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Control design of an atmospheric solid oxide fuel cell/gas turbine hybrid system: Variable versus fixed speed gas turbine operation

Rory Roberts [a], Jack Brouwer [a,*], Faryar Jabbari [a], Tobias Junker [b], Hossein Ghezel-Ayagh [b]

[a] National Fuel Cell Research Center, University of California, Irvine, CA 92697, United States
[b] FuelCell Energy, 3 Great Pasture Road, Danbury, CT 06813, United States

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Abstract

This study is focused on a hybrid fuel cell/gas turbine (FC/GT) system with an atmospheric pressure solid oxide fuel cell (SOFC). The impact of the gas turbine rotational speed on dynamic performance and controllability of a hybrid system is investigated. The transient response of the FC/GT system to perturbations in the power demand has been investigated. Two operational strategies of gas turbines are compared: (1) fixed speed operation, and (2) variable speed operation. For both operation strategies, a wide range of power production is numerically simulated. The results show that variable speed operation is superior for the FC/GT hybrid configuration studied. Variable speed operation allows a 50% turn down in power with no additional balance of plant equipment required. The system efficiency is maintained above 66% for variable speed operation compared to 53% for fixed speed operation with auxiliary combustion.

Keywords: Solid oxide fuel cell; Gas turbine; Control; Hybrid; Dynamic; Transient; Load following

1. Introduction

Fuel cell/gas turbine (FC/GT) hybrid systems are recognized to be very efficient power plants with negligible emissions. The integration of a gas turbine and fuel cell in a FC/GT hybrid power plant is one of the major ongoing R&D activities in the US [1,2]. The impetus for the development of the FC/GT hybrid system includes: achieving high electric efficiencies, reducing power plant cost, and increasing overall system capacity for generation of power. The gas turbine not only offers a means of providing air flow through the system but also generates net electrical power from the waste heat of a high temperature fuel cell stack such as a solid oxide fuel cell (SOFC).

In parallel with the hybrid system development, substantial research is being performed to reduce the cost and increase the reliability of SOFC stacks. Compared to tubular SOFCs, planar SOFCs are anticipated to have higher power densities (higher density packaging) and to operate at lower operating temperatures (thinner electrolyte). Operating at lower temperature benefits the stability of materials used in SOFCs, widens the range of suitable materials, and increases the durability of the fuel cell. Metallic interconnects may be used in the stack design if temperatures are low enough such that the oxidation rates are acceptable. Sealing issues with SOFC stacks become less difficult when operating at lower temperatures. However, low-temperature SOFCs introduce some challenges in the design of hybrid FC/GT systems. The hybrid system performance is dependent on the turbine inlet temperature, and lowering the fuel cell temperature makes it harder to raise and to manage the gas turbine inlet temperature. Operating the SOFC at lower temperatures introduces more flexibility in the hybrid configuration and design.

Two distinct flow designs are possible when integrating a gas turbine with a fuel cell stack. The first design replaces the gas turbine combustor directly with the fuel cell stack. This configuration results in the stack being pressurized at the operating pressure of the gas turbine. The second system replaces the combustor of the gas turbine cycle with a high temperature recuperator and places the fuel cell stack at the exhaust of the gas turbine. This configuration results in the fuel cell stack being operated slightly above atmospheric pressure. Note that the latter cycle with a near atmospheric SOFC stack is a novel

* Corresponding author. Tel.: +1 949 824 7302x221; fax: +1 949 824 7423.
E-mail address: jb@nfcrc.uci.edu (J. Brouwer).

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Nomenclature

BOP	balance of plant
CIT	cathode inlet temperature (°C)
FC/GT	fuel cell/gas turbine hybrid
GT	gas turbine
n	compressor/turbine rotational speed (RPM)
P	pressure (kPa)
SOFC	solid oxide fuel cell
SOFC/GT	solid oxide fuel cell/gas turbine hybrid
T	temperature (°C)
TIT	turbine inlet temperature (°C)

Greek letter

η	isentropic efficiency

Superscripts

in	inlet
out	outlet

configuration for SOFC stacks in hybrid configuration that has not been analyzed previously in the literature.

Fig. 1 presents a schematic of the system. A low temperature planar SOFC is well suited for this configuration because the operating constraints introduced by the recuperator materials require the SOFC to operate at a lower temperature. At temperatures below 1200 K, the recuperator material may be selected from a variety of super-alloys; for example high-nickel alloys such as Inconel 625. However as mentioned earlier, the SOFC/GT system of Fig. 1 poses challenges to control and thermal management of the system during rapid load following operation. During operation, this system can be exposed to many different perturbations. For example, load perturbations or changes in ambient conditions such as temperature and pressure. Changes in fuel supply can also occur in the case of peak shaving for natural gas supplies. For initial analysis of SOFC/GT systems, dynamic models provide the tools necessary for development and testing of these hybrid systems during conceptual design stages. In this work, load disturbances are evaluated and their effects on the thermal management of the system are studied. The main objective of the study is to arrive at solutions and/or control architectures for maintaining fuel cell and gas turbine inlet temperatures during severe load changes.

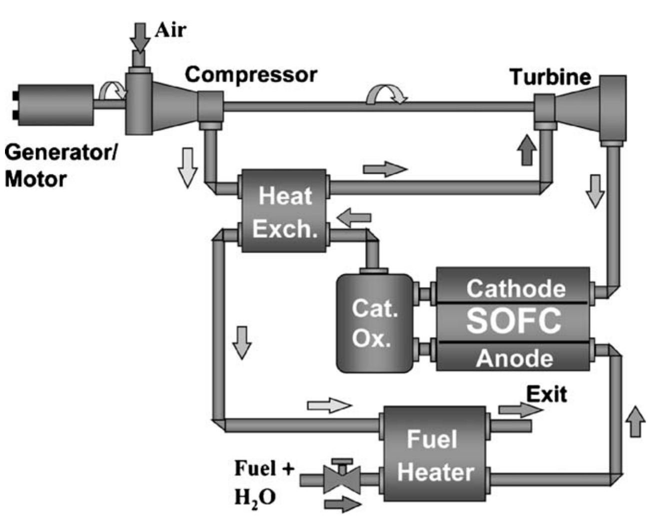

Fig. 1. Atmospheric SOFC/GT hybrid system.

Much work has been done by others in numerical transient modeling of FC/GT hybrid systems. At Inha University in Incheon, Korea, the integration of a tubular SOFC with an existing Solar Turbine's Mercury 50 gas turbine was presented [3]. Three scenarios of part load operation were compared to investigate which one was the most efficient. It was found that reducing the power of the SOFC and the gas turbine at the same time provided the highest system efficiency. Similar results were found at the University of Genova, Italy, where a SOFC/GT system with a pressurized SOFC was analyzed for design and part load performance. Two cases were presented: (1) fixed speed GT, and (2) variable speed GT [4]. The variable speed GT provided a more efficient and flexible system with respect to part load operation. Additionally, the variable speed GT provided more accurate control of the tubular SOFC stack temperature [4]. Typically large gas turbine engines are connected to the grid via mechanical gears and synchronous generators because of their lower rotational speed and the high efficiency and reactive power capabilities of such connections. Small gas turbine engines must operate at high rotational speeds to raise overall efficiency and are thus better suited to high-speed alternators, rectification, and inverter use in grid connections.

Use of advanced control concepts to improve the overall performance of fuel cell based power systems has been gaining progressively more attention. Often, the design of a control system is focused on deployment of controllers that address fast transient responses of the system; due to environmental changes (temperature or fuel composition) or for rapid load following. A typical hybrid power system often includes several components: reformers, heat exchangers, combustors, turbine, and fuel cell. Such a system is expected to operate over a range of operations (e.g., from 50% to 100%). For high performance, it is important that an appropriate combination of components and actuation/sensing mechanisms be chosen. This ensures that the system can operate smoothly and safely in the desired range, with adequate flexibility and with free capacity in the actuators. Additionally, high performance controllers can be designed to improve the transient behavior.

In this paper, we discuss how the overall system structure and control architecture is altered to improve the envelope of operation through use of different subsystems (e.g., cathode bypass or auxiliary combustor) or through different input/output pairings (e.g., fixed versus variable speed GT operation). The scope of this study is the application of linear controllers (proportional or proportional plus integral) to different control and system architectures. The bases of performance evaluation are comparisons of system efficiency and system balance of plant (BOP) simplicity. The overall goal is to determine whether use of a variable speed gas turbine is superior to using a gas turbine with constant (fixed) speed design with respect to minimum BOP, performance envelope, and system efficiency.

2. Approach

2.1. Solid oxide fuel cell and BOP models

Dynamic models have been developed to simulate the dynamic response of SOFC systems. Details of the dynamic models of system components including fuel cell, recuperator (heat exchangers), and catalytic oxidizer/combustor are described elsewhere [5–8]. An anode supported planar SOFC is assumed in this study. SOFC voltage–current characteristics were based on theoretical and semi-empirical loss terms, derived from the work of Kim et al. [9]. Additional internal resistance losses are incorporated to account for interconnects in the SOFC stack assembly when going from cell to stack performance.

2.2. Gas turbine model

The gas turbine is modeled as a compressor and turbine mechanically linked via a common shaft and thermodynamically linked to the fuel cell process via a heat exchanger. From first principles, the exhaust temperature for either compressor or turbine can be calculated:

$$T^{\text{out}} = f(T^{\text{in}}, P^{\text{in}}, P^{\text{out}}, \eta) \quad (1)$$

where T and P refer to temperature and pressure, and η is isentropic efficiency. Isentropic efficiencies for either compressor or turbine are found from constitutive equations:

$$\eta = g(n, T^{\text{in}}, P^{\text{in}}, P^{\text{out}}) \quad (2)$$

where n is compressor or turbine rotational speed.

These constitutive equations assume different forms depending on the approximation, e.g., linear in speed and parabolic in pressure ratio or linear in speed and linear in pressure ratio [10]. The unknown coefficients are determined via least squares parameter estimation using manufacturer's performance curves relating compressor and turbine inlet temperatures, pressure ratios, flow rates, and shaft speed. The model is completed by inclusion of the angular momentum equation for shaft inertia dynamics and a permanent magnet generator model with DC link [6].

3. Results

The SOFC/GT hybrid system is analyzed by performing load perturbations on the power demanded from the system. The power demand is ramped down from 100% to 50% total power of the SOFC/GT hybrid system. Two control schemes for the gas turbine are evaluated and presented below.

The total plant power, in this case study, is 350 kW corresponding to 100% of rated power and the power setpoint is ramped down at a rate of 3 kW min^{-1} to 175 kW (50% power). To maintain the desired power trajectory, the SOFC current density is manipulated to achieve zero tracking error.

In all cases, the fuel utilization across the SOFC is controlled to 85% via manipulation of the fuel flow. The utilization of 85% was chosen for higher system efficiency and lower catalytic oxidizer temperature, which is bound by material constraints in the recuperator. The actual fuel utilization is estimated from calculations utilizing the stack current and fuel flow with an assumed fuel composition.

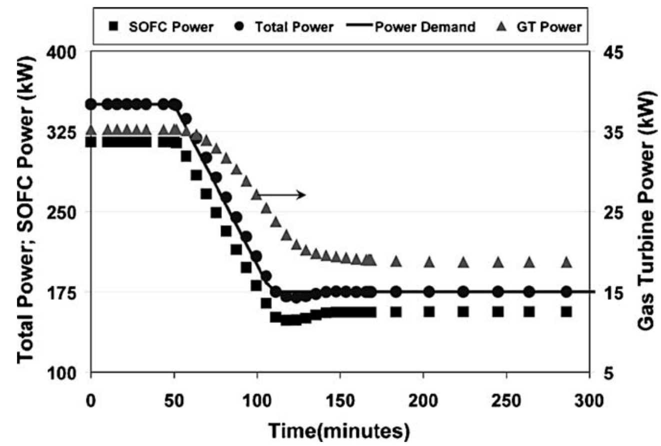

Fig. 2. Power demanded and produced by SOFC/GT hybrid system and components for fixed speed GT. Some lines are not visible in charts #2, 6, 10, and 13.

3.1. Fixed speed gas turbine operation

The base case is configured to have a gas turbine operated at fixed speed. Typically, large MW-scale gas turbines with synchronous generators are designed to operate at constant speed. Dual shaft microturbine generators with a free turbine and a generator assembly are also designed to operate at a constant speed. The generator load is manipulated to maintain constant gas turbine shaft speed.

3.1.1. Base case

The base system is presented in Fig. 1. The system is designed with a minimal number of actuators for the generator voltage, SOFC current density, and the fuel flow valve. Fig. 2 presents the total system power along with the SOFC and gas turbine power. The gas turbine power decreases from 35 to 18 kW as the turbine inlet temperature (TIT) decreases (see Fig. 3). All temperatures

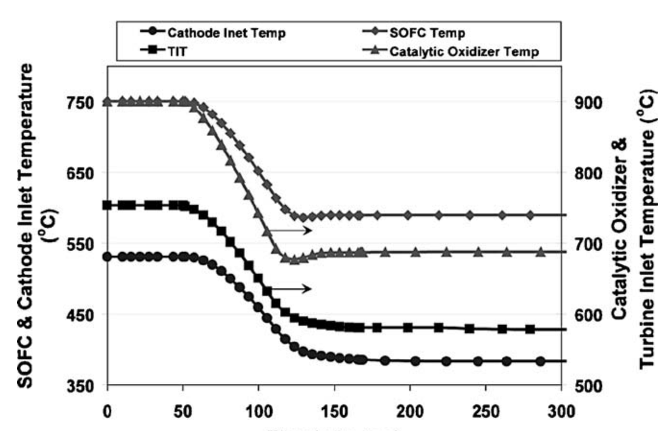

Fig. 3. Temperatures of SOFC, catalytic oxidizer, turbine and cathode inlet for fixed speed GT.

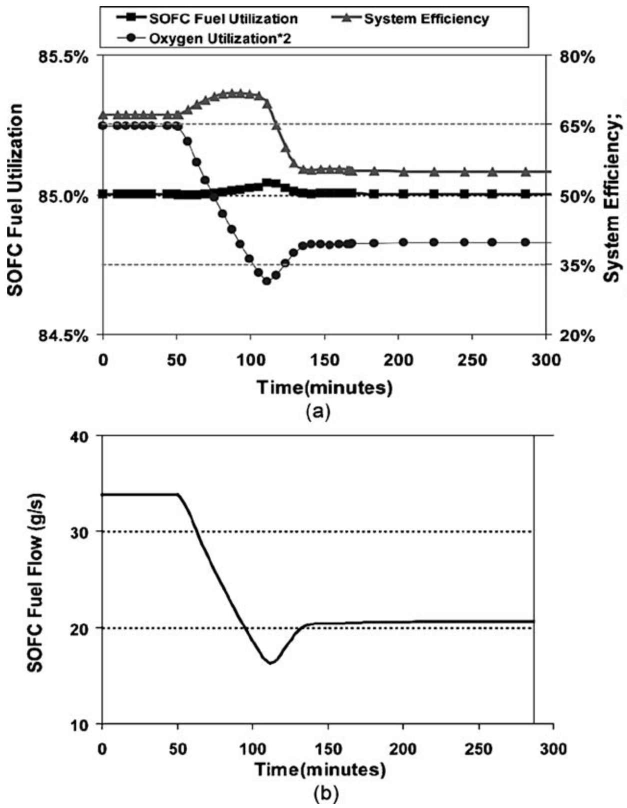

Fig. 4. (a) Fuel utilization and system efficiency, and (b) fuel flow for fixed speed GT.

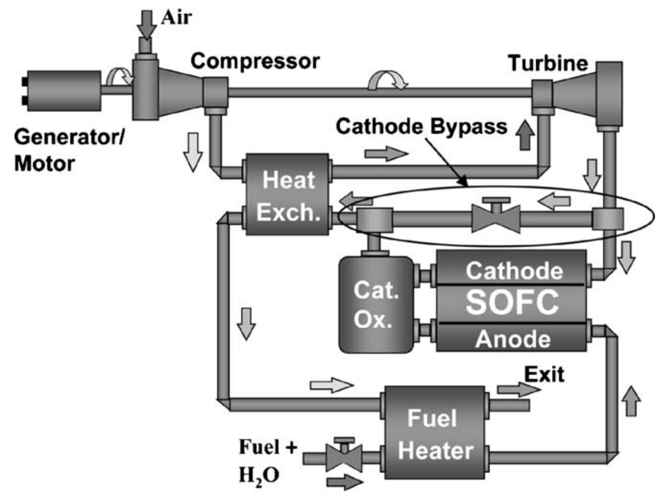

Fig. 5. SOFC/GT hybrid system with fixed speed GT and cathode bypass.

throughout the system dramatically decrease as the load demand decreases. Fig. 3 presents the TIT, catalytic oxidizer, SOFC, and cathode inlet temperature (CIT). The SOFC moves from its operating temperature of 750 to below 600 °C, which is below the allowable temperature for SOFC operation. The CIT drops below 400 °C, again, too cold for SOFC operation.

The fuel flow in Fig. 4b decreases as the SOFC power is decreased but it increases slightly after the power demand reaches 175 kW due to the increase in SOFC power. The SOFC power increases to make up for the drop in gas turbine power, which is delayed due to the thermal inertia in the system. The increase in fuel flow to the SOFC for the same overall system power production resulted in a reduction of system efficiency (see Fig. 4a). The gas turbine shaft speed is maintained at 90 kRPM via manipulation of the generator voltage (not shown). During the transient, the compressor mass flow will be maintained at or very near its initial value, as the rotational speed is kept constant.

Because the turbine is operated at constant speed, the compressor air mass flow cannot be manipulated. At low power demands, constant speed results in excess air mass flow (higher air-to-fuel ratio), which in turn results in a very low operating temperature for the SOFC. However, in practice, the fuel cell voltage increases as load demand decreases due to lower polarization and resistive losses. This results in less heat being generated by the fuel cell. Since less heat is produced, less air flow needs to be supplied to the fuel cell. Therefore, in contrast to the results of dynamic simulation at fixed turbine speed, it is desired to decrease the air-to-fuel ratio as the load demand from the system decreases to compensate for the reduction in heat generation. A fixed speed gas turbine alone cannot decrease the air-to-fuel ratio, but instead it increases the air-to-fuel ratio as demonstrated by the dynamic simulation case study. To increase the SOFC operating temperature at lower power demands, the mass flow to the cathode must be decreased and/or the CIT must be increased.

3.1.2. Cathode bypass

To manipulate the flow of air through the fuel cell and thus to control its temperature, a cathode bypass valve is added (see Fig. 5). This will allow reduction of mass flow through the SOFC, but will also result in a reduction of oxygen supplied to the SOFC and thus an increase of the oxygen utilization. The bypass valve was assumed to be limited to 80% or less of full flow rate.

Fig. 6 presents the total, SOFC, and gas turbine power. The gas turbine power is much lower than in the base case without the bypass. The lower gas turbine power is caused by a reduction in TIT (see Fig. 7). When mass flow is bypassed around the

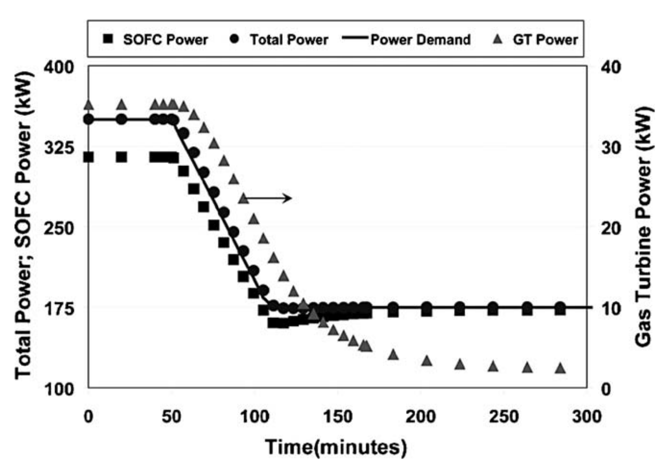

Fig. 6. Power demanded and produced by SOFC/GT hybrid system and components for fixed speed GT with cathode bypass.

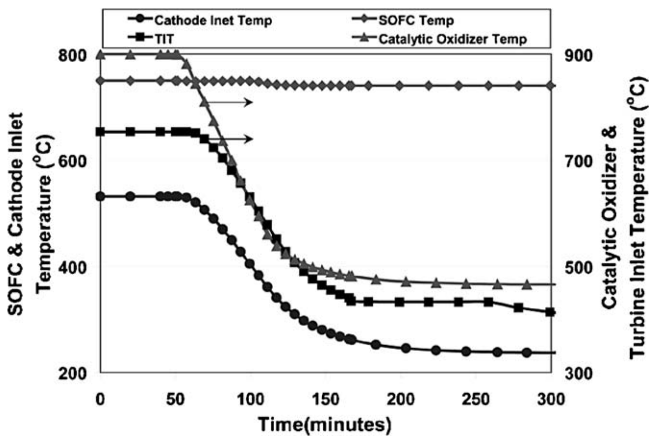

Fig. 7. Temperatures of SOFC, catalytic oxidizer, turbine and cathode inlet for fixed speed GT with cathode bypass.

SOFC, less heat is recuperated into the system resulting in a lower TIT than in the base case. In this design, stack temperature is maintained at the cost of a lower TIT. As is shown in Fig. 7, the CIT reaches extremely low values, which are lower than the desirable SOFC operating temperature.

The system efficiency increases initially during the ramp down in power (see Fig. 8a), but then decreases due to the low gas turbine power. Fuel utilization is maintained at 85% by the fuel flow controller as presented in the previous case. Despite the lower gas turbine output the system efficiency is higher than in the previous case. The higher efficiency is a result of more efficient operation of the SOFC. As before, the compressor speed and mass flow are maintained at the initial value before the transient.

The more efficient operation of the SOFC is attributed to the SOFC operating temperature being controlled close to 750 °C (see Fig. 8a) via manipulation of the cathode bypass fraction (see Fig. 8b). The bypass valve saturates, resulting in a small setpoint deviation for the SOFC temperature of 10 °C. The oxygen utilization is 80%, which is very high (see Fig. 8a) for SOFC operation on air. Typically, this would result in operating the fuel cell in a mass transfer controlled region, with very high cathode polarization. In this study, oxygen concentration effects on the Nernst potential are accounted for, but cathode polarization due to oxygen diffusion limits is only accounted for in a bulk concentration polarization term. Nevertheless, the result is of value because it illustrates that a cathode bypass by itself is not sufficient for proper system control.

3.1.3. High pressure auxiliary combustor

Instead of using a cathode bypass, a combustor is added to the high-pressure exit of the recuperator just before the turbine inlet (see Fig. 9) to maintain a high TIT and SOFC temperature. Raising the TIT will in turn raise the turbine exit temperature (TET) and thus the CIT, and the SOFC temperature. Therefore, fuel flow to the auxiliary combustor is manipulated to control SOFC temperature.

Total power, SOFC, and gas turbine power are presented in Fig. 10. Co-firing an auxiliary combustor before the turbine increases both CIT and TIT (see Fig. 11) in case of low power demands. The increase in the TIT increases the power output of the turbine. The gas turbine power increases during the entire ramp-down in power. This control scheme provides enhanced operation of the gas turbine.

The SOFC/GT hybrid system with co-fire has the lowest system efficiency (see Fig. 12a). Any time fuel is added to the combustor instead of the SOFC, there is a reduction in system efficiency.

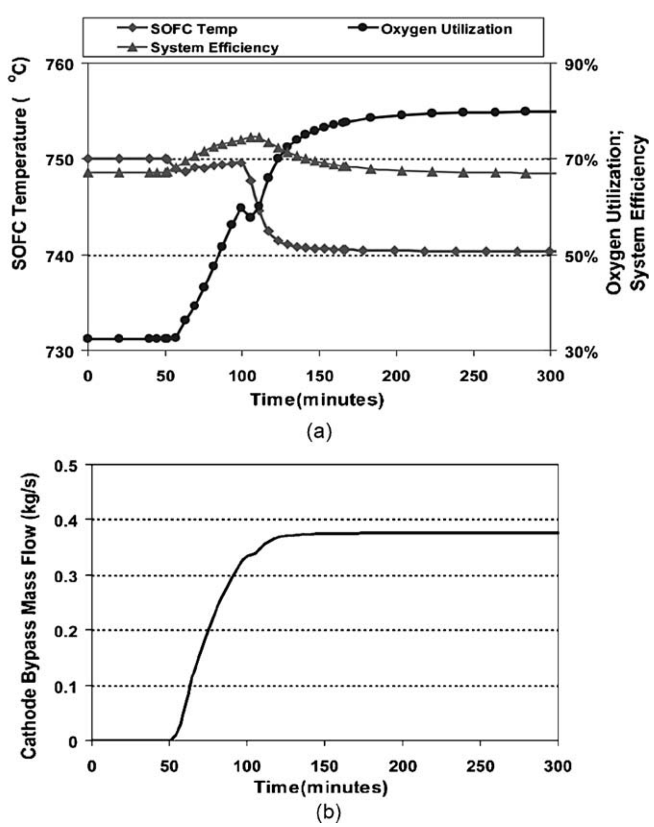

Fig. 8. (a) SOFC temperature, oxygen utilization, and system efficiency, and (b) cathode bypassed mass flow for fixed speed GT with cathode bypass.

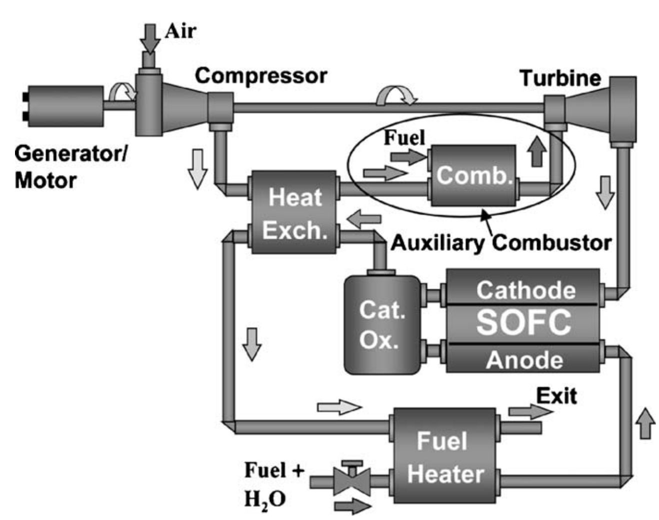

Fig. 9. SOFC/GT hybrid system with fixed speed GT with high-pressure auxiliary combustor.

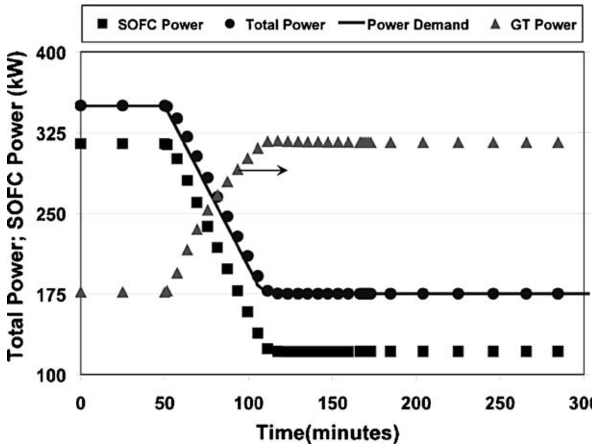

Fig. 10. Power demanded and produced by SOFC/GT hybrid system and components with high-pressure auxiliary combustor.

The SOFC operating temperature was maintained (see Fig. 12a). The corresponding fuel flow to the auxiliary combustor is shown in Fig. 12.

The auxiliary combustor is successful in maintaining the SOFC temperature and provides a good means to manage to the entire system thermally. The auxiliary combustor increases the gas turbine power. Also, the high air mass flow rate and high CIT will reduce the temperature gradients within the SOFC stack by reducing the change in air temperature through the cathode compartment. While successfully controlling the hybrid system, adding an auxiliary combustor leads to a less efficient system at lower power demands. Note, that the cathode bypass and auxiliary combustor can also be used simultaneously. This will increase the system efficiency to 58% compared to 53% if the auxiliary combustor is used by itself.

3.2. Variable speed gas turbine operation

From a careful examination of the simulation results for the previous cases, it is deducted that better control and higher performance can be achieved by reducing the mass flow through the system at lower power demands. A gas turbine capable of

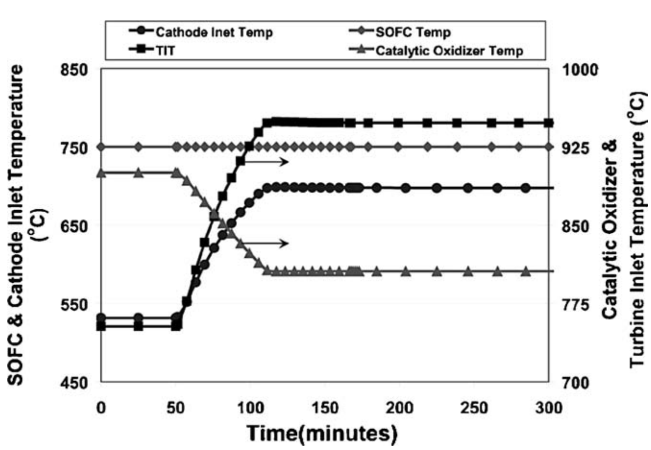

Fig. 11. Temperatures of SOFC, catalytic oxidizer, turbine and cathode inlet for fixed speed GT with high-pressure auxiliary combustor.

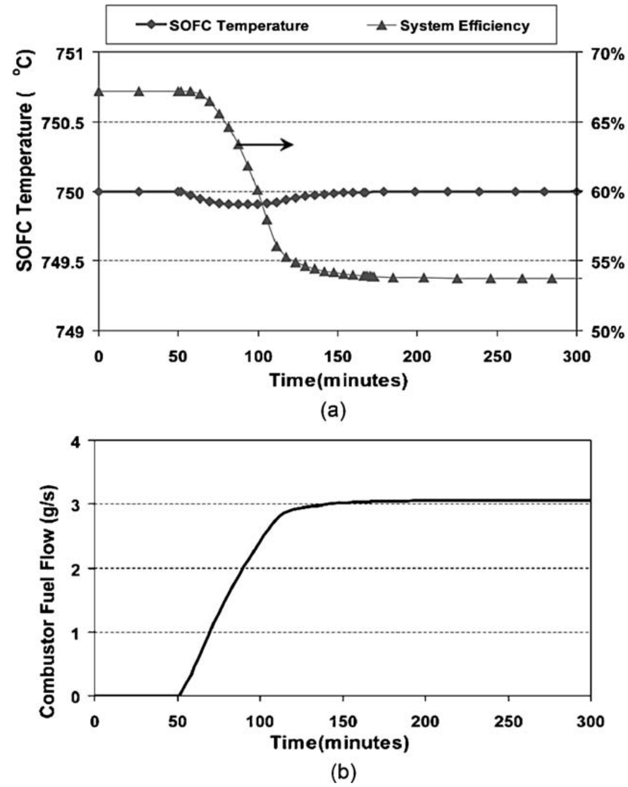

Fig. 12. (a) SOFC temperature and system efficiency, and (b) fuel flow to combustor for SOFC/GT with high-pressure auxiliary combustor.

variable speed operation is able to manipulate the mass flow through the system when needed and to resolve the operational problems encountered in the fixed speed operation. An example of a gas turbine with variable speed is a high-speed single shaft microturbine with a permanent magnet alternator. The system configuration is the same as presented in Fig. 1, but with a variable speed gas turbine.

Fig. 13 presents the load demand along with the power produced by the SOFC/GT hybrid and components. The gas turbine power becomes negative implying that it is consuming rather than producing power. This mode of turbine operation is often

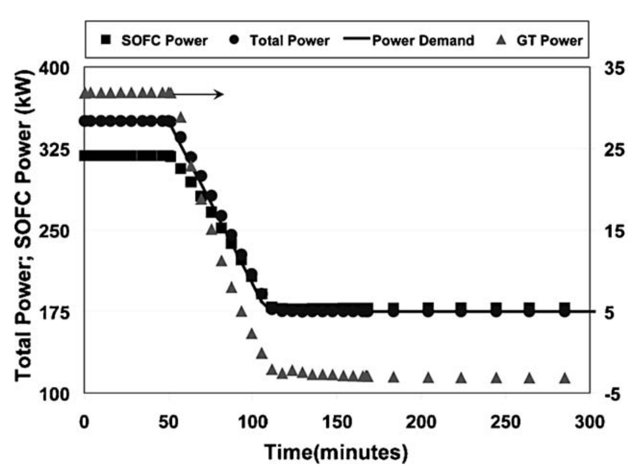

Fig. 13. Power demanded and produced by SOFC/GT hybrid system and components for SOFC/GT with variable speed GT.

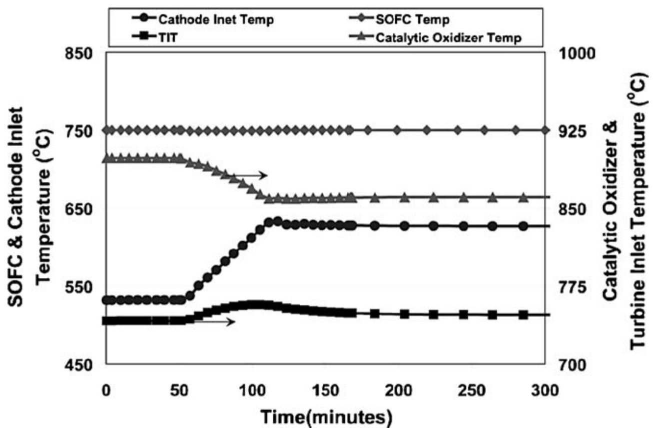

Fig. 14. Temperatures of SOFC, catalytic oxidizer, turbine and cathode inlet for SOFC/GT with variable speed GT.

referred to as "motoring" mode. The reason for motoring is that the heat recovered from the SOFC is not sufficient to overcome the power requirements for the air compression. Fig. 14 presents the temperatures of SOFC, catalytic oxidizer, turbine and cathode inlet. The catalytic oxidizer temperature decreases due to a lower amount of fuel in the anode off-gas and cathode mixture, despite the reduction in air flow rate. The TIT increases as the system power and compressor mass flow (Fig. 15a) decreases.

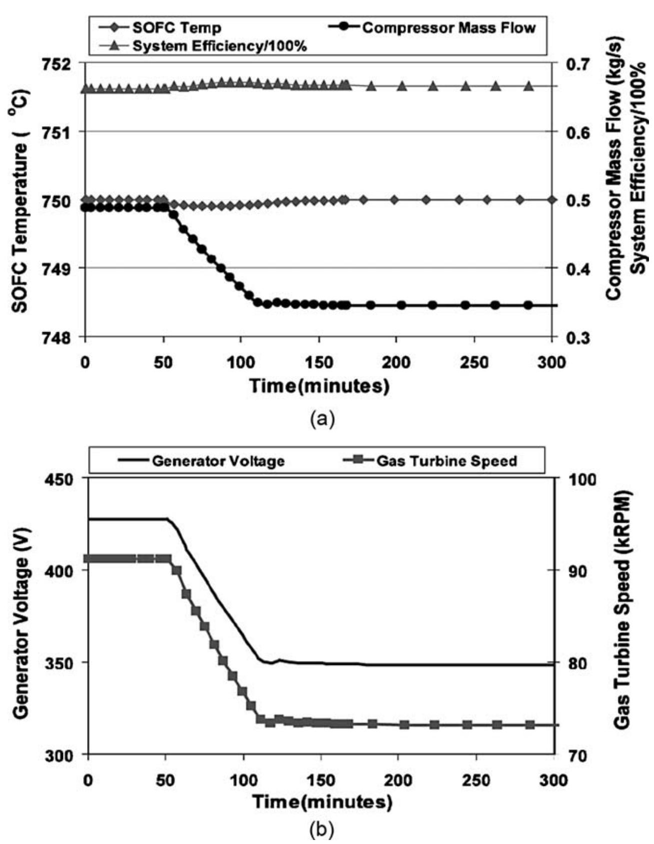

Fig. 15. (a) SOFC temperature, compressor mass flow, and system efficiency (b) alternator voltage and gas turbine shaft speed for SOFC/GT with variable speed GT.

The system efficiency remains at 66%, which is the highest efficiency among all cases (see Fig. 15a). Effectively, the SOFC temperature is maintained at 750 °C (see Fig. 15a) via manipulation of the gas turbine speed. Fig. 15b presents generator voltage and gas turbine speed. Via the generator voltage, the load on the gas turbine is manipulated to control the gas turbine speed. This influences the compressor mass flow (see Fig. 15a), which in turn affects the SOFC temperature.

As can be seen from these results, operation of the gas turbine at variable speed allows for full control of the FC/GT hybrid system. The SOFC operating temperature and cathode inlet temperature are maintained according to the design values and limits, and yet, the efficiency of the system is maintained at very high values. The system with a variable gas turbine offers a simpler and possibly less expensive alternative as compared to the systems with constant speed turbines.

4. Summary and conclusions

Four SOFC/GT hybrid system plant designs were presented with results of their transient behavior to a load demand change from 100% to 50% power. Three system designs operate the gas turbine with a fixed speed, and one system design operates the gas turbine with a variable speed. For the fixed speed cases, additional actuators (cathode bypass or auxiliary combustor) were required to maintain the SOFC operating temperature. A bypass valve was used in the fixed speed case for the cathode flow to reduce the mass flow entering the SOFC, but this resulted in an unacceptably high oxygen utilization in the cathode as well as a decreased recuperator temperature. The system with an auxiliary combustor did not provide an attractive solution to the fuel cell temperature control either, because it resulted in a less efficient system.

The variable speed gas turbine control design offers a straightforward system design that meets all operational constraints. In this system, additional actuators are not required to maintain the fuel cell temperature. Operating the gas turbine at variable speed not only provides sufficient control of the SOFC temperature, but it also increases the system efficiency. Albeit, during low power operations, motoring of the gas turbine is necessary. As was shown by Costamagna et al. [4], a variable speed gas turbine increases the efficiency and the range of operation of a pressurized fuel cell hybrid system. The results presented in this work arrive at the same conclusion for an atmospheric fuel cell hybrid system. The elimination of additional actuators in the SOFC/GT hybrid system will potentially reduce the system cost and increase the durability and reliability of the system.

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