

Nonlinear Model Predictive Control Methodology for Efficiency and Durability Improvement in a Fuel Cell Power System

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Governments and private investors are becoming aware of the problems derived from the energy dependency on fossil fuels and other non-renewable energies. In this context, proton exchange membrane fuel cells (PEMFC), which use hydrogen as fuel, are gaining increasing attention as clean and efficient energy conversion devices for a broad range of applications, such as automotive, stationary combined heat and power and portable systems.

To operate properly, different physical variables have to be measured from the PEMFC. This makes it possible to implement feedback control techniques that can improve the lifetime and efficiency of the system. Moreover, efficiency and degradation of the PEMFC are greatly affected by the internal conditions. While a certain amount of these measurements are feasible using the existing sensor technology, there are parts of the system that are inaccessible. Henceforth, modelling [1] and model-based observation and identification of parameters [2] are compelling research

topics in the field. Regarding the efficiency in PEMFC-based systems, it is accepted in the scientific community that the air supply subsystem and its power consumption play a crucial role in the maximization of the performance and thus, this subsystem has to be considered in a control strategy.

Regarding degradation, the lifetime of PEMFCs is mainly reduced as a result of catalyst metal (Pt) degradation and carbon-support corrosion. Three degradation categories can be distinguished [3]: baseline degradation, cycling degradation and incident-induced degradation. The baseline degradation is due to

long-term material degradation and it is irreversible and unavoidable (it exists as long as the fuel cell is operating). Moreover, degradation mechanisms are accelerated by cycling conditions [3]. Finally, severe degradation occurs when the fuel cell is subject to an unexpected incident which may cause global or local reactant starvation. Controllers can aid to avoid global and local starvation and reduce the impact of cycling as well as the impact of unexpected operating changes.

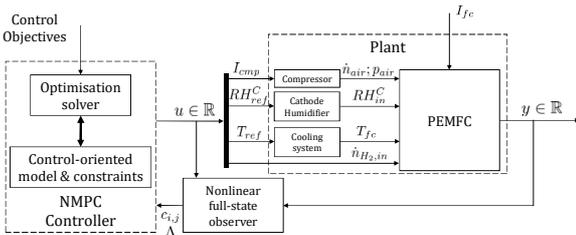


Figure 2. Closed-loop control scheme of the case study.

Using advanced control techniques that consider the inherent nonlinear behaviour in PEMFC systems, the improvement of efficiency and durability can be achieved. In this sense, nonlinear model predictive control (NMPC) [4] has an intrinsic capability of considering several manipulable variables and control objectives (multi-objective control) as well as the capability to deal with system constraints in a systematic and straightforward manner. Moreover this control strategy allows including system disturbances handling in the control loop. In this paper, a methodology based on a NMPC strategy is proposed to maximise the efficiency, and at the same time, improve the durability of a PEMFC power system. The proposed controller makes use of a state-of-the-art nonlinear observer to estimate the internal conditions of the system and includes the estimated states in the control objective function. The New European Driving Cycle (NEDC) is the load profile considered as case study.

The system is presented in Figure 1 and it contains four main parts: 1) The PEMFC stack and load; 2) The hydrogen delivery and recirculation auxiliaries; 3) The air delivery and humidification auxiliaries; 4) The refrigeration system. As showed in Figure 2, the manipulable inputs of the NMPC strategy are the compressor current I_{cmp} , the reference cathode relative humidity RH_{ref}^C and the reference system temperature T_{ref} . The total efficiency (η) of the system in Figure 1 is defined as

$$\eta = \frac{P_{net}}{P_{tot}} = \frac{P_{fc,elec} - P_{cmp} - P_{aux}}{H_{2,used} \Delta H},$$

where $P_{fc,elec}$ is the electrical power generated by the PEMFC that depends on the current demanded by the load plus the auxiliaries current consumption. P_{cmp} is the power consumed by the compressor to inject the air into the cathode

of the PEMFC [6]. P_{aux} is the power consumption of the auxiliaries (hydrogen recirculation and refrigeration systems) which is considered constant in this work and has been quantified experimentally in a test benchmark. The total power given to the system is defined as the total used hydrogen $H_{2,used}$ multiplied by the hydrogen high heating value ΔH . Therefore, considering that the control objectives are to maximize the efficiency η and to reduce the degradation in the PEMFC, the optimisation problem of the NMPC is defined as follows:

$$\begin{aligned} & \text{maximize} && \eta \\ & \text{subject to} && c_{H_2,min} < c_{H_2,j} \leq c_{H_2,max} \\ & && c_{O_2,min} < c_{O_2,j} \leq c_{O_2,max} \\ & && \Lambda_{min} < \Lambda_j \leq \Lambda_{max} \end{aligned} \quad \text{with } j \in [1, \dots, n],$$

being c_{H_2} and c_{O_2} the hydrogen and oxygen concentrations along the discretised (n volumes) anodic and cathodic channels of the PEMFC. These values have to remain between a maximum and a minimum to avoid possible starvation in the fuel cell. Λ is the water content in the membrane, which has to be optimal to hydrate correctly the membrane without flooding the fuel cell. The prediction model of the NMPC, whose states are the oxygen, hydrogen and water vapour concentrations along the gas channels, is a simplified version of the simulation model. However, it considers P_{cmp} and P_{aux} as parasitic loads fed by the fuel cell and it takes into account the anode stoichiometry for the calculation of the consumed hydrogen. Moreover, the prediction model includes an electrochemical model that considers the concentrations and the water content in the membrane (which depends on the water concentrations in the gas channels). As usual in all MPC strategies, the controller requires a state feedback that considers the measurement or estimation of the states. To obtain the internal values of the concentrations and water content without the need of using additional and expensive sensors, a nonlinear observer is implemented. The observer also uses a simplified version of the simulation model to estimate the gas concentrations. These values are used to update the state of the NMPC prediction model before the optimisation algorithm is able to compute the optimal values of the control actions that guarantee that the efficiency is maximum while avoiding local and global starvation of the PEMFC. Figure 3 shows a detail of the simulation results for the estimation of the hydrogen concentration in the midpoint of the anode gas channel.

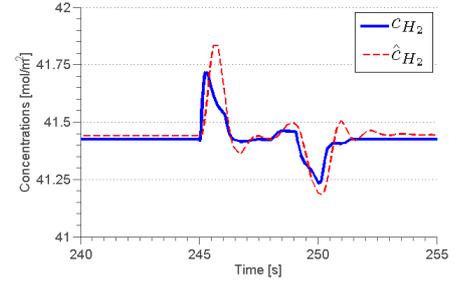


Figure 3. Hydrogen observation in the anode.

The PEMFC simulation model used in this work [1,5] is derived from the discretisation of the partial differential equations that define the nonlinear dynamics of the system, considering spatial variations [1] along the gas channels in order to model the internal concentration values considered as restrictions in the optimization problem. In addition, the cathode of the PEMFC includes a two-phase multi-scale water transport model that combines macroscopic two-phase flow of water with mesoscopic pore filling effects in the cathode diffusion and catalyst layers [5]. This water transport model is discretised perpendicularly to the membrane and it considers the ratio of liquid to vapour water in the cathode catalyst layer. Single-cell voltage is modelled with the Butler-Volmer equation

$$V_{fc,cell} = E_r - \frac{RT}{\alpha 2F} \left[\ln\left(\frac{i}{i_0}\right) - \ln\left(\frac{p_{O_2}}{p_{O_2}^{ref}}\right) \right] - iR_{ohm},$$

where E_r is the ideal potential voltage of the fuel cell, α is the cathode heat transfer coefficient and R_{ohm} is the internal area resistance of the membrane. The exchange current density i_0 is influenced by the liquid to water ratio.

The main contribution of this work is the improvement of the efficiency of a PEMFC power system while guaranteeing conditions that also improve its durability. Adopting the NMPC scheme with the distributed parameter model and the nonlinear observer, the efficiency of the PEMFC-based system can be maximized guaranteeing at the same time the appropriate internal gas concentration profiles to avoid global and local hydrogen and oxygen starvation and proper membrane humidification.

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