Dynamic and Transient Analysis of Power Distribution Systems With Fuel Cells—Part II: Control and Stability Enhancement

Kourosh Sedghisigarchi, *Student Member, IEEE,* and Ali Feliachi, *Senior Member, IEEE*

***Abstract*—The objective of this paper is to analyze the dynamics of distribution systems that contain fuel cells and to enhance the stability of these systems by controlling the fuel cells. The models used in this second part of the two-part paper are the solid-oxide fuel cell (SOFC) models developed in part one. The fuel-cell control loops through the power conditioning units are first explained using a one-machine infinite bus system. Then, fuel cells are integrated into a power distribution test system, which initially contains gas turbines only. Simulation results show how a combination of fuel cells and gas turbines can help control frequency fluctuations, and supply power after islanding of the distribution system.**

***Index Terms*—Distributed generation, frequency control, fuel cell, stability enhancement.**

I. Introduction

DISTRIBUTED[1] generators (DGs) are penetrating the distribution system in large numbers, making it a dynamic system. The dynamic behavior of these DGs, following a loss of power supply from the substation or a large disturbance within the distribution system, needs to be analyzed and control actions might need to be taken to maintain the integrity of the system and supply the customers without interruptions. Disturbances, such as a loss of the substation power, a short circuit, or loading changes will trigger dynamic behavior that was unheard of in distribution systems. Fuel cells are dc voltage sources that can be connected to electric power networks through power conditioning units such as dc/ac inverters [1]–[3], [7]. The fuel-cell inverter is controlled to maintain constant power output under fast transient disturbances.

Kariniotakis and Stavrakakis [4], [5] have addressed the effects of DGs on power system dynamics, but their two-part paper investigates specifically diesel engines and wind turbines. These papers deal with diesel engines and wind turbines which are first modeled [4] and then the effect of wind penetration level is analyzed using a small-size-isolated power system [5].

Investigation of the effect of fuel cells on stability of distribution systems is a current research topic, with very few publications available. Hatziadoniu, Lobo, Pourboghrat, and Daneshdoost [9] describe a simplified fuel-cell model and explain the effect of the mix between fuel cell and gas turbine generation on system stability. Zhu and Tomsovic [10] study load following using a microturbine and fuel cell, which is based on Padullés model [11].

This paper uses the dynamic fuel-cell model developed in part I. It considers temperature dynamics as well as several types of voltage losses, making the model completely different from the models used in [9] and [10]. The paper concentrates on solid-oxide fuel cells (SOFCs). Designed power/voltage controllers for their power conditioning units are demonstrated on a test system to improve power delivery during fast transients.

The paper is organized as follows. In Sections II and III, basic aspects of power/voltage control of grid-connected SOFC are explained. In Section IV, the test system is presented and simulation results are given. Two case studies are presented in Sections V and VI. In the first case, all installed DGs are gas-turbines and in the second case, fuel cells and gas turbines are used. The first case is a modified version of the system given in Okuyama, Kato, Wu, and Yokomizu's paper [1]. Simulation results are only used for comparison with the second case. Stabilization time and overshoot of frequency fluctuations of these two scenarios are also compared.

II. Active Power Output

A. Active Power Output

Consider a fuel cell connected to a power system, the node voltage equation for this system is written as $\mathrm{I_{Bus}} = \mathrm{Y_{Bus}}\mathrm{V_{Bus}}$. Let $\bar{\mathrm{V}}_{\mathrm{ac}}$ and $\bar{\mathrm{I}}_{\mathrm{ac}}$ be the injected fuel-cell node voltage and current, then the real power output of the fuel cell is

$$\mathrm{P} = \mathrm{Re}(\bar{\mathrm{V}}_{\mathrm{ac}}^{*}\bar{\mathrm{I}}_{\mathrm{ac}}) = \mathrm{Re}(\bar{\mathrm{V}}_{\mathrm{ac}}^{*}\mathrm{Y_{Bus}}\bar{\mathrm{V}}). \tag{1}$$

B. SOFC Connected to an Infinite Bus

The output active power of a SOFC connected to an infinite bus as shown in Fig. 1 is

$$\mathrm{P} = \frac{\mathrm{V_{ac}}\mathrm{V_{S}}\sin\psi}{\mathrm{X_s}+\mathrm{X_T}} \tag{2}$$

where

$$\mathrm{V_{ac}} = \mathrm{k}\mathrm{V_{dc}} \tag{3}$$

$$\mathrm{I_{dc}} = \frac{\mathrm{k}\mathrm{V_s}\sin\psi}{\mathrm{X_s}+\mathrm{X_T}} \tag{4}$$

[1]

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The authors are with the Advanced Power Engineering Research Center at Lane Department of Computer Science and Electrical Engineering, West Virginia University, Morgantown, WV 26506-6109 USA (e-mail: kourosh@csee.wvu.edu; alfeliachi@mail.wvu.edu).

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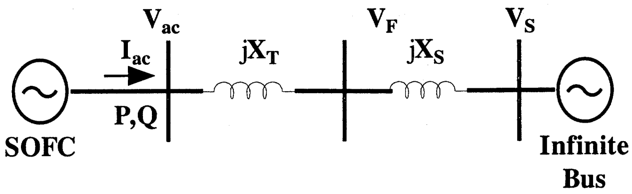

Fig. 1. Solid oxide fuel cell connected to infinite bus.

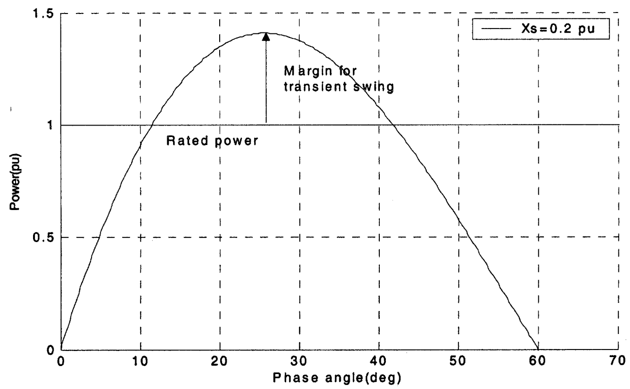

Fig. 2. SOFC active power versus firing angle.

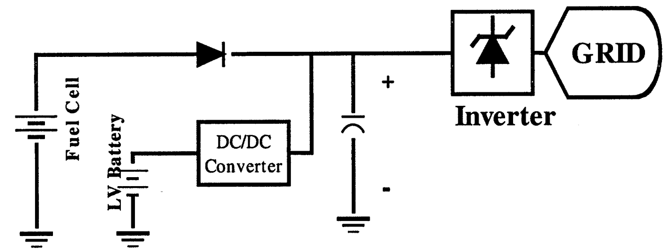

Fig. 3. Fuel cell and auxiliary source.

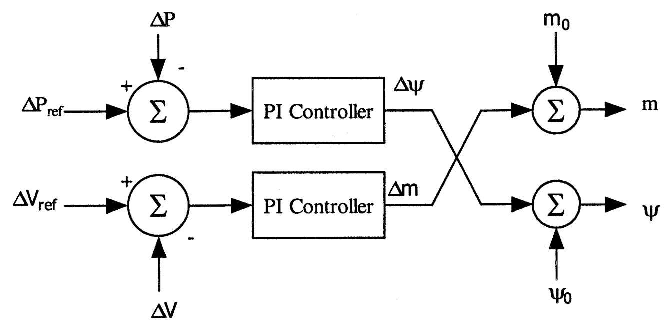

Fig. 4. Fuel-cell control scheme.

X_T and X_s are the transformer and transmission line reactances. The power generation of the fuel cell is

$$P = \frac{kV_{dc}V_S \sin\psi}{X_s + X_T} \tag{5}$$

V_{dc} as expressed in [7] is

$$V_{dc} = V_o - r\frac{kV_s \sin\psi}{X_s + X_T} - f_1\left(\frac{kV_s \sin\psi}{X_s + X_T}\right) - f_2\left(\frac{kV_s \sin\psi}{X_s + X_T}\right) \tag{6}$$

$$k = \frac{m}{V_B 2n\sqrt{2}} \tag{7}$$

where m is modulation index, n is transformer ratio, and f_1 and f_2 are nonlinear logarithmic functions. Equations (5) and (6) show that the power output is a function of k and ψ, t is the angle between $\bar{V}_{ac}, \bar{V}_S$.

The distributed utility model of Fig. 1 is simulated in MATLAB/SIMULINK. It is a 100-kW [7] fuel cell, and the transformer and transmission line reactances are 0.1 p.u.

The output active power as a function of the firing angle is shown in Fig. 2 [8]. The active output power can reach 1.4 p.u. by changing the firing angle relative to the infinite bus.

III. SOFC CONTROLS

In this section, the basic power/voltage control aspects of a fuel cell are explained. They will be used in a later section when the fuel cell is part of a distribution system.

For proper operation of a fuel cell, the consumed fuel in the stack needs to be controlled. This fuel-cell utilization is defined in this section after the power/voltage controls are explained. Also, the grid-connected fuel cell needs to have a battery as an auxiliary energy source or storage as shown in Fig. 3. The battery allows start-up control, load transient control, and optimum energy usage control [1].

The dynamic characteristics of fuel cells are highly dependent on fuel-cell sizes and types. For instance, polymer electrolyte membrane (PEM) fuel cells have fast dynamics that are different from SOFCs of larger sizes (e.g., 5–10-kW PEMs versus SOFCs of sizes 200 kW–2 MW).

A. Power/Voltage Control

Control actions are through the power conditioning unit (PCU) specifically: [2], [7]

1) Power control: done by adjusting the firing angle of the inverter for fast transient variations.
2) Voltage control: done by adjusting the modulation index of the converter, which affects the magnitude of the converter output voltage.

Power control can also be achieved through control of the input fuel flow, but this has a large time constant and will not affect the transient behavior.

Fuel-cell power and voltage controllers presented here are proportional-integral (PI)-type controllers, which adjust the firing angle and modulation index of the converter according to the power and voltage deviations, respectively, as illustrated in Fig. 4.

The fuel-cell inverter has the capability to adjust its firing angle quickly so that the inverter maintains constant power output under fast transient disturbances.

The output fuel-cell voltage is not allowed to go under a minimum limit, which may cause trouble in synchronism. In this case, a dc/dc boost converter before the dc/ac PWM inverter is suggested by others. In this paper, voltage level compensation is done using the inverter modulation index signal.

Hence, the fuel-cell inverter has power modulation capabilities that enhance the voltage level of the system. The modulation index controller increases the value of the modulation index in order to enhance voltage regulation. The value of the modulation index is between 0 and 1.

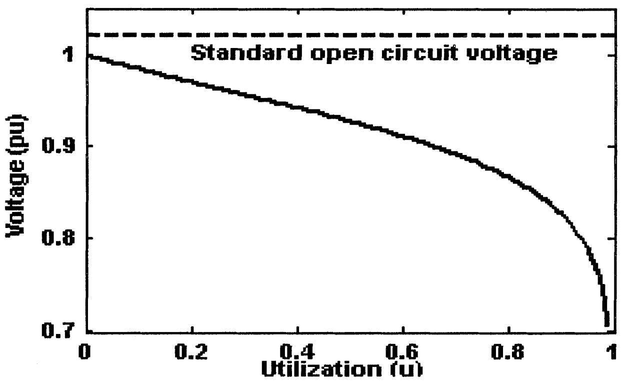

Fig. 5. Cell voltage (per unit) versus cell utilization.

B. Utilization Control

Cell utilization (u) is defined as follows:

$$\mathrm{u} = \frac{\mathrm{N}_{\mathrm{H}_2}^{\mathrm{in}} - \mathrm{N}_{\mathrm{H}_2}^{\mathrm{o}}}{\mathrm{N}_{\mathrm{H}_2}^{\mathrm{in}}} \tag{8}$$

where $\mathrm{N}_{\mathrm{H}_2}^{\mathrm{in}}$ and $\mathrm{N}_{\mathrm{H}_2}^{\mathrm{out}}$ are input and output hydrogen flows.

Fig. 5 shows the steady-state cell voltage of a fuel cell versus cell utilization.

Cell utilization has to be kept between upper and lower bounds normally $0.7 < \mathrm{u} < 0.9$ otherwise underused and overused conditions will occur as follows:

- Underused fuel $\mathrm{u} < 70\%$: (The cell voltage would rise rapidly.) The current of the fuel cell is not allowed to be below the minimum stack current. This constraint has been considered in the proposed dynamic model.
- Overused fuel $\mathrm{u} > 90\%$: (fuel starvation and permanent damages to the cells). The current of the fuel cell is not allowed beyond the maximum stack current. This constraint has been considered in the dynamic model.

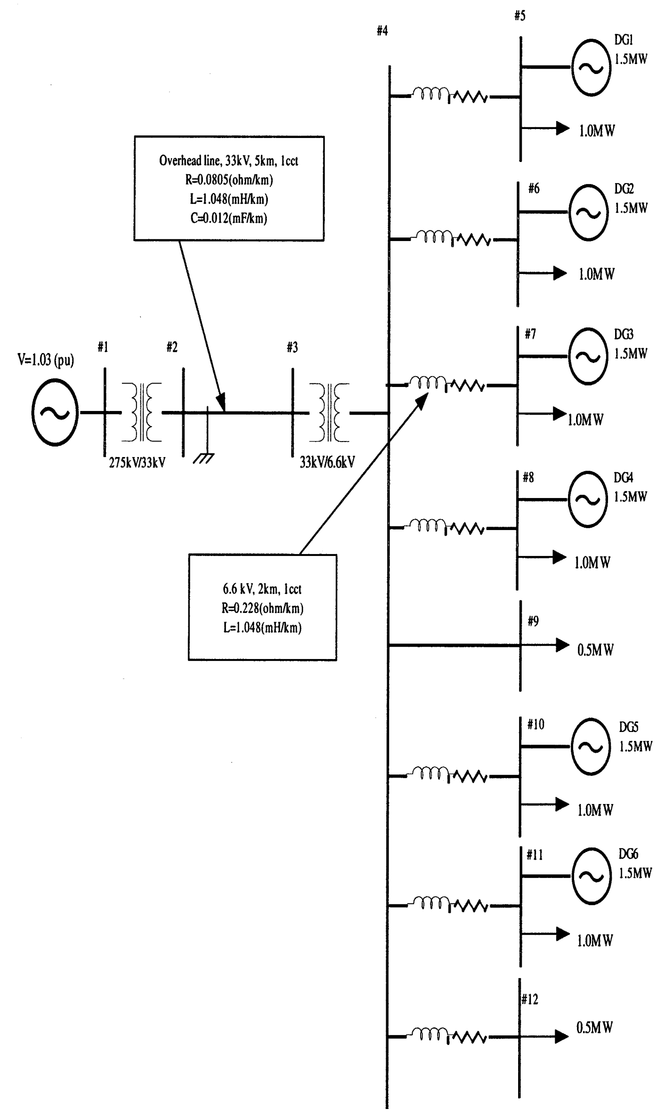

Fig. 6. Distribution system.

IV. Test System

The purpose of this paper is to address the stability of a distribution system that contains fuel cells. The control aspects described above and the SOFC model developed in the companion paper [8] are demonstrated on the test system shown in Fig. 6. This system is described next.

A. Distribution System

The system is shown in Fig. 6. It is a 6.6-kV system. The high-voltage supply side at bus 1 is 275 kV which is stepped down to 33 kV at bus 2 and transmitted over 33-kV overhead line to bus 3 and the voltage is stepped down again to 6.6 kV at bus 4. Buses 5 through 12 are load buses all connected to bus 4 through a line. These buses have loads and/or distributed generators. The loads at buses 9 and 12 are 0.5 MW at the rating voltage of 6.6 kV. One-megawatt load is represented by an impedance load of $\mathrm{R} + \mathrm{jX} = 43.56 + \mathrm{j}139$. The total load in the distribution system is 7 MW. This test system is a modified version of the test system given in [1]. The total capacity of the distribution system is 9 MW which is larger than the total load.

B. Simulation Process

The simulation process has three steps.

1) *Load flow and steady state*:
   Local load of buses 5, 6, 7, 8, 10, and 11 are fully supplied by their local DGs and the power flow from bus 4 to these buses is approximately zero. The size of each DG is 1.5 MW. The other two 0.5-MW loads at buses 11 and 13 are fed by the substation.
2) *Disturbance*:
   A three-phase short circuit occurs close to bus 2 on the 33-kV line.
3) *Fault Clearing: Islanding*:
   The 33-kV line is disconnected 0.3 s after the short circuit, then the 6.6-kV distribution system is isolated from the upper system. After disconnection, the distribution system continues operating independently with its own DGs.

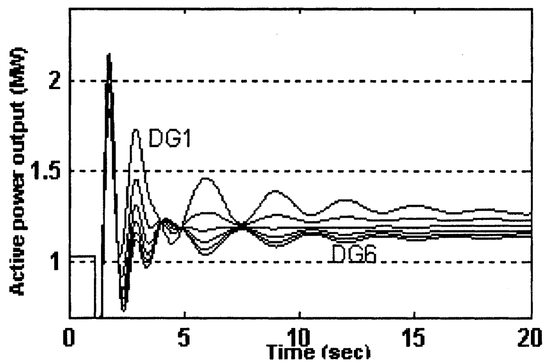

Fig. 7. Active power output response (Case I).

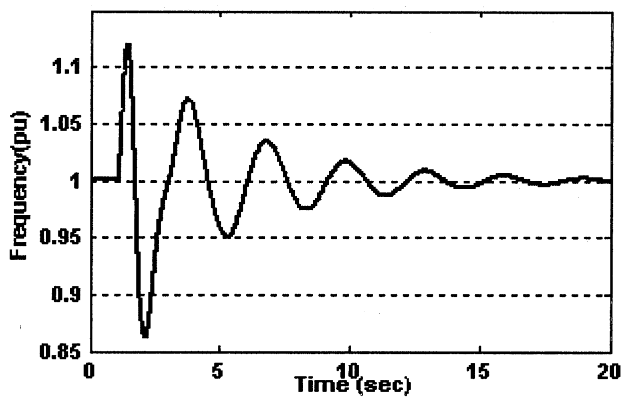

Fig. 8. Frequency response (case I).

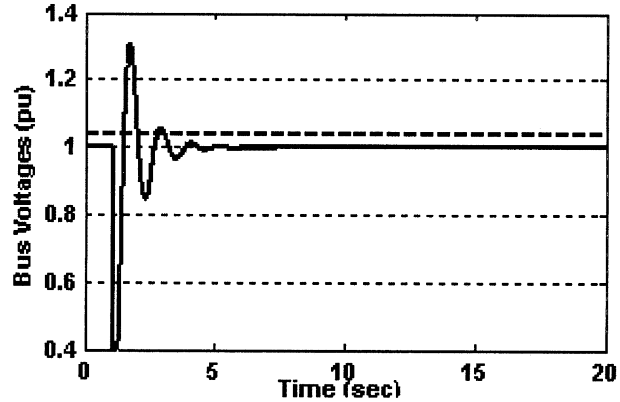

Fig. 9. Voltage response (case I).

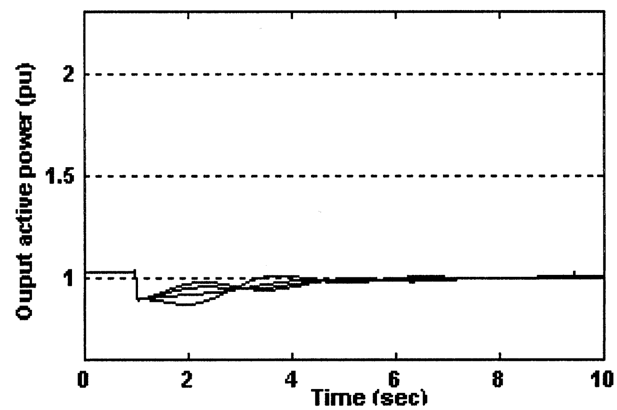

Fig. 10. Active power output response (Case II).

V. Case I (All DGs Are Gas Turbines)

The gas turbines are synchronous generators modeled using subtransient models. Block diagrams and data of the voltage regulator (AVR) and governor are the ones given in [1]. The parameters are the same for all of the machines except for the time constant of the prime movers T_m. DG1 has the smallest T_m and the fastest speed response among all of the DGs. Values of the T_m for DG1 to DG6 are 0.6, 0.9, 1.2, 1.5, 1.8, and 2.1 s, respectively.

A. DG's Outputs

Before the islanding, the active power output of each DG is set to supply the local load. After the disconnection of the distribution system, each DG's output is changed to keep the balance between power supply and demand. The setting of the active power output of a DG is the summation of the active power load in the same bus and inverse power flow from the DG.

B. Simulation Results

Fig. 7 shows the change of DG's active power output. DGs with smaller T_m can respond quickly to the disturbance and can increase the output quickly in order to supply power to buses 9 and 12 where DGs are not installed. DGs with large T_m cannot increase their outputs fast enough and the output active power will be different.

The frequency response is shown in Fig. 8. The frequency drop is more than 13%, which is outside the standard limits. It takes more than 18 s for frequency to be stabilized. Finally, there is little frequency drop.

Bus voltages are shown in Fig. 9. The voltage settling time is about 5.5 s.

VI. Case II (Fuel Cells and Gas Turbines)

SOFC generators are installed on buses #10 and #11 to replace the gas turbines. These two fuel cells have similar parameters as in [7]. In the steady state, fuel cells supply their local loads and power transfer from bus #4 to load buses is approximately zero.

After a load-flow problem is solved, the initial parameters are computed for each fuel cell as described in part I. Fig. 10 shows the active power output responses of the gas turbines and fuel cells.

The frequency responses of the machines are shown in Fig. 11. Frequency drop is now less than 1%.

Voltage responses of the buses are plotted in Fig. 12. Bus voltages reach their operating points very fast (less than 4–5 seconds) by setting suitable voltage PI controller gains which affect the modulation index of the inverter. PI controller gains are tuned using trial and error.

Active power output of fuel cells have been shown in Fig. 13. Phase angle and modulation index of fuel cells are set in such a way as to increase the active power output and recover the lack of power after islanding.

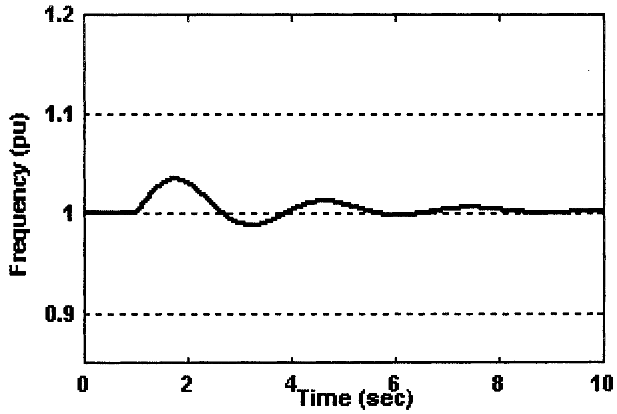

Fig. 11. Frequency response (case II).

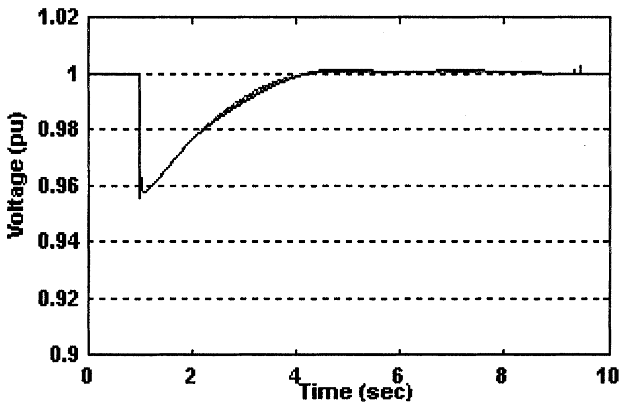

Fig. 12. Voltage response (case II).

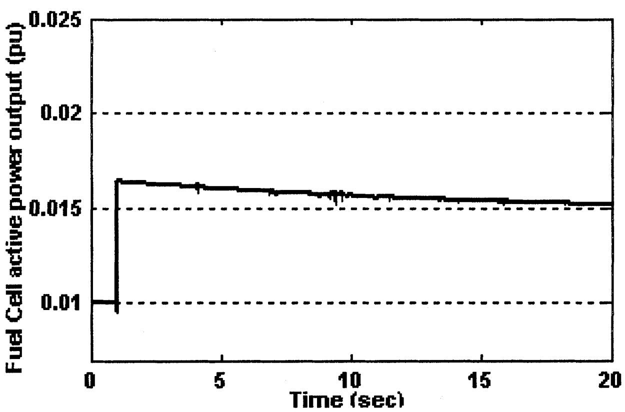

Fig. 13. Fuel cells active power output (case II).

The frequency responses of these case studies are shown in Fig. 14.

Power conditioning units respond very quickly to their modulation index and phase angle changes since they are solid-state devices. They play a role similar to power system stabilizers (PSSs) of large turbo generators. PSSs are supplementary signals through exciters, used to dampen oscillations rather than control through the governor or primemover.

Firing angle control causes more power delivery to the system in a short period of time and less frequency variations. Modulation index and voltage regulation have similar characteristics.

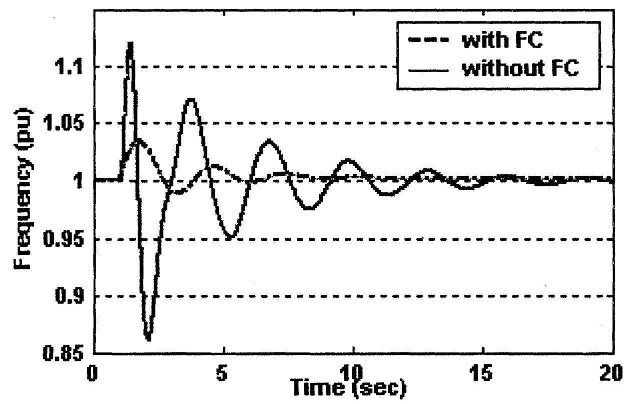

Fig. 14. Comparison of frequency responses of two case studies.

Simulation results show that the increase in the ratio of the fuel-cell power to gas turbine power can improve the stability more and vice versa. For example, instead of using 1.5-MW fuel-cell units, if they were only 0.5 MW, higher frequency overshoot and longer settling time would result.

VII. Conclusion

In this second part of the two-part paper, SOFC models, developed in part one, are used to analyze the stability of power distribution systems containing fuel cells as DGs.

First, the fuel-cell power/control issues are explained through power conditioning units which are equipped with PI controllers. The fuel-cell stack current has been limited so that the cell utilization is controlled, avoiding cell damages.

A comparison between a power distribution test system with only gas turbines and a system with both fuel cells and gas turbines is performed. PI controller gains have been chosen by trial and error to obtain the best performance. A more systematic way of setting these parameters is being investigated by the authors.

Simulation results show how fuel cells can improve reliability and power delivery of distribution systems. Frequency fluctuations after islanding are considerably reduced compared to the case when only gas turbines are used as DGs.

Fuel cells are dynamic devices and their penetration into the distribution system will affect the behavior of this system, but control of these devices can enhance the stability of the overall system. This paper demonstrates these aspects using a test system and it shows promising results.

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Kourosh Sedghisigarchi (S'01) received the Bachelor and Master degrees in electrical engineering from Sharif University of Technology, Tehran, Iran, in 1994 and 1997, respectively. He is currently pursuing the Ph.D. degree in the Lane Department of Computer Science and Electrical Engineering Department at West Virginia University, Morgantown, where he is a Graduate Research Assistant.

His research interests include distributed generation, fuel cells, modeling, power distribution systems, and control.

Ali Feliachi (SM'86) received the Diplôme d'Ingénieur en Electrotechnique from Ecole Nationale Polytechnique of Algiers, Algiers, Algeria, in 1976, and the M.S. (1979) and Ph.D. (1983) degrees in electrical engineering from the Georgia Institute of Technology, Atlanta.

Currently, he is Full Professor and the holder of the endowed Electric Power Systems Chair position in the Lane Department of Computer Science and Electrical Engineering at West Virginia University (WVU), Morgantown, where he has been since 1984. He is also the Director of the Advanced Power and Electricity Research Center at WVU. He has been working in the field of large-scale systems and power systems for 25 years, and has appeared in many publications.

Dr. Feliachi is a member of ASEE, Pi Mu Epsilon, Eta Kappa Nu, and Sigma Xi. He received an ASEE Dow Outstanding Young Faculty Award in 1987, and the following awards from the College of Engineering at WVU: Leadership (1989), Research (1991), and Graduate Teacher (1991), and in 1994, he received the Claude Benedum Distinguished Scholar Award for the Sciences and Technology from WVU.