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Authors

Mueller, Fabian
Tarroja, Brian
Maclay, James
et al.

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Design, Simulation and Control of a 100 MW-Class Solid Oxide Fuel Cell Gas Turbine Hybrid System

Fabian Mueller[1]
e-mail: fm@nfcrc.uci.edu

Brian Tarroja
e-mail: bjt@nfcrc.uci.edu

James Maclay
e-mail: jdm@nfcrc.uci.edu

Faryar Jabbari
e-mail: fjabbari@uci.edu

Jacob Brouwer
e-mail: jb@nfcrc.uci.edu

Scott Samuelsen
e-mail: gss@uci.edu

Department of Mechanical and
Aerospace Engineering,
National Fuel Cell Research Center,
University of California, Irvine,
Irvine, CA 92697

A 100 MW-class planar solid oxide fuel cell synchronous gas turbine hybrid system has been designed, modeled, and controlled. The system is built of 70 functional fuel cell modules, each containing 10 fuel cell stacks, a blower to recirculate depleted cathode air, a depleted fuel oxidizer, and a cathode inlet air recuperator with bypass. The recuperator bypass serves to control the cathode inlet air temperature, while the variable speed cathode blower recirculates air to control the cathode air inlet temperature. This allows for excellent fuel cell thermal management without independent control of the gas turbine, which at this scale will most likely be a synchronous generator. In concept the demonstrated modular design makes it possible to vary the number of cells controlled by each fuel valve, power electronics module, and recirculation blower, so that actuators can adjust to variations in the hundreds of thousands of fuel cells contained within the 100 MW hybrid system for improved control and reliability. In addition, the modular design makes it possible to take individual fuel cell modules offline for maintenance while the overall system continues to operate. Parametric steady-state design analyses conducted on the system reveal that the overall fuel-to-electricity conversion efficiency of the current system increases with increased cathode exhaust recirculation. To evaluate and demonstrate the conceptualized design, the fully integrated system was modeled dynamically in MATLAB-SIMULINK®. Simple proportional feedback with steady-state feed-forward controls for power tracking, thermal management, and stable gas turbine operation were developed for the system. Simulations of the fully controlled system indicate that the system has a high efficiency over a large range of operating conditions, decent transient load following capability, fuel and ambient temperature disturbance rejection, and the capability to operate with a varying number of fuel cell modules. The efforts here build on prior work and combine the efforts of system design, system operation, component performance characterization, and control to demonstrate hybrid transient capability in large-scale coal synthesis gas-based applications through simulation. Furthermore, the use of a modular fuel cell system design, the use of blower recirculation, and the need for integrated system controls are verified. [DOI: 10.1115/1.3207868]

Keywords: solid oxide fuel cell, modular design, blower recirculation, parametric analysis, integrated system control

1 Introduction

Solid oxide fuel cell (SOFC) gas turbine hybrid systems are an attractive emerging electrical power generation technology. A SOFC directly converts fuel to electricity, allowing the potential to generate power at higher efficiency than by conventional means, while providing clean and reliable electricity [1]. SOFC gas turbine hybrid technology is being developed by power companies with support from government programs and university research [2–6]. A recent focus is to develop large SOFC technology that operates on coal syngas to improve efficiency and emissions performance of coal-fired power plants and to reduce our dependence on more scarce fuels, such as natural gas, or imported fuels, such as liquefied natural gas (LNG), for power generation. For SOFC technology to be commercially competitive and to become a reality at the large scale required for coal-based systems, the technology will have to be cost effective, thermodynamically efficient, and operate robustly with some transient capability.

The goal of the present research is to design, simulate, and control a 100 MW-class coal syngas-based SOFC gas turbine hybrid system that can achieve high system efficiency and reject fuel composition and ambient temperature disturbances with transient capability in a design that can maintain operability during maintenance for improved reliability. The objective is to provide insights into effective system design and integrated system control. The approach is to use parametric analyses of the steady-state system design [7] and dynamic operation system modeling [8–13] to develop and demonstrate a system design and integrated system control strategy, which meet the goals of the study.

Prior simulation work in SOFC gas turbine hybrids has been focused on the area of system design or operation [7,14–21]; individual component understanding [13,22–27], as well as transient analyses and control development [9,12,28–38]. The effort here builds on prior work and combines the efforts in system design, system operation, component understanding, and control to demonstrate and understand the potential hybrid capabilities and limitations as applied to large-scale coal-based applications through simulation. In the process various simulation techniques, as well as novel system and control design concepts, are developed and explored.

2 System Design

2.1 Modular System Design Concept. The system must be designed and controlled to achieve high efficiency while operating

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[1] Corresponding author.

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reliably within operating constraint requirements. The operating requirements of SOFCs are very stringent and form challenging design criteria. Operating requirements will vary for different fuel cell systems, but a general set of requirements for fuel cell stacks and SOFC systems in general is presented below.

1. Fuel and oxidant cannot be depleted in any single fuel cell within the stack [36,38,39]. This is required in order to maintain fuel cell voltage, as well as to avoid oxidation and reduction in the electrodes. Fuel and oxidant utilization must be less than 95% and 35%, respectively.
2. Fuel should be sufficiently converted to a hydrogen-rich mixture before entering the fuel cell. The cell entrance electrochemical activity needs to be maintained and fuel quality needs to be sufficient to not degrade the fuel cell, for example, by coking. When operating on coal syngas, particulates that can block gas diffusion paths and corrosive elements and catalytic poisons must be removed prior to entering the cell.
3. The fuel cell operating temperature needs to be maintained [29,32,38] across the entire cell cross section. This is both to maintain ionic conduction of the electrolyte and corresponding electrochemical activity, as well as to avoid fuel cell degradation through thermal stresses.
4. Thermal stresses should be avoided to minimize mechanical failure of fuel cell materials. Convective cooling of the fuel cell by cathode air flow is required, but is constrained. The maximum temperature difference across the fuel cell must be less than 200 K [27,32,36,38,39].
5. Reasonable fuel cell voltage should be maintained at all times to avoid fuel cell degradation that can be caused by high local heat production rates [38,40].

In 100 MW-class planar SOFC gas turbine hybrid systems hundreds of thousands to millions of individual fuel cells must be used, depending on the size and performance of each cell. Each cell must have the proper amount of fuel and air, must operate at sufficiently less than the limiting current density, and must comprise temperatures that are maintained within operating requirements. It is critical that fuel, air, and current be as uniform as possible among each of the cells and that each cell operates within nearly the same operating constraints and conditions. However, not all cells will operate identically and air, fuel, current, temperature, and other parameter variations will exist within a well-designed operating system. The challenge is to assure that each system actuator, such as a valve, will sufficiently affect many cells, making it possible to manipulate the operating condition of individual cells using a limited number of actuators. More actuators can improve individual cell control and provide system control flexibility, but with added cost and system complexity. The number of cells controlled by each fuel valve and power electronics module can be readily adjusted; however, adjusting the air flow through sections of the system is more challenging especially when a single gas turbine is used for the entire system.

The desire to vary the number of cells controlled by a single air actuator and the ability to take some of the cells offline for maintenance while the system continues to operate motivated the modular system design that is presented in Fig. 1. The system configuration makes use of parallel fuel cell modules (in which the number of cells can vary in the design). The entire system contains only one single shaft gas turbine as an air source for the fuel cell. This gas turbine also generates additional electric power as a synchronous generator (constant shaft speed). However, individual air control valves and a recycle blower in each fuel cell module can manipulate each module air flow rate and cathode inlet temperature, which improves thermal management of the fuel cells. Individual or multiple fuel valves and power electronics can be applied within each module for improved controllability.

The tradeoff of this system design compared with designs with fewer modules and fewer actuators is that, although greater control is possible, the redundancy of system components will likely increase system costs. However, the nature of scaling fuel cell technology makes a modular design well-suited to fuel cell systems. The exact number of cells that each blower, fuel valve, and power electronics module controls can vary. It may be desired for each stack within a module to have its own power electronics or fuel valves. The desired number of cells that one should control with each actuator can only be determined by system developers for particular designs, since it is very challenging to determine the effects of manufacturing tolerances, dependability, reliability, and manufacturing quality control on the system performance. However the modular system approach is not only attractive, but required for all large fuel cell systems, making it possible to vary the number of cells each actuator controls. The modular approach also makes it possible for individual modules to be taken offline for maintenance while the system continues to operate. Thus, the current effort studies some general features of a modular design that could be applied to large fuel cell systems.

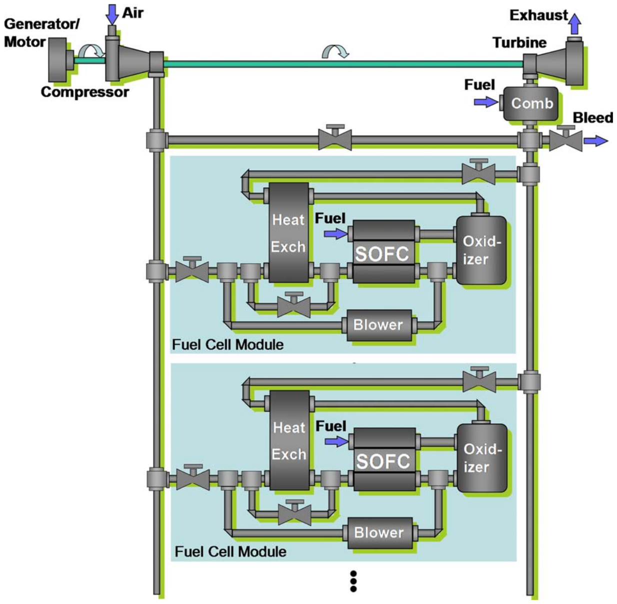

Fig. 1 Modular fuel cell hybrid system configuration

The fuel cell modules pictured in Fig. 1 were designed to operate efficiently within the operating requirements and constraints (presented above) for various compressor air flow rates (depending on the ambient temperature and the number of system modules online). For thermal management of the fuel cell at part load conditions, it is desired to manipulate both the cathode air flow rate and cathode inlet temperature [32]. Fuel cell temperatures are maintained by manipulating the air flow through the fuel cell. Blower recirculation makes it possible to re-utilize the proper amount of air to adjust the air flow through the fuel cell without manipulating the gas turbine speed. Heat exchanger bypass makes it possible to control the cathode inlet air temperature to minimize thermal stresses within the fuel cell. By manipulating the blower recirculation ratio and heat exchanger bypass, it is possible to maintain the required fuel cell air flow and cathode inlet temperature condition (for thermal management) for a range of compressor flow rates. This makes it possible to thermally manage the fuel cell at various power levels with a synchronous gas turbine generator.

In the system design it is assumed that a coal gasifier is integrated with the power block, providing a hydrogen-rich synthesis gas feed to the fuel cell. A combustor is placed before the turbine to maintain sufficiently high turbine inlet temperatures during start-up and low power conditions. In addition, the heat from the turbine exhaust can either be integrated into a bottoming cycle (e.g., steam cycle) or utilized in the gasification process [14,21].

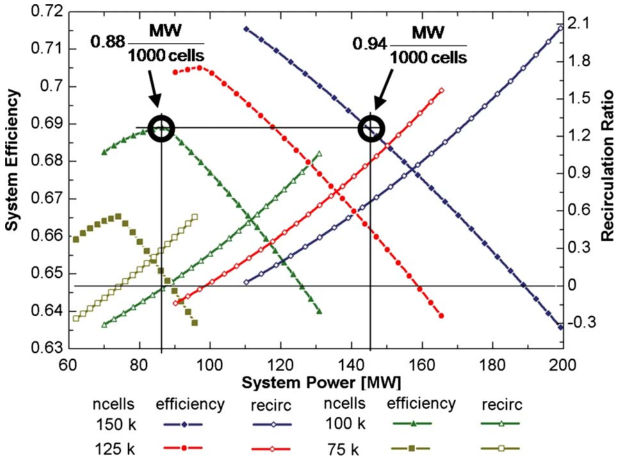

Fig. 2 System design parametric analysis

Neither the gasifier, the bottoming cycle, nor integration with such components is studied herein. Rather, the focus is on the hybrid system power block. As will be demonstrated, the system can achieve high efficiency and can be controlled to achieve transient load following capability, with ambient temperature and fuel variation disturbance rejection.

2.2 System Design Parametric Analysis. The system is designed to accommodate various amounts of fuel cell bypass air and blower recirculation. At the system design point it is desired to maximize fuel cell power and to avoid fuel cell bypass air. Bypass air will decrease the turbine inlet temperature and decrease efficiency. However, it is not straightforward to determine whether an increase in blower recirculation will increase or decrease the system efficiency. In fact, Zhang et al. [19] demonstrated cathode air recirculation will increase system efficiency, while Tarroja et al. [7], demonstrated cathode air recirculation will decrease efficiency. It is hypothesized that the efficiency effects of blower recirculation depend on the system configuration, as well as other parameters, such as fuel cell operating temperature, and blower and compressor efficiencies. Hence a steady-state system design parametric analysis on the cathode air recirculation ratio was conducted on the proposed system to maximize system efficiency as a function of cathode air recirculation ratio within the constraints presented above.

A steady-state system design parametric analysis of the system is presented in Fig. 2. The analysis was conducted in engineering equation solver (EES) by applying the model described in Ref. [7] to the current system configuration (see Fig. 1). It was assumed that the system operated on pure hydrogen, as would be the case for a gasifier that includes carbon separation for sequestration. In terms of modeling, the only difference in the present work compared with Ref. [7] was that the fuel cell surface area was increased, heat losses were removed, and a constant 10% pressure drop in the fuel cell stack was assumed. The system design approach was to set the compressor air flow rate, pressure ratio, and fuel cell utilization constant, as shown in Table 1. This was done so that one could design the overall system to use a single gas turbine engine driving a synchronous generator (at constant speed). The heat exchanger effectiveness was determined in order to achieve a 1000 K cathode inlet temperature, and the blower recirculation ratio was determined in order to achieve cathode and anode fuel cell exit temperatures of 1050 K. Using EES parametric analysis the number of fuel cells was iterated, and system efficiency was determined for a range of operating power by varying the fuel cell current density. Parametric analysis results of the system efficiency and depleted air recirculation ratio are presented in Fig. 2. Note that negative recirculation ratio indicates air bypassing the fuel cell (i.e., air bypass is equivalent to negative air flow through the blower).

Table 1 Important constants in the system design parametric analysis

Fuel cell module	
Fuel utilization	85%
Cell dimension	40×40 cm^2
Blower isentropic efficiency	85%
Gas turbine	
Compressor air flow rate	8 kmol/s
Pressure ratio	4
Compressor isentropic efficiency	79%
Turbine isentropic efficiency	84%
Anode inlet temperature	750 K
Cathode inlet temperature	1000 K
Fuel cell exit temperature	1050 K

With air recirculation it is possible to thermally manage a larger fuel cell for a given gas turbine air flow. The recirculation ratio increases with increased power because more air flow through the fuel cell is needed to reject the supplementary heat generated within the fuel cell at higher power. On the other hand, recirculation decreases the system efficiency for a given fuel cell size. However, a larger fuel cell (with more fuel cells) is always more efficient for a given power level. The increased number of cells results in an increased power range and higher efficiencies for a given power level as fuel cells operate more efficiently at lower current density.

The most interesting result is that blower air recirculation makes it possible (in the given configuration) to raise the system power per fuel cell at a given efficiency. Considering the maximum system efficiency of 100,000 cells (i.e., no bypass or recirculation), a larger system at the same efficiency with some blower recirculation will be generate more system power per cell at the same efficiency. As shown in Fig. 2, the system power per cell for the peak efficiency of 100,000 cells is 0.88 MW per 1000 cells, while at 150,000 cells for the same system efficiency the system power per cell is 0.94 MW per 1000 cells. While recirculation always decreases efficiency for a given fuel cell size for a constant air flow rate, blower air recirculation could potentially allow the integration of a larger fuel cell with maintained system power per cell, resulting in a system efficiency increase.

The number of cells, which can be integrated into a system with a given compressor air flow rate is limited by the ability to control the cathode inlet air temperature by bypassing air around the heat exchanger. As more air is recirculated less air preheat is required from the heat exchanger until the point where no heat exchanger is needed and control of the cathode inlet temperature is lost.

Increasing blower recirculation results in increased parasitic losses. However, by recirculating more of the cathode stream it is possible to increase the fuel cell to gas turbine power ratio, resulting in a system efficiency benefit because the fuel cell is more efficient than the gas turbine. In addition, by recirculating more of the cathode stream the combustor and turbine inlet temperatures increase. Increased turbine inlet temperature further increases the turbine efficiency helping to increase the overall system efficiency. Careful consideration must be taken with the depleted fuel combustor as the combustor temperature tends to increase with increased recirculation. Overall, a system efficiency tradeoff exists between the blower parasitic loss and an efficiency gain due to larger fuel cell to gas turbine power ratios and increasing turbine inlet temperature. Depending on the system configuration and operating parameters, it appears that blower recirculation can both increase and decrease system efficiency.

The use of blower recirculation in addition to potential efficiency benefit makes it possible to effectively control the air flow through the fuel cell without needing to manipulate the compressor air flow. This makes it possible to use the same fuel cell

Table 2 Constants in the system dynamic parametric analysis

Fuel cell module	
No. of modules	70
No. of stacks per module	10
No. of cells per stack	250
Cell dimensions	40×40 cm
Blower isentropic efficiency	85%
Gas turbine	
Shaft speed	3600 rpm
Comp. design speed	3800 rpm
Comp. design inlet temperature	298 K
Comp. design pressure ratio	6.5
Comp. design isentropic efficiency	85%
Comp. design mass flow rate	360 kg/s
Turbine design speed	3600 K
Turbine design inlet temperature	980 K
Turbine design pressure ratio	6
Turbine design isentropic efficiency	85%
Turbine design mass flow rate	339 kg/s

module in large 100 MW-class centralized systems or smaller multiple megawatt systems for distributed generation. In large systems, it is desired to use synchronous generators where control of the compressor air flow is more challenging than with variable speed turbines. Use of a recirculation blower in these large systems makes it possible to effectively manage fuel cell temperatures without varying the compressor inlet air. For large-scale systems multiple modules can be integrated with a single synchronous gas turbine, while a few modules can be integrated with a smaller variable speed gas turbine for distributed generation applications. Simulation results indicate system efficiencies greater than 65–70% can be achieved in large systems with cathode air recirculation (see Fig. 2).

3 Detailed System Operation Analyses

3.1 Steady-State System Operation Analysis. With an effective system design, a dynamic model of the integrated system was developed to characterize the steady-state system operation, as well as to develop and demonstrate transient capability and disturbance rejection of the controlled system. In the steady-state design analysis the isentropic efficiencies of the compressor and turbine were maintained at constant values regardless of the gas turbine operating conditions. In the dynamic model gas turbine performance maps were used to capture system operation impacts on the gas turbine. By using gas turbine performance maps and resolving each system state, the effects of varying operating pressure and turbine inlet temperature on gas turbine efficiency are captured. Hence the dynamic system operating characteristics will be different than those of the system design analysis where the gas turbine efficiency performance is kept constant.

The dynamic modeling methodology utilized herein has been used to develop models that compare well with single cells undergoing dynamic transients [13], as well as integrated simple cycle SOFC systems [9], SOFC/GT hybrid systems [18], and proton exchange membrane stationary fuel cell systems [41]. Furthermore the modeling methodology has been used to investigate integrated fuel cell controls [8,9,11,12,35,42]. Because the modeling methodology and equations have been previously presented [8,9,11–13,18,35,37,41–45], the model will only be briefly summarized here.

The model is based on the physics and chemistry that govern the fuel cell system, and is developed by resolving conservation of mass, energy, and momentum principles, with corresponding electrochemistry, chemical kinetics, heat generation, and heat transfer. Each of the primary system components (SOFC, compressor, turbine, oxidizer, heat exchangers, and blower) are modeled individually and integrated to form the system. The flow between each of the components is resolved for molar flow rate, species mole fraction (CH_4, CO, CO_2, H_2, H_2O, N_2, and O_2), temperature, and pressure. In this fashion dynamics of individual components and interactions among system components are captured to simulate the system dynamic response.

The simplifications employed in this case include a quasidimensional approach for resolving geometrical features of the heat exchanger and fuel cell. Components are spatially discretized using control volumes. Resulting time ordinary differential equations for each control volume are then solved using SIMULINK® stiff differential equation solver ODE 15s. Within each control volume only the physical and chemical processes that affect the time scale of interest in the dynamic simulation are considered (>10 ms). Processes, such as electrochemical reaction rates and electric current flow dynamics, are assumed to occur at a time scale that is faster than that of interest to the model. Conservation equations and chemical kinetics are applied to each control volumes. Transport phenomena, such as heat transfer and ion and fluid flow, are then resolved between control volumes. Details regarding model constants and system configuration are presented in Table 2. A more complete description of the modeling approach is presented in Ref. [42] with additional details presented in Ref. [43].

The full steady-state system performance for a large range of power from 60 MW to 170 MW is presented in Fig. 3. It is assumed that ambient temperature is constant at 298 K. In the

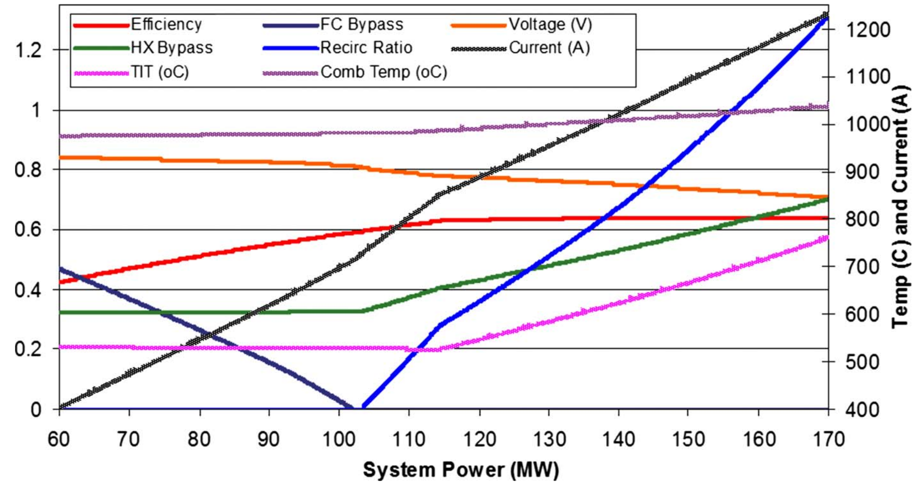

Fig. 3 Steady-state system performance (70 fuel cell modules with an ambient temperature of 298 K)

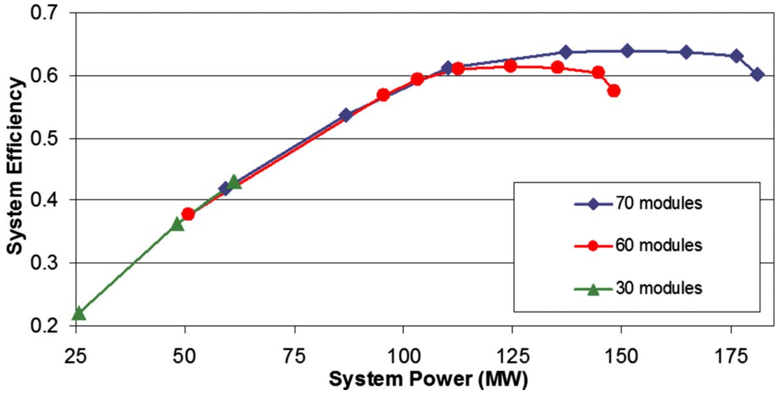

Fig. 4 Impact of the number of fuel modules on system efficiency versus system power

system performance simulation, the fuel cell power is manipulated by varying the fuel cell current. The fuel utilization was maintained at 80% by varying a current-based-fuel-controller [9], the cathode inlet temperature was maintained at 1000 K by manipulating the recuperator bypass valve, and the cathode air outlet temperature was maintained at 1150 K by manipulating the blower recirculation until the blower power saturated at zero, at which point the fuel cell exit temperature was controlled by bypassing the air around the fuel cell modules. The simulation indicates blower recirculation is effective at controlling the fuel cell temperature in a power range from about 105 MW to 170 MW. In the operating range in which blower recirculation provides thermal management, the system efficiency remained nearly constant near 64% lower heating value. The system efficiency decreased when compressor air bypasses the fuel cell, also a means of thermal management, as supplementary fuel must be burned in the gas turbine combustor to maintain the turbine inlet temperature to ensure positive gas turbine power (at low power the compressor power demand may become greater than the power generated in the turbine). This further indicates the effectiveness of blower recirculation and makes it the preferred method of thermal management between the two control strategies.

As blower recirculation increases, both combustor and turbine inlet temperatures increased. To maintain the cathode inlet temperature the heat exchanger bypass increased with increased blower recirculation. The number of fuel cells that can be integrated with a given compressor flow rate is limited by the ability to control the cathode inlet air temperature. At high recirculation ratios recirculation alone provides sufficient heat to preheat the inlet air causing an inability to use heat exchanger bypass to control the cathode inlet temperature.

The system can operate over a wide power range with different numbers of modules online. Figure 4 shows system efficiency versus power for 30, 60, and 70 modules online. The system can operate with varying amount of modules online; however, the system is most efficient with the full 70 modules online. With more modules offline the system efficiency, as well as the maximum system power, decreases. The near linear overlap region of Fig. 4 is due to compressor air bypassing the fuel cell module. In this region the system efficiency is essentially independent of the number of modules online for a given system power. The flat region in the 70 and 60 module case is where blower recirculation is used to control the fuel cell temperature. During operation it is likely that only a few modules will need to be taken offline at any particular time, in which case the system efficiency and maximum system power could be nearly maintained.

3.2 Integrated Control Development. Prior work [8,11,12,35,38,42,43] has demonstrated through simulation that with proper control, SOFC systems can be developed to have significant transient load following capability and disturbance rejection. In this section transient load following and disturbance rejection controls are developed based on the controls presented in Ref. [12,42] for the conceptualized system. Overall, the control system contains six primary controllers: (1) fuel cell current/combustor temperature controller, (2) fuel cell fuel flow/system power tracking controller with a current governor, (3) heat exchanger bypass/cathode inlet temperature controller, (4) blower recirculation and fuel cell module bypass/fuel cell temperature controller, (5) air bleed/compressor surge controller, and (6) supplementary combustor fuel/gas turbine inlet temperature controller. The controls developed are demonstrated in Sec. 3.3.

In the developed control system, the fuel cell current is used to control the flow of fuel cell depleted fuel, which directly affects combustor temperature. The combustor temperature is also affected by the compressor air flow, extent of recirculation, and fuel flow. It is possible to control the combustor temperature by either manipulating the fuel cell fuel flow or the fuel cell current. Since the fuel cell fuel flow is being provided by a coal gasifier, the response time of the fuel flow is expected to be slow. Therefore, the fuel flow controller will not likely be able to maintain the combustor temperature during load transients. Consequently, to maintain the system within operating constraints, the combustor temperature is controlled by manipulating the fuel cell current. This is possible because the amount of fuel entering the combustor can be independently manipulated by consuming more or less fuel in the fuel cell by changing the fuel cell current, which can be manipulated rapidly [42]. The implemented fuel cell current/combustor temperature controller is presented in Fig. 5.

The system power is tracked by varying the fuel cell power by manipulating the system fuel flow. Controlling the fuel cell power through fuel flow is more sluggish than control by manipulating the current, however, it is necessary to maintain safe operating conditions at all times at the cost of transient performance. Feedforward manipulation in the combustor temperature controller will increase the current and fuel flow simultaneously, increasing power. Slight offsets in power will be rejected by fuel flow ma-

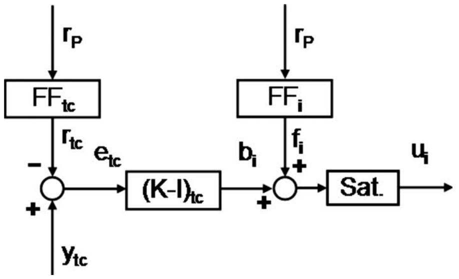

Fig. 5 Fuel cell current/combustor temperature controller

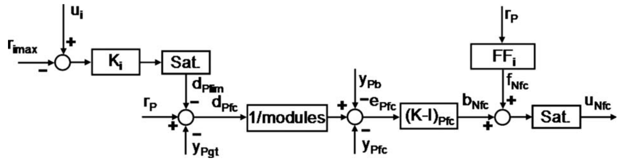

Fig. 6 Fuel cell fuel flow/system power controller with a maximum current governor

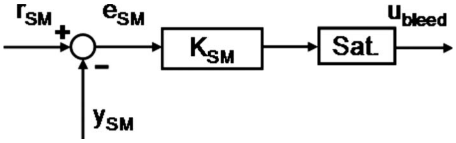

Fig. 8 system bleed surge protection controller

nipulation based on power feedback. Combustor temperature variations, during transients and during disturbances, will be maintained by fuel cell current manipulation based on combustor temperature feedback. However, the fuel cell current is limited, and a current reference governor on power demand must be implemented into the power controller to avoid the current from saturating, in which case the combustor temperature control will be lost. The fuel flow/fuel cell power controller implemented in the system model is presented in Fig. 6. A current governor is integrated with this controller.

The fuel cell temperature is controlled by manipulating the amount of air through the fuel cell. The cathode inlet air temperature is controlled by bypassing more or less flow around the cathode air recuperator using a simple feedback and feed-forward controller with constant feedback gain, as shown in Fig. 5. The amount of air through the fuel cell is manipulated without controlling the gas turbine by either bypassing air around the fuel cell if the compressor air flow rate is too large or by recirculating cathode depleted air using a blower if the compressor air flow rate is too low. To avoid loop interaction between the blowers and the bypass, the fuel cell temperature set point in the bypass controller is set at 1149 K and the fuel cell temperature set point in the blower controller is 1150 K. In this fashion, the fuel cell temperature will be controlled by the blower until the blower power saturates at zero, at which point the fuel cell temperature will be controlled by bypassing air around the fuel cell modules. Manipulating the recirculation blower speed to control the fuel cell temperature is similar to the fuel cell thermal management implemented in Ref. [12] with the compressor air being essentially a necessary disturbance on the fuel cell air flow rate in terms of temperature control. Note that both the fuel cell bypass and blower fuel cell temperature controllers are in the form of simple feed-forward with constant proportional feedback control.

The gas turbine operates at 3600 rpm. The power balance between the turbine and compressor is modeled as generator power. While the compressor is not manipulated directly to control the fuel cell temperature, it is necessary that the compressor does not surge. Surge of the compressor must be avoided at all costs, as surge will result in oscillations that can severely damage the gas turbine, as well as the fuel cell. Compressor surge can be a problem when ambient temperature varies due to density effects on the compressor flow rate. It is possible to avoid surge by bleeding pressurized air to reduce the pressure of the system. Bleed of pressurized air results in efficiency loss and is not desired but may be required to avoid surge. Before pressurized air bleed manipulation can be implemented to prevent surge, a technique must be developed to detect surge and quantify the distance from the surge margin. Using compressor performance maps, along with knowledge of compressor shaft speed, pressure ratio, and compressor inlet temperature; it is possible to quantify the surge margin. From the pressure ratio and gas turbine shaft speed it is possible to use the compressor map to obtain the compressor flow rate. From this information it is possible to evaluate the surge margin (SM), as shown in Fig. 7 from a linear surge line using simple trigonometry expressed in the equations below

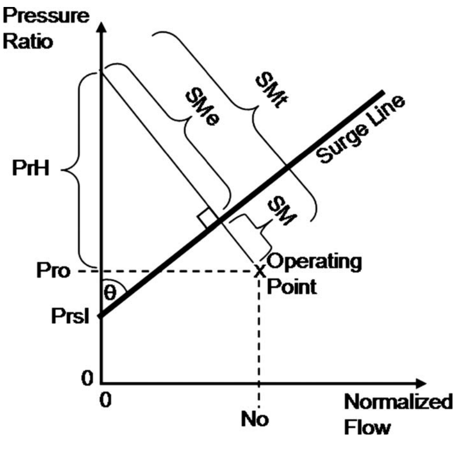

Fig. 7 Geometric representation of the evaluation of surge margin

$$\mathrm{SM}t = \frac{No}{\cos\,\theta} \tag{1}$$

$$\mathrm{Pr}H = No \cdot \tan\,\theta \tag{2}$$

$$\mathrm{SM}e = (\mathrm{Pr}H + \mathrm{Pr}o - \mathrm{Pr}sl) \cdot \sin\,\theta \tag{3}$$

$$\mathrm{SM} = \mathrm{SM}t - \mathrm{SM}e \tag{4}$$

where SM is the surge margin, No is the normalized flow, Pro is the pressure ratio, and Prsl is the linear surge line pressure ratio at zero normalized flow. With the surge margin quantified, a proportional controller, as shown in Fig. 8, can be used to bleed compressed air to avoid surge. Saturation is used such that the bleed output is only positive. This control approach starts using compressed air bleed once the surge margin becomes less than a reference value (r_{SM}).

In addition to avoiding surge, the gas turbine power must always be positive. At low power, when the turbine inlet temperature tends to decrease due to fuel cell bypass, the turbine will not make enough power to drive the compressor without supplementary combustor fuel. Therefore a supplementary combustor fuel/gas turbine power/turbine inlet temperature cascade controller was implemented in the system, as shown in Fig. 9. The controller controls the turbine inlet temperature by manipulating the supplementary fuel flow at the turbine inlet combustor such that the gas turbine power does not become negative. The controller makes use of saturation and a dead zone, where the block output is zero unless the gas turbine temperature error is greater than 20 K. If the turbine inlet temperature error is greater than or equal to 20 deg, the zone output is the input minus 20 deg. If the turbine inlet

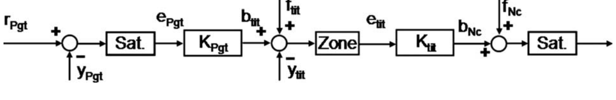

Fig. 9 Supplementary combustor fuel/turbine inlet temperature/gas turbine power cascade controller

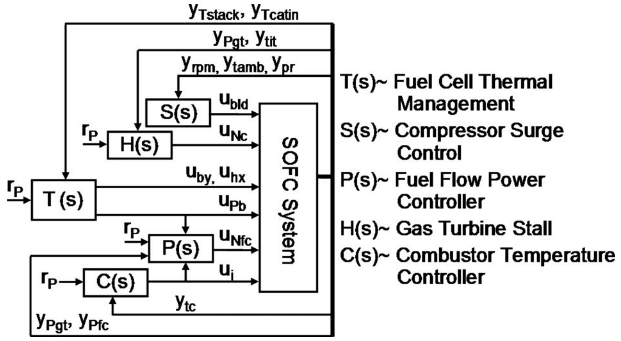

Fig. 10 Integrated system controller

Table 3 Integrated system controller constants

Fuel cell current combustor temperature controller		
K_{tc}	10 A/K	Temperature proportional feedback gain
I_{tc}	0.005 A/K	Temperature integral feedback gain
Sat.	0–1405 A	Current saturation
System power control with maximum current governor		
r_{imax}	1325 A	Maximum individual cell current
K_i	75 kW/A	Governor proportional feedback gain
K_{Pfc}	0.02 kmol/kW s	Power proportional feedback gain
I_{Pfc}	1×10^{-4} kmol/kW s	Power integral feedback gain
SAT_i	>0 kW	Reference power saturation
SAT_{Nfc}	0–1 kmol/s	Module fuel flow saturation
System bleed compressor surge protection controller		
r_{SM}	0.05	Reference surge margin
K_{SM}	10	Surge margin feedback proportional gain
SAT	0–0.75	Bleed saturation
Heat exchanger bypass cathode inlet temperature controller		
$r_{T\ catin}$	1000 K	Reference cathode inlet temperature
$K_{T\ catin}$	0.05 1/K	HX bypass proportional feedback gain
$I_{T\ catin}$	5×10^{-4}	HX bypass integral feedback gain
Blower recirculation fuel cell thermal controller		
$r_{T\ stack}$	1150 K	Reference fuel cell stack temperature
$K_{T\ stack}$	100 kW/K	Module blower power proportional feedback gain
SAT	>0.1 kW	Module blower power saturation
Fuel cell bypass fuel cell thermal controller		
$r_{T\ stack}$	1149 K	Reference fuel cell stack temperature
$K_{T\ stack}$	0.5 1/K	Module bypass proportional feedback gain
SAT	0–0.85	Module bypass saturation
Gas turbine controller		
r_{Pgt}	0.2 MW	Minimum gas turbine power
K_{Pgt}	1000 K/MW	Gas turbine power proportional feedback gain
K_{tit}	0.01 kmol/K s	Turbine inlet temperature proportional gain
Zone	±20 K	Turbine temperature error dead zone
SAT_{Pgt}	0–1	Gas turbine power error saturation
SAT_{Nc}	$>1\times10^{-7}$	Supplementary fuel saturation

temperature error is less than or equal to -20 deg the zone output is the input plus 20 deg. This helps minimize the amount of unnecessary supplementary combustor fuel used during transient operation.

All six of the controllers were implemented into the system using steady-state data from 80% fuel utilization operation at 298 K ambient temperature. Feedback is used to reject disturbances and to maintain the system within operating constraints during load transients. A summary of the complete control system is presented in Fig. 10, illustrating the control loops used in the system. Control constants used in the transient simulations are presented in Table 3 for all the control loops.

3.3 Transient System Evaluation.

To evaluate the system transient load following and disturbance rejection capabilities, the integrated system simulated response to a power demand increase and decrease was investigated under constant ambient temperature and fuel composition conditions. The system simulated response to a variable demand with variable diurnal ambient temperature and variable fuel composition was then further evaluated.

The system response to a power demand increase from 60 MW to 170 MW at 2 MW/s is presented in Fig. 11. A relatively slow ramp rate was considered such that the fuel flow increase was not too rapid. In this case the system power was tracked except for the last 20 MW, where the power demand was limited by the fact that maximum fuel cell current was reached. The tracking error was caused by the blower power demand on the fuel cell in addition to the system power demand. The blower power demand overshoots its steady-state condition due to the inertia of the blower. Once the blower power demand decreased the system power was tracked.

The system response to a load decrease from 170 MW to 60 MW at 2 MW/s is presented in Fig. 12. In the simulation the power decrease was well tracked. In the load increase and decrease simulations, the combustor, turbine inlet, and fuel cell temperatures were well maintained. The fuel cell temperature was maintained within 2 deg using fuel cell module bypass and variable blower recirculation demonstrating effective thermal control of the system. The system avoided the surge margin, and the gas turbine power remained positive. The fuel cell voltage remained high indicating sufficient fuel remained within the fuel cell and that current did not become excessive. The conceptualized system with implemented feed-forward feedback type control was capable of following significant loads.

In the field, SOFC systems will have to follow loads during ambient temperature and perhaps fuel composition variations. The transient capability of the current system has been evaluated for power ramps without disturbances. However, the feedback used in the current control system development should be able to reject disturbances during transients, as well as disturbances in ambient temperature and fuel composition. To further evaluate the conceptualized system, the transient load, fuel hydrogen concentration, and ambient temperature were perturbed, as shown in Fig. 13. Simulated system responses for these perturbations are presented in Fig. 14. The system power demand was tracked within approximately 20 MW during each of the transient power demand perturbations. At high ambient temperature gas turbine power was lost, and the system was not capable of tracking high system power demand because the fuel cell was not able to make up for all of the lost gas turbine power. Due to integral power feedback, the system power was tracked at steady state as long as the fuel cell current did not saturate.

During the transients and significant disturbances the fuel cell temperature was maintained within 2 K, showing effective control of the fuel cell temperature. The combustor and turbine inlet temperatures were well maintained within operating requirements. The amount of fuel within the fuel cell and the fuel cell voltage was well maintained indirectly by controlling the combustor temperature. Overall, the dynamic system simulation demonstrates that the designed system has substantial transient capability and can be controlled to operate within operating constraints during significant power demand perturbations with disturbances in fuel and ambient temperature.

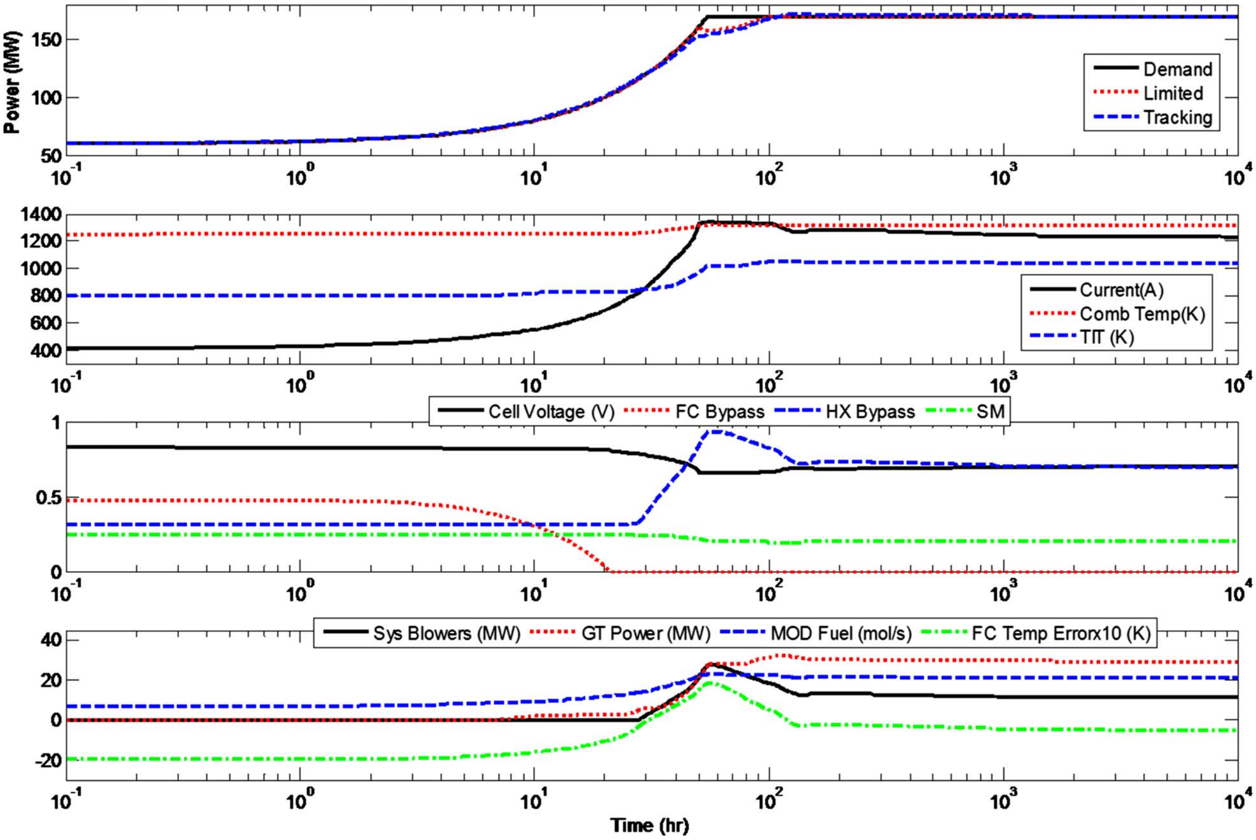

Fig. 11 Controlled system simulation of a 2 MW/s 60–170 MW load increase

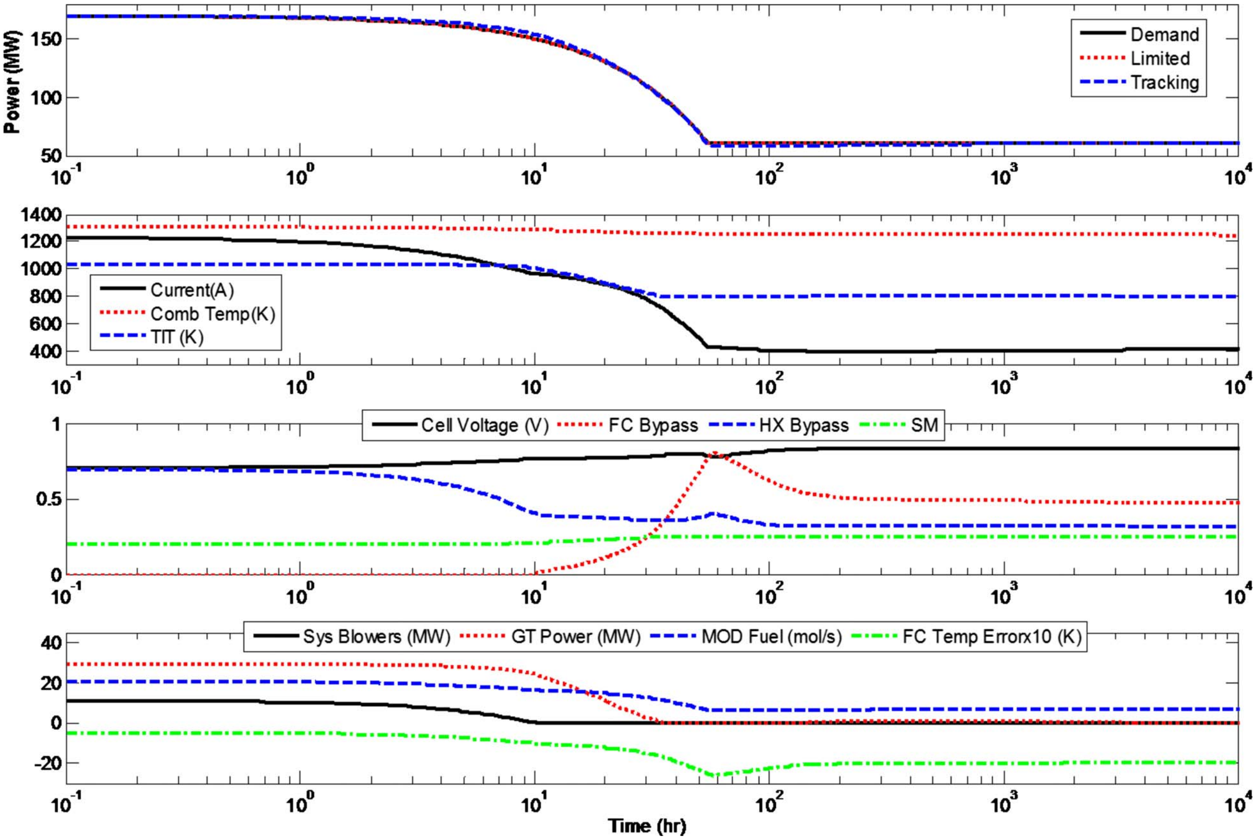

Fig. 12 Controlled system simulation of a 2 MW/s 170–60 MW load decrease

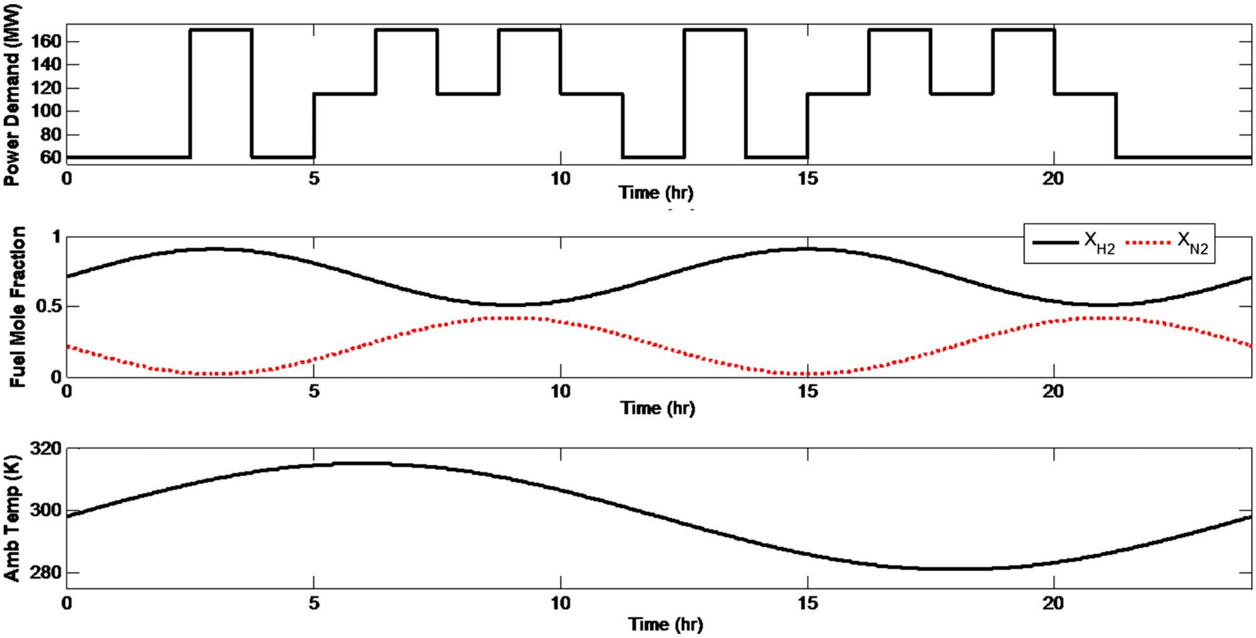

Fig. 13 Simulated load demand, fuel variation, and ambient temperature diurnal variation

4 Summary and Conclusion

A 100 MW-class solid oxide fuel cell synchronous gas turbine hybrid system with operational system efficiencies exceeding 60% has been conceptualized, simulated, and demonstrated to have significant transient load following and disturbance rejection capability with implemented controls. The system concept was developed for high efficiency, performance, and reliability at an operating scale compatible with coal-based systems. The effort demonstrates the following:

(1) the use of blower recycle to increase the system efficiency

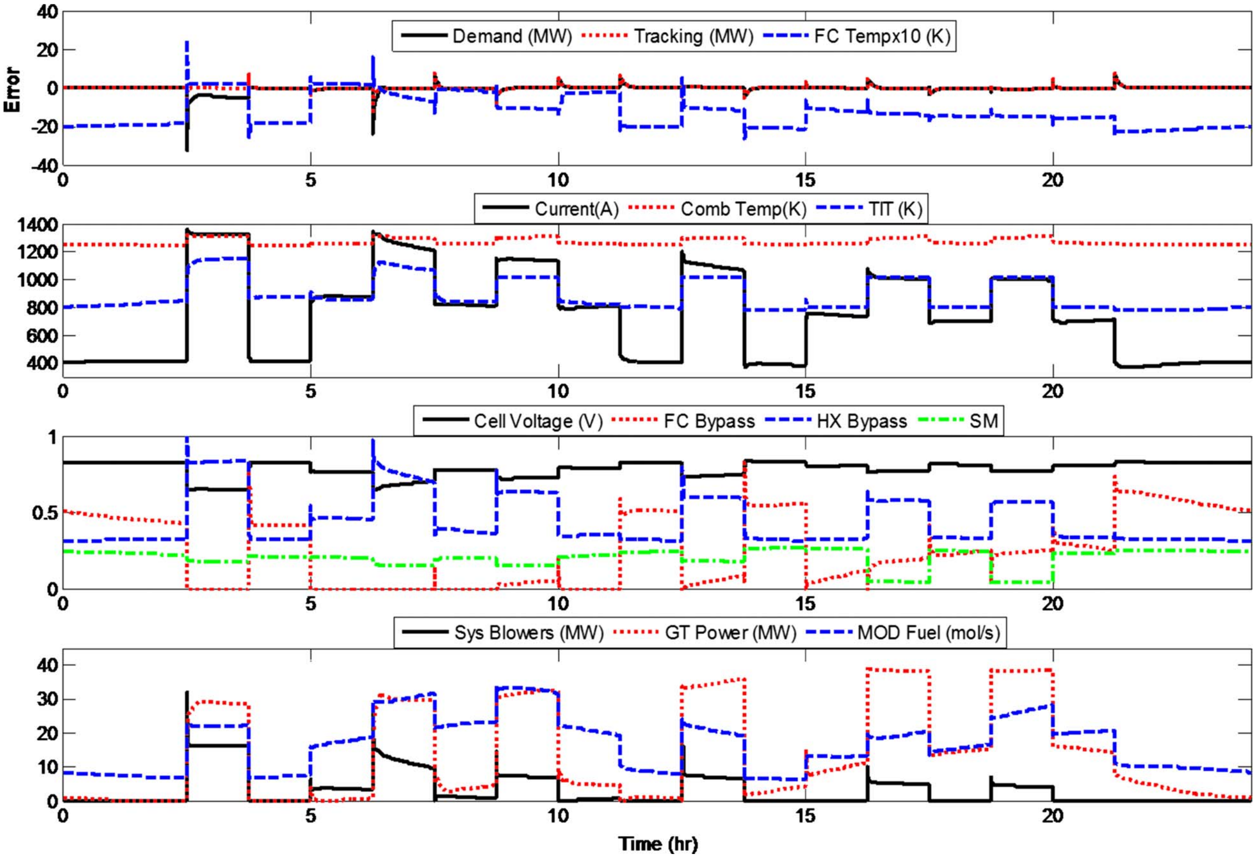

Fig. 14 Controlled system response to the simultaneous load, fuel, and ambient temperature disturbance, as shown in Fig. 13

and to provide improved thermal management of the fuel cell without the need to manipulate the gas turbine air or bypass air around the fuel cell

(2) a modular system design in which modules can be taken offline for maintenance as the system continues to operate and the ability to vary the number of cells each actuator controls

(3) the effectiveness of simple feedback regulation with steady-state feed-forward control for transient load following with disturbance rejection in large systems without independent control of the gas turbine

(4) fuel cell current manipulation to control the combustor temperature

(5) controls to prevent both surge and maintain gas turbine operation during transients and disturbances

(6) steady-state system design and dynamic modeling for the development of integrated systems and controls

While many contributions are made, the paper reveals the need for further research. For example, (1) the blower can be integrated within the system in various ways, which should be studied through a comprehensive design iteration, (2) coal gasification should be thermally integrated with the hybrid system and simulated to understand dynamics and to develop the required controls, and (3) to improve the lifetime of the stack, thermal stresses within the fuel cell during transients should be minimized by implementing advanced control strategies that can minimize temperature gradients within the fuel cell. The current system configuration and controls are fairly general and applicable to a wide range of particular system designs providing critical insights into the possibility of operating SOFC gas turbine hybrid systems at high efficiency in 100 MW-class applications with transient operation and disturbance rejection capabilities. The possibility for improvements in reliability and performance through system and controls advancements could further motivate the advancement of SOFC systems.

References

[1] Williams, M. C., Strakey, J. P., Surdoval, W. A., and Wilson, L. C., 2006, "Solid Oxide Fuel Cell Technology Development in the U.S.," Solid State Ionics, **177**(19–25), pp. 2039–2044.

[2] Williams, M. C., Strakey, J., and Sudoval, W., 2006, "U.S. DOE Fossil Energy Fuel Cells Program," J. Power Sources, **159**(2), pp. 1241–1247.

[3] Williams, M. C., Strakey, J. P., and Singhal, S. C., 2004, "U.S. Distributed Generation Fuel Cell Program," J. Power Sources, **131**(1–2), pp. 79–85.

[4] Williams, M. C., Strakey, J. P., and Surdoval, W. A., 2005, "The U.S. Department of Energy, Office of Fossil Energy Stationary Fuel Cell Program," J. Power Sources, **143**(1–2), pp. 191–196.

[5] 2007, "SECA Wraps First Phase With SOFCs on Way to Commercial Reality," Fuel Cells Bull., 2007(7), p. 4.

[6] 2007, "Siemens SOFC System Exceeds DOE Objectives," Fuel Cells Bull., 2007(1), pp. 5–6.

[7] Tarroja, B., Mueller, F., Maclay, J., Brouwer, J., 2008, *Parametric Thermodynamic Analysis of a Pure Hydrogen Solid Oxide Fuel Cell Gas Turbine Hybrid System Design Space*, Berlin, Germany, ASME, New York, pp. 1–12.

[8] Mueller, F., 2005, "Design and Simulation of a Tubular Solid Oxide Fuel Cell System Control Strategy," Masters thesis, Department of Mechanical and Aerospace Engineering, University of California, Irvine, Irvine, CA.

[9] Mueller, F., Brouwer, J., Jabbari, F., and Samuelsen, S., 2006, "Dynamic Simulation of an Integrated Solid Oxide Fuel Cell System Including Current-Based Fuel Flow Control," ASME J. Fuel Cell Sci. Technol., **3**(2), pp. 144–155.

[10] Mueller, F., Brouwer, J., Kang, S., Kim, H.-S., and Min, K., 2007, "Quasi-Three Dimensional Dynamic Model of a Proton Exchange Membrane Fuel Cell for System and Controls Development," J. Power Sources, **163**(2), pp. 814–829.

[11] Mueller, F., Jabbari, F., Brouwer, J., Roberts, R., Junker, T., and Ghezel-Ayagh, H., 2007, "Control Design for a Bottoming Solid Oxide Fuel Cell Gas Turbine Hybrid System," ASME J. Fuel Cell Sci. Technol., **4**, pp. 221–230.

[12] Mueller, F., Jabbari, F., Gaynor, R., and Brouwer, J., 2007, "Novel Solid Oxide Fuel Cell System Controller for Rapid Load Following," J. Power Sources, **172**(1), pp. 308–323.

[13] Brouwer, J., Jabbari, F., Leal, E. M., and Orr, T., 2006, "Analysis of a Molten Carbonate Fuel Cell: Numerical Modeling and Experimental Validation," J. Power Sources, **158**(1), pp. 213–224.

[14] Verma, A., Rao, A. D., and Samuelsen, G. S., 2006, "Sensitivity Analysis of a Vision 21 Coal Based Zero Emission Power Plant," J. Power Sources, **158**(1), pp. 417–427.

[15] Chan, S. H., Ho, H. K., and Tian, Y., 2003, "Modelling for Part-Load Operation of Solid Oxide Fuel Cell-Gas Turbine Hybrid Power Plant," J. Power Sources, **114**(2), pp. 213–227.

[16] Costamagna, P., Magistri, L., and Massardo, A. F., 2001, "Design and Part-Load Performance of a Hybrid System Based on a Solid Oxide Fuel Cell Reactor and a Micro Gas Turbine," J. Power Sources, **96**(2), pp. 352–368.

[17] Rao, A. D., and Samuelsen, G. S., 2003, "A Thermodynamic Analysis of Tubular Solid Oxide Fuel Cell Based Hybrid Systems," ASME J. Eng. Gas Turbines Power, **125**, pp. 59–66.

[18] Roberts, R., and Brouwer, J., 2006, "Dynamic Simulation of a Pressurized 220 kW Solid Oxide Fuel-Cell–Gas-Turbine Hybrid System: Modeled Performance Compared to Measured Results," ASME J. Fuel Cell Sci. Technol., **3**(1), pp. 18–25.

[19] Zhang, X., Li, J., Li, G., and Feng, Z., 2007, "Cycle Analysis of an Integrated Solid Oxide Fuel Cell and Recuperative Gas Turbine With an Air Reheating System," J. Power Sources, **164**(2), pp. 752–760.

[20] Kuchonthara, P., Bhattacharya, S., and Tsutsumi, A., 2003, "Energy Recuperation in Solid Oxide Fuel Cell (SOFC) and Gas Turbine (GT) Combined System," J. Power Sources, **117**(1–2), pp. 7–13.

[21] Kuchonthara, P., Bhattacharya, S., and Tsutsumi, A., 2005, "Combination of Thermochemical Recuperative Coal Gasification Cycle and Fuel Cell for Power Generation," Fuel, **84**(7–8), pp. 1019–1021.

[22] Bessette, N. F., 1994, "Modeling and Simulation for Solid Oxide Fuel Cell Power Systems," Doctorate thesis, Georgia Institute of Technology, Atlanta, GA.

[23] Burt, A. C., Celik, I. B., Gemmen, R. S., and Smirnov, A. V., , 2004, "A Numerical Study of Cell-to-Cell Variations in a SOFC Stack," J. Power Sources, **126**(1–2), pp. 76–87.

[24] Costamagna, P., Costa, P., and Antonucci, V., 1998, "Micro-Modelling of Solid Oxide Fuel Cell Electrodes," Electrochim. Acta, **43**(3–4), pp. 375–394.

[25] Ferrari, M. L., Traverso, A., Magistri, L., and Massardo, A. F. , 2005, "Influence of the Anodic Recirculation Transient Behaviour on the SOFC Hybrid System Performance," J. Power Sources, **149**, pp. 22–32.

[26] Marsano, F., Magistri, L., and Massardo, A. F., 2004, "Ejector Performance Influence on a Solid Oxide Fuel Cell Anodic Recirculation System," J. Power Sources, **129**(2), pp. 216–228.

[27] Nakajo, A., Stiller, C., Harkegard, G., and Bolland, O., 2006, "Modeling of Thermal Stresses and Probability of Survival of Tubular SOFC," J. Power Sources, **158**(1), pp. 287–294.

[28] Tucker, D., Lawson, L., and Gemmen, R., 2005, "Characterization of Air Flow Management and Control in a Fuel Cell Turbine Hybrid Power System Using Hardware Simulation," *ASME Power Conference*, Chicago, IL, ASME, New York.

[29] Ferrari, M. L., et al., 2005, "Control System for Solid Oxide Fuel Cell Hybrid Systems," *ASME Turbo Expo 2005: Power for Land, Sea and Air*, Reno-Tahoe, NV, ASME, New York, pp. 1–9.

[30] Gaynor, R., Mueller, F., Jabbari, F., and Brouwer, J., 2008, "On Control Concepts to Prevent Hydrogen Starvation in Solid Oxide Fuel Cells," J. Power Sources, **180**(1), pp. 330–342.

[31] Haynes, C., 2002, "Simulating Process Settings for Unslaved SOFC Response to Increases in Load Demand," J. Power Sources, **109**(2), pp. 365–376.

[32] Inui, Y., Ito, N., Nakajima, T., and Urata, A., 2006, "Analytical Investigation on Cell Temperature Control Method of Planar Solid Oxide Fuel Cell," Energy Convers. Manage., **47**(15–16), pp. 2319–2328.

[33] Jurado, F., and Jose Ramon, S., 2003, "Adaptive Control of a Fuel Cell-Microturbine Hybrid Power Plant," IEEE Trans. Energy Convers., **18**(2), pp. 342–347.

[34] Kandepu, R., Imsland, L., Foss, B. A., Stiller, C., Thorud, B., and Bolland, O., 2007, "Modeling and Control of a SOFC-GT-Based Autonomous Power System," Energy, **32**(4), pp. 406–417.

[35] Kaneko, T., Brouwer, J., and Samuelsen, G. S., 2006, "Power and Temperature Control of Fluctuating Biomass Gas Fueled Solid Oxide Fuel Cell and Micro Gas Turbine Hybrid System," J. Power Sources, **160**(1), pp. 316–325.

[36] Mueller, F., et al., 2006, "Control Design for a Bottoming Solid Oxide Fuel Cell Gas Turbine Hybrid System," *Fuel Cell Science, Engineering and Technology*, Irvine, CA, ASME, New York.

[37] Roberts, R., 2005, "A Dynamic Fuel Cell-Gas Turbine Hybrid Simulation Methodology to Establish Control Strategies and an Improved Balance of Plant," Doctorate thesis, Department of Mechanical and Aerospace Engineering, University of California, Irvine, Irvine, CA.

[38] Stiller, C., Thorud, B., Bolland, O., Kandepu, R., and Imsland, L., 2006, "Control Strategy for a Solid Oxide Fuel Cell and Gas Turbine Hybrid System," J. Power Sources, **158**(1), pp. 303–315.

[39] Roberts, R., Brouwer, J., Jabbari, F., Junker, T., and Ghezel-Ayagh, H., 2006, "Control Design of an Atmospheric Solid Oxide Fuel Cell/Gas Turbine Hybrid System: Variable Versus Fixed Speed Gas Turbine Operation," J. Power Sources, **161**(1), pp. 484–491.

[40] Selimovic, A., Kemm, M., Torisson, T., and Assadi, M., 2005, "Steady State and Transient Thermal Stress Analysis in Planar Solid Oxide Fuel Cells," J. Power Sources, **145**(2), pp. 463–469.

[41] Min, K., Brouwer, J., Auckland, J., Mueller, F., and Samuelsen, S., 2006, "Dynamic Simulation of a Stationary PEM Fuel Cell System," *Fuel Cell Science, Engineering and Technology*, Irvine, CA, ASME, New York.

[42] Mueller, F., Gaynor, R., Auld, A. E., Brouwer, J., Jabbari, F., and Samuelsen,

G. S., 2008, "Synergistic Integration of a Gas Turbine and Solid Oxide Fuel Cell for Improved Transient Capability," J. Power Sources, **176**(1), pp. 229–239.
[43] Mueller, F., 2008, "The Dynamics and Control of Integrated Solid Oxide Fuel Cell Systems: Transient Load-Following and Fuel Disturbance Rejection," Doctorate thesis, Department of Mechanical and Aerospace Engineering, University of California, Irvine, Irvine, CA.
[44] Mueller, F., Jabbari, F., Brouwer, J., Junker, T., and Ghezel-Ayagh, H., 2006, "Linear Quadratic Regulator for a Bottoming Solid Oxide Fuel Cell Gas Turbine Hybrid System," *International Colloquium on Environmentally Preferred Advanced Power Generation*, Newport Beach, CA, ASME, New York.
[45] Roberts, R. A., Jack, B., Liese, E., and Gemmen, R. S., 2006, "Dynamic Simulation of Carbonate Fuel Cell-Gas Turbine Hybrid Systems," ASME J. Eng. Gas Turbines Power, **128**, pp. 294–301.