

Model Predictive Control for Water Balance in an Evaporatively Cooled PEM Fuel Cell System

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This paper introduces a Model Predictive Control (MPC) approach to achieve water balance in an Evaporatively Cooled (EC) Fuel Cell System. An overview of the case study system and MPC scheme is presented, followed by simulations that show MPCs effectiveness on the thermal module of an EC system, whilst providing useful information on how a liquid cooled condenser and air-cooled radiator can be coupled.

Introduction

An EC stack is cooled by injecting liquid water into the cathode air-stream; the cooling function is de-coupled from the fuel cell stack as heat is dissipated as the latent heat of evaporation. This negates the need for separate liquid cooling channels and results in high power density stacks. An EC system utilises a condenser downstream of the stack in order to produce sufficient liquid water for re-injection. The condenser can be used in place of other heat exchangers within a system, such as a vehicle radiator in an automotive context, or as an additional component. Reactant humidification is not required. The simplicity, modularity and scalability of EC technology means that it is well-suited for commercialization across automotive range extender and primary mover applications.

Whilst a water tank provides a 'buffer' for rapid load transients, over the course of a duty cycle it is necessary that system thermal performance is accurately controlled on-line and the level of water in the system is maintained [1]. Current control strategies on water balance for EC Systems are rather limited. An existing PID-based (Proportional-Integral-Derivative) strategy has been developed that allows manipulation of several actuators (flow rate, pressure and cathode stoichiometry) in order to achieve water balance [2]. However, the problem of water balance is a Multi-Input Single-Output (MISO) control problem and a PID-based logic is not ideally suited to handle the multiple actuator signals or long dynamics as PIDs are responsive (meaning they make adjustments based on past and present states rather than predicting future behaviour).

An MPC replaces the PID and uses a reference model to predict system response. It can therefore be used to preempt the final state and set the actuators accordingly, improving convergence time and avoiding oscillations in controlled and manipulated signals.

An EC system model has been developed by Fly and Thring [2] with a thermal module based on a liquid cooled condenser connected to a standard automotive radiator (Figure 1). The use of a liquid cooled condenser and radiator, rather than an air-cooled condensing radiator provides integration flexibility in relation to current electric vehicle thermal management systems. However, it presents an additional challenge as there are two coupled cooling loops and the strategy to run the two in parallel does not have a unique solution.

This work involves developing an MPC approach using Fly's model that can be used to control the net water in an EC system, focusing on the heat exchangers only. The results and learning are transferable to other components within the system beyond the heat exchanger.

EC System Case Study

The Evaporatively Cooled Fuel Cell System under study is shown in Figure 1. In this case, the thermal module of the system consists of a liquid-cooled heat exchanger and radiator. This figure focusses on key components of the Air, Thermal and Water modules of the system. Net water is defined as follows:

$$\text{Net water} = \text{separated condensed water} - \text{injected water}.$$

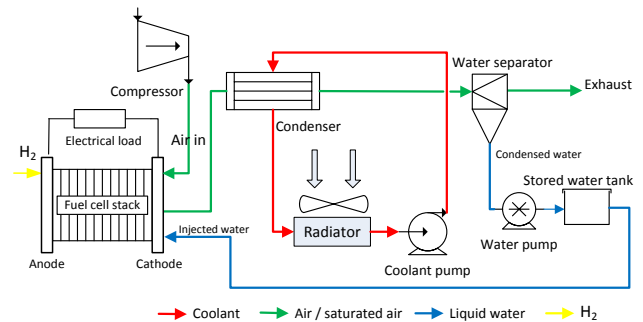


Figure 1. EC System with liquid cooled condenser [2]

Closed-loop MPC Scheme

The closed-loop control scheme implemented in this work focuses on the actuation of the thermal module (Figure 2). The two actuators (manipulated signals) are the coolant flow rate (or coolant pump voltage) and the radiator air

mass flow rate (or fan voltage). In this case, variables that can be used to help water recovery such as pressure and air stoichiometry are not considered as they affect the stack and system performance, and have limitations based on other hardware in the system (such as back pressure valve response). The target is the net water of the system. The water needed to cool the stack (injected water) is considered a measured disturbance (available information). The system output is the current value of net water, which allows the control feedback (water separator efficiency is taken into account).

Figure 3 shows the results of the MPC scheme compared to a PID scheme under a specified load demand cycle (30 kW system). In these graphs the net water target is 0. Changes in load demand affect the net water value, requiring the control method to act accordingly. Notice the advantages of the MPC scheme compared to the PID scheme. The MPC is faster and more efficient to achieve the target, whereas the PID (cascade control scheme presented in [1]) has some oscillations and is slower. Figure 4 shows the responses of the actuators for the same scenario. The control signals also present better responses for the MPC case. The coolant flow rate signal has less oscillations and faster settling times. The duty signal is the same presented in Figure 3. In the extreme case, the PID has yet to stabilise before a new action is required. In the case of a condenser for the system, this is not necessarily overly critical, but oscillations or spikes in controlled variables of the fuel cell could result in compromised performance or durability.

In this case, the MPC has a control cost function that aims at achieving net water target by minimising actuator effort. Since there are two actuators, there is also the possibility of a cost function based on actuators parasitic load. In this scenario, an actuator signal could be optimised to achieve net water target by minimising the parasitics consumption.

Conclusions and recommendations

A new method of control based on Model Predictive Control (MPC) has been introduced to achieve net water targets in an Evaporatively Cooled (EC) Fuel Cell System. The control scheme implemented showed the advantage of predicting system behaviour to obtain better and faster control responses, as well as optimised actuator (manipulated) signals. Additionally, the use of a net water target > 0 g/s can be implemented, with appropriate cost functions, for a water recovery strategy. The performance of the heat exchanger could be improved further by using the pressure and the air stoichiometry as variables.

References

- [1] A. Fly, R.H. Thring, Temperature Regulation in an Evaporatively Cooled Proton Exchange Membrane Fuel Cell Stack, *International Journal of Hydrogen Energy* (2015) 11976-11982.
- [2] A. Fly, R. H. Thring, System thermal and Water Balance in an Evaporatively Cooled PEM Fuel Cell Vehicle, IMechE Conference on Vehicle Thermal Management Systems (VTMS11), May 15-16, 2013.

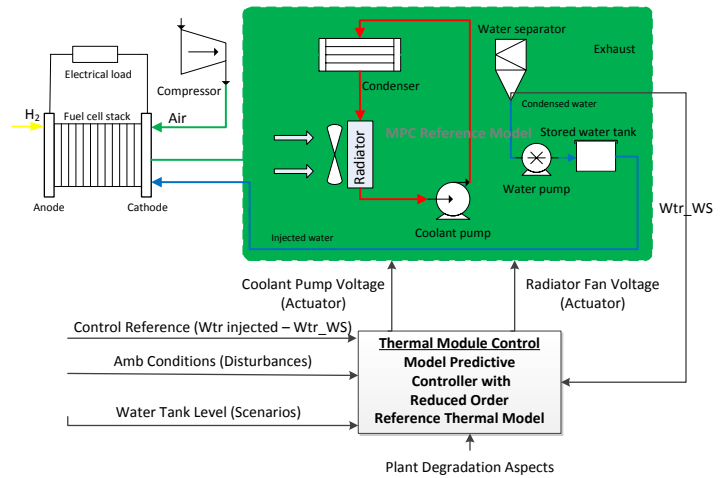


Figure 2. EC System MPC Thermal Control Scheme

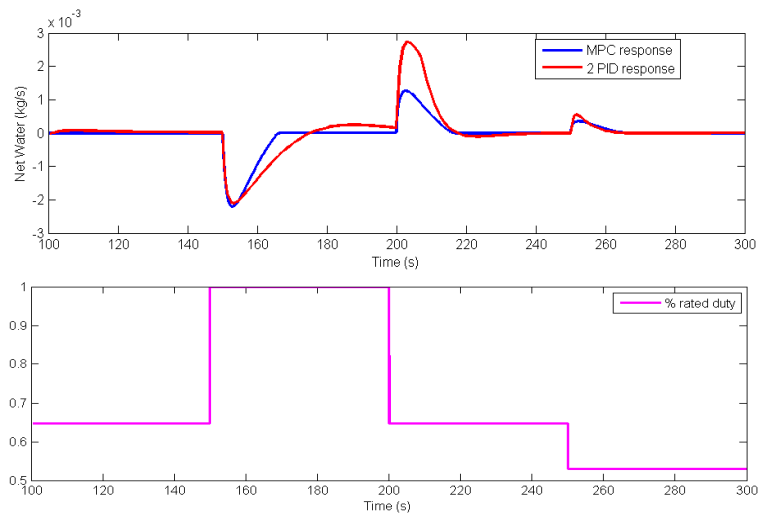


Figure 3. Net water response for a given load demand cycle

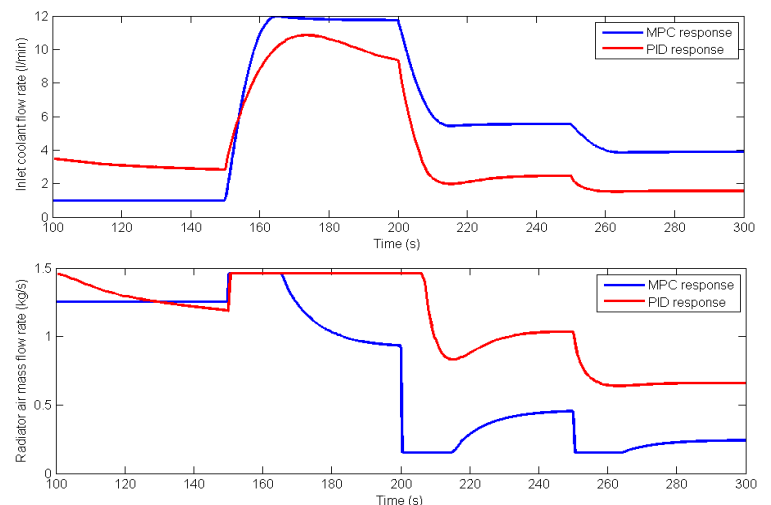


Figure 4. Actuators signals for load demand cycle in Figure 3