Fuel Cell Based Distributed Generation System

Jin-Woo Jung, *Student Member, IEEE*, and Ali Keyhani, *Fellow, IEEE*

***Abstract*—The paper presents a circuit model and controllers of fuel -cell -based distributed generation systems (DGS) in a standalone AC power supply. A dynamic model of the fuel cell is considered. To boost low -output DC voltage of the fuel cell to high DC voltage and to compensate for its slow response during the transient, two full-bridge DC -to -DC converters are adopted and their controllers are designed: a unidirectional full-bridge DC -to -DC boost converter for the fuel cell and a bidirectional full-bridge DC -to DC -buck/boost converter for the battery. For a three-phase DC -to -AC inverter, a discrete-time state space model in the stationary *dq* reference frame is derived, and two discrete-time -sliding mode controllers are designed: a voltage controller in the outer loop and a current controller in the inner loop.**

***Index Terms*—Distributed generation systems, standalone, fuel cells, dynamic modeling, isolated full-bridge DC -to -DC power converter, three-phase PWM inverter, sliding-mode control.**

I. INTRODUCTION

Environmentallyfriendly distributed generation systems (DGS) such as fuel cells, wind turbines, hydro turbines or photovoltaic arrays are rapidly increasing around the world because they can meet both the increasing demand –for electrical power and environmental regulation of green house gas emissions [1]-[7]. Outstanding advances in Power Electronics and energy storage devices for transient backup have accelerated the penetration of the DGS into electric power generation plants.

These DGS technologies can be used for various applications to a standalone, a grid interconnection, cogeneration, standby, peak shavings, etc., and have many benefits such as environmental-friendliness, modular electrical generation, increased reliability, high power quality, uninterruptible power service, cost savings, on-site generation, and expandability, etc.

The fuel cells are electrochemical devices that convert chemical energy directly into electrical energy by the reaction of hydrogen from fuel and oxygen from the air without regard to climate conditions, unlike hydro or wind turbines and photovoltaic array.. Thus, the fuel cells are among the most attractive DGS resources for power delivery. However, batteries need to be placed in parallel or in series with the fuel cells as a temporary energy -storage element to support startup or sudden load changes because fuel cells cannot immediately respond to such abrupt load changes.

Sedghisigarchi and Feliachi [7] have addressed the fuel-cell dynamic model, and control and stability of the grid-connected DGS, but their two-part paper deals with only PI controllers and does not feature energy storage devices for transient backup. Also, a three-phase PWM inverter is not considered in these papers.

.

In this paper, simulation studies that cover all the slow dynamics of the fuel cell, the voltage-current polarization curve of the stack, a unidirectional full-bridge boost converter for the fuel cell, a bidirectional full-bridge buck/boost DC- to -DC power converter for the battery, and a three-phase DC -to -AC inverter are performed for the fuel-cell-powered DGS to put the battery in parallel to the fuel cell in a standalone AC power supply.

Specifically, to boost low -output DC voltage of the fuel cell to high DC voltage and to compensate for its slow response during the transient, two full-bridge DC -to -DC converters are adopted and an

This research was supported in part by the National Science Foundation under the grant NSF ECE 0501349 and ECE 0105320.

J. W. Jung is with Samsung SDI Co., Korea (e-mail: jung.103@osu.edu).

A. Keyhani is with the Department of Electrical and Computer Engineering, The Ohio State University, Columbus, OH 43210, USA (e-mail: keyhani.1@osu.edu).

978-1-4244-1933-3/08/$25.00 ©2008 IEEE

adaptive proportional controller is designed. For a three-phase DC -to -AC inverter, two discrete-time sliding mode controllers are designed to guarantee good performance -- such as nearly zero steady-state inverter -output -voltage error, low THD, good voltage regulation, robustness, fast transient response, and protection of the inverter against overload under linear/nonlinear loads. To demonstrate the proposed circuit model and control strategies, a simulation test-bed using Matlab/Simulink is developed for the standalone AC power generation with a three-phase AC 120 V/60 Hz/50 kVA.

II. Fuel -Cell -Based Distributed Generation Systems in a Standalone AC Power Supply

The fuel cell cannot immediately respond to power demand during start-up or sudden load changes due to its slow dynamics. As a result, energy -storage elements, such as batteries or flywheels, deliver the remaining power to the load for the transient.

Fuel -cell stack voltage, battery position, and the topology of DC -to -DC boost converters can be selected variously according to the designers . In this paper, a low -voltage DC output of the fuel cell is used along with the unidirectional boost converter to avoid reliability deterioration by stacking a number of series cells. A low -voltage battery for backup is connected in parallel to the high-voltage-side DC bus through a bidirectional buck/boost converter so that difficulties in battery management can be significantly reduced. In addition, an isolated full-bridge DC -to -DC power converter is chosen to boost low -output DC voltage of the fuel cell because its topology is suitable for high power applications.

Figure 1 depicts the DGS unit with the battery in parallel to the fuel cell.

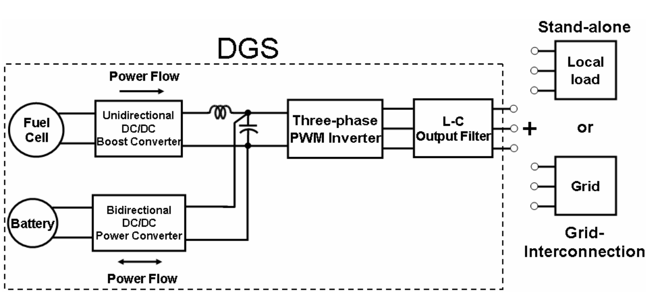


Fig. 1. Configuration for two applications.

Fig. 2 depicts a configuration of the DGS with a parallel -connected fuel cell and battery for the standalone AC power plant. It consists of a fuel cell, a battery, unidirectional and bidirectional isolated full-bridge DC -to -DC power converters, a three-phase DC -to -AC inverter, an L-C output filter, and a three-phase local load.

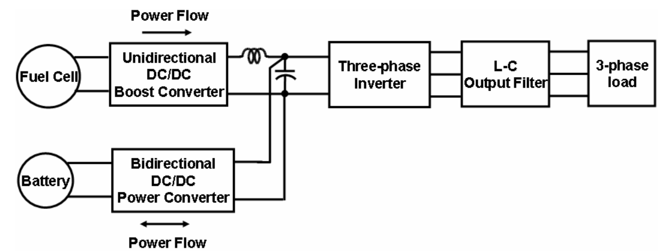


Fig. 2. Configuration of a fuel -cell -based DGS in a standalone AC power supply.

Fig. 3 shows a real -system diagram of the DGS that consists of a reformer, a stack, a fuel processor controller, a unidirectional boost converter, a bidirectional buck/boost converter, a 3-phase DC -to -AC inverter, a supervisory controller, two DSP controllers, and a 3-phase load in the standalone AC power generator. As described in Fig. 3, the fuel -processor controller controls the reformer to produce hydrogen for the power requested from the supervisory controller and monitors the stack current and voltage. The supervisory controller communicates with the fuel -cell processor controller to equalize the power available from the stack to the power requested by the load, and to coordinate protections of the fuel cell. Also, it controls the DSP controllers 1 and 2 for the DC and AC power regulation with sensed -output voltages/currents. The DSP controller 1 supervises the gating signals of unidirectional and bidirectional DC -to -DC power converters, and the DSP controller 2 regulates the gating signals of the three-phase DC -to -AC inverter.

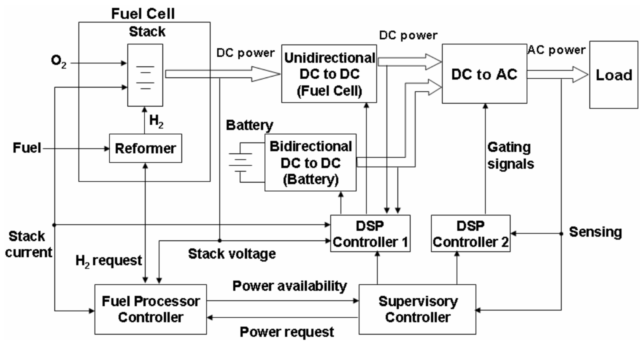


Fig. 3. Detailed system diagram of the DGS with fuel cell and battery.

III. MODELING OF THE FUEL CELL

Among the several types of fuel cells categorized by the electrolyte used, four are promising for distributed generation systems: the Phosphoric Acid fuel cell (PAFC), Solid Oxide fuel cell (SOFC), Molten Carbonate fuel cell (MCFC), Proton-Exchange-Membrane fuel cell (PEMFC).

All of the fuel cells produce electricity by electrochemical reaction of hydrogen and oxygen. Oxygen can be easily obtained from compressing air, whereas hydrogen gas, required to produce DC power, is indirectly gained from the reformer using fuels such as natural gas, propane, methanol, gasoline, or from the electrolysis of water.

A typical configuration of an autonomous fuel -cell system is described in Fig. 4. As shown in this figure, the fuel -cell plants consist of three main parts: a reformer, stack, and power conditioning unit (PCU). First, the reformer produces hydrogen gas from fuels and then provides it for the stack. Second, the stack has many unit cells in series to generate the higher voltage needed for their applications because a single cell that consists of electrolytes, separators, and plates, only produces approximately 0.7 V DC. Last, the PCU, including power converters, converts a low -voltage DC from the fuel cell to a high -voltage DC and/or a sinusoidal AC.

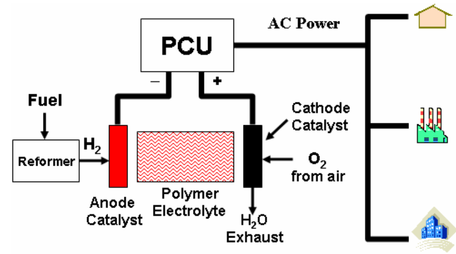


Fig. 4. Configuration of the fuel-cell system.

A. Dynamics of the Reformer

For dynamic modeling of the fuel cells, the reformer and stack, which determine the dynamic response of the fuel -cell system, are further described. Fig. 5 shows a detailed block diagram of the fuel cell system to illustrate its operation.

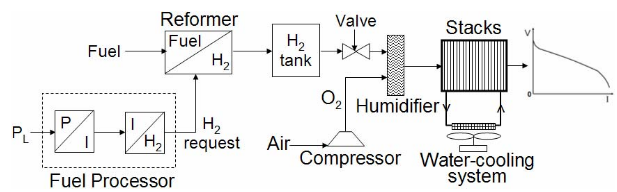


Fig. 5. Detailed block diagram of the fuel -cell system.

As depicted in Fig. 5, the fuel -cell system consists of the fuel -cell stack and auxiliary systems -- such as a fuel -cell processor to request the hydrogen gas, a reformer, an air compressor to provide pressurized oxygen flow through the cathode, a valve to control the hydrogen flow through the anode, a humidifier to add moisture to the hydrogen and oxygen gases, and a water-cooling system to remove heat from the stack.

Among the auxiliary systems stated above, the reformer significantly affects the dynamic behavior of the fuel -cell system because it takes several minutes to tens of seconds to convert the fuel into hydrogen depending on the demand of the load current as illustrated in Fig. 6. Thus, to investigate an overall operation of fuel -cell -powered systems, the dynamics of the reformer need to be considered and may be represented by a second -order transfer -function model or a first -order time -delay model. In this paper, a first -order transfer -function is used for the dynamic model of the reformer.

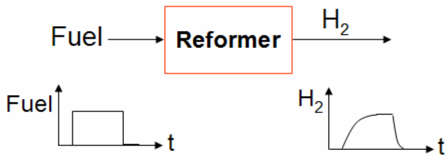


Fig. 6. Dynamic model of the reformer.

B. The Voltage-Current Polarization Curve of the Fuel -Cell Stack

The response of the stack that produces electrical DC power from hydrogen and oxygen is much faster than that of the reformer. A voltage-current polarization curve of a fuel -cell stack represented in Fig. 7 also needs to be considered for the practical model of the fuel cell. That is, cell voltage decreases as the stack current increases.

Fig. 7 shows a static voltage-current characteristic curve of a single fuel cell. As illustrated in the figure, there exist three regions of polarization: activation, ohmic, and concentration. First, in the region of activation polarization, the cell voltage drops rapidly with even a small current increase. Second, in the region of ohmic polarization, where the fuel cell normally operates, the cell voltage linearly decreases as current increases. Last, in the region of concentration polarization, the voltage collapses sharply when the current exceeds the upper limit of safe operation; as a consequence, operation in this region should be avoided because the fuel cell may be damaged primarily due to the starvation of hydrogen.

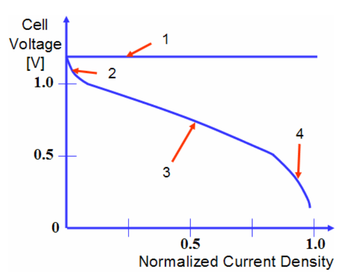


Fig. 7. V-I polarization curve of a single fuel cell.

1. Theoretical EMF or ideal voltage (1.16 V)
2. Region of Activation Polarization (Reaction Rate Loss)
3. Region of Ohmic Polarization
4. Region of Concentration Polarization (Gas Transport Loss)

In this paper, the Proton Exchange Membrane (PEM) example of , out of four promising fuel cells, is investigated. Based on an electrochemical process in [10], a Simulink model is developed for the V-I polarization curve of the fuel -cell stack as illustrated in Fig. 8.

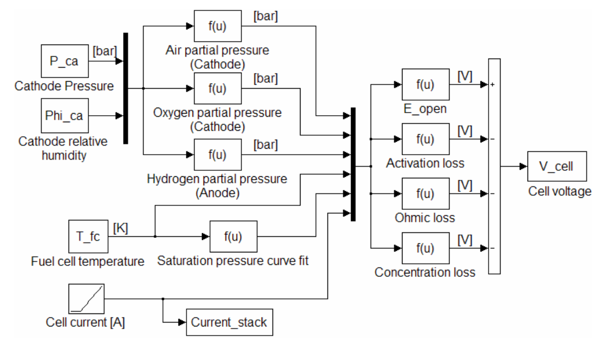


Fig. 8. Simulink model for the V-I polarization curve.

In this figure, the polarization curve of the fuel cell is generated using regression models with current, fuel -cell temperature, vapor -saturation pressure, and oxygen and hydrogen partial pressures. In particular, the oxygen and hydrogen pressures can be estimated from cathode pressure and relative humidity and vapor saturation pressure.

To obtain the voltage-current polarization curve of the fuel- cell stack, the following assumptions are made:

- Fuel cell temperature is 80°C at all times.
- Gas distribution is uniform.
- Anode relative humidity is equal to cathode relative humidity and the value is 75%.
- The ratio of pressures between the interior and exterior of the channel is large enough for the orifice to be choked.
- The Nernst's equation is applied.
- The cell utilization is 85%.

Based on the above assumptions, the polarization curves of the stack of 250 cells in series for various cathode pressures [1, 1.2, 1.4, 1.6, 1.8, 2 bar] are shown in Fig. 9. As represented in this figure, the linearized polarization curve corresponding to cathode pressure (p_{ca}) of 1.2 bar is selected for a 50 kW PEM fuel cell, and it will be used for Simulink model of the fuel -cell stack.

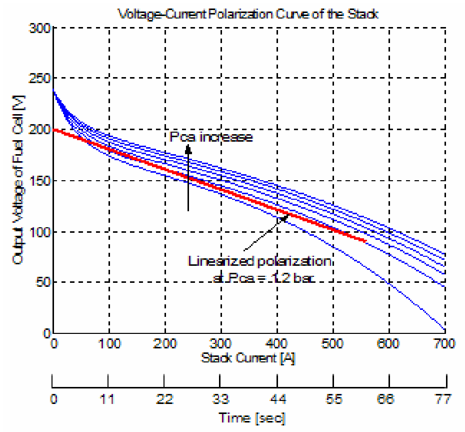


Fig. 9. V-I polarization curves at different cathode pressures (p_{ca}).

Note that the fuel cell has a slow dynamic response during the transient. At initial startup, it takes 90 seconds for the fuel cell to reach steady state. Whenever there is a change in power demand, the fuel cell takes 60 seconds to reach a new steady state because the hydrogen flow rates can be slowly adjusted to meet the power demand . To compensate for such a sluggish fuel-cell response, an energy storage device such as a battery may be required to achieve the end-use needs. For a 50 kW PEM fuel cell, this implies that during startup (90 sec), the energy storage requirement is 4500 kJ or 1.25 kWh. Furthermore, dynamic load changes should be supported by the batteries for 60 seconds. For lead-acid batteries, about a 20 % change of the nominal charge state may be reasonable to avoid deep discharge and to guarantee long service life, as well as reserve capacity in the case of an extended fault with the fuel cell. Fig. 10 shows a discharge curve of the fuel cell and battery to determine the battery capacity. Considering only 20 % discharge of the nominal battery charge state for 90 seconds (startup), the minimum storage requirement of the batteries to support the fuel cell during all transients is about 22,500 kJ or 6.25 kWh.

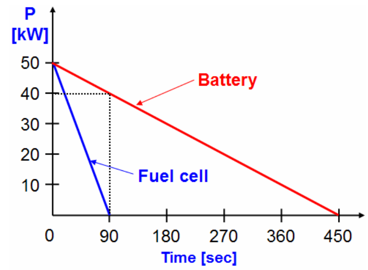


Fig. 10. Discharge curve of the fuel cell and battery.

UNIDIRECTIONAL/BIDIRECTIONAL FULL-BRIDGE DC -TO -DC POWER CONVERTERS

To boost the low -output DC voltage of the fuel cell to high DC voltage, a forward DC -to -DC boost converter, a push-pull DC -to -DC boost converter or an isolated full-bridge DC -to -DC power converter can be selected. Among these power converters, two phase-shifted full-bridge DC -to -DC converters, which are among the most attractive topologies for high power generation, are adopted as described in Fig. 11: a unidirectional full-bridge DC -to -DC boost converter for the fuel cell and a bidirectional full-bridge DC- to -DC boost/buck converter for battery.

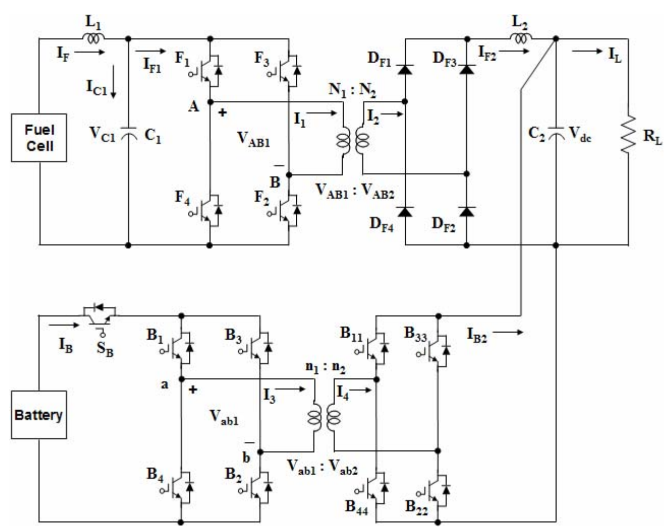


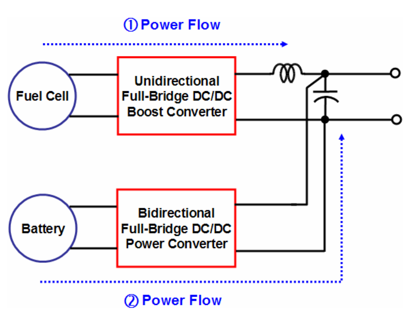
Fig. 11. Unidirectional/bidirectional DC -to -DC power converters.

In Fig. 11, the unidirectional power -converter system for the fuel cell consists of a fuel cell, an input filter (L_1, C_1), a full-bridge power converter "1" (F_1 to F_4), a high -frequency transformer

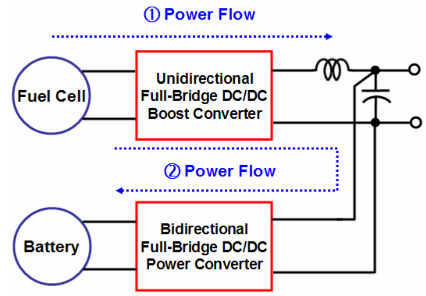
(N_1:N_2), a bridge-diode (D_{F1} to D_{F4}), and an output filter (L_2, C_2), whereas the bidirectional power converter system for the battery consists of a battery, a static switch (S_B), two full-bridge power converters "2" (B_1 to B_4) and "3" (B_{11} to B_{44}), and a high -frequency transformer (n_1:n_2).

Fig. 12 shows power flows of DC -to -DC power converters for battery discharge and recharge. As shown in Fig. 12, the unidirectional full-bridge DC -to -DC boost converter permits only unidirectional power flow from the fuel cell to the load because a reverse current can damage the fuel cell, and the response speed of the power converter should be slow enough to meet the slow dynamic response of the fuel cell. On the other hand, the bidirectional full-bridge DC -to -DC power converter allows bi-directional power flows for battery discharge and recharge, and its response also should be fast [enough?] to compensate for the slow dynamics of the fuel cell during start-up or sudden load changes.

For the battery -discharge mode illustrated in Fig. 12 (a), which occurs with startup or a sudden load increase, the fuel cell starts delivering electrical power to the load; and the battery instantly provides power until the fuel cell reaches a fully operational state. After the transient operation, only the fuel cell feeds electrical power to the load. For battery -recharge mode shown in Fig. 12 (b), the battery absorbs the energy overflow from the fuel cell to prevent DC-link voltage V_{DC} from being overcharged during a sudden load decrease, and then the battery is recharged by the fuel cell in a steadystate until it reaches a nominal voltage.



(a)



(b)

Fig. 12. Power flows of DC -to -DC power converters.
(a) Battery discharge. (b) Battery recharge.

power converters, a simulation test bed using Matlab/Simulink is developed.

Fig. 13 shows a Simulink model of the fuel cell consisting of a power request, a power -to -current conversion, a first-order transfer function for the transient response of the reformer, a controlled - current source, a linearized polarization curve for the modeling of the stack, and a controlled -voltage source.

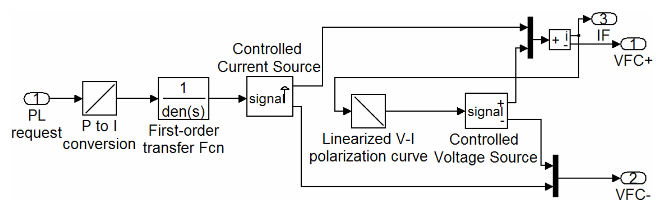


Fig. 13. Simulink model of the fuel cell.

CONCLUSIONS

This paper has described the circuit model and controller design of the fuel-cell-powered DGS to put the battery in parallel to the fuel cell in a standalone AC power supply.

A simulation test-bed using Matlab/Simulink is presented, which includes the dynamic model of the fuel cell, the unidirectional full-bridge DC -to - DC boost converter (fuel cell), the bidirectional full-bridge DC -to -DC buck/boost converter (battery), and the three-phase DC -to -AC inverter.

Especially, a new topology with a static switch on the side of battery which can control both directional power flows is proposed for the bidirectional full-bridge DC -to -DC buck/boost converter. For three power converters, the controllers are designed: an adaptive proportional controller for two DC -to -DC power converters and two discrete-time sliding mode controllers for the three-phase DC -to -AC inverter.

REFERENCES

[1] M. N. Marwali and A. Keyhani, “Control of Distributed Generation Systems, Part I: Voltages and Currents Control,” *IEEE Transaction on Power Electronics*, vol. 19, pp. 1541-1550, Nov. 2004.

[2] M. N. Marwali, J. W. Jung, and A. Keyhani, “Control of Distributed Generation Systems, Part II: Load Sharing Control,” *IEEE Trans. on Power Electronics*, vol. 19, pp. 1551-1561, Nov. 2004.

[3] A. A. Chowdhury, S. K. Agarwal, D. O. Koval, “Reliability modeling of distributed generation in conventional distribution systems planning and analysis,” *IEEE Transactions on Industry Applications*, vol. 39, pp. 1493-1498, Sept.-Oct. 2003.

[4] T. Monai, I. Takano, H. Nishikawa, and Y. Sawada, “Response characteristics and operating methods of new type dispersed power supply system using photovoltaic fuel cell and SMES,” *IEEE Power Engineering Society Summer Meeting*, vol. 2, pp. 874-879, July 2002.

[5] J. L. Del Monaco, “The Role of Distributed Generation in the Critical Electric Power Infrastructure,” *IEEE-Power Engineering Society Winter Meeting*, vol. 1, pp. 144 –145, 2001.

[6] L. Philipson, “Distributed and Dispersed Generation: Addressing the Spectrum of Consumer Needs,” *IEEE-Power Engineering Society Summer Meeting*, vol. 3, pp. 1663 – 1665, 2000.

[7] K. Sedghisigarchi and A. Feliachi, “Dynamic and Transient Analysis of Power Distribution Systems With Fuel Cells—Part I: Fuel-Cell Dynamic Model,” *IEEE Transactions on Energy Conversion*, vol. 19, pp. 423-428, June 2004.

Jin-Woo Jung received the B.S and M.S degrees in Electrical Engineering from Hanyang University, Seoul, Korea in 1991 and 1997, respectively and Ph.D. degree in the Department of Electrical and Computer Engineering, The Ohio State University, Columbus, OH, USA, in 2005. From 1997 to 2000, he worked at Digital Appliance Research Laboratory, LG Electronics Co., Seoul, Korea. He is currently working at Corporate R&D Center, Samsung SDI Co., Korea. His research interests are in the area of distributed generation systems, fuel cell systems, electric machines, AC motor drives, power converters, and control.

Ali Keyhani is a fellow of IEEE and recipient of the Ohio State University College of Engineering Research Award for 1989, 1999 and 2003. From 1967 to 1972, he worked for Hewlett-Packard Co. and TRW Control. Currently, he is a Professor of Electrical Engineering at the Ohio State University, Columbus, OH. He was the past Chairman of Electric Machinery Committee of IEEE Power Engineering Society and the past editor of IEEE Transaction on Energy Conversion. He is the director of OSU Electromechanical and Mechatronic Systems laboratory. Dr. Keyhani's research activities focus on the control of distributed energy systems, design and modeling of electric machine, control and design of Power Electronic systems, DSP-based virtual test bed for design, control of power systems, automotive systems, modeling, parameter estimation and failure detection systems.