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Control of a methanol reformer system using an Adaptive Neuro-Fuzzy Inference System approach

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Introduction

This work presents a stoichiometry control strategy for a reformed methanol fuel cell system, which uses a reformer to produce hydrogen for an HTPEM fuel cell. One such system is the Serenus H3-350 battery charger developed by the Danish company Serenegy® which this work is based on. Figure 1 shows a picture of the system.

Figure 1: The Serenus H3-350 Reformed Methanol Fuel Cell system produced by Serenergy®.

Figure 2 shows a block diagram of the layout of the system.

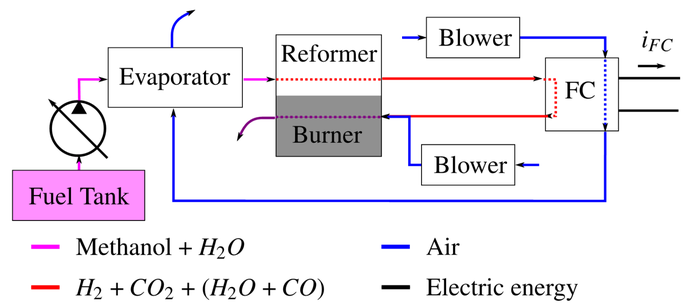

Figure 2: Diagram of the Serenus H3-350 Reformed Methanol Fuel Cell system produced by Serenergy®.

To avoid starving the fuel cell of hydrogen, it is important to know how much hydrogen is produced at any given time.
It is not practical to measure the hydrogen production online and the standard control system of the H3-350 system assumes full reformation. However, the degree of reformation varies with the reformer temperature and the fuel flow. The stoichiometry set point is therefore set to 1.5, which is a safe distance from the recommended minimum of 1.15. This means that more methanol than necessary is consumed in some operating points and the stoichiometry approaches the minimum limit in others.
The reformed gas composition can be calculated with some accuracy if the temperature of the reformer bed is known exactly. This is, however, not the case here as the temperature measurement in the reformer is placed in the bulk material next to the bed and not in the bed itself. Figure 3 shows an illustration of this issue.

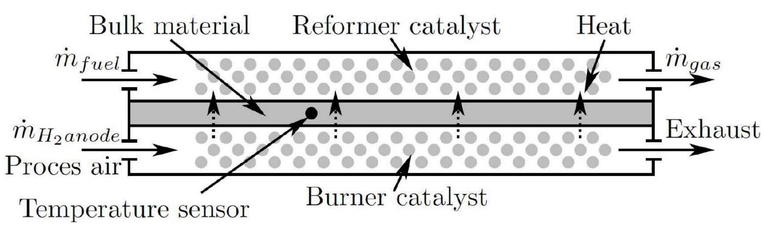

Figure 3: Concept drawing of the reformer and burner of the Serenus H3-350.

This means that as the flow is increased, the reformer bed is cooled, the temperature gradient between the burner and the reformer bed becomes steeper, and the temperature measurement becomes unreliable.

Modeling

This work proposes a method which uses Adaptive Neuro-Fuzzy Inference Systems, ANFIS, trained on experimental data to predict the reformed gas composition. ANFIS is a neuro-fuzzy modeling approach which uses linguistic variables and parameters which are trained using a neural network to mimic the behavior of a physical system. Arbitrary precision can be achieved by increasing the complexity of the models. The ANFIS function in MATLAB is used to train the ANFIS models in this work. Figure 4 shows the ANFIS structure.

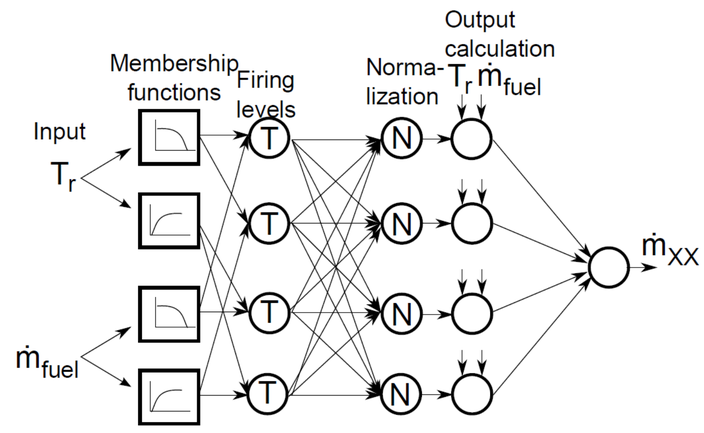

Figure 4: ANFIS model structure with two membership functions. T marks the use of a T-norm and N marks the normalization of the firing levels.

Models of the H_2, CO_2, CO and methanol slip have been developed but here only the hydrogen model is of interest.
The identification experiments have been performed on a test setup where the fuel cell is replaced with a gas analyzer. Figure 5 shows the temperatures and pump flows used in the identification experiment as well as the resulting hydrogen mass flow and the ANFIS model fit.

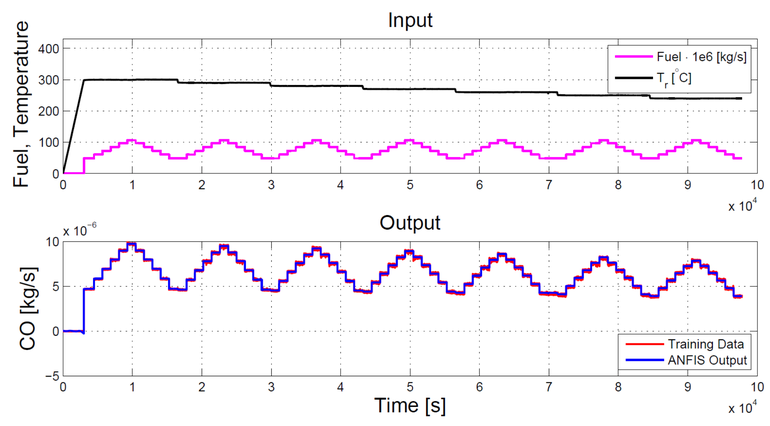

Figure 5: Output of the ANFIS model for the hydrogen content in the reformed gas. Inputs are reformer temperature, T_r, and the fuel flow.

The ANFIS model shows good correlation with the measurements and the model is therefore deemed to be valid. Figure 6 shows the stoichiometry calculated using full reformation and the ANFIS model during a series of load changes.

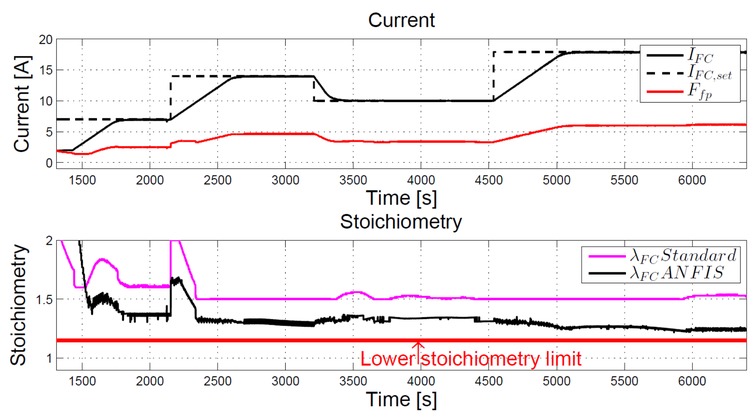

Figure 6: Observed fuel cell stoichiometry during a series of load changes.

The actual stoichiometry is very different from the one which is assumed using full reformation and approaches the lower stoichiometry at higher currents.

Control

The method proposed in this work is based on an ANFIS model which is the reverse of the one in Figure 5. This means that it is trained with the hydrogen production and the reformer temperature as inputs and the fuel flow as output.
The necessary hydrogen production at a certain fuel cell current and stoichiometry set point is calculated online and fed to the ANFIS model as illustrated in Figure 7.

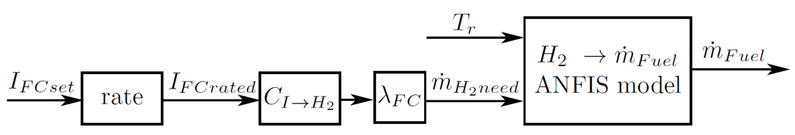

Figure 7: Block diagram of the ANFIS fuel predictor. $rate$ is a rate limiter which ensures time for the reformed gas to spread in the system. λ_{FC} is the desired fuel cell stoichiometry and $C_{I\to H_2}$ converts the fuel cell current set point to an equivalent hydrogen mass flow.

This algorithm is implemented in a LabVIEW program and tested on a Serenus H3-350 module. The load pattern used in the experiment is shown in Figure 8 together with the stoichiometry measured during the experiment.
The stoichiometry set point is 1.25 during the experiment, which is a safe distance from the lower limit of 1.15.
The stoichiometry is kept constant during the load changes but the measurement is subject to noise from the temperature measurement.

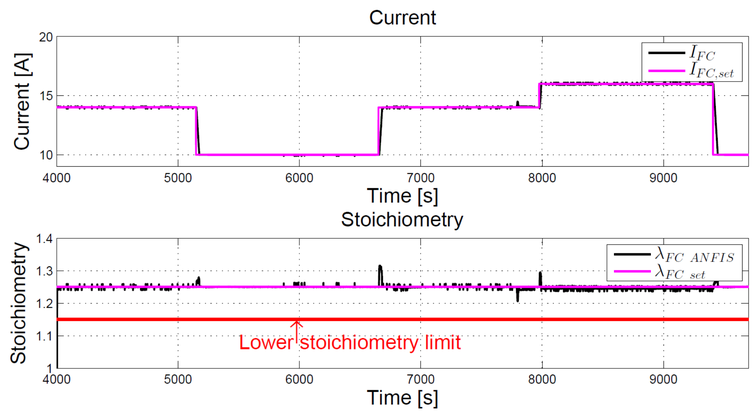

Figure 8: Observed fuel cell stoichiometry during a series of load changes.

The stoichiometry shown in figure 8 is calculated using an ANFIS model which is based on the same data as the predictor. This is a general problem in this kind of system. To give another indication of the validity of the method, the fuel cell voltage during a load change is plotted in Figure 9.

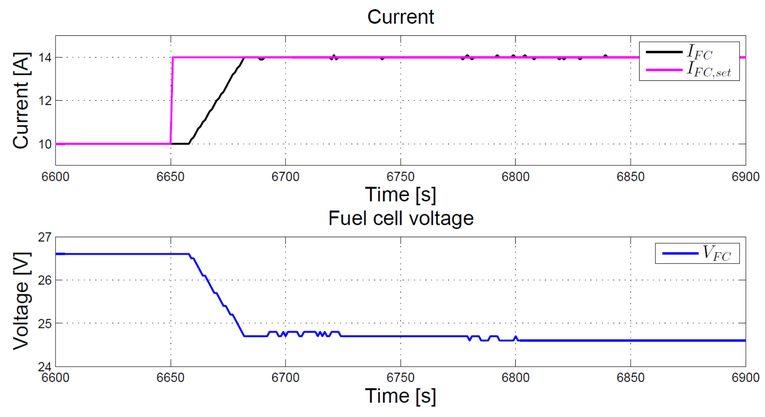

Figure 9: Fuel cell voltage during a load change

If a fuel cell is starved of hydrogen, the voltage will drop. There is no sign of this happening in this case.
The efficiency from the higher heating value system efficiency is plotted in Table 1.

Current [A]	Relative change %
10	+20.2
14	+7.1
16	-6.8

Table 1: Higher heating value to electricity efficiency at different fuel cell currents

The efficiency is higher at both 10 and 14 [A] using the ANFIS predictor. This is because the fuel flow is lower at these operating points using the ANFIS predictors than with the standard controller. The opposite is the case at 16 [A] but here the stoichiometry using the standard control is dropping towards the lower stoichiometry limit.

Conclusion

In this work the problem of controlling the stoichiometry of a Reformed Methanol Fuel Cell system is presented and a solution based on an ANFIS model is proposed. The ANFIS models are trained using experimental data obtained using a gas analyzer. The method has been tested experimentally in a Serenus H3-350 module. The method is capable of controlling the fuel cell anode stoichiometry both in steady state and during transients.
The efficiency at the lower operating points is higher using the ANFIS fuel predictor but it is lower at the high operating point because of the higher constant stoichiometry

Future Work

The ANFIS models can be improved by performing long term gas measurements and including reformer catalyst degradation as an input.
Models of the mass flow of CO_2, CO and the methanol which passes unreformed through the reformer have also been developed and used in a dynamic model of the Serenus H3-350 module.
These models could also be incorporated in a diagnostic system in connection with a fuel cell model to catch incipient faults before the system is harmed.

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