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Linear Quadratic Regulator for a Bottoming Solid Oxide Fuel Cell Gas Turbine Hybrid System

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The control system for fuel cell gas turbine hybrid power plants plays an important role in achieving synergistic operation of subsystems, improving reliability of operation, and reducing frequency of maintenance and downtime. In this paper, we discuss development of advanced control algorithms for a system composed of an internally reforming solid oxide fuel cell coupled with an indirectly heated Brayton cycle gas turbine. In high temperature fuel cells it is critical to closely maintain fuel cell temperatures and to provide sufficient electrochemical reacting species to ensure system durability. The control objective explored here is focused on maintaining the system power output, temperature constraints, and target fuel utilization, in the presence of ambient temperature and fuel composition perturbations. The present work details the development of a centralized linear quadratic regulator (LQR) including state estimation via Kalman filtering. The controller is augmented by local turbine speed control and integral system power control. Relative gain array analysis has indicated that independent control loops of the hybrid system are coupled at time scales greater than 1 s. The objective of the paper is to quantify the performance of a centralized LQR in rejecting fuel and ambient temperature disturbances compared with a previously developed decentralized controller. Results indicate that both the LQR and decentralized controller can well maintain the system power to the disturbances. However, the LQR ensures better maintenance of the fuel cell stack voltage and temperature that can improve high temperature fuel cell system durability. [DOI: 10.1115/1.3155007]

Keywords: SOFC hybrid, gas turbine, control design, relative gain array, linear quadratic regulator, Kalman filter

1 Introduction

Because of high efficiency and low pollutant emissions characteristics, solid oxide fuel cell/gas turbine (SOFC/GT) hybrid systems are receiving increasingly more attention as potential future electric power generators. The Department of Energy has been supporting the development of SOFC/GT hybrids for distributed generation, as well as large scale stationary power applications [1–3]. SOFC systems are highly integrated electrochemical generators that directly convert fuel and oxygen to electricity.

SOFC systems contain hundreds to thousands of individual fuel cells that must operate with sufficient electrochemical active species at a constant temperature. To achieve high system efficiencies, it is desired to electrochemically react the majority of the fuel. However, fuel and oxygen cannot be depleted in the fuel cell [4–6]. Fuel and oxygen cannot be depleted in the fuel cell to maintain fuel cell voltage, as well as to avoid oxidation and reduction in the electrodes. The hydrogen and oxygen utilization must be less than 95% and 35%, respectively. In addition to not depleting electrochemical reactants within the fuel cell, the fuel cell operating temperature need to be maintained [4,7,8]. This is both to maintain ionic conduction of the electrolyte and to avoid fuel cell degradation through thermal fatigue. To maximize fuel cell durability, the fuel cell temperature should be maintained within 15°C, but ideally the less temperature variation the better. The fuel cell voltage should also be maintained at all times to avoid fuel cell degradation caused by high local heat production

rates [4,9]. Good control systems and strategies are required to operate these systems safely within tight operating constraints. Control strategies must allow hybrid systems to follow a desired load demand and to reject process disturbances, e.g., in ambient temperature and fuel energy content on the system operating conditions.

The system investigated in this work (see Fig. 1) is a 250 kW bottoming SOFC/GT hybrid system, as described and modeled by Mueller et al. [5]. The fuel cell provides approximately 85% of the system power, the remainder comes from the gas turbine. Fuel is internally reformed to hydrogen and carbon dioxide. This endothermic reaction cools the stack [10]. Additional cooling needed by the fuel cell is provided from air moved by the compressor. To adjust to altering operating conditions, the air flow rate can be manipulated via a variable speed operation of the gas turbine [11]. The temperatures of the heat exchanger, turbine inlet, and cathode inlet can be influenced by burning supplementary fuel in the combustor. All system balance-of-plant components must operate in unison for successful electrical generation. The gas turbine must provide the necessary air for the fuel cell. On the other hand, the fuel cell along with the supplementary combustor must generate sufficient thermal energy to drive the gas turbine. Sufficient system thermal exhaust must be recuperated to sufficiently process the fuel prior to the fuel cell and to preheat the fuel cell inlet air all so that the power generated by the fuel cell and gas turbine meets the system power demand.

In previous studies, a decentralized controller was shown to be viable for tracking system power, while maintaining the system within operating constraints for the entire operating range subject to ambient temperature fluctuations and fuel content perturbations [5]. The decentralized controller contains four primary control loops: (1) system power control via manipulation of the fuel cell current, (2) stack temperature cascade control manipulating the air

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Fig. 1 Bottoming SOFC/GT hybrid system with variable speed GT and supplemental oxidizer fuel

flow to the fuel cell via manipulation of the gas turbine speed, (3) combustor temperature control via manipulation of supplementary fuel flow to the combustor, and (4) cell voltage control via manipulation of the anode fuel flow during fuel content perturbations.

Relative gain array (RGA) analysis indicated [5] that the decentralized control loops in the investigated system are coupled at time scales greater than 1 s (see Fig. 2). The analysis of coupled time scales was done based on Refs. [12,13]. Due to the coupling, a centralized multi-input-multi-output (MIMO) controller is expected to provide control benefits. Decentralized controllers have demonstrated the capability of tracking system power during transients and disturbances while maintaining SOFC operating conditions within constraints. However, centralized control may provide more robust and tighter control of the fuel cell that could result in improved durability, reliability, and overall longer system lifetime—all of which are desired in practice.

Centralized multi-input-multi-output control systems have been considered for advanced alternative power generation, including hydro-electric [14], wind generation [15,16], energy storage devices [17], proton exchange membrane fuel cell systems [13,18,19], and molten carbonate fuel cells [20], but have not been studied extensively for solid oxide fuel cell gas turbine hybrid systems. The challenge in SOFC/GT systems is to track the system power, while maintaining sufficient fuel within the fuel cell and controlling the fuel cell and combustor temperatures as close as possible. The tight operating requirement with interactions and coupling between gas turbine, fuel processor, and fuel cell make SOFC/GT hybrid control particularly important.

We show how to address these challenges by developing a centralized MIMO control system for SOFC/GT hybrid system. Specifically, a linear quadratic regulator (LQR) was investigated

Fig. 2 Relative gain array analysis [5] for fuel cell current/system power input/output pairing

to minimize output variance with minimal controller actuation accounting for coupling within the system. Such feedback is ideal for high temperature fuel cells gas turbine systems that must be controlled with minimal variation during operation to maximize system durability and reliability and to increase system lifetime. In the paper, the performance of the linear quadratic regulator is compared with a previously developed decentralized controller in rejecting disturbances in ambient temperature and perturbations in fuel content. Particular attention is taken in the ability of each controller to maintain the fuel cell voltage and fuel cell temperature, which is critical in ensuring system durability and reliability. Development of the centralized control strategy is divided into two steps: (1) model development and (2) controller design. These steps are described in detail below and analyzed in the context of tracking power and rejecting disturbances on the system.

2 LTI Model Development

Development and evaluation of controllers is based on the non-linear dynamic model developed by Mueller et al. [5]. The model is based on physical modeling of the system, using mass and energy conservation principles; it captures heat transfer in the heat exchanger, reformer, and fuel cell, steam reforming and electrochemical kinetics, and gas turbine shaft dynamics and gas turbine off-design performance from compressor and turbine performance maps. Experimental validation of component models is presented in Refs. [21–23].

A linear quadratic regulator was designed in the MATLAB/SIMULINK® framework based on a reduced order linear time-invariant (LTI) model. Development of the reduced order LTI model comprises three steps: (1) model linearization, (2) model reduction, and (3) verification of performance of reduced order linear model versus the nonlinear model.

2.1 Model Linearization. LQR state feedback design is based on linear control theory. Therefore, the previously developed nonlinear model [5] was linearized using MATLAB/SIMULINK® built-in methods. To minimize numerical error and to facilitate tuning of the LQR and Kalman filters, inputs and outputs were scaled, as illustrated in Fig. 3. The following operating point was selected for linearization:

1. fuel cell current=42 A
2. fuel cell temperature=1000 K
3. combustor temperature=1140 K
4. fuel utilization=85%
5. ambient temperature=298 K
6. fuel=100% methane

The operating point is a high power nominal operating condition. From the operating point, the system was linearized in the following form:

$$\dot{x} = Ax + Bu + B_1 t_{amb} + B_2 x_{fuel} \quad (1)$$

$$y = Cx + Du + D_1 t_{amb} + D_2 x_{fuel}$$

where x , u , and y , represent, respectively, the deviation of each state, input, and output from the point of linearization. The states represent the system species mole fraction, temperature, and shaft speed from each of the transient conservation equation in the non-linear model. Model inputs are the fuel cell current, gas turbine power, anode fuel flow, and combustor fuel flow. System measurable outputs were considered to be the system power, the fuel cell temperature, the combustor temperature, the fuel cell voltage, and the gas turbine shaft speed. In addition to the system parameters, the linear state space representation accounts for the effect of deviations in the ambient temperature (t_{amb}) and the fuel's methane mole fraction (x_{fuel}) on the system's states and

Fig. 3 Centralized control system for robust tracking and disturbance rejection

outputs. The model should match the nonlinear model's dynamic response close to the operating point.

Upon analysis of the linear system's poles and zeros, it was found that the system was marginally stable. The gas turbine shaft speed state was found to be on the real axis. The GT's speed is determined from a dynamic momentum balance on the turbine shaft as follows:

$$J \frac{d\omega}{dt} = \tau_{\text{turbine}} - \tau_{\text{compressor}} - \tau_{\text{generator}} = \sum \tau \quad (2)$$

Since mechanical damping (friction) has been neglected, the shaft's physical response characteristics lead to what is called "rigid body rotation." Letting the output $\omega = y$ and the input $\sum \tau = u$, this can be written as the following transfer function in the Laplace domain:

$$G(s) = \frac{1}{J \cdot s} \quad (3)$$

i.e., it has a pole at the origin. To stabilize the GT, a local proportional feedback loop for the turbine speed was added and the linearization was repeated. To clarify this strategy, the linearized plant, including the GT shaft speed feedback, is highlighted in Fig. 3.

Stabilizing the system in this way is justified because a commercial gas turbine will be equipped with a speed controller as well. This way, the GT controller becomes an integral part of the model and not of the centralized controller. With this GT shaft speed feedback loop, the inputs to the controlled system are (1) turbine speed setpoint, (2) fuel cell current, (3) anode fuel flow-rate, and (4) combustor fuel flowrate.

2.2 Model Reduction. The linearized plant has 70 states. It is desired to reduce the order of the plant model to make it less susceptible to numerical error and to reduce computational burden. The reduced order state space model has the same structure as the full state model

$$\begin{aligned} \dot{x}_r &= A_r x_r + B_r u + B_{1r} t_{\text{amb}} + B_{2r} x_{\text{fuel}} \\ y &= C_r x_r + D u + D_{1r} t_{\text{amb}} + D_{2r} x_{\text{fuel}} \end{aligned} \quad (4)$$

In a first step, unobservable and/or uncontrollable states were removed since they do not contribute to the model's input-output behavior. The resulting minimum realization has 58 states. In a second step the states with the least effect on the system response

were removed. This was accomplished by determining each state's Hankel singular value. The Hankel singular value represents the effect that each state has on the system response [12]. The states with the least effect on the system response (smallest Hankel singular value) were then removed in order of smallest to largest Hankel value, ensuring the linear system's time and frequency responses were not substantially affected after each removal.

It was found that reducing the model to 27 states with Hankel singular values greater than 10^{-3} reduced the model sufficiently for control development and maintained good system representation. Frequency responses of selected inputs/outputs for the full state linear model and the reduced order linear model are shown in Fig. 4.

2.3 Verification of Performance of Reduced Order Linear Model Versus the Nonlinear Model.

To evaluate the effects of linearization and model reduction, the open loop time responses of the full linear, the reduced linear, and the nonlinear models were compared for a representative disturbance. A 40°C diurnal temperature fluctuation and a 5% decrease in the fuel's methane mole fraction were selected (Fig. 5). This provides a means to evaluate the system linearization, model reduction, and the open loop response of the system. It is important to note that in all time response figures, time "0" represents the time of the instantaneous

Fig. 4 Selected Bode frequency response of the full state linear model (solid line) and the reduced order linear model (dotted line)

Fig. 5 Simultaneously simulated instantaneous 5% decrease in the fuel's methane mole fraction at time 0 and a 40°C diurnal temperature fluctuation

fuel composition perturbation. Presented simulations are 48 h to demonstrate 24 h of diurnal temperature perturbation before and after the fuel composition perturbation.

- (a) *Ambient temperature perturbations.* The response to a 40°C diurnal temperature fluctuation is shown in Fig. 6. Both the linear and reduced order model response match the nonlinear system well. The simulated diurnal temperature fluctuation causes fluctuations in system power of more than 5 kW, in stack temperature of more than 10°C, and in combustor temperature of more than 20°C. This demonstrates the need for a feedback controller on the system.
- (b) *Fluctuations in fuel composition.* In addition to ambient temperature perturbations, disturbances in the fuel concentration can affect the system substantially. The open loop responses of the three system models to a 5% reduction in the fuel's methane mole fraction are shown in Figs. 7 and 8 for a short and long time scale, respectively. In both time scales, the linear models are a decent approximation of the nonlinear model's dynamic behavior. Fuel composition perturbations cause a slight drift away from the equilibrium point. It will be shown, that feedback is beneficial in keeping the system close to the equilibrium point. The 5% reduction in the fuel methane mole fraction results in a 10 kW reduction in system power, a 30 mV reduction in average cell voltage, and a 40°C reduction in the combustor temperature. This demonstrates that small changes in the fuel composition

can have substantial effects on the fuel cell power and combustor temperature and need to be compensated for by the controller.

3 Control Design

As shown above, disturbances in ambient temperature and fuel composition have a substantial effect on the system's operating point, i.e., feedback control is required for disturbance rejection.

The centralized control structure contains two feedback gain matrices: (1) the LQR feedback gain and (2) the Kalman filter gain. To decouple the design process, the feedback gains were determined as follows.

1. The state feedback gain was determined in the reduced order linear model.
2. The Kalman filter was added to the state feedback controller.
3. The complete designed controller was implemented in the full nonlinear system.

Because the LQR's state feedback is only proportional, a small tracking error will exist. Therefore, a small integral gain feedback loop on system power is added to the control design, as shown in Fig. 3.

3.1 Linear Quadratic Regulator. The LQR feedback gain (K_{states}) is determined by minimizing the following cost function:

Fig. 6 Nonlinear, linear, and reduced order model open loop response to a 40°C diurnal temperature perturbation. Note that the linear and reduced lines overlap in all the figures and that all the lines overlap in the system power, fuel cell temperature, rpm, and combustor temperature figures.

Fig. 7 Nonlinear, linear, and reduced order model open loop short time response to an instantaneous 5% decrease in the fuel's methane mole fraction. Note that the linear and reduced lines overlap in all the figures and that all the lines overlap in the rpm and combustor temperature figures.

$$J = \int_0^{\infty} (y^T Q y + u^T R u) dt \quad (5)$$

$$y = Cx + Du$$

Performance of the LQR is tuned via Q and R . In their simplest form, these are diagonal matrices. The main goal of the controller is to track the system power as closely as possible. Fuel cell and combustor temperatures should be maintained close to their

setpoints of 1000 K and 1140 K, respectively. GT shaft speed and cell voltage are allowed to vary but must remain in a safe operating range. There are no hard constraints on the system inputs.

Table 1 summarizes the initial guess for the LQR weights. A large weight will be used for system power, a smaller weight for stack and oxidizer temperatures, and a small weight for GT shaft speed and voltage. The input weights are all small.

Performance of state feedback control was evaluated using the

Fig. 8 Nonlinear, linear, and reduced order model open loop long time response to an instantaneous 5% decrease in the fuel's methane mole fraction. Note that the linear and reduced lines overlap.

Table 1 Initial guess of LQR weights

Setpoint weights: Q	
System power	500
Fuel cell temperature	200
Combustor temperature	200
Turbine speed	1
Cell voltage	1
Input weights: R	
Current	10^{-5}
Turbine speed setpoint	10^{-5}
Anode fuel flow	10^{-5}
Combustor fuel flow	10^{-5}

same disturbances used above for model validation (Fig. 5). With this initial tuning, the controller demands a negative combustor fuel flow, which is not possible. While this could be addressed by increasing the combustor fuel input penalty, it was found that increasing the penalty cost functional on voltage led to conditions under which this negative flow was no longer required. Furthermore, it was found that reducing the GT shaft speed weight

Table 2 Tuned LQR weights

Setpoint weights: Q	
System power	500
Fuel cell temperature	200
Combustor temperature	200
Turbine speed	0.01
Cell voltage	200
Input weights: R	
Current	10^{-5}
Turbine speed setpoint	10^{-5}
Anode fuel flow	10^{-5}
Combustor fuel flow	10^{-5}

resulted in better control of the fuel cell temperature. This is because varying the speed of the GT varies the air flow through the fuel cell thus facilitating improved control of the fuel cell temperature. The adjusted LQR weights are shown in Table 2.

The response of the retuned LQR is presented in Fig. 9. Applied to the linear model, the LQR can track power to within 10 W and maintain the fuel cell temperature to within 2°C . The fuel cell voltage and combustor temperature are essentially constant. Please note that in controlled system responses, the controllers are active from the beginning to the end of the simultaneous fuel composition disturbance and diurnal ambient temperature disturbance of the simulation, with time 0 indicating the time of the instantaneous fuel composition perturbation.

3.2 Kalman Filter. Since only a few of the linear model's states can be measured, states must be estimated, e.g., via a Kalman filter, to implement the LQR. For the system shown in Eq. (4), it takes the following form:

$$\hat{\dot{x}}_r = A_r \hat{x}_r + B_r u + B_{1r} t_{\text{amb}} + k_{\text{est}}(y - C_r \hat{x}_r - D u - D_{1r} t_{\text{amb}}) \quad (6)$$

The states ($\hat{x}_r$) are estimated from the known state feedback inputs and outputs and the ambient temperature change. Note that perturbations in the fuel's methane mole fraction (x_{fuel}) are not included because they are not measurable. The estimator gain k_{est} updates the states such that the measurements are correctly predicted by the linear model.

The filter is tuned by adjusting the process and measurement noise covariance matrices via the Kalman command in MATLAB (see Ref. [12] for general information on Kalman filters). With these covariance matrices the Kalman filter gain can be tuned to be more sensitive to process (state) noise or to measurement (output) noise. The error in the estimated states will primarily be caused by perturbations in the fuel's methane mole fraction, which cannot be measured directly. To determine initial covariance values, the effect of fuel perturbations (x_{fuel}) on the states (via B_{2r}) and the measurements (via D_2) was investigated (Eq. (4)). The effects on the states are approximately three orders of magnitude stronger than the effect on the measurements. As an initial guess, the process covariance noise was set to 10^{-4} , and the measurement

Fig. 9 Controlled system response of the designed LQR applied to the linear model

Fig. 10 Simultaneously simulated 20% instantaneous reduction in the fuel's methane mole fraction at time 0, and a 40°C diurnal temperature perturbation

covariance noise was set to 10^{-7} . After a few iterations it was found that decreasing the penalty on the measurement covariance noise to 5×10^{-9} resulted in better control.

The performance of the feedback control using estimated states is similar to the performance of the feedback control from actual states. Slight error in tracking the combustor temperature resulted from state estimation because the states are estimated without information about fuel variations. Immediately after a change in the fuel's methane mole fraction, there also is a voltage tracking error because voltage depends on the fuel composition.

3.3 Integral Power Feedback. To ensure zero tracking error of the system power, integral control of the system power is implemented via manipulation of the stack current. This was applied to the SOFC rather than the GT because its power can directly be controlled via the stack current and because this is a very fast acting controller. The other controlled variables (fuel cell temperature, combustor temperature, voltage, and gas turbine shaft speed) are not augmented with integral control because offset-free tracking is not essential.

4 Control Results

To demonstrate controller performance both the original decentralized controller and LQR are compared for a 20% reduction in the fuel's methane mole fraction and a 40°C diurnal temperature perturbation (Fig. 10). The LQR is applied to both the linear and nonlinear models. Figures 11 and 12 show, respectively, the results for the long term and the short term responses.

In the nonlinear model the LQR tracks the power with zero offset, the stack temperature within 5 K, the combustor temperature within a few kelvin, and the cell voltage within a few millivolts. This shows the system can robustly track power, while rejecting disturbances. The largest offsets from desired setpoints are in the fuel cell and combustor temperatures. These offsets are attributed to errors in the estimated states, since fuel composition information is not accounted for in the estimator (Eq. (6)), as well as to the nonlinear behavior of the system. Nonetheless, the controller is capable of rejecting the applied disturbances with only minor offsets from desired operating conditions. Both of these disturbances are very large compared with the disturbances such a system will likely see in practice. The controller can handle even larger disturbances; however, the variations in the fuel cell and combustor temperature will become bigger.

Compared with the decentralized controller the centralized controller performed slightly better. Due to the integral feedback on power, both controllers track the system power offset-free. The central controller maintains the cell voltage and the stack temperature within tighter bounds than the decentralized controller. The decentralized controller was able to maintain the cell voltage within 0.1 V, while the LQR maintained cell voltages within 0.04 V for a 60% cell voltage control improvement. In terms of the fuel cell temperature, the decentralized controller maintained the fuel cell temperature within 14 °C, while the LQR maintained the fuel cell temperature within 8 °C for a 40% improvement in fuel cell temperature control. Such improvement

Fig. 11 Controlled system long-term (40 h) response to the disturbance of Fig. 10 using the control system with LQR feedback controller and the decentralized feedback controller

Fig. 12 Controlled system short-term (80 s) response to the disturbance of Fig. 10 as controlled by the LQR feedback controller and the decentralized feedback controller

in the fuel cell voltage and fuel cell stack temperature correlate to increased fuel cell durability, reliability, and overall system life-time.

The centralized controller performed better than the decentralized controller because the central controller manipulates all inputs based on all the outputs, accounting for interactions among them. For example, the LQR responded to the fuel perturbation, by manipulating the fuel flow, maintaining close control of the fuel cell voltage during the transient. The decentralized

controller also responded to the fuel perturbation by manipulating the fuel flow, but was not able to maintain the fuel cell voltage, as well as the centralized LQR. The centralized LQR is able to account for such interactions and allowing for direct trade-offs among different objectives while the decentralized controller cannot.

On the other hand, the decentralized controller achieved better control of the oxidizer temperature, which was controlled independently by manipulating the oxidizer fuel flow. Because rejection of fuel perturbations and maintenance of cell temperature are more important than tight control of the oxidizer temperature the new controller is an improvement over the previously developed decentralized control strategy.

5 Discussion

Both the decentralized and centralized controllers are stable and maintained the system within operating constraints during the fuel composition and ambient temperature disturbances. A centralized controller is a higher order controller that is generally more challenging to implement in a system. However, centralized MIMO controllers can be effectively used to more closely maintain the fuel cell voltage and minimize fuel cell temperature variations due to disturbances. In the present analyses the centralized controller achieved a 40% reduction in the fuel cell temperature fluctuation caused by the disturbances. Such an improvement can improve fuel cell durability, reliability, and stack lifetime in the field.

Due to the relative complexity of developing centralized controllers compared with decentralized controllers, it is not

expected that fuel cell manufacturers will immediately implement centralized controls in first generation systems. However, as high temperature fuel cell technology matures, the development and implementation of centralized controllers for high temperature fuel cells may provide performance improvements as well as durability, reliability, and system lifetime improvements.

6 Conclusions

The LQR was developed and implemented in MATLAB/SIMULINK® and was applied to a detailed nonlinear model of the system. This allowed for evaluation of the centralized controller compared with a decentralized controller for hybrid systems. As predicted by RGA analysis, the central controller performed better than the decentralized controller in rejecting common disturbances to hybrid fuel cell systems.

The overall performance of different control designs can vary depending on the cycle. The overall system configuration used for this research was designed with controllability in mind. The variable speed turbine and supplementary combustor fuel allow for effective response to operating conditions and disturbances. Other system configurations might not be as amenable to decentralized control and may benefit even more from centralized controllers, as investigated in this study.

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Nomenclature

$A, B, C,$ and D = state space matrices
 G = transfer function
 J = moment of inertia (kg m^2), LQR cost function
 K = feedback gain matrix
 P = steady state error covariance
 Q = LQR output weight matrix
 R = LQR input weight matrix
 t_{amb} = variation in ambient temperature from 298 K
 u = input deviation from operating point
 x = state deviation from operating point
 x_{fuel} = deviation in fuel's methane mole fraction
 y = output deviation from operating point
 k, K = gain

Greek Letters

Θ = angle (rad)
 τ = torque ($\text{kg m}^2 \text{s}^{-2}$)

Subscripts and Abbreviations

amb = ambient
 C = compressor
comb = combustor
est = estimator
FC = fuel cell
 G = generator
 r = reduced order system
sys = system
SS = steady-state
 T = turbine
temp = temperature

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