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TRANSIENT ANALYSIS OF SIMULTANEOUS MULTIVARIABLE SIGNALS ON FUEL CELL/GAS TURBINE HYBRID TO DEFINE CONTROL STRATEGIES FOR CATHODE PARAMETERS AND COMPRESSOR STALL

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ABSTRACT

Transients in a hybrid system composed of a solid oxide fuel cell (SOFC) and a gas turbine (GT) were evaluated during simultaneous manipulation of system airflow bypasses and turbine electric load. The three airflow bypass valves selected for study were chosen for their potential application in controlling dynamic excursions of the main fuel cell and gas turbine parameters in the system. The objective of this work was to understand the physical behavior by the simultaneous operation of the bypass valves along with the turbine electric load in order to formulate scenarios of control on the key parameters relevant to system failure, specifically from compressor stall and surge. Empirical data was collected using the National Energy Technology Laboratory Hybrid Performance project hardware simulation of a SOFC/GT hybrid. Step changes were implemented in all three valves for various open/close valve commands and increase/decrease of the turbine electric load simultaneously. The transient response of process variables was analyzed to determine the potential for mitigating or aggravating compressor stall and surge during load excursions.

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INTRODUCTION

Hybrid fuel cell gas turbine systems have the potential to become the next generation of electric production in terms of high efficiency and low emission alternative power. Significant research has focused on describing different ways to manage fundamental process variables to couple the electrochemical fuel cell with the thermo-mechanical gas turbine system. For example, the air flow coming from the compressor to the fuel cell must be managed in order to prevent excessive temperature gradients in the electrolyte of the fuel cell when the electrochemical reaction is perturbed by load changes or fuel composition variations. Also, the thermal effluent of the fuel cell must be regulated to control the synchronous speed and electric load of the GT.

Control of hybrid systems has been associated with advances in the understanding of the physical relationships between controlled and manipulated-constrained variables. It has been demonstrated, in several models and experiments, that hybrid system parameters are nonlinear, complex to describe, and strongly coupled [1 – 7]. The use of a control approach has also been studied in order to select the best strategy and methodology required for the system for its inherent nonlinearities, constraints, and a complex coupling of variables [8-11].

In 2006, Mueller et al. [8] developed a dynamic model that allowed pairing input/output decentralized control of the hybrid system. This approach demonstrated transient load-following capability over a wide range of power, temperature, and fuel composition conditions. In 2008, Mueller et al. [9] used simple proportional feedback controls with steady state feed-forwards control for power tracking and thermal management. The bypass for recuperators and a variable speed blower were used for thermal management of the fuel cell with independent control of the gas turbine.

Kroll et al. [10] presented control simulation strategies to comply with the requirements of solid oxide fuel cell gas turbine (SOFC/GT) hybrids for safety operations. In that work, two bypass valves were used simultaneously to control the SOFC stack temperature and pressure over the entire operating range. Specific boundary conditions were considered within the control structure to ensure failure-free operations.

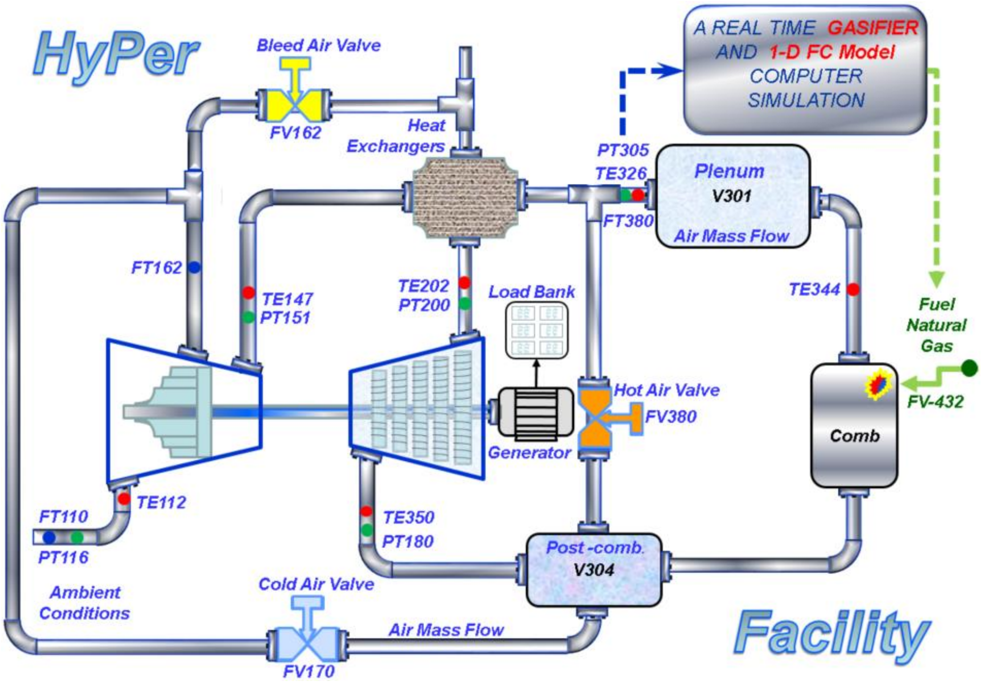

Figure 1. HyPer Facility Schematic Overview

The U.S. Department of Energy (DOE), National Energy Technology Laboratory (NETL) in Morgantown, WV has been investigating ways to couple a high temperature Solid Oxide Fuel Cell (SOFC) with a Gas turbine (GT) system.

Figure 1 shows a schematic of the Hybrid Performance (HyPer) facility at NETL and its airflow bypass control actuators configuration. This facility uses a cyber-physical fuel cell composed of hardware driven by a real time fuel cell model. The hardware of the cyber-physical fuel cell is coupled with the recuperated gas turbine cycle, where the conditions of the cathode air flow are taken by the model to perform a real time fuel cell simulation. The output of the model, effluent heat, pressure, and temperature are matched with the real hardware through a fuel valve and volumes installed in the facility. The HyPer system also contains three different manipulated bypass control valves, Bleed Air bypass (BA), Cold Air bypass (CA), and Hot Air bypass (HA) that provide control of different variables in the operational envelope of the system. The BA bypass valve is used to discharge air from the compressor plenum to the atmosphere. The CA bypass valve is used to divert air from the compressor directly into the turbine inlet through the post-combustor volume, effectively bypassing the recuperators and the fuel cell. The HA bypass valve is used to drive air preheated by the recuperators into the turbine inlet through the post combustor volume, effectively bypassing the fuel cell system. The bypasses valves are also shown in Figure 1. In addition, the balance of the plant is composed of turbomachinery, a synchronous power generator, a variable load bank, two parallel recuperators, pressure vessels that emulate the volumes and flow impedance of the fuel cell, and the associate piping. The cathode and air manifold volume between compressor and turbine in the hybrid system studies is 200 times larger than the original path volume of an industrial gas turbine.

In 2011, Tsai et al. [11] examined the impact of the cathode airflow control on system performance using the HyPer facility. He found that without simultaneous operation of the different actuators, it was problematic to control the turbine speed and cathode parameters via load or auxiliary fuel. Simultaneous actuator operation is essential to effectively manage the cathode flow and the synchronous speed of the turbomachinery.

In 2013, Pezzini et al. [12], use the HyPer system to run experiments with the purpose of designing an emergency shutdown procedure based on the manipulation of the bleed, cold air valve, and the electric load. This emergency shutdown is very important to avoid suddenly compressor turndown and consequently the possible rupture of the membrane of the fuel cell. The results indicated the actuator response was required to avoid compressor stall and its catastrophic effect on the system equipment.

In 2014, Pezzini et al. [13] evaluated the impact of the cold air bypass on compressor performance. It was found that this actuator improves significantly surge margin, but has a non-linear response with respect to turbine efficiency and speed. Based on these results, showing a high degree of coupling and constrained variables, a Model Predictive Controller (MPC) was suggested by Restrepo et al. [14] in 2016 to control the facility. In that work, the suggested MPC was simulated using all the air bypasses of the HyPer facility and the electric load simultaneously. MPC is a control methodology with the capacity to manage system constraints and be adaptive to regulate nonlinearities.

It is evident in the scientific community that the fuel cell and turbomachinery constraints of any hybrid layout play an important role for the future implementation of hybrid power systems. Compressor stall is one of those constraints, and perhaps the most important. If the compressor stall occurs during hybrid operation, the fragile fuel cell membrane will be broken, and the whole system will fail.

The main focus of this work is to evaluate simultaneous operation of actuators on critical process variables. It is very important to understand the transient behavior on the compressor map while simultaneous operation of air bypass valves and electric load are performed. The study was developed to predict the direction and sizes of the over and undershoots of the pressure ratio and compressor flow on the compressor map imposed by variation on electric load and simultaneous bypass manipulation. In addition, other fuel cell/gas turbine key variables of operation such as cathode air flow, fuel mass flow, turbine inlet temperature, among others, are examined. To avoid further complexities with electrochemical processes, the fuel cell was assumed to be electrochemically inactive during the actuator movements. Future work will include airflow actuation fully coupled to the cyber-physical fuel cell.

NOMENCLATURE

The nomenclature parameters used in this work are:

BA	Bleed Air Valve
CA	Cold Air Valve
DOE	Department of Energy
EL	Electric Load
FC	Fuel Cell
FFDoE	Full Factorial Design of Experiments
GT	Gas Turbine
HA	Hot Air Valve
HyPer	Hybrid Performance
NETL	National Energy Technology Laboratory
MIMO	Multi-input Multi-output
MPC	Model Predictive Control
OFAT	One Factor at a Time
SOFC	Solid Oxide Fuel Cell
SOFC/GT	SOFC and Gas Turbine Hybrid System

HyPer Instrumentation

This section describe the instrumentation on the main variables used in this work.

Compressor Inlet Flow (FT-110). Compressor inlet flow is measured using an annubar flow element, which produce a mechanical average of the difference between stagnation and static pressure in the inlet pipe to determine flow. The time response is 300 ms.

Fuel Cell Simulator Flow (FT-380). Inlet airflow through the fuel cell simulator is measured at the entrance of the plenum volume using an annubar flow meter similar to FT-110.

Swift Fuel Valve (FV-432). This Woodward Swift ES valve is a 2.54cm sonic needle and nozzle operated at high speed capable of implementing fast natural gas flow changes.

Rotational Speed Measurement (ST-502). Rotational speed is measured by an optical sensor. The optical sensor provides a 1200HZ signal.

Temperatures at the compressor inlet (TE-112), cathode inlet (TE-326), Turbine inlet (TE-350) and exhaust (TE-202) are the main temperatures used in this work.

Pressure at the compressor inlet (PT-116), Compressor discharge (PT-151), and system pressure loss (PDT-158) are the main pressure used in this work.

For most detailed description of the components and instrumentation of the HyPer facility can be found in [2], [4], and [7].

Test Procedure

A 3^4 full factorial design of experiments (FFDoE) was performed in the HyPer facility over approximately four days of continuous operation. The work presented herein makes use of the transients obtained during the FFDoE experiments when bypass valves and electric load were operated simultaneously.

During the experiments, the CA bypass valve was opened/closed at levels of 40, 60, and 80%. The HA bypass valve was opened/closed at levels of 20, 50, and 80%. The BA bypass valve was opened/closed at levels of 86, 88, and 90%. The levels for CA and HA represent percent of valve **opening**, but the levels on BA represent percentage of **closing**. The levels of the electric load on the turbine generator were 0, 25, and 50 kW. The levels selected for the four factors were based on a screening test where the equipment was ran very close to the limits of operation for different parameters such as turbine exhaust temperature, combustor skin temperature, and compressor stall margin. The factors and their experimental levels (set-points) are summarized in Table 1. Also, the fuel cell model was not included in these experiments, and the facility was operated under speed control using the fuel valve, FV-432 in Figure 1.

Table 1. Test levels (set-points) for valves and EL.

Factor	Symbol	Low Level 1	Inter. Level 2	High Level 3
CA Valve (%)	CA	40	60	80
HA Valve (%)	HA	20	50	80
BA Valve (%)	BA	90	88	86
Electric Load (kW)	EL	0	25	50

More details about the experimental setup, the design of the experiments, and the steady state results were reported by Restrepo et al. in [15], and [16].

ANALYSIS

An analysis was completed to understand the transient dynamics and evaluate the system performance of the key process variables related to the compressor. Four test runs of the total 81 FFDoE simultaneous actuator changes were chosen for case studies. These points were selected because they reflect opposing combinations of actuator response and electric load. In addition, the cathode inlet mass flow, cathode inlet temperature, fuel mass flow, turbine inlet, and exhaust temperature were monitored under this analysis.

A Test Run is defined by step changes performed during the simultaneous manipulation of all three bypass valves and electric load. Figures 3 through 6 include three sections each. Each figure is labeled with (a), (b), and (c) for each Test Run. Label (a) for each figure shows the transient results on the compressor pressure ratio, compressor mass flow, and system pressure loss. Label (b) for each figure shows the transient excursion and the surge margin position before and after the step changes on the compressor map. Label (c) for each figure shows the thermal changes in turbine inlet temperature and turbine exhaust gas temperature, fuel cell cathode temperature, flow, and the fuel mass flow.

The fuel mass flow in the HyPer normally represents the heat effluent from the SOFC, but in these tests, it represents the energy required to maintain constant turbine speed under the specified electric load condition.

Figure 2 shows the operating points and the surge line on the turbomachinery compressor map. The **orange square** represents the steady state operating point of maximum CA bypass valve, 100% open, at 50 kW turbine load. The **orange triangle** represents the operating point of maximum HA bypass valve, 100% open, at 50 kW turbine load. The **orange circle** represents the point with zero bypasses, at zero kW of electric load. These results were reported by Tucker et al. in [7] when the experiments were carried out using one actuator/factor at the time (OFAT).

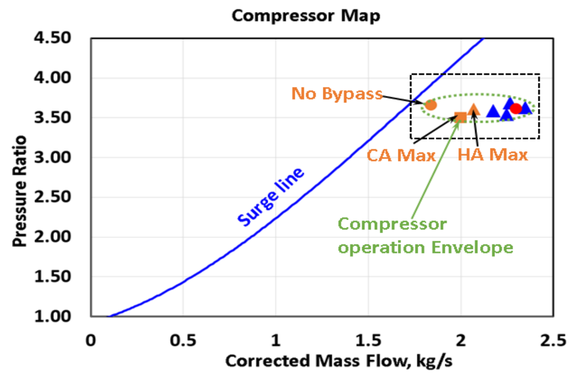

Figure 2. Steady State Operating Points on the Compressor Map

The **blue triangles** in Figure 2 represent the steady state maximum/minimum inlet mass flow and pressure ratio when the simultaneous actuators were operated. The **red circle** is the operating point when all the factors of the FFDoE are set at their central levels, CA=60%, HA=50%, BA=88%, and EL=25kW.

All the points shown in Figure 2 will be overlaid in **label b** of each of the following figures for comparison to steady state data. It can be seen in Figure 2 that simultaneous operation of the valves can effectively improve the compressor surge margin in steady state operation. The green dashed line represents the possible steady state operating envelope on the compressor map, including single and simultaneous operation of the control valves.

Test Run 1. CA +40%, HA+60%, BA -2%, EL -25kW

Table 2 shows the initial and final positions of the bypass valves, in percent opening for the CA and HA bypasses, and percent of closing for BA. The electric load step change is shown in kW.

Table 2. Initial and final set point settings for valves and electric load

	CA (%)	HA (%)	BA (%)	EL (kW)
Initial	40	20	88	50
Final	80	80	86	25

The top of the Figure 3a shows the results on the compressor pressure ratio, compressor inlet mass flow, and system pressure loss. The two bottom figures are the zoom marked as the dashed circle in figure 3a. This dashed zone shows the transient effect in these two parameters. These transient responses were the results of the bypasses and load variation on the rotational shaft of the turbomachine. For this test, the compressor mass flow increased 0.07 kg/s (3%). This was because all valves were opened, resulting in less resistance in flow through valves and pipes. This was confirmed by the decreasing system pressure loss, about 12 kPa. It is observed that the pressure achieves steady state in less than 3 seconds. But the mass flow takes around 15 seconds to stabilize.

Figure 3b shows the compressor map. It is shown that in this test run the surge margin increases because system pressure loss decreased. The dashed rectangle shows the limits of the pressure ratio and inlet mass flow. It can be seen that the transient response is practically kept inside of the dashed rectangle (steady state limits). The final steady state is achieved without overshoot, similar to a second order highly damped system, but still in the direction of increasing the surge margin. The transient response does not have a dynamic path, as seen in other tests.

It was demonstrated in previous experiments by Tucker et al. [7] that the fuel mass flow (energy requirement) is not affected by the HA bypass, and that the turbine inlet temperature is impacted by the CA bypass. But the BA acts as a shaft load in the turbomachinery. Figure 3c shows the results of the simultaneous bypasses manipulation while change electric load. Figure 3c also shows the decreasing in turbine inlet temperature ($\Delta T \approx$ -60ºC). This was because of the opening in the CA bypass. The decreasing in cathode mass flow ($\Delta \dot{m} = -0.6$ kg/s) was caused by the opening of the CA and HA bypasses.

The fuel mass flow is kept constant even when the electric load was removed. This implies the effects of the CA bypass reduction in turbine inlet temperature with the BA bypass shaft loading offset the reduction of electric load. The cumulative effect of turbine inlet temperature reduction and bleed air load against the improved pressure loss was equal to the 25 kW electric load reduction.

Test Run 2. CA +40%, HA+30%, BA -4%, EL +25kW

Similar to Test Run 1, all the valves were further opened in test Run 2, but the load was changed from an unloaded condition to 25 kW of electric load in one step. Table 3 shows the initial and final set point settings.

Table 3. Initial and final set point settings for valves and electric load

	CA (%)	HA (%)	BA (%)	EL (kW)
Initial	40	50	90	0
Final	80	80	86	25

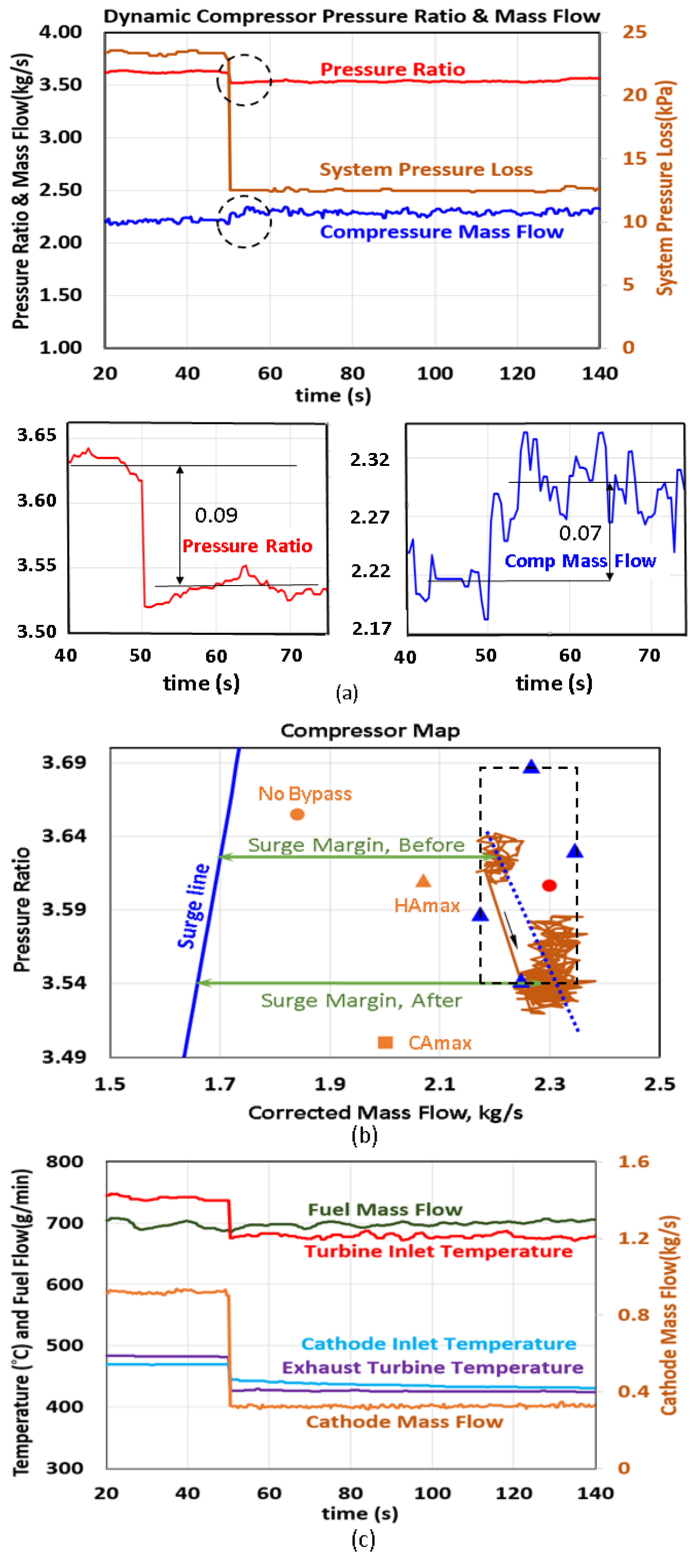

Figure 3. Transient Response of Key Parameters on the Compressor, Cathode inlet, and Turbine of the HyPer.

Figure 4a shows the pressure ratio and inlet mass flow, and both parameters exhibited an undershoot transient. The system pressure loss decreased primarily due to the opening of CA bypass.

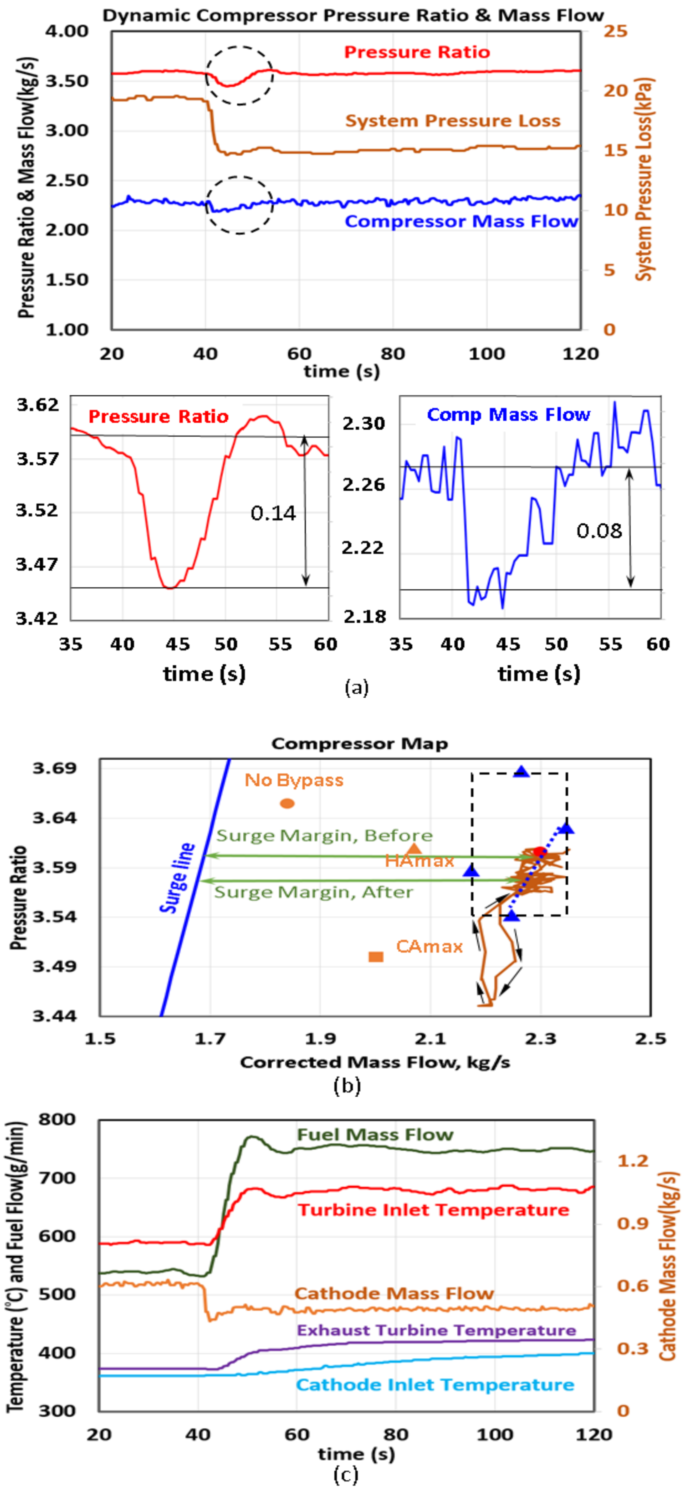

Figure 4. Transient Response of Key Parameters on the Compressor, Cathode inlet, and Turbine of the HyPer.

Figure 4b shows a significant excursion down the compressor map, outside of the dashed rectangle. The steady state change in pressure ratio was 0.03. But the amplitude of the pressure ratio undershoot was 0.15. It was 500% greater than the vertical change of the corresponding steady state pressure ratio. This confirmed the low underdamped behavior on the turbomachinery parameters. Upon initial movement of the actuators, the trajectory on the compressor map resulted in decreased pressure ratio at a constant flow, increasing the surge margin. This was followed by a slight reduction in the surge margin along the return path to the steady state value. The transient time for both variables was around 25 seconds. This sharply contrasts the results for Test Run 1, where the valves were all opened, but the load was decreased, and no unstable transient response was seen. The results imply that the direction of load change significantly impacts the dynamic response to simultaneous valve actuation.

Figure 4c also shows significant changes in fuel mass flow. The fuel mass flow increase was accompanied with an overshoot, and the pressure ratio showed an undershoot at the same time. The fuel flow mass increased due to the requirement of the system for more energy because the increased electric load and additional bleed air shaft load. The pressure ratio reduced due primarily to the increase electric load requirement. The pressure ratio decrement was mitigated somewhat due to the reduction in pressure loss observed when the CA and BA were opened further.

Test Run 3. CA -20%, HA+30%, BA +2%, EL -50kW

In Test Run 3, CA and BA were both reduced, having the effect of reducing surge margin, while electric load is rejected, having the effect of increasing the surge margin. The HA was simultaneously increased, reducing the cathode airflow, but otherwise was not expected to drive transient behavior. Table 4 shows the initial and final set points settings.

Table 4. Initial and final set point settings for valves and electric load

	CA (%)	HA (%)	BA (%)	EL (kW)
Initial	60	50	86	50
Final	40	80	88	0

Figure 5a shows that the pressure ratio and inlet mass flow have an overshoot in the same direction. These overshoots are also not insubstantial, 0.24 and 0.19 kg/s, respectively, representing a 6% and 8% deviation. The final variation on pressure ratio and inlet mass flow was only 0.02 and 0.01 kg/s, respectively. The system pressure loss increased due to the reduction of CA bypass flow. The system pressure loss increased was 3kPa. The transient for pressure ratio was 30 seconds in duration and for the mass flow was around 20 seconds.

Figure 5b shows the dynamic excursion outside of the dashed rectangle. The steady state change in pressure ratio was around the 0.02, but the amplitude of the pressure ratio overshoot was 0.24. This represented a tenfold overshoot compared with the steady state pressure ratio change. This overshoot in pressure ratio was due to the removal of electric load on the shaft of the turbomachine. Again, the initial trajectory was further from the stall line. In any case, the dynamic path was parallel to the stall line.

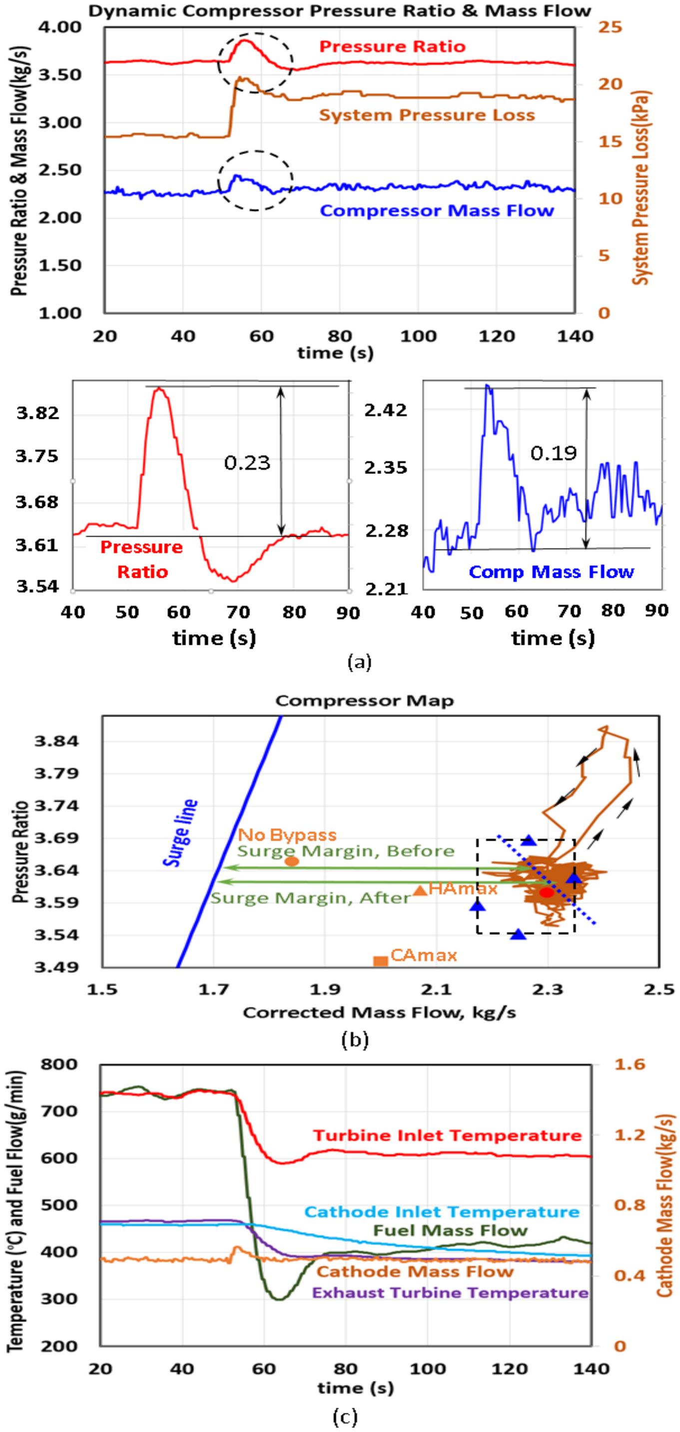

Figure 5. Transient Response of Key Parameters on the Compressor, Cathode inlet, and Turbine of the HyPer System

Figure 5c shows the detriment in fuel mass flow with overshoot due to the sudden loss of electric load. Since the cathode airflow was not significantly impacted by the step change, the HA actuation was sufficient to offset the reduction in CA and BA. Since the steady state compressor flow and pressure ratios were similar, the reduction of CA and BA were approximately offset by the 50 kW electric load reduction, in terms of the compressor surge margin.

Test Run 4. CA -20%, HA+30%, BA -2%, EL +50kW

In Test Run 4, the decrease in CA and increase in electric load were expected to decrease the surge margin, while the increase in BA would increase the surge margin. The initial position of the CA valve represented a high degree surge margin. The test was done in one step, and the test levels are included in Table 5.

Table 5. Initial and final set point settings for valves and electric load

	CA (%)	HA (%)	BA (%)	EL (kW)
Initial	80	50	88	0
Final	60	80	86	50

Figure 6a shows that the pressure ratio and inlet mass flow have a similar transient behavior after the step changes. In this case, an under/overshoot transient was observed. The system pressure loss increased by about 3kPa because of the CA valve reduction and the electric load increase. In this case, the transient in the pressure ratio and compressor mass flow was 25 seconds long. The volume of the system acts as capacitance for competing physical processes. Since the BA and CA were acting in opposition, flow through each valve is interdependent, and several seconds are required to establish a flow equilibrium.

Figure 6b shows the dynamic excursion on the compressor map outside of the dashed black rectangle. This was indicative of the competing processes that occurred during compressor transient operation. The initial sharp decrease in compress flow resulted in a substantial degradation of the surge margin. This was followed by a pressure decrease and a subsequent increase in flow that increased the surge margin. The transient continued through the initial steady state operating point before the pressure ratio continued to rise at a constant flow, decreasing the surge margin again. In response to the pressure ratio increase, the flow increased, increasing the surge margin before returning to a steady state on the map. The pressure ratio steady state change was 0.04, but the total overshoot amplitude was 0.25 as shown in Figure 6b. The physical delays in process phenomena represent significant control challenges, but also control opportunities.

Overall, the transient behavior could not be summarized as combination of single actuator responses, indicating the need for more exploration of simultaneous actuator response to better understand physical process coupling issues and opportunities.

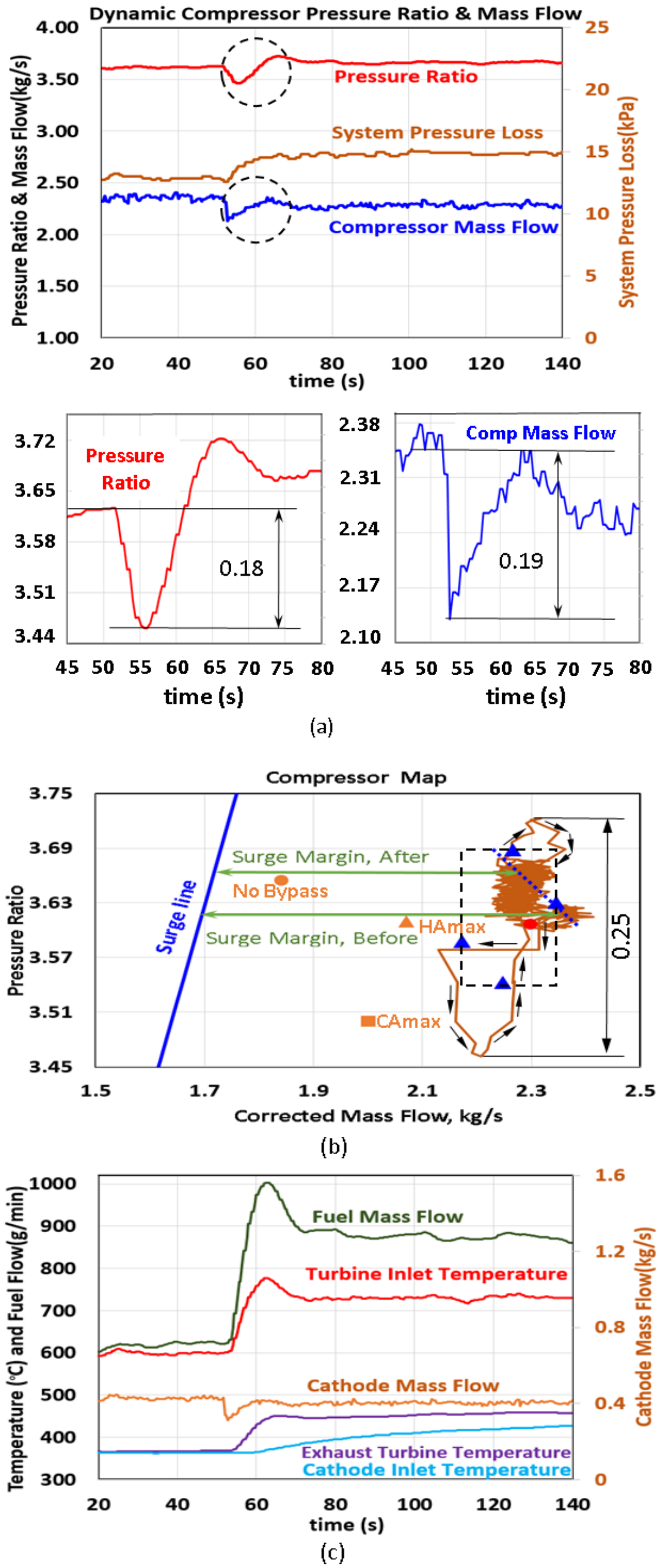

Figure 6. Transient Response of Key Parameters on the Compressor, Cathode inlet, and Turbine of the HyPer System

CONCLUSIONS

Simultaneous actuator control will be essential to take advantage of flexibilities inherent to fuel cell turbine hybrid power systems, especially considering the high degree of constraints in these systems due to material limits. The stall in turbomachinery compressors is one of the main constraints of hybrid power systems.

This study was done to analyze the effects of the simultaneous operation of the actuators on the compressor dynamics. It was observed that simultaneous steps changes in the actuators can represent high amplitude fluctuations compressor dynamics. The transient overshoots observed in the compressor map during step changes of the bypass valves and electric load could be a source of failure in the operation of the compressor, but could also represent opportunities for mitigating compressor surge during load transients. Two cases were studied with a sudden electric load increase, but with different simultaneous bypass valve operation. In one case, the surge margin was dramatically decreased by over 30%, while in the other case, the surge margin was increased by over 10% without a non-linear trajectory on the compressor map.

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