

Development of Model Predictive Controller for SOFC-IC Engine Hybrid System

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ABSTRACT

Fuel cell hybrid systems have emerged rapidly in efforts to reduce emissions. The success of these systems mainly depends on implementation of suitable control architectures. This paper presents a control system design for a novel fuel cell – IC Engine hybrid power system. Control oriented models of the system components are developed and integrated. Based on the simulation results of the system model, the control variables are identified. The main objective for the control design is to manage fuel, air and exhaust flows in a way to deliver the required load on the system within local constraints. The controller developed for regulating flows in the system is based on model predictive control theory. The performance of the overall control system is assessed through simulations on a nonlinear dynamic model.

INTRODUCTION

The efforts to reduce emissions and fuel consumption with improved system performance have led to development of various hybrid systems. Fuel cell hybrid systems involve a number of operating requirements for efficient operation. The typical operating requirements include prevention of air and fuel starvation, prevention of carbon deposition, maintaining voltage output, maintaining operating temperature and avoiding thermal stresses. Such systems with multiple processes are complex with nonlinearities, noise and disturbances. The performance of these systems is often dependent on more than a single variable; hence there is a need to develop a comprehensive multivariable controller which can accommodate all the above mentioned effects.

A number of studies have been conducted for control design to prevent air and fuel starvation of fuel cell

systems [1-8]. Mueller et al [1] describe a novel baseline controller for rapid load following of solid oxide fuel cells. Feedback controllers are developed to regulate fuel depletion and for the fuel cell thermal management. Pukrushpan et al [2] describe the dynamic modelling and analysis of a fuel cell system. The analysis in [2] provides the basis for the control development which is described in Pukrushpan et al [3]. The work presents system modelling and feedback control design for air and fuel regulation.

On similar lines Bao et al [7, 8] describe a control oriented model for a PEM fuel cell system and compare different controllers for the system. Bao et al [7] have elaborated on three different control configurations namely, a decentralised PI control, a multivariable state feedback control and a nonlinear adaptive control. The results show that the multivariable controller obtain improved transient response as well as disturbance rejection capability as compared to the decentralized controller [7].

Vahidi et al [4] have proposed a hybrid fuel cell system where a small auxiliary power source allows improved control over oxygen starvation during rapid current transitions. A model predictive controller manages the current distribution between the fuel cell and the auxiliary power source. Further study by Vahidi et al [5] describes a model predictive controller for current management for a hybrid system in which an ultracapacitor bank supplements the fuel cell operation during transients. The objectives of the controller are to regulate the excess oxygen ratio of the fuel cell and the state of charge of the ultracapacitor [5].

The solid oxide fuel cell – IC engine hybrid system described in this paper, has its performance dependent on the flows in and through the system components. The

system has nonlinear processes with outputs dependent on multiple inputs. The constraints imposed on the system components are due mainly to the limits of operating temperature to avoid degradation of materials, limitations by reaction kinetics, avoid pollutant formation. The main objective for the multivariable controller is to manage fuel, air and exhaust flows in a way to deliver the required load on the system while maximizing fuel efficiency within local constraints. The dynamic response of the each system component varies, with the reformer being slower than the fuel cell and engine. The ability of the model predictive controller to predict future control action by penalizing any undesired behaviour within prescribed constraints makes it suitable for solution of the control problem proposed. In the following sections, this paper describes the system configuration, control problem, approach followed for control design, results and discussion.

SYSTEM DESCRIPTION

The system, as depicted in Figure 1, consists of a solid oxide fuel cell supplied by fuel from a steam reformer and air from a compressor. The turbocharged engine is supplied by a primary liquid fuel such as diesel. The exhausts from the fuel cell and reformer are fed into the IC engine.

The excess hydrogen from the fuel cell anode assists in improving combustion while the oxygen depleted air from the cathode along with water vapour from the anode act as diluents. The load on the system is shared by solid oxide fuel cell and the IC engine together. The engine handles majority of the transient load while the fuel cell operates at a base load. The system is suitable for a bus or a delivery truck cycle.

An initial steady state and transient analysis done on the fuel cell – IC Engine system [9, 10] suggested that effective management of the flows into and out of the system can result in optimum operation of the system.

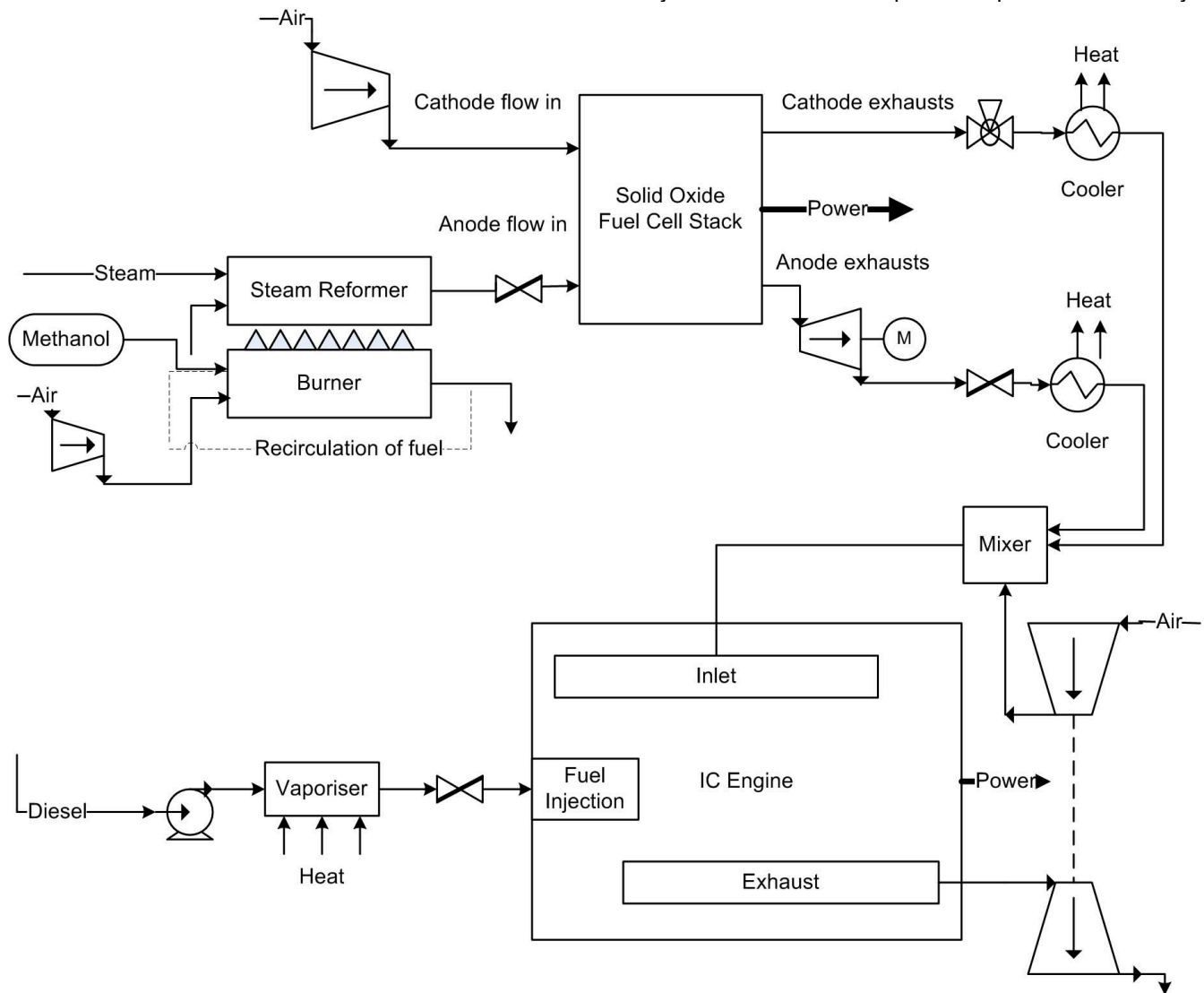


Figure 1 – System Schematic

Introducing trace amount of hydrogen into a diesel engine can improve combustion and thermal efficiency [11]. The high cetane number of hydrogen can cause knocking and hence requires a diluent such as nitrogen [11]. Nitrogen as a diluent was better for engine performance while water as diluent is better for emission reduction [11]. The oxygen depleted air from the fuel cell cathode and the water vapour from the fuel cell anode serve this purpose. The exhaust from the reformer except hydrogen, are fed together with the exhausts from the fuel cell as a form of externally supplied EGR (Exhaust Gas Recirculation).

The amount of hydrogen entering the engine depends on the amount of excess fuel supplied to the fuel cell. This can be controlled by controlling the utilization factor μ_f defined as the ratio of hydrogen consumed to the hydrogen supplied to the fuel cell.

$$\mu_f = \frac{W_{H_2,used}}{W_{H_2,in}}$$

The efficiency of the fuel cell is proportional to the utilization factor [12]; hence a very low utilization factor results in greater amount of hydrogen in the engine but lower fuel cell efficiency. Since the fuel cell operation can be potentially more efficient than the engine, it is suggested to maintain an optimum utilization factor. The excess oxygen ratio λ_{O_2} , value must be such that air starvation in the fuel cell is avoided.

$$\lambda_{O_2} = \frac{W_{cathode}}{W_{O_2,used}}$$

The effects of introducing effluents from the fuel cell and the reformer in the engine results in elimination of the conventional EGR valve from the engine exhaust system. It also affects the oxygen concentration in the engine and the combustion chemistry. The conventional diesel engine EGR system is complicated to control as compared to an externally supplied mixture which can be regulated as per requirement. The airpath control of the engine with the VGT (Variable Geometry Turbocharger) vane position and EGR valve position is complicated due to the interaction of the flow paths for the EGR and VGT in the exhaust manifold, nonlinear behaviour of turbochargers and common shaft between the compressor and turbine [13]. The externally supplied inert gases or external EGR greatly simplifies the control problem between the VGT and conventional EGR valve.

CONTROL PROBLEM

INTRODUCTION TO MODEL PREDICTIVE CONTROL

Model predictive control (MPC) is a control strategy that involves online optimisation of the process and prediction of future control signals over a prediction horizon. The basic structure of a model predictive controller is given in Figure 2.

The MPC strategy

The MPC strategy as describe by Camacho et al [14] is described here. The future outputs are predicted for the next time instant, $t+1$ using prediction model. These future errors are calculated on the basis of past input and output and future control actions. The future control actions are determined by minimizing a criterion which consists of a cost function and constraints. This criterion is such that is maintains deviations from reference trajectory to a minimum.

The model predictive controller follows a receding horizon concept. The optimisation is performed for a future time interval $[i, i+N-1]$. At time $t=i$, the optimisation results in the future control action $u(t)$ over this horizon. The control action at the time t , $u(t|t)$ is sent to the process model while the other signals computed are rejected. The process model then generates the future output for time $(t+1)$ giving $y(t+1)$. This output is further used to compute the future control action $u(t+1|t+1)$ over the time interval $[i+1, i+N]$.

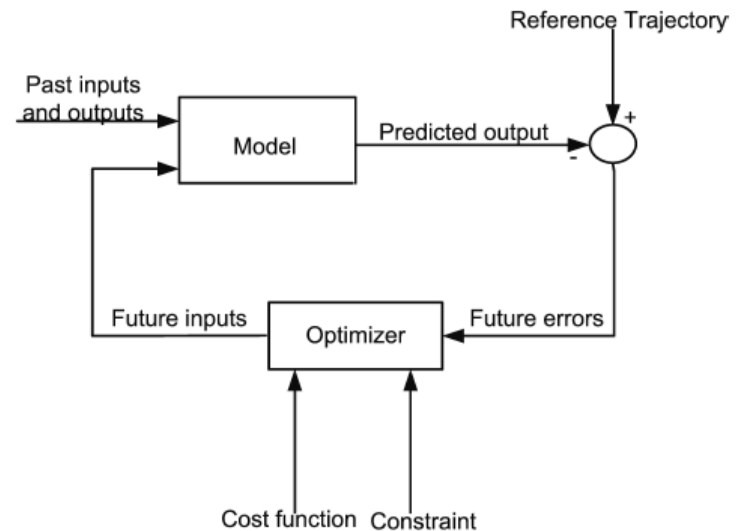


Figure 2 – Structure of Model Predictive Controller [14]

The main components of the Model Predictive Controller are:

- Prediction Model

The prediction model is used to predict future outputs based on the past input and outputs as well as future control actions [14]. The prediction model is an important part of the Model Predictive Controller and is required to be able capture the system dynamics and accurately produce outputs [14]. The prediction model can include a disturbance model along with the process model. The inclusion of the disturbance model allows taking into effect of the disturbances on future outputs.

- Objective function

The weights define the penalty if the input and output values deviate from the desired values. The optimizer produces future control actions by minimizing a cost function which enshrines the control objectives. The cost function is used for obtaining the control law [14]. The general expression for an objective function is [14]:

$$J(N_1, N_2, N_u) = E \left\{ \sum_{j=N_1}^{N_2} \delta(t) [y(t+j) - r(t+j)]^2 + \sum_{j=1}^{N_u} \lambda(j) [\Delta u(t+j-1)]^2 \right\}$$

Where N_1 , N_2 are the minimum and maximum cost horizons and N_u is the control horizon.

$\delta(t)$ defines the weighting function on the outputs, while $\lambda(j)$ defines the weighting on the inputs. These parameters are used as controller tuning parameters. The higher the weight, the lesser is the deviation allowed for the signal. The selection of weights has an effect on stability and performance of the system [15]. The output weights ensure minimum deviation of outputs from reference trajectories while the input weights penalise the control action within the specified constraints.

The objective function is subject to constraints:

$$u_{\min} \leq u(t) \leq u_{\max} \quad \forall t$$

$$du_{\min} \leq u(t) - u(t-1) \leq du_{\max} \quad \forall t$$

$$y_{\min} \leq y(t) \leq y_{\max} \quad \forall t$$

- Control law

The control horizon defines the number of changes the control action can make. The selection of the prediction and control horizon has effect on the system. A long prediction horizon is desirable for better performance control while a short control horizon results in a more robust system [15]. The selection of prediction horizon such that it covers the period of any non-minimum phase behaviour, ensures elimination of this behaviour from the objective function [14].

The control law is essentially defined by the control horizon N_u . The control horizon defines the allowed number of changes in the control action during optimisation [16]. Hence for an interval $N_u < N_2$ there are no changes in the control signal.

$$\Delta u(t+j-1) = 0 \quad j > N_u$$

The requirement is to develop a model predictive controller to regulate the air and fuel flows in the system. The cost function to be minimized to obtain future control actions consists of expressions for deviation of outputs from setpoint values and regulation of inputs within prescribed constraints. A linear system model is used as a prediction model. The controller calculates the air and fuel flow inputs to the fuel cell and the VGT and external-

EGR actuators position for the engine. The development of linear controllers for a nonlinear system is done by linearizing the system model at a specific operating point. The linearization of the system can be done by direct linearization or by identifying linear models directly with system identification.

CONTROLLER OBJECTIVES

The controller objectives are derived from steady state analysis in Chaudhari et al [9] and dynamic system simulations in Chaudhari et al [10]. The controller can be developed to adjust the flows into the fuel cell cathode and anode with the following control objectives:

- Maintain excess air ratio in the fuel cell $\lambda_{O_2}=2$
- Regulate the flow fuel in the reformer such that the utilization factor μ_f is minimum 70% and maximum 95%.
- Within the limits of the above two objectives ensure the fuel cell supplies a steady base load.

The control objectives for the engine include:

- Regulate the oxygen-to-fuel ratio (OFR) to a determined set point and above 4.3 at all times.
- Regulate the amount of hydrogen to a minimum of 5% and a maximum of 20%.
- Regulate the fraction of external EGR to a determined set point.
- Within the above constraints supply power to the load demand.

The control problem for the system requires the regulation of air and fuel flow into the system to ensure that the appropriate performance variables values are achieved. The inputs to the system include the following:

- Fuel flow in the reformer (W_{ref_in})
- Compressor-Motor voltage for air flow in the fuel cell (V_{cm})
- Desired current of the fuel cell (I_{fc})
- Diesel fuel flow into the engine (W_{di})
- VGT pane position for air flow in the engine (x_{vgt})
- External EGR valve position for inert gas flow in the engine (x_{xegr})

The corresponding performance variables of the system include: