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Comparative Performance Assessment of 5kW-Class Solid Oxide Fuel Cell Engines Integrated with Single/Dual-Spool Turbochargers

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Abstract— **The purpose of this study is to investigate the performance of 5kW-Class Solid Oxide Fuel Cell/Gas Turbine (SOFC/GT) hybrid systems with two typical turbine configurations widely used in the gas turbine industry, namely single- and dual-spool gas turbines. Even though their operations are based on the same physical principles, their performance characteristics and operation parameters vary considerably due to different designs. As the most relevant results of an SOFC/GT performance analysis, the comparison of the load operation regime and the dependence of some crucial variables (such as power, SOFC temperature, and turbine shaft speed) on control variables are presented. The part-load operation and load transition are also analyzed to provide guidelines in developing safe and optimal load transition strategies.**

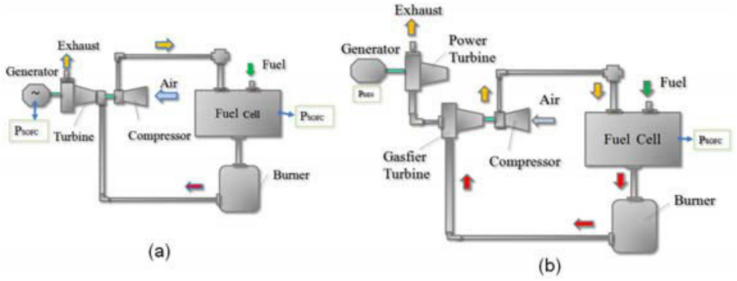

Fig. 1. SOFC/GT Hybrid schematic: single-shaft (a) and dual-shaft (b).

I. INTRODUCTION

The Solid Oxide Fuel Cell (SOFC), which operates at elevated temperatures (∼1000degC), is particularly well suited to combine with a gas turbine as the bottoming cycle in a hybrid SOFC-GT configuration. The efficiency of such a system can potentially exceed 60% and even approach 70% for future optimized designs [1]-[4].

Various layouts for hybrid SOFC/GT plant have been proposed in literature. Two distinct hybrid designs, topping and bottoming SOFC/GT systems, have been developed [5], [6]. 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 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. Additionally, it has been shown that a wide range of operation can be supported by burning residue and supplementary fuel in the afterburner. The dynamic analysis of a planar SOFC/GT model has been performed to understand the open-loop system dynamic characteristics [7]. It was shown that the system is susceptible to power shutdown when an abrupt load increase is applied. The analysis in [7] revealed that the shutdown is initiated by the gas turbine through the shaft dynamic coupling with the SOFC air supply system.

This paper, as an extension of our previous work [8], addresses the following topics: First, the capability of the two different SOFC/GT designs is compared in terms of part-load performance envelopes, system efficiency, and SOFC temperature level. Second, the dependency of crucial system parameters on the control variables, namely the fuel flow, SOFC current density, and generator loads, is analyzed and admissible ranges for control variables and advantageous load operation points are identified through model based analysis. Furthermore, applying the derived operation points, the shutdown behavior of the SOFC/GT cycles during load changes is explored through the analysis of their corresponding region of attractions.

The remainder of this paper is organized as follows: in the next section the SOFC/GT dynamic model is presented. Performance evaluations at the steady state and during transient are presented in Section III and IV, respectively, followed by conclusions.

II. MODEL DESCRIPTION

The hybrid SOFC/GT system analyzed in this work is intended as an auxiliary power unit (APU) for military and commercial heavy-duty vehicle applications. The system is designed to have a rated power of around 5kW. The utility of a dual-shaft gas turbine, shown in Fig. 1(b), is explored in comparison with its single shaft counterpart (Fig. 1(a)) in achieving efficient steady state operation and smooth transient response for a highly coupled SOFC/GT system. The key system components include an SOFC stack, a compressor, a catalytic burner (CB), and turbines which drive a generator (GEN). Other components, such as the reformer and heat exchangers, are not included in this work in order to focus on the coupling dynamics between the SOFC and the GT.

In the single-shaft design (Fig. 1(a)), the turbine drives both the compressor and the generator through a mechanical shaft; the former delivers the air needed for the SOFC stack operation and the latter provides additional electrical power for the system. On the other hand, the split-shaft design (Fig. 1(b)) has two turbines. One is a gasifier turbine driving

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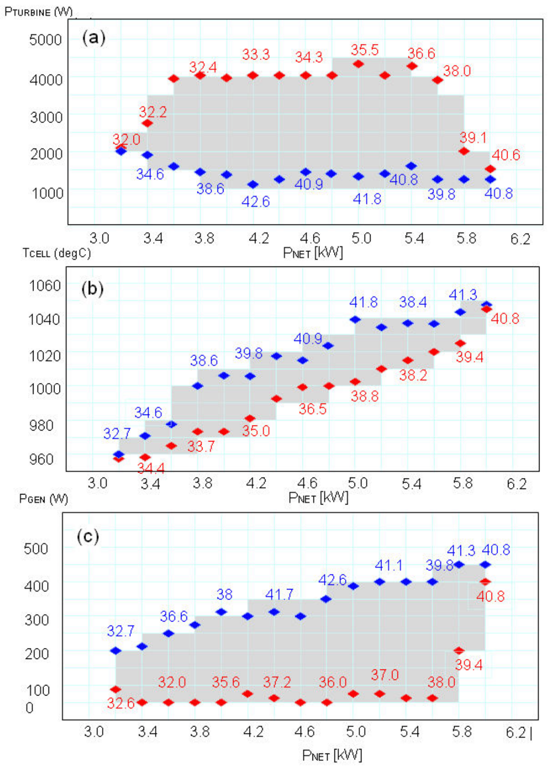

Fig. 2. Steady-state operating regimes of a single-shaft SOFC/GT cycle: (a) turbine power, (b) fuel cell temperature, and (c) generator load as functions of net power. The numbers shown in the boundary lines are efficiencies.

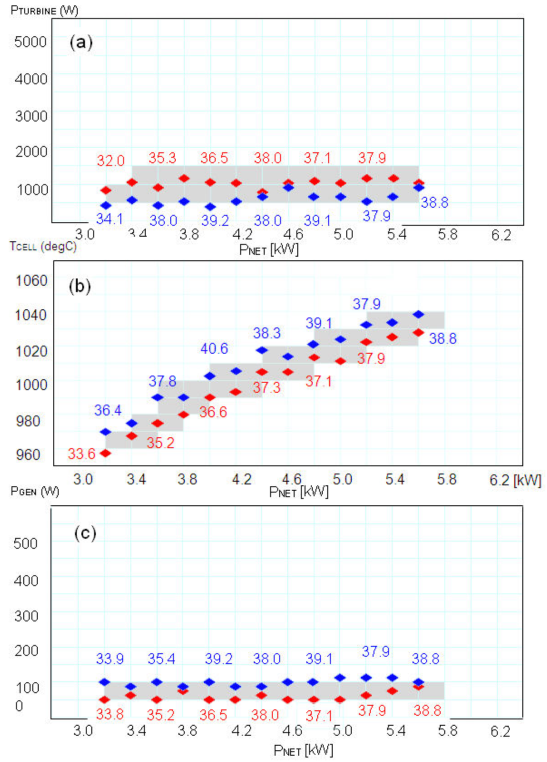

Fig. 3. Steady-state operating regimes of a dual-shaft SOFC/GT cycle: (a) turbine power, (b) fuel cell temperature, and (c) generator load. The numbers shown in the boundary lines are efficiencies.

a compressor and another is a free power turbine driving a generator.

In a tubular SOFC design, the following modeling strategies have been implemented to reduce the complexity of the resulting model without a significant compromise on the accuracy: (1) Based on the physical structure of the SOFC, five temperature layers are defined, namely the temperatures for the fuel bulk flow, air bulk flow, PEN (Positive electrode-Electrolyte-Negative electrode assembly), injector, and injector air. The anode, cathode, and electrolyte are treated as one single entity. (2) The fuel is a mixture of six species, consisting of methane(CH_4), carbon monoxide(CO), carbon dioxide(CO_2), hydrogen(H_2), steam(H_2O) and nitrogen(N_2). (3) The SOFC can be treated as a distributed parameter system in order to capture the spatial distribution along the flow field for variables such as temperature, species concentration, and current density. The governing equations are described using discretization technique [9]. In this modeling effort, the cell is divided into n axial sections and each section is considered as a lumped parameter sub-system. The GT model incorporates a compressor, shaft rotational speed dynamics, and turbine sub-models. The compressor performance data used in this study is in the form of compressor and turbine maps [11]. In addition, in modeling the catalytic burner (CB), the mass/temperature dynamics are taken into account. Detailed modeling procedures are omitted in this paper due to space limitation. Interested readers can refer to [7],[8].

III. STEADY-STATE PERFORMANCE EVALUATION

In this section, we first calculate the steady state operation regimes for the two different design options. Three control variables are varied independently within their respective limits. Each combination determines an output power and an operation point of the system.

A. Operation Envelopes

Figs. 2 and 3 show the steady-state operation ranges for a single- and dual-shaft SOFC/GT hybrid model, respectively. Steady state operation exists only in the shaded areas. The power ranges of two designs are very close: 3.0-6.0kW for the single-shaft design and 3.0-5.7kW for the dual-shaft design. This is because the SOFC has been built up under the same design conditions and the turbines have been modeled to produce similar power at the rated speed for the purpose of comparison study. For the single shaft system, the efficiency varies from 32.0% to 42.6%, while for the dual shaft, a narrower range of efficiency window is observed for its entire operating range, namely, from the lowest 32.0% to the highest 39.2%. The dual-shaft hybrid system show slightly better part-load performance than the single-shaft system does. The efficiency values are plotted along the boundary lines of the operation regimes depicted in Figs. 2 and 3. The efficiencies are higher in the lower boundary points of the turbine power (P_{Turb}) while the low efficiencies are found in the lower boundaries of the SOFC temperature (T_{CELL}) and the generator load (P_{GEN}). For the high fuel flow and low

P_{GEN} combination, which is outside the shaded area on the low efficiency side, the turbine speed is steadily climbing far beyond the valid range (overspeed) and the fuel cell is also over cooled and therefore the voltage is expected to be low. On the other hand, the cause of infeasible operation related to the other extreme end (low fuel flow, high P_{GEN}) is due to the fuel/air starvation in the fuel cell stack along with the high SOFC temperature.

The single-shaft design has a wider operation range as shown in the plot of the turbine power than the dual shaft case. This is because in the dual-shaft model, the compressor pressure ratio is shared by gas- and power-turbines. The decrease in the turbine power is mainly due to the less pressure ratio applied to one stage in the dual-shaft configuration. Besides, the single-shaft design has a higher power split ratio (P_{GEN}/P_{NET}) compared with the dual-shaft design. The reduced turbine power operation range in the dual-shaft model leads to the decrease in the power split ratio. In dual-shaft design, the lower/upper boundaries of P_{GEN} are almost flat over the entire P_{NET} region. In contrast, the upper boundary of the P_{GEN} in the single-shaft design decreases by more than 50% from the maximum P_{GEN}. This means that the small(large) generator load variation is expected for the dual(single)-shaft design, when a load is changed along the high efficiency boundary line.

The figures also show that the fuel cell temperatures increase with increase in P_{NET}. Maintaining relatively high-level of SOFC temperature can be made possible in the high load operation regime, (e.g., 1040degC can be achieved over the region more than 5.0kW in the single design and 5.2kW in the dual design). In addition, based on the steady state performance data, it is found that a load operation with fairly constant temperature in the SOFC seems feasible but very limited, depending on load operation range. The range for which the P_{NET} can vary while the temperature is kept constant is almost the same for part or full load operation for single shaft design, see Fig. 2(b). However, for the dual shaft counterpart, this range becomes narrower as the P_{NET} decreases (see Fig. 3(b)), which indicates that it is more difficult to maintain the same temperature as the load changes for the dual shaft system. It is also noticeable that maintaining a constant shaft speed is doable over the entire load interval for both the single- and dual-shaft designs.

B. Analysis of part-load operation

In this section, the system part-load behavior is investigated. The strategies for part-load operation and for transient from one operation point to another are discussed.

1) Single-shaft SOFC/GT Design: The operation of the SOFC/GT plants is dictated by three different control inputs, namely the fuel flow, the current density, and the generator power. Therefore, there exist multiple ways of achieving a prescribed load following objective. This study investigates load change schemes to explore the control design space to achieve fast and safe load following operation. To illustrate the concept and the analysis method, we consider two load points with $P_{NET} = P_A$ and $P_{NET} = P_B$. By analyzing the feasible input regimes for each operating point and the overlap in the two corresponding regions, we gain insight on how to achieve efficient part load operation while facilitating fast load following. As a representative example, the feasible input setpoints matching the powers of 5.0kW and 5.7kW are calculated as displayed in Fig 4 for the single-shaft design. The crucial system variables such as the fuel cell temperature and system efficiency are shown in the operating area. The areas highlighted in Fig 4(a) and (b) indicate that the combination of the corresponding inputs can generate the specified power. The white area represents input points that cannot meet the power demand. Major observations and findings concerning the load operation are summarized as follows:

- Region of feasible control inputs: As P_{NET} increases from lower power(5.0kW) to a higher power(5.7kW), the entire operating regime shifts in the fuel flow W_{Fuel} and the SOFC current (I_{COM}) plane such that more power from the fuel cell stack can be produced. This is the case with both single- and dual-shaft designs. Note that at a constant net power, the efficiency is inversely proportional to the fuel flow since $\eta = P_{NET}/(W_{Fuel} \cdot LHV)$ and thus the corresponding fuel flows at the power of 5.0kW and 5.7kW can be readily calculated from the efficiency data of Fig 4(a) for the entire feasible operating range. Outside this region, either too much (upper right area) or not enough (lower left) power will be produced.
- Sensitivity of part load efficiency to control variables: From Fig 4(a), it is observed that high efficiency setpoints are located in the upper boundary of the operating regime while low efficiency setpoints are situated in the lower boundary line. The high efficiency of the hybrid system under study can be achieved if the operation can be sustained under a low fuel flow, a low fuel cell current, and a high generator load. In other words, maximizing the power split ratio P_{GEN}/P_{NET} under the constraints of $P_{NET} = P_{FUEL}(I_{COM}) + P_{GEN}$ is the way of achieving the high efficient operation. This observation reveals the fact that the selection of P_{GEN} as a control variable can not only expand the operating region, but also make significant contribution to achieve a high efficiency of the SOFC/GT hybrid system.
- Temperature variation analysis: The operating domains of the fuel cell temperature at 5.0kW and 5.7kW are computed to be [1002,1020]degC and [1025,1048]degC, respectively. This means that during the load change from 5.0kW to 5.7kW, maintaining the cell temperature constant is not likely to happen. However, minimizing the fuel cell temperature variation can be achieved by well coordinated input combinations. In this particular example, the setpoints from (η, I_{COM}, P_{GEN})=(39.5,1750,350) at 5.0kW to (38.9,2100,300) at 5.7kW leads to the smallest fuel cell temperature variation of 5^{o}C. It is also noticeable that in case of a load increase operation, keeping constant

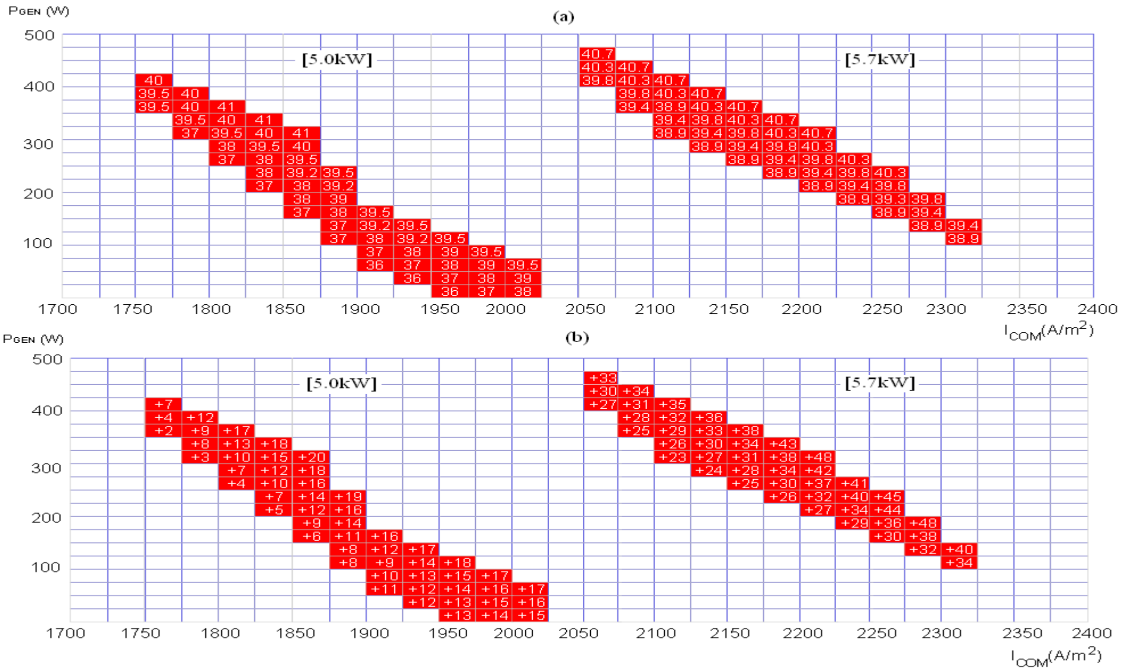

Fig. 4. The single-shaft operating regime to produce the net powers of 5.0kW and 5.7kW. (a) system efficiency map, (b) fuel cell temperature variation (T_{CELL}-1000degC) as functions of SOFC current density and a generator load.

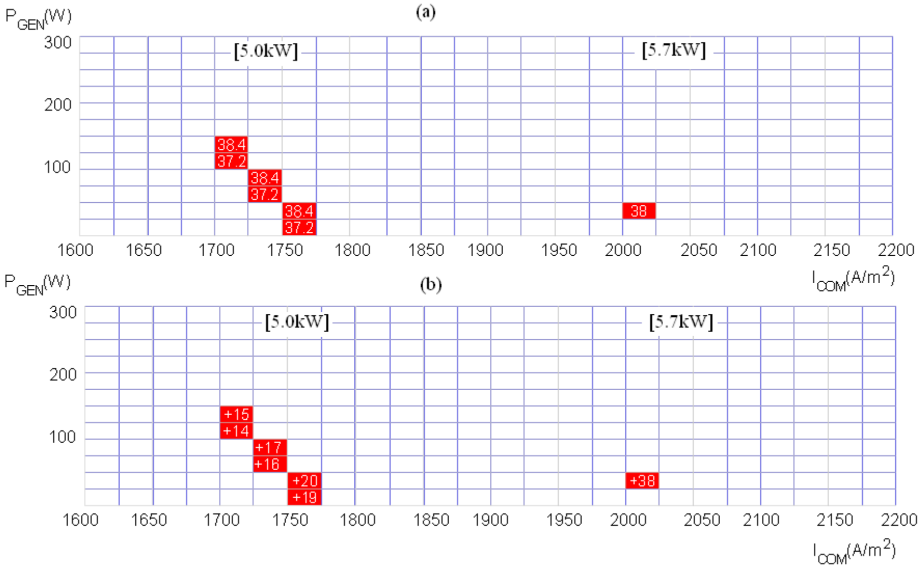

Fig. 5. The dual-shaft operating regime to produce the net powers of 5.0kW and 5.7kW. (a) system efficiency, (b) fuel cell temperature as functions of a generator load and a SOFC current density.

fuel cell temperature and achieving high efficiency are competing requirements, the cell temperature deviation can be minimized at the cost of the system efficiency. However, in case of load decrease scenario, the two-fold purpose to achieve the high efficiency and minimal fuel cell temperature change is achievable. It should be noted that the result depends on the size and direction of load operations.

2) Dual-shaft SOFC/GT Design: The performance analysis for a dual-shaft SOFC/GT cycle has been also conducted with respect to the critical factors and the results are shown in Fig 5. The plots show the feasible setpoints of the efficiency (Fig 5(a)) and fuel cell temperature (Fig 5(b)) at system output power of 5.0kW and 5.7kW. Even though the two-shaft design of the hybrid SOFC/GT cycle is advantageous in mechanical design because of its simplicity, the operating range is considerably smaller in comparison to the single-shaft configuration as shown in Fig 5. The load change from 5.0kW to 5.7kW in the dual shaft configuration leads to less change in the fuel cell temperature and the shaft speed than the single-shaft configuration.

As shown in Fig 4, under a constant fuel flow (see $\eta = 41\%$ at 5.0kW in Fig 4), the temperature increases as the fuel cell current (generator load) increases (decreases). This suggests that between the two competing factors, namely (a) increase in SOFC current increases the temperature and (b) decrease in generator load decreases the temperature, the former is more dominant. However, the generator load shows a very attractive feature that it can exert constant influence on the SOFC temperature at the different power levels. For example, the temperature differences attributed to the generator load variations is 14degC and 13degC respectively at the power of 5.0kW and 5.7kW. Hence, in case a SOFC current and fuel flow are considered as manipulated variables for the power control objective as claimed by [10], the generator load can be utilized as an alternative control element for an SOFC temperature management.

IV. DYNAMIC PERFORMANCE EVALUATION

It has been established that the hybrid SOFC/GT system is susceptible to shutdown when a sudden load increase is applied [7]. In this analysis, we use the operating envelope identified earlier to characterize the shut-down mechanism.

A. *Shutdown Problem*

In this section the region of attraction (ROA) of two SOFC/GT models is identified and analyzed in light of the shutdown phenomenon. For an equilibrium state corresponding to a load P_{NET}, the region of attraction is defined as all possible initial states from which the trajectories will converge to the equilibrium. We denote $x_{ss}(P_{NET})$ and $ROA(P_{NET})$ as the steady state and region of attraction respectively for a given power demand P_{NET}. Then the ROA provides a numerical tool to capture and understand the shutdown phenomenon. For example, consider the case that the system is settled at an equilibrium point $x_{ss}(P_A)$, but it is required to step up the power to P_B with $P_A < P_B$, the system will shutdown if

$$x_{ss}(P_A) \notin ROA(P_B). \tag{1}$$

On the other hand if

$$x_{ss}(P_A) \in ROA(P_B), \tag{2}$$

the system can reach the new desired equilibrium.

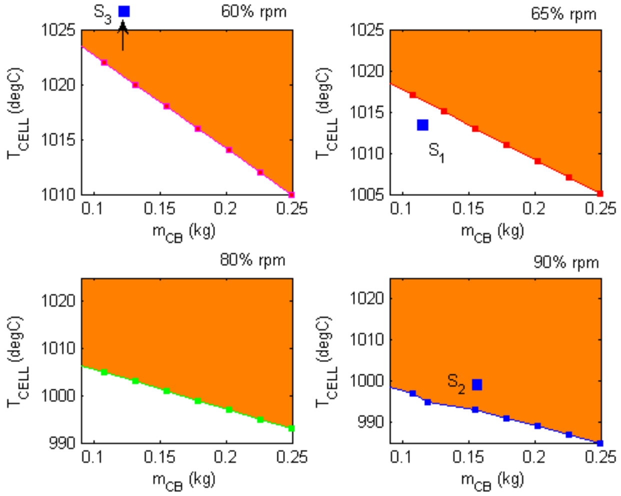

Fig. 6. ROA sketch for a single-shaft SOFC/GT model with a net power of 5.7kW and input setting (W_{Fuel},I_{COM},P_{GEN})=(0.002,2100,390). The ROA of a SOFC temperature and a CB mass are computed under four different initial turbine shaft speeds. The equilibrium point is (rpm,T_{CELL},m_{CB})=(65% rpm, 1039degC, 0.117kg).

TABLE I

THE LOAD OPERATION POINTS TO ILLUSTRATE THE SHUTDOWN BEHAVIOR OF SINGLE- AND DUAL-SHAFT SOFC/GT SYSTEMS

P_{NET}	Single
4.6kW	S_1→Input: $(0.0016, 1800, 200)$ S_1→State: $(65, 1016, 0.127)$ S_2→Input: $(0.0019, 1750, 0)$ S_2→State: $(90, 1002, 0.151)$
5.0kW	S_3→Input: $(0.0017, 1900, 350)$ S_3→State: $(60, 1038, 0.124)$
5.7kW	S_4→Input: $(0.002, 2100, 390)$ S_4→State: $(65, 1039, 0.117)$
P_{NET}	Dual
4.6kW	D_1→Input: $(0.00175, 1750, 100)$ D_1→State: $(65, 1014, 0.147)$
5.0kW	D_2→Input: $(0.00185, 1850, 100)$ D_2→State: $(67, 1017, 0.148)$
5.7kW	D_3→Input: $(0.0021, 2000, 50)$ D_3→State: $(67.0, 1042, 0.153)$

The region of attraction are computed in terms of three dominant states, namely the fuel cell temperature, the CB mass, and the shaft speed, as investigated in the previous study [7]. The three dimensional region of attraction of P_{NET}=5.7kW with input settings (W_{Fuel},I_{COM},P_{GEN})=(0.002,2100,390) is sketched on the cell temperature and CB mass dimension as the shaded areas in Fig. 6 for four different shaft speeds. From the region of attraction boundaries it can be seen that if the initial condition for the mass and the rotational speed is high, then the required initial condition for the temperature is lowered. This trend can be explained by noting that the higher the initial temperature, mass, and rotational speed are, the higher turbine power is. The energy provided to the GT shaft increases as temperature, mass and rotational speed increase. Thus, for example to reach the stable equilibrium starting at low mass, low rotational speed and P_{NET}=5.7kW, the temperature has to be high in order to make up for the energy needed to support the load on the GT shaft.

To illustrate a situation when system shutdown occurs, three load operation scenarios are evaluated in the single-shaft SOFC/GT system as shown in Table I. S_1, S_3, S_4 are operation points with the highest efficiency for their specified powers of 4.6/5.0/5.7kW while S_2 is the lowest efficiency point at the power of 4.6kW. In case of the load change from 5.0kW(S_3) to 5.7kW(S_4), it can be shown that the equilibrium point of 5.0kW resides within the ROA of 5.7kW with a large margin to the lower boundary line. On the other hand, in case of two load manuevers from 4.6kW(S_1, S_2) to

5.7(S_4), the equilibrium point with 4.6kW(S_1) falls slightly outside of the ROA of 5.7kW as shown in Table I(65%rpm) while that of S_2 is located far above the lower boundary of the ROA. This means that the load change from 4.6kW(S_1) to 5.7kW(S_4) leads the system to shutdown while the other two operations, namely $S_2 \rightarrow S_4$ and $S_3 \rightarrow S_4$ transient are sustainable due to the sufficient initial kinetic energy in the turbine and thermal energy in the SOFC exhaust.

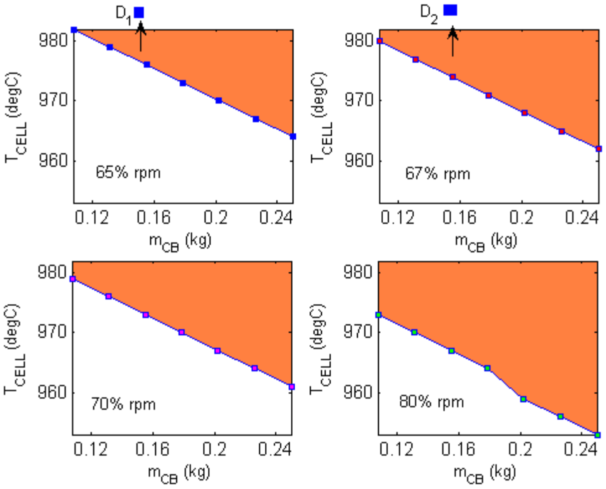

Fig. 7. ROA lower boundary for a dual-shaft SOFC/GT model for P_{NET}=5.7kW and (W_{Fuel},I_{COM},P_{GEN})=(0.0021,2000,50). The equilibrium point is (rpm,T_{CELL},m_{CB})=(67% rpm, 1042degC, 0.15kg).

A dual-shaft gas turbine design has been also studied to examine the operating characteristics and the load following performance for an SOFC/GT. We consider an open-loop response when a net power switches from 4.6kW(D_1)/5.0kW(D_2) to 5.7kW(D_3) which is the same load change conditions used in the single-shaft model analysis. The corresponding input settings are (W_{Fuel},I_{COM},P_{GEN})=$(0.00175,1750,100)_{D1}$, $(0.00185,1850,100)_{D1}$, and $(0.0021,2000,50)_{D3}$ which offer the highest efficiency set points at the powers of 4.6/5.0/5.7kW, respectively. Fig. 7 display that both equilibrium points of 4.6kW(D_1) and 5.0kW(D_2) are contained in the ROA at the power of 5.7kW(D_3). In contrast to the turbine shaft speed in the single-shaft load change of $4.6kW \rightarrow 5.7kW$, one can notice that the small amount of the generator power (50W) is applied due to the low power split ratio and thereby the dual-shaft SOFC/GT becomes less vulnerable to the system shutdown under aggressive load change.

V. CONCLUSIONS

This study has examined the characteristics of SOFC/GT hybrid cycles from the fundamental operating regime to the part load performance. Two different mechanical designs are assumed: dual shaft and single shaft as the compressor driving turbine mechanism. From the results of this study, the following conclusions are obtained. First, the single-shaft design provides wide operation envelopes compared to the dual shaft operation when the same compressor model is employed in the SOFC/GT system. The gap between the operation ranges stems from their mechanical designs in that a compressor discharge pressure in a dual-shaft design is shared by two turbines of a turbocharger and thus the power split ratio becomes much smaller than that of the single-shaft design. The dual shaft cycle would require a higher compressor pressure ratio to achieve the operating envelope to be comparable to the conventional single-shaft design. Furthermore, the system efficiency is less sensitive to the load in part load operation in the dual shaft design in comparison to the single-shaft cycle. Second, turbine shaft speed control through a generator load manipulation in both SOFC/GT configurations can be effective in enhancing the part load efficiency and maintaining the fuel cell temperature variation at its minimal. However, its usefulness is more pronounced in a single-shaft design. Third, by analyzing the region of attraction, the responses to the load change of the dual-shaft model has been proved to be more robust against the shutdown problem than its single-shaft counterpart. The dynamic load response could be further improved by using more advanced model based controllers. This is a part of our ongoing research.

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