Dynamics, Optimization and Control of a Fuel Cell Based Combined Heat Power (CHP) System for Shipboard Applications

Vasilis Tsourapas, Anna Stefanopoulou and Jing Sun

Abstract—In this paper, a natural gas fuel processor system (FPS), a proton exchange membrane fuel cell (PEM-FC) and a catalytic burner (CB) are integrated in a combined heat power (CHP) generation plant. The FC provides the power based on electrochemical reaction of hydrogen (H\textsubscript{2}). The FPS generates the hydrogen from natural gas and the CB provides the energy for preheating the FPS inlet flows by burning any excess H\textsubscript{2} from the FC exhaust. The coupling of these three systems poses a challenging optimization and control problem. The goal is to analyze the open loop dynamics and design a controller that achieves optimal steady state operation and acceptable transient performance, i.e., mitigates the H\textsubscript{2} starvation and regulates reactor temperatures. We show in simulations that an observer based feedback controller, which relies on temperature measurements of two reactors, speeds up the transient response fivefold, as compared to the baseline when no feedback control is employed.

I. INTRODUCTION AND MOTIVATION

Combined heat power (CHP) systems based on fuel cells and fuel processing technologies have great potential for future shipboard applications. In addition to the benefits offered by implementing fuel cell and fuel processor technology within the all-electric ship framework, such as cleaner shipboard power generation, efficient electric power distribution, flexible hull design, silent operation and low thermal acoustic signature, higher efficiency can be achieved by the CHP systems with the incorporation of a catalytic burner. For steady state operations, as much as 16% efficiency improvement can be achieved with the CHP systems over the stand alone fuel cell power generation systems [1].

The CHP system, depicted in Fig. 1, consists of a proton exchange membrane fuel cell (PEM-FC) stack that generates electric power, a fuel processing system (FPS) that converts a hydrocarbon fuel to a H\textsubscript{2} rich mixture to be fed to the fuel cells, and a CB that recovers any excessive H\textsubscript{2} leaving the fuel cells to provide the preheating energy for the reformer. Other auxiliaries, such as the air blower, fuel pump, heat exchangers, are also integral parts of the CHP system. The complicated configuration and closely coupled dynamics, together with the large thermal inertia and therefore slow transients associated with the fuel processor, impose a very challenging control problem.

In order to achieve the overall maximum efficiency, the integrated CHP system has to work very close to its operating boundary (Fig. 3). This optimal set-point selection, however, puts the system in a very vulnerable position during system transitions. When a load is suddenly applied, the CHP system may not be able to provide sufficient H\textsubscript{2} and heat fast enough to sustain the operation under the new load condition, thereby leading to temporarily H\textsubscript{2} starvation or system shutdown. These problems can be avoided by slowing down the load drawn from the fuel cell through a slew rate or a load governor [2]. The load deficit in this case can be provided through hybridization [3], with an additional electrical power source which can increase cost and complexity. Another typical approach that does not rely on hybridization is to increase the system operating range by producing high rates of hydrogen, thus lowering FC utilization and CHP efficiency.

Operating at optimal steady state and thus capitalizing the benefits of the CHP system will be made possible only if the controlled system responds very fast to FC load changes. Otherwise, one has to resort to sub-optimal setpoints, i.e., to trade the efficiency for improved safety margin. In this paper we design a controller that speeds-up the natural CHP dynamics and supplies hydrogen to the fuel cell while maintaining optimum reactor temperatures. The feedback controller is based on measuring reactor temperatures and estimating the spatially averaged composition of reactant flow through the series of CHP components.

II. AN OVERVIEW OF THE CHP SYSTEM

A low pressure CHP system with a rated power of 250kW is used as the platform for our investigation in this
paper. For shipboard power applications, a key enabling technology is the on-board fuel reforming, and a critical requirement is the fast load following capability. In this application, we consider the catalytic partial oxidation reforming technology, because of its fast (relative to steam reforming) transient response.

The FPS, depicted in Fig. 1, is composed of four main reactors, namely, the hydro-desulfurizer (HDS), the catalytic partial oxidation (CPOX), the water gas shift (WGS), and the preferential oxidation (PROX). The later are assumed to poisons the PEM fuel cell catalyst, it has to be eliminated using water in the gas shift converter (WGS) and air in the preferential oxidizer (PROX). The later are assumed to take place in the CPOX: partial oxidation (POX) and total oxidation (TOX) [6], [7]:

\[
\begin{align*}
(POX) & \quad CH_4 + \frac{1}{2}O_2 \rightarrow CO + 2H_2 \\
\Delta H_{\text{pox}}^0 & = -0.036 \times 10^6 \text{ J/mol} \quad (1) \\
(TOX) & \quad CH_4 + 2O_2 \rightarrow CO_2 + 2H_2O \\
\Delta H_{\text{tox}}^0 & = -0.8026 \times 10^6 \text{ J/mol}. \quad (2)
\end{align*}
\]

Hydrogen is produced only by the POX reaction while heat is mostly generated by the TOX reaction. As shown in Fig. 2, the balance between the two is dictated by the molar ratio of \( O_2 \) to \( CH_4 \), \( \lambda_{O2C} = n_{O2}/n_{CH4} \), where \( n_i \) is the number of moles of the species \( i \). Moreover, since the CPOX products are also highly dependent on the CPOX reactor temperature \( T_{CPOX} \), the optimum balance between the two reactions has to be determined.

Carbon monoxide (CO) is also created along with \( H_2 \) in the POX reaction, as can be seen in (1). Since CO poisons the PEM fuel cell catalyst, it has to be eliminated using water in the gas shift converter (WGS) and air in the preferential oxidizer (PROX). The later are assumed to operate perfectly thus eliminating all the CO in the stream. The \( H_2 \) -rich mixture leaving the PROX enters the anode of the fuel cell stack where the electro-chemical reaction takes place to convert \( H_2 \) to electrical power. The flow from the anode is then supplied to the catalytic burner (CB) where the excess \( H_2 \) is burnt using the air supplied through a blower. Finally, the flow from the CB is fed to two separate heat exchangers (HEX), one to preheat the air and one to pre-heat the fuel before they enter the FPS and thereby increasing the overall utilization of the fuel.

In [1], a 19 state, nonlinear, dynamic and control oriented model for the CHP system has been developed based on the fuel processor system in [8]. This model is employed in this work for optimization analysis, performance evaluation and control design.

III. STEADY STATE EFFICIENCY OPTIMIZATION

For the system to work efficiently in an integrated fashion, each component has to be conditioned properly in terms of its operating temperature, humidity, and pressure. This is achieved by controlling the air and fuel intakes of the FPS. The strong physical coupling of the CHP components, shown in Fig. 1, will eventually dictate the optimal set-points for the system.

To determine the optimal steady state operating points with respect to the overall system efficiency, the following optimization problem is formulated

\[
\max_{u_f, u_a} \eta_{CHP} = \frac{V \cdot I_{st}}{W_{CH4, used} \cdot Q_{CH4, LHV}}. \quad (3)
\]

The objective is to maximize the overall efficiency, \( \eta_{CHP} \), which is defined as the ratio of the FC output power \( V \cdot I_{st} \) over the energy used \( W_{CH4, used} \cdot Q_{CH4, LHV} \), where \( W_{CH4, used} \) is the amount of fuel used and \( Q_{CH4, LHV} \) its lower heating value. The optimization variables are the fuel valve command, \( u_f \), and the air blower command, \( u_a \), both ranging from 0 to 100\%, corresponding to minimum and maximum actuator inputs respectively, or to minimum and maximum flows.

The modified gradient descent method was employed to solve the optimization problem [9]. The corresponding iterative algorithm is given as

\[
u_{k+1} = u_k - a_k \cdot \nabla \eta_{CHP}^T(x_k) \quad (4)
\]

where \( a_k \) is the iteration step, \( \nabla \eta_{CHP}^T(x_k) \) is the gradient vector which corresponds to the \( \eta_{CHP} \) increasing direction and \( u = [u_f \ u_a]^T \). The iteration step size, \( a_k \), is kept constant until no further increasing steps can be found and is then reduced by the bisection method up to the desired accuracy.

Convergence of the gradient algorithm to a global maximum can be verified given the convex form of the efficiency map for the whole range of FC loads. An example of the efficiency map is given in Fig. 3 for the FC load\(^1\) of 100A. The maximum efficiency for this load is 33.6% while the optimal setpoint is \( [u_f^* \ u_a^*] = [0.75 29.00] \). Using the same procedure for each operating load the

\(^1\)In this paper, the term “load” is synonymous to the current drawn from the fuel cell.
optimal steady state setpoint map can be determined for the actuator inputs \( u^* = [u_{f}^*, u_{a}^*]^T = f_u(I_{st}) \) and other critical operating variables (eg. \( T_{cpox}^* = f_{cpox}(I_{st}) \)) that can serve later as controller setpoints.

As illustrated in Fig. 3, the optimal operating setpoint lies close to the operating boundary of the system. This trend is observed for the whole range of operating loads of the system. The operating boundary \( (I_{CHP} = 0\%) \) is defined as the locus of points where the produced amount of \( \text{H}_2 \) is less than the required amount by the FC, given a specific load at steady state operation. As a result, the system is susceptible to steady state \( \text{H}_2 \) starvation during uncompensated loads. To avoid modeling errors and react fast to load variations, a combination of feedforward and feedback control is required.

It is important to point out, that according to the optimization results, all the optimal operating points, independent of the load drawn from the FC, occur at \( \lambda^{O2C} = 0.69 \) and \( T_{cpox}^* = 980 \text{K} \). Note here that the optimization of the overall CHP efficiency (3), corresponds to a CPOX oxygen to carbon ratio \( (\lambda^{O2C}) \) that is greater than the value for maximum \( \text{H}_2 \) production at the CPOX reactor \( (\lambda^{O2C} = 0.5 \) as indicated in Fig. 2).

In order to explain this result, one has to notice that while both POX and TOX reactions in (1)-(2) are exothermic, the TOX releases 20 times more heat than the POX reaction. For the integrated CHP system the CPOX temperature, which is highly coupled to the \( \text{H}_2 \) production, is a function of both the heat released by the reactions inside the CPOX and the temperature of the incoming air and fuel flows which are heated by the energy supplied through the CB. Moving \( \lambda^{O2C} \) towards 0.5, will promote \( \text{H}_2 \) production but suppress the TOX reaction which only occurs for \( \lambda^{O2C} > 0.5 \). Thus the contribution of the TOX reaction to the CPOX temperature will be reduced and, as a result, the CPOX reactor has to rely on preheating the inlet flows by the CB. Since both outputs (the \( \text{H}_2 \) and heat) are essential for the system to function properly, \( \lambda^{O2C} = 0.69 \), the optimal point, reflects a balance between the \( \text{H}_2 \) production in the FPS and heat generation externally in the CB and internally in the CPOX reactors for steady state operation. It is important to note that the overall CHP optimum is not defined through optimization of individual components.

IV. OPEN LOOP DYNAMICS

Examining the transient performance of the system using static feedforward control enables us to gain insight on the system dynamics. In this section we examine the open loop system dynamics by utilizing the optimal steady state setpoint maps derived from the optimization results described in Sec. III. For a given load, the fuel and air operating setpoint are defined by the feedforward maps. Since the maps were optimized for steady state operation the open loop control is not adequate to prevent \( \text{H}_2 \) starvation when a large step change in load is demanded.

The FPS introduces a considerable lag in \( \text{H}_2 \) generation due to the multiple volumes and reactors involved, thus has a slower time constant than the fuel cell stack when a step change in the demanded load is applied. Consequently, the maximum possible rate at which the load can be increased is dictated by the FPS and the \( \text{H}_2 \) production dynamics.

The open loop response of the system for two consecutive load steps, one 90-100A and another 100-150A, is shown in Fig. 4. For the initial small step of 90-100A, the fuel processor manages to provide the fuel cell with the required amount of \( \text{H}_2 \) in order to meet the load demand. For the second larger step of 100-150A though, the \( \text{H}_2 \) generation is below the demanded \( \text{H}_2 \) level for a considerable period of 10 seconds. Starving a fuel cell for 10 seconds can cause extended membrane damage and jeopardizes the life span of the stack. Moreover,
65 K overshoot in the CPOX temperature within 15 sec is observed, which can have damaging consequences for the CPOX reactor. Both issues are highlighted on Fig. 4.

There are three critical processes that affect the generation of H$_2$ during load changes and cause the H$_2$ starvation problem. Analyzing those processes will provide insight in the control problem and the system design.

The first critical process was found to be the CB temperature variation during a step change in load. When a step load is applied the H$_2$ flow is depleted at a rate faster than it is produced, due to the slow time constant of the FPS. This results in reduction or even elimination of the H$_2$ flow to the catalytic burner, which in turn results in a temperature reduction in the CB and eventually a temperature reduction of the inlet air and fuel flows. However, the thermal inertia and large time constant of the CB can maintain the temperature to a level that does not affect the H$_2$ production of the FPS. A comparison of the CHP system, where the CB temperature is a function of H$_2$ in anode exhaust with an imaginary system where the CB temperature is maintained constant at a nominal value is given in Fig. 5a and b. The two responses are almost identical, with the constant CB temperature response (Fig. 5b) exhibiting slightly less undershoot. Consequently, the CB temperature variation during load increase is not the main cause of the H$_2$ starvation problem.

As mentioned earlier the feedforward controller based on the steady state optimization places the system close to its operating boundaries and therefore making it susceptible to H$_2$ starvation. A non-optimal map implies increased excess fuel usage which implies increased H$_2$ production in steady state. As a result the difference between the required H$_2$ and the produced is expanded leading to increased safety margins at the price of reduced efficiency. In the case shown in Fig. 5c, there is an efficiency reduction from 33.5% to 28.7%.

The third and most important cause of the H$_2$ starvation can be attributed to reactor sizing issues. The large residence time of the HDS, due to the slow kinetics of the fuel desulphurization [10], imposes the requirement of a relatively large volume compared to the adjacent volumes of the MIX and the HEX. The combination of the large volume in the fuel path, the small volume of the air path and the large flow of air compared to the fuel flow causes the MIX pressure to built up at a rate faster than the HDS pressure during transients. In turn the pressure difference between those volumes initially exhibits an undershoot until the HDS pressure manages to built up again as illustrated in Fig. 6. Since the fuel flow is a function of the pressure gradient, the same undershoot is observed for the fuel flow which causes the oxygen to carbon ratio $\lambda_{O2C}$, to overshoot.

Based on the CPOX reaction map, given in Fig. 2, an overshoot in $\lambda_{O2C}$ from its nominal steady state operating point 0.69 to 1.15 implies a steep decrease in H$_2$ production. One way to illustrate this is by decreasing the HDS volume in the model. Fig. 5d compares the response of the original system, with $V_{HDS}=0.3$ m$^3$, with an imaginary system that has a considerably smaller HDS volume of 0.1 m$^3$. For the later case, the H$_2$ starvation problem disappeared. If future advances in the desulphurization process produce a compact HDS reactor, then the transient performance of the system would improve dramatically.

V. FEEDBACK CONTROL DESIGN & ANALYSIS

In this section we investigate the effectiveness of using observer based feedback control in improving the transient performance of the CHP system. In particular, our objective is to eliminate the H$_2$ starvation problem and to control the CPOX temperature overshoot while maintaining efficient steady state operation by utilizing the optimized feedforward maps.

A. Selection of Feedback Variables

The control architecture is based on setpoint error regulation, using the setpoint maps defined in Sec. III through the plant optimization. The controller is implemented by augmenting integrators to the estimator based feedback controller. In deciding which signals need to be regulated and are best suited as feedback variables in the controller,
one has to consider the control requirements (namely, H₂ and T_{cpox} regulation), the sensitivity of measured signals to the fuel and air actuators, as well as the ease of measuring those signals. Ideally we would choose the CPOX temperature T_{cpox} and the partial pressure of H₂ leaving the anode P_{H₂} as the feedback variables, as they are linked directly to the control objectives. However, since P_{H₂} is difficult to measure, we choose the CB temperature T_{cb} shown in Fig. 7, illustrate that for the optimal setpoint dynamics due to the associated thermal inertia. It should be also pointed out that the sensitivity plots, shown in Fig. 7, illustrate that for the optimal setpoint temperature T_{cb} is designed using the process noise covariance Q_{L} and the measurement noise covariance R_{L} given below

\[ Q_{L} = diag[[0 1 0 1 0 1]], \quad R_{L} = diag[[0.01 0.01]]. \]  

(11)

Recognizing that measuring all 19 states is impossible, we design a state estimator to provide the needed information for state feedback. The state estimator is expressed as

\[ \dot{\hat{x}} = A_{p} \cdot \dot{\hat{x}} + B_{p} \cdot \hat{\delta}w + B_{w} \cdot \hat{\delta}w + L \cdot (\hat{\delta}z - \hat{\delta}\hat{z}) \]  

(12)

where \( L = SC_{T}R_{L}^{-1} \) and \( S \) is the solution to

\[ A_{p}S + SA_{p}^{T} - SC_{T}R_{L}^{-1}C_{z}S + B_{p}Q_{L}B_{p}^{T} = 0. \]  

(14)

The observer gain L is designed using the process noise covariance Q_{L} and the measurement noise covariance R_{L} given below

\[ Q_{L} = diag[[0 1 0 1 0 1]], \quad R_{L} = diag[[0.01 0.01]]. \]  

(15)

The control signal \( u = [u_f u_a] \), when the observer based controller is implemented in the nonlinear CHP model is given by

\[ u = -K_{I} \cdot \hat{\delta}q - K_{P} \cdot (\hat{x} - \hat{x}_0) + u_0 \]  

(16)

VI. PERFORMANCE EVALUATION

The estimator based feedback control scheme, compared to the open loop controller, manages to improve the transient performance of the CHP system (Fig. 8). It is interesting to note that the feedback controller overshoots fuel and slows down air command initially, in order to regulate \( \lambda_{O2C} \) around its optimal value and resolve the undershoot of fuel flow that was observed on the open loop system (Fig. 6). As a result, the H₂ production increases smoothly and the H₂ starvation problem reduced.
Furthermore, the CPOX reactor temperature overshoot is substantially reduced. Application of the observer based feedback controller yields a small overshoot which is negligible compared to the open loop performance where $T_{\text{CPOX}}$ overshoots to 1060 K within 15 sec.

Even when feedback control is applied, the CHP transient response still exhibits a short period of $T_{\text{CPOX}}$ overshoot which can be attributed to the lag due to the multiple reactor volumes in the flow. A constant rate limiter can be implemented in order to eliminate the starvation by slowing down the rate at which the current is drawn from the FC. Without feedback, a rate limiter of 4A/sec would be required, while for the state or the observer based feedback a rate limiter of 20A/s is adequate to eliminate the problem. Thus the maximum transient speed has been increased by a factor of five.

Finally, it is important to note that the performance achieved with the proposed controller, that utilizes only temperature measurements, is comparable to the performance of the controller developed in [11] for the FPS-FC system, that utilizes $T_{\text{CPOX}}$ and $y_H_2 = P_{H_2}/P_{H_2}$ (i.e. $H_2$ partial pressure sensor). The later measurement is significantly faster than $T_{cb}$, since it involves pressure dynamics instead of temperature. Thus, implementing a CB into an FPS, besides increasing significantly the steady state efficiency, also provides an indirect measurement of the $H_2$ starvation that is easy to measure and can be utilized to control the transient response. Summarizing the overall CB contributions to the FPS, we can conclude that the CB

- significantly improves steady state efficiency
- does not degrade the transient performance of the plant due to the thermal inertia
- provides an indirect measurement of the $H_2$ produc-

VII. CONCLUSIONS

In this paper, the control oriented model of a fuel cell based CHP system, developed in [1] is employed for steady state optimization and control design. Using the gradient algorithm, the air and fuel setpoints that yield maximum overall efficiency are determined for every load of the FC. The system characteristics and dynamic properties are analyzed. The processes responsible for the poor transient open loop performance are identified. A feedback control scheme is designed using only the temperature measurements of the CPOX and the CB reactors. Our results show that the $H_2$ starvation is mitigated and the CPOX temperature overshoot is minimized during a large load step when the proposed feedback controller is implemented. Moreover, a 500% increase in the maximum transient speed of the CHP plant is achieved. Finally it is proven that implementing a CB into a FC reformer is beneficial to the system. Robustness analysis and complexity reduction of the controller are yet to be examined.

REFERENCES