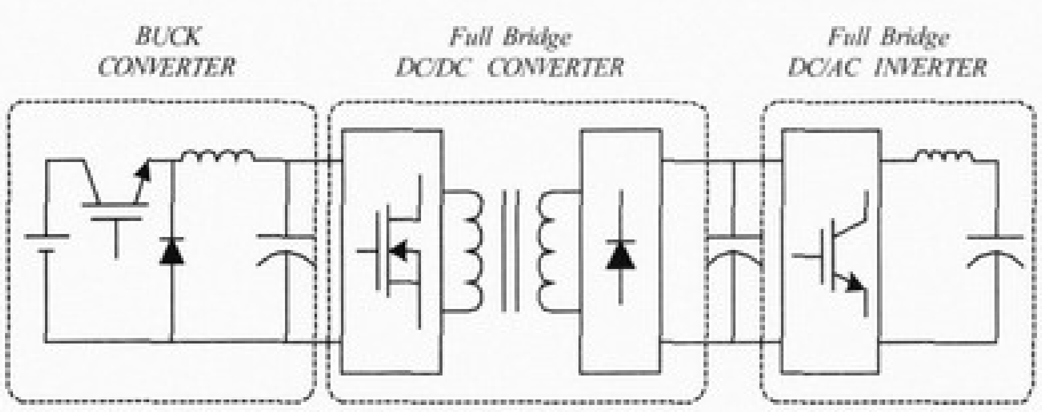


Fig. 2 The overall system for fuel cell generation

2.2 Fuel Cell Simulator

The proposed fuel cell simulator using a simple buck converter is shown in Fig. 3.

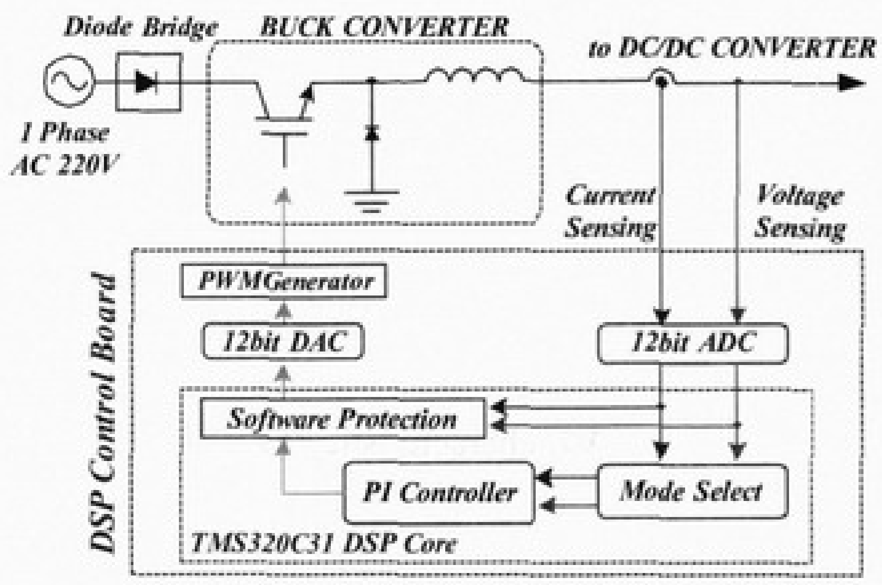


Fig. 3 Proposed fuel cell simulator (buck converter)

The voltage and current for the fuel cell simulator are controlled by a simplified linear function. We designed the fuel cell simulator in the rating of a 3kW proton exchange membrane fuel cell (PEMFC). The proposed linear function of the ohmic region is represented as follows:

$$V_{out} = V_{acti.} \quad (at \quad 0 < I_{out} < I_{ini.})$$

$$V_{out} = \frac{V_{concent.} - V_{acti.}}{I_{sat.} - I_{ini.}} I_{out} - \left(\frac{V_{concent.} - V_{acti.}}{I_{sat.} - I_{ini.}} I_{ini.} - V_{acti.} \right) \quad (1)$$

$$(at \quad I_{ini} < I_{out} < I_{sat.})$$

$$V_{out} = 0 \quad (at \quad I_{out} < I_{sat.})$$

To obtain DC output for the characteristic of the actual fuel cell we designed the fuel cell simulator to accept an input voltage of AC 220V (DC 311V) and output a voltage of DC 39~60V.

Fig. 4 shows a typical V-I performance curve for a cell. The output characteristics of the fuel cell are separated into three categories: activation, ohmic, and concentration regions. The operation region of the actual fuel cell generation system is ohmic region.

In this paper, the designed simulator is operated in the activation region and the ohmic region. In the activation region, the simulator was controlled to maintain the constant output voltage and in cases where the constant output current will overflow, shutdown was controlled, because the concentration region breaks down the characteristics of a fuel cell [1][2][6][7].

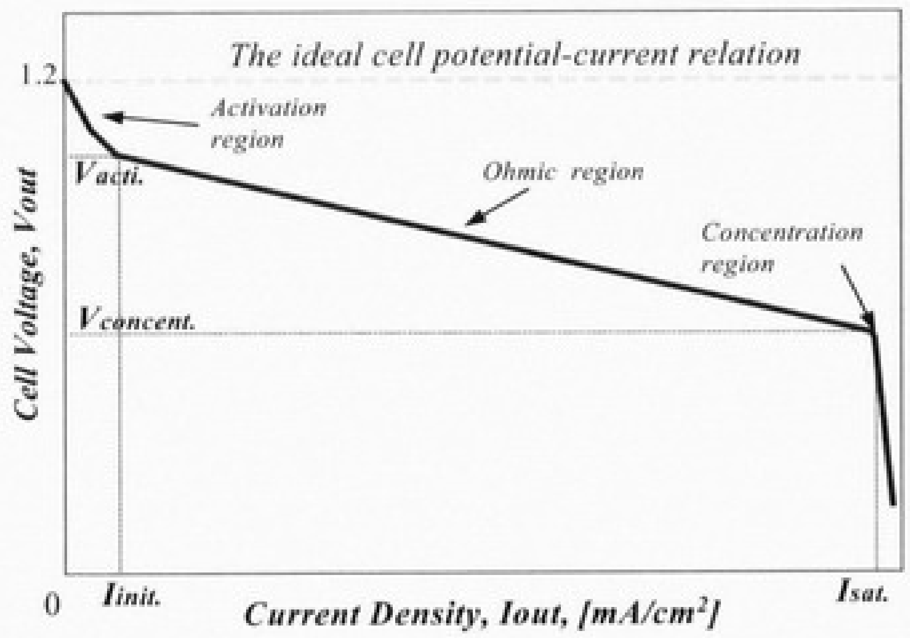


Fig. 4 V-I characteristic of a cell

First, we can detect the output voltage and current. And using an AD converter, if the detected values come into the DSP, the reference value of the V-I characteristic curve for the fuel cell is made, and outputted by the DA converter. The output signal generated by the DA converter is compared with a saw-tooth wave and controlled into the switch of a buck converter.

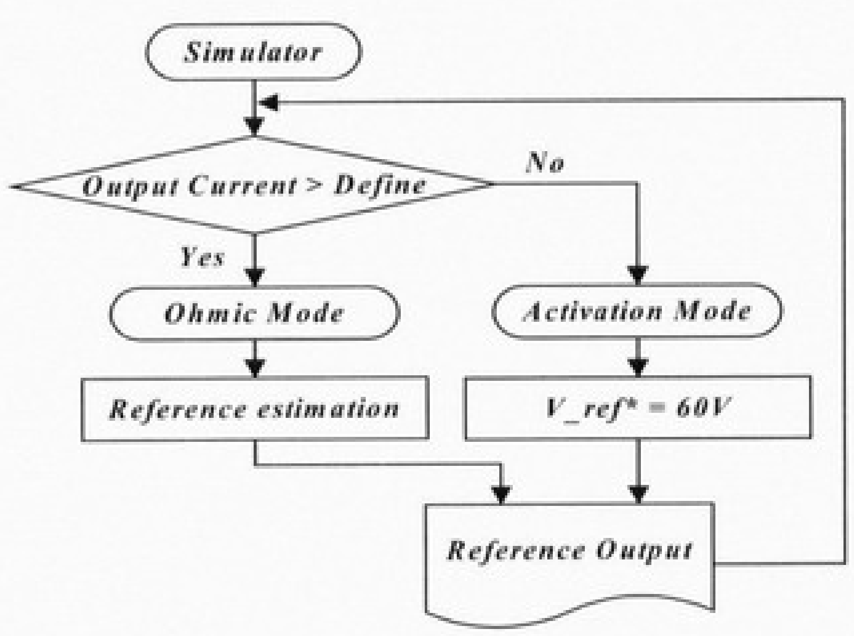


Fig. 5 Control algorithm flowchart

The control algorithm of the FC simulator can be expressed by a simple flowchart as shown in Fig. 5.

The main algorithm can be explained as follows: 1) define the FC parameters, such as the output power of the FC, the output voltage, and the current, 2) measure the output voltage and current, 3) select modes, such as activation, ohmic, and concentration regions, and 4) calculate the reference voltage according to the operational mode.

We can measure the output voltage and current. If the current value is greater than the defined value, the FC simulator is controlled in the ohmic mode; if it is less than the defined value, it is controlled in the activation mode.

Table 1 shows the design parameters of the fuel cell simulator.

Table 1 Fuel cell simulator parameters

Parameter	Value
Output Power	3 [kW]
Input Voltage	220[Vac]
Switching Frequency	15[kHz]
Output Voltage	39 ~ 60[Vdc]
Output Current	41.6 ~ 76.9 [A]
Output Inductance	2.2 [mH]
Output Capacitance	6600[uF]

2.3 Full Bridge DC/DC Converter

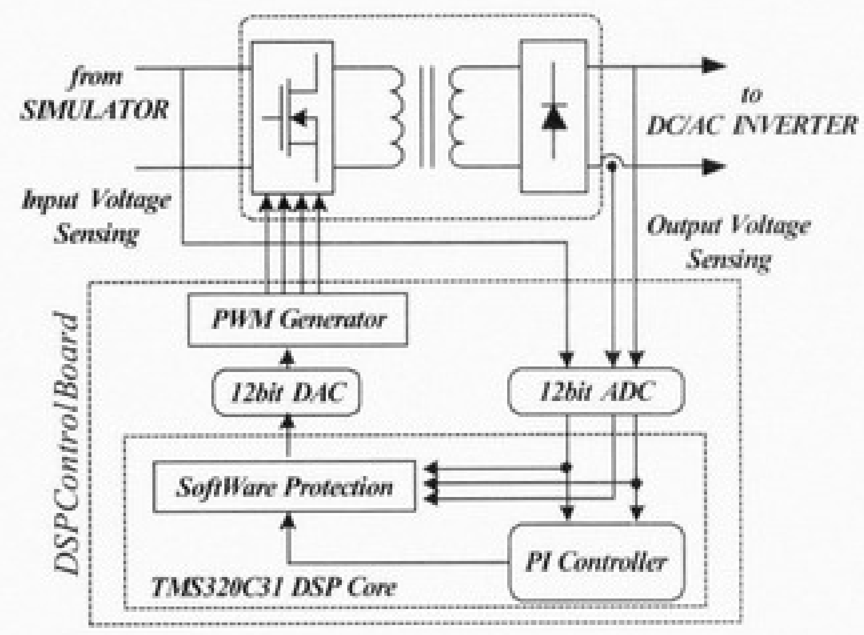


Fig. 6 Block diagram of full bridge DC/DC converter

The full bridge DC/DC converter including DSP control block is shown in Fig. 6. The output voltage of the full bridge DC/DC converter can be held constant using a PI controller. The converter design includes the capability to detect over current, over voltage and other shut down conditions to prevent damage to the system.

The operation waveforms of the full bridge DC/DC converter are shown Fig. 7.

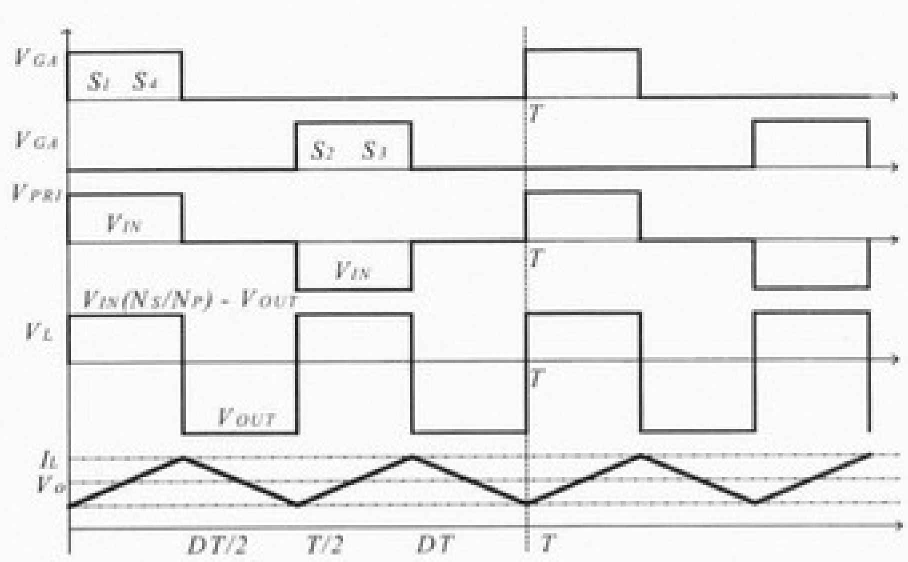


Fig. 7 Operation waveforms of full bridge converter

During one half cycle of the full-bridge converter, Eq. (2) below implies that the average inductor voltage is zero.

$$(V_{IN} \cdot \frac{1}{n} - \frac{1}{2}V_O)\frac{DT}{2} = \frac{1}{2}V_O\frac{(1-D)T}{2} \qquad (2)$$

From Eq. (3), the transfer function for the full-bridge DC/DC converter is defined as

$$M = \frac{V_O}{V_{IN}} = 2 \cdot D \cdot \frac{1}{n} \qquad (3)$$

Where n is the turns-ratio of the transformer (N_P:N_S). Our design uses a turns-ratio of 1:13 to account for switching loss by leakage inductance.

Table 2 shows the design parameters of the full bridge DC/DC converter.

Table 2 Full bridge DC/DC converter parameters

Parameter	Value
Output Power	3[kW]
Input Voltage	39~60[Vdc]
Switching Frequency	17[kHz]
Turn ratio (N_P:N_S)	1:13
Output Voltage	380[Vdc]
Output Current	7.5[A]
Output Inductance	2.5[mH]
Output Capacitance	1100[uF]

2.4 Single Phase DC/AC Inverter

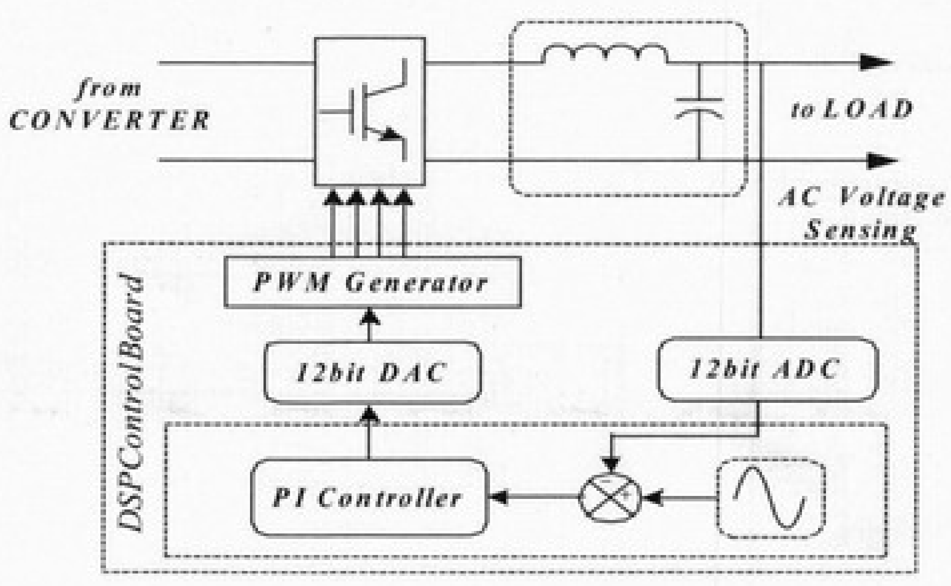


Fig. 8 Block diagram of single phase DC/AC inverter

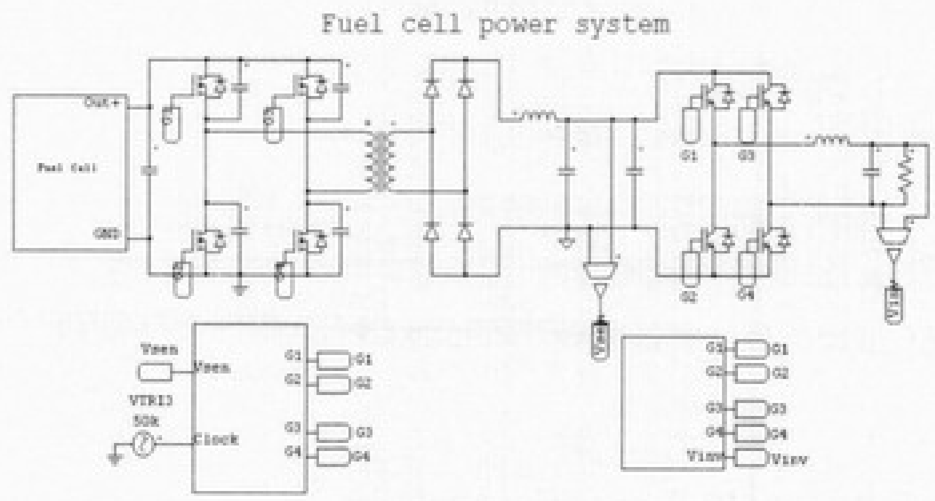
The block diagram of the full bridge DC/AC inverter including the DSP (TMS320C31) control block is shown in Fig. 8. The controller consists of a DSP board, a digital signal processor that processes voltage feedback signals, and an I/O control unit. The output voltage of the inverter can be held at constant voltage and constant frequency. The control technique the inverter uses is the instantaneous voltage control method and SPWM.

Table 3 Inverter parameters

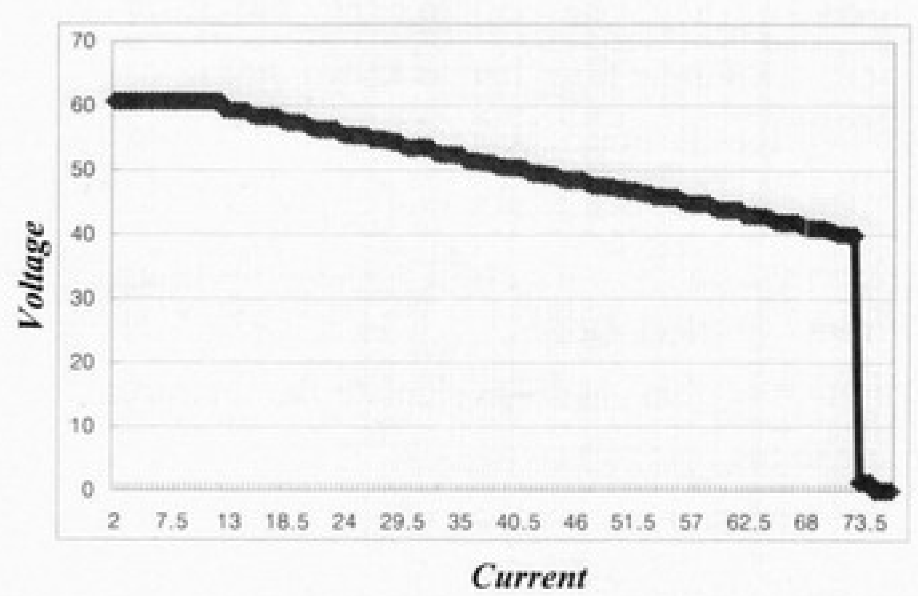
Parameter	Value
Output Power	3[kW]
Input Voltage	380[Vdc]
Output Voltage	220[Vac]
Switching Frequency	4.5[kHz]
Output Inductance	900[uH]
Output Capacitance	20[uF]

3.Simulation and Experimental Results

The performance of the proposed FC simulator has been verified through simulation and experimental tests. Fig. 9 shows the simulation schematic diagram and its output V-I characteristics.



(a) Simulation schematic diagram for the proposed FC simulator



(b) Simulation V-I result

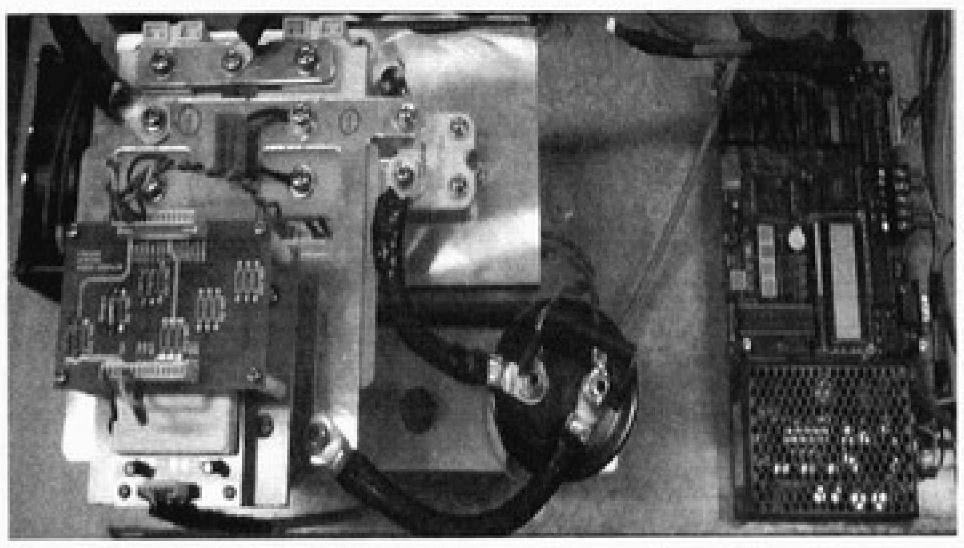
Fig. 9 Simulation characteristics of the proposed FC simulator

Fig. 10 shows the actual experimental setup and results, respectively. As shown in Fig. 9(b) and Fig. 10(b), it is noted that the highly nonlinear V-I curve could be obtained from the FC simulator and it is certified that the experimental result agrees with the simulation.

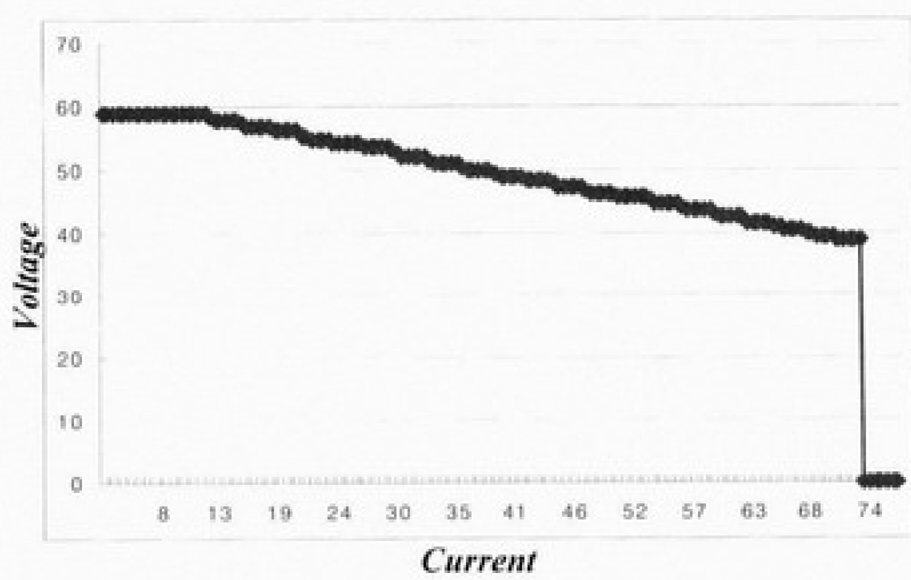
Fig. 10(c) shows its dynamic output characteristics. When the load current changes from 20A to 50A, the transient response is plotted. Then, the stack is stabilized to 50A and 46V after approximately 0.05s. Of course, since the electrochemical reaction time of fuel cells is constant in the short term, the transient response actually shows how the load reacts to a specific change.

With the successfully developed FC simulator, the entire FCG system, rated with 3kW has been built at Sungkyunkwan Univ. as shown in Fig. 13. The detailed experimental waveforms are obtained and displayed in Figs.11 and 12.

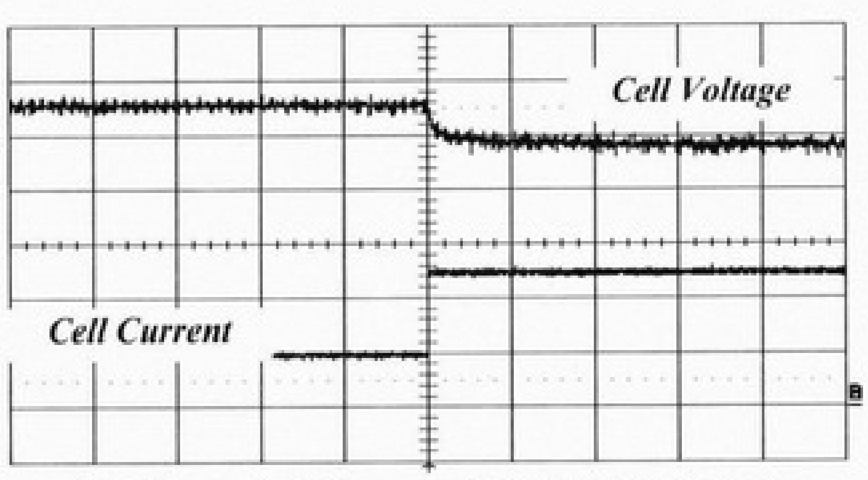
From the experimental results, it is certified that with the low and nonlinear voltage of the FC simulator, 39[V] to 60[V], the full-bridge dc-dc converter generates the constant 380[V] dc output and the full-bridge inverter successfully outputs 220V/60Hz AC voltage and current at a 3kW resistive load. This output has low harmonics and is proper for various domestic loads.



(a) Actual hardware configuration of FC simulator

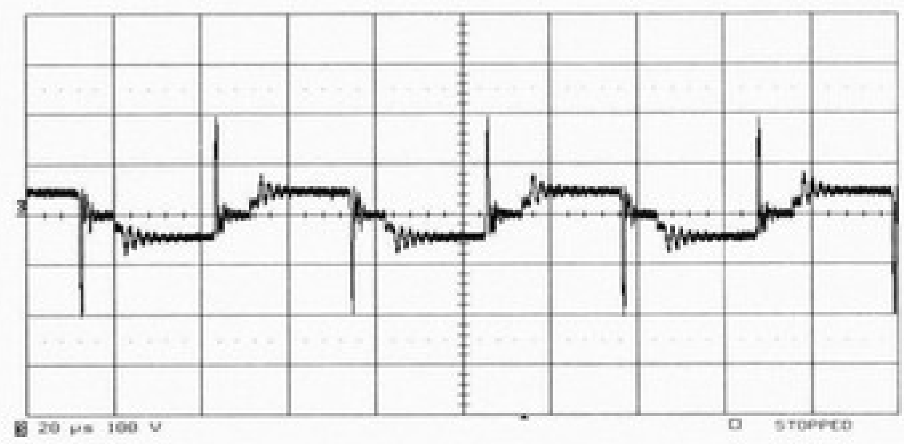


(b) Experimental V-I result

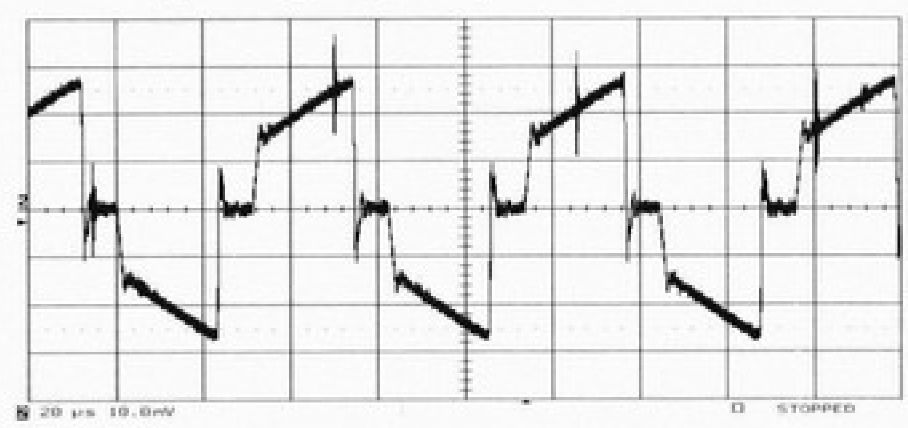


(c) Dynamic V-I curve (10V/div, 20A/div)
(load change : 20A → 50A)

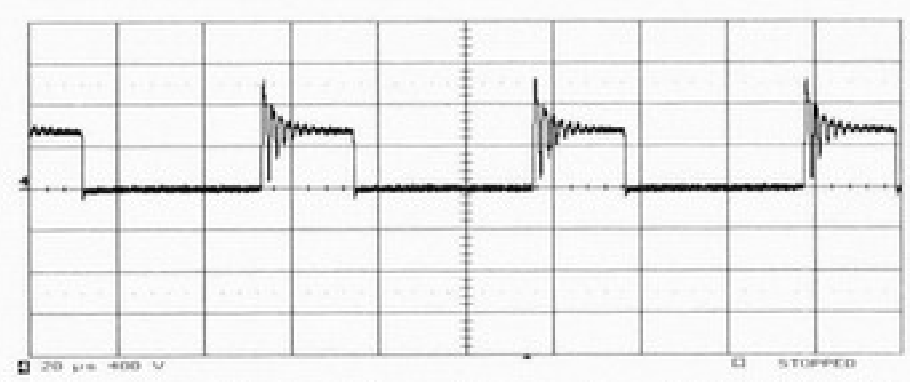
Fig. 10 Experimental characteristics of the proposed FC simulator



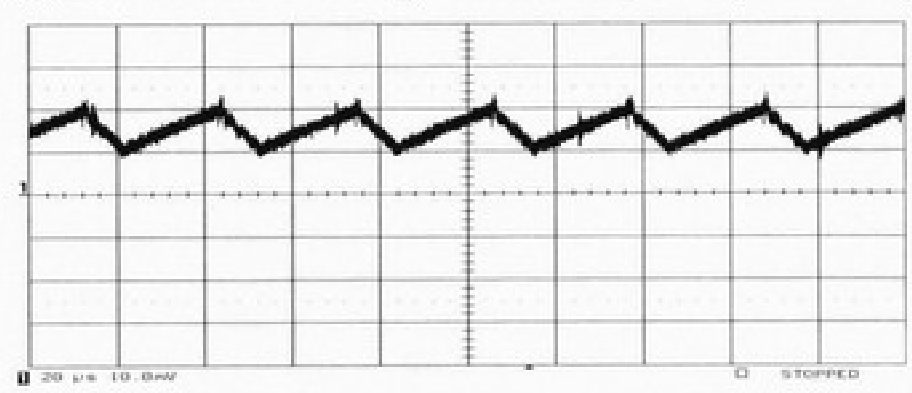
(a) Voltage at primary side (100V/div.)



(b) Current at primary side (50A/div.)

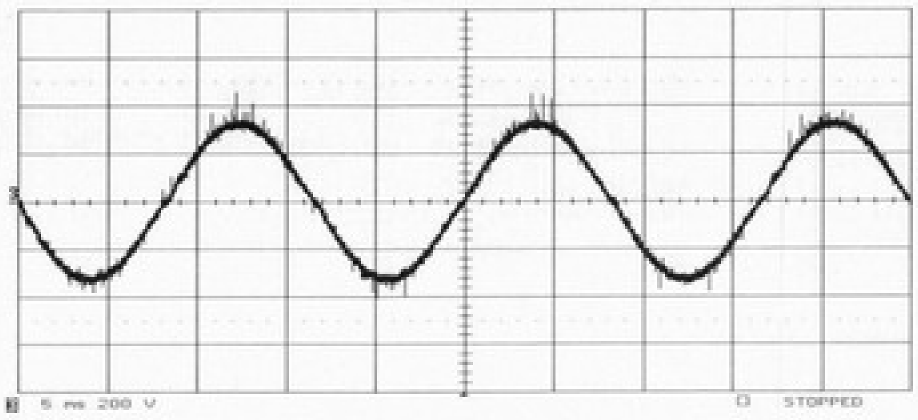


(c) Rectifier diode voltage of secondary side (400V/div.)

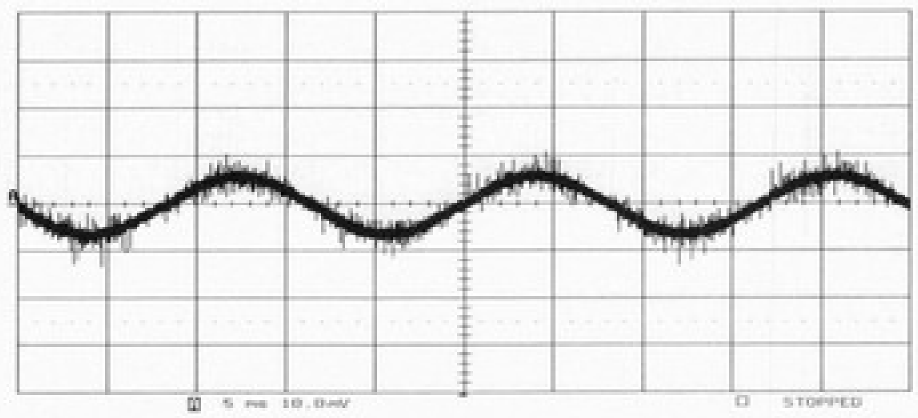


(d) Output inductor current (5A/div.)

Fig. 11 Experimental voltage and current waveforms of the full-bridge dc-dc converter (20us/div.)



(a) Output voltage (200V/div.)



(b) Output current (40A/div.)

Fig. 12 Experimental voltage and current waveforms of the full-bridge dc-ac inverter (3kW load, 5ms/div.)

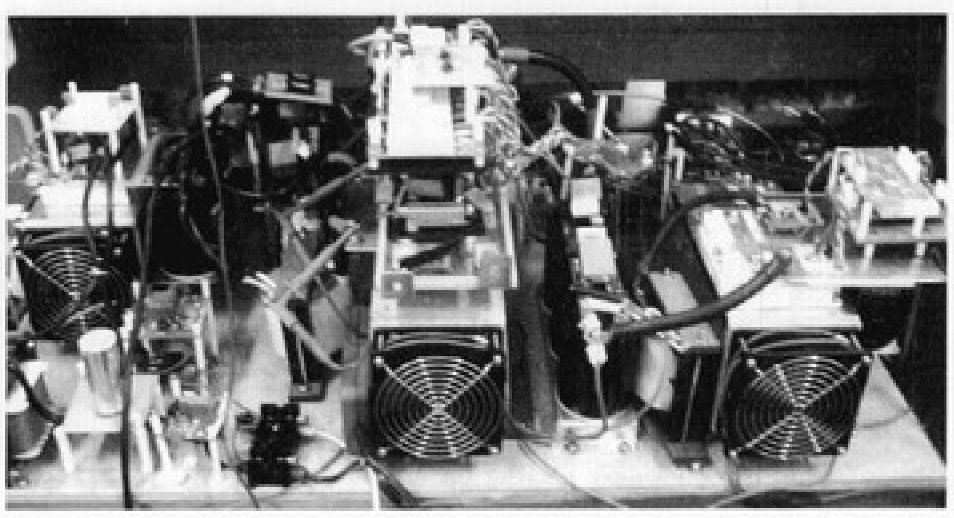


Fig. 13 Experimental test bed of the developed FC generation system.

5. Conclusions

In this paper, a FC simulator, which can generate the actual V-I characteristic of a PEMFC, has been proposed. Based on the FC simulator, a 3kW FCG system has been developed. The simulation and experimental performance of the developed system suggests that it can be effectively applied to domestic applications, such as Residential Power Generation (RPG). Moreover, the proposed FC simulator can be used to simplify the difficult task of developing PCS for FC applications.

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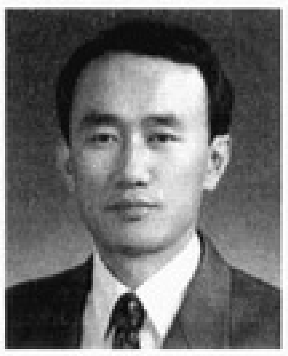

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