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CHALLENGES FOR ALTERNATIVE PROPULSION SYSTEMS: CONTROL OF FUEL CELLS

Herausforderungen alternativer Antriebssysteme: Regelung der Brennstoffzelle

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ABSTRACT

The dramatic increase in CO2 emissions and the ongoing global warming require a paradigm shift in future mobility concepts. One possible strategy is the use of vehicle propulsion systems that draw their power from a fuel cell. Here, electrical energy is generated directly from the chemical energy stored in hydrogen. Based on renewable primary energy sources, from which the hydrogen is generated via electrolysis, this opens up the possibility of sustainable mobility. For the use of fuel cells in vehicles, however, there are still many challenges to be solved, which are mainly focused on the durability. The control of fuel cell systems plays a key role in this context. The present article highlights current research work in this field.

KURZFASSUNG

Der alarmierende Anstieg von CO2-Emissionen sowie das Voranschreiten der globalen Erwärmung erfordern einen Paradigmenwechsel bei zukünftigen Mobilitätskonzepten. Eine mögliche Variante sind Fahrzeugantriebe, die die Antriebsleistung aus einer Brennstoffzelle beziehen. Dabei wird elektrische Energie direkt aus der in Wasserstoff gespeicherten chemischen Energie erzeugt. Ausgehend von erneuerbaren Primärenergiequellen, durch welche der Wasserstoff via Elektrolyse bezogen wird, ergibt sich dadurch die Möglichkeit zur nachhaltigen Mobilität. Für den Einsatz von Brennstoffzellen in Fahrzeugen sind allerdings noch zahlreiche Herausforderungen zu bewältigen, welche sich vor allem auf die Lebensdauer konzentrieren. Die Regelung von Brennstoffzellensystemen spielt dabei eine Schlüsselrolle. Der vorliegende Beitrag beleuchtet aktuelle Forschungsarbeiten in diesem Gebiet.

1. INTRODUCTION

Considering the current situation regarding pollutant emission regulations in Europe, especially the trend of banning polluting vehicles from city centers, the need for clean energy solutions in the automotive sector is becoming more obvious every day. Due to their efficiency and zero-emission characteristic, electric vehicles with battery and fuel cell (FC) technology seem to be a promising track to take. Compared to purely battery powered electric vehicles (BEV), which are more suitable for short driving ranges, vehicles equipped with FC technology can also cover longer routes. Another advantage is the fast refilling of hydrogen as opposed to the relatively long battery charging.

However, from a practical point of view, it is not reasonable to employ a fuel cell stack alone. Rather it is combined with an energy storage system, such as a battery package. The reason behind this is that when supplying the power requested by the vehicle control unit, the actual power change of the fuel cell stack has to be limited by time constants of several seconds to avoid hydrogen and/or oxygen starvation which would seriously damage the stack. Thus, to fulfill all requested power trajectories, support comes from the battery package mentioned above. This effectively results in a so-called fuel-cell hybrid electric vehicle. One of the main control challenges associated with such a dual power source configuration is the proper dynamic load distribution between battery and fuel cell. Fig. 1 illustrates the various subsystems that are required to control the vehicle propulsion. The top-level control scheme manages the power flows from and between the individual subsystems at all times and under all circumstances. It does so by communicating with the fuel cell system control unit, the battery management system as well as with the driver and the vehicle environment.

Control on the level of the fuel cell has to ensure that the demanded electrical power is provided while hydrogen consumption as well as degradation of the fuel cell are minimised. Unfortunately, it is just dynamic power trajectories and fuel cell lifetime that contradict each other.
To extend the lifetime, degrading operating conditions (e.g. fuel starvation, excessive pressure differences across the membrane, flooding or dry-out) have to be prevented, which requires precise control of the balance-of-plants components, especially during transient operation. Therefore, advanced control methods are required, especially for highly dynamic PEM fuel cell automotive operation with implicit consideration of service life maintenance.

In this article insights will be given into current research regarding energy management strategies (top-level control) of fuel cell hybrid electric vehicles as well as model-based control schemes for fuel cell systems.

2. ENERGY MANAGEMENT STRATEGIES

In the top-level, optimal energy management strategies are employed which direct the power flow between the fuel cell stack and the battery and ensure that the power demand from the driver is met. Such strategies can be roughly categorized as either heuristic (rule-based) or mathematically more profound optimization approaches, see e.g. [Hu2015]

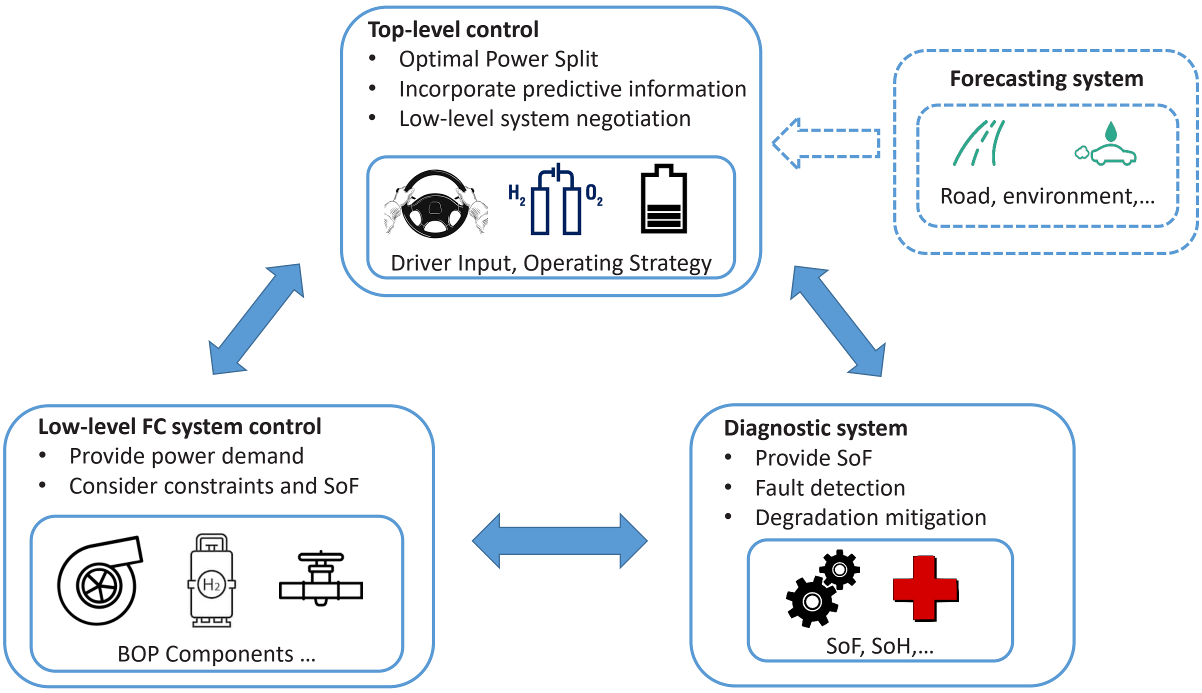

Fig. 1: Control System of a fuel cell hybrid electric vehicle

or [Zheng2012]. Heuristic strategies can be easily designed and implemented in real-time computers, however, a globally optimal power distribution cannot be guaranteed. In contrast, mathematically profound optimization approaches ensure optimality at the expense of a significantly higher computational effort. In this context, optimality would entail that the energy management strategy should pursue optimization goals, such as the minimization of hydrogen consumption and maximizing the lifetime of the fuel cell system, when distributing the power demand between the fuel cell and the battery. In addition, the superordinate energy management must determine the power distribution under consideration of various system constraints. On the one hand, state of charge and current power capability of the battery must be considered. On the other hand, a description about the possible dynamic response of the fuel cell system must be provided and each interconnected sub-system must deliver its current states, such as state of charge (SoC), state of health (SoH) and state of function (SoF). This entails accurate state estimation and monitoring concepts for both the fuel cell and the battery, see e.g. [Ritz2018a] and [Ham2018].

If predictive load information is available, this can be readily employed in the optimization strategy as it is an effective means to avoid sharp load transients. A crucial point in this context is the numerical efficiency of the optimization strategy, as e.g. information on the future route (including road slope and traffic situation) as well as real-time optimization of the FC system power and the power distribution are required. Predictive control strategies are currently widely investigated to operate the fuel cell and the battery within their optimal regions based on their current states. Thereby, the optimal region can be viewed from three different perspectives: optimizing fuel efficiency, mitigating degradation or to ensure robustness against uncertainties. For example, optimizing fuel efficiency can lead to higher values for depth of discharge (DoD) of the battery, whereas focusing on robustness will lead to a rather conservative operating strategy. Ideally, degradation models for the fuel cell as well as for the battery and their associated SoH estimates are considered in the optimization process to mitigate degradation and to ensure proper operation of the fuel cell during its complete lifetime. To validate the predictive control strategy, worst case scenarios are being investigated. Thus, the effect of uncertainties and stochastic influences regarding the vehicle environment (e.g. road, driver, meteorological conditions, payload, etc.) are incorporated into the mentioned scenarios.

To sum up, the top-level control distributes the power demand between the fuel cell stack and the battery while receiving feedback from the two components about their respective states and operating in a safe and efficient region. Predictive control ensures optimality, especially that the information about the future route is available.

3. MODELING AND PARAMETERIZATION OF FUEL CELL MODELS

Automotive applications of fuel cells are challenging due to variable operating conditions, load cycles, start-up and shutdown cycles, humidity cycles, freeze-thaw cycles and air contamination. Moreover, automotive fuel cell systems are operated dynamically, which means that the set points are changed continuously during operation. In order to successfully integrate the fuel cell system into the electric power train and to prevent degradation and thus prolong lifetime, it is important to understand the transient behaviour of the fuel cell stack. Thereby, the availability of accurate, yet computationally efficient fuel cell models is of crucial importance, [Kra2019]. Associated with this is the need to efficiently parametrize a given model from a concise and cost-effective experimental data set. In this section approaches for real-time capable FC models will be presented.

In dynamic fuel cell models, one has to distinguish between models with spatial resolution of the various thermodynamic quantities. They allow detailed insights into the processes inside the fuel cell, such as local distribution of current density or liquid water formation. To achieve this, such models require the numerical solution of partial differential equations and are therefore normally not real-time capable. Yet, there are first approaches of real-time fuel cell models with spatial resolution of species, [Mur2018].

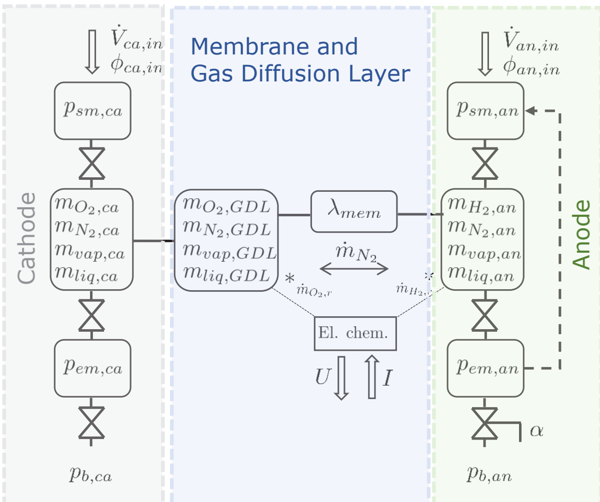

Fig 2: Structure of zero-dimensional fuel cell model

For the task of advanced control or state observation for real-time diagnostics, zero dimensional models have been found to constitute the right balance between level of detail and numerical effort. They are numerically far more efficient at the expense that they do not provide any spatial resolution, hence the term “zero dimensional”.

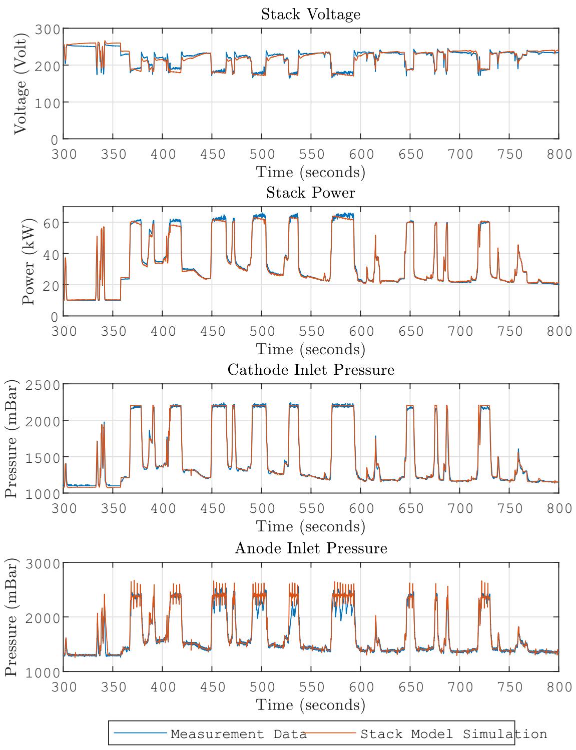

Fig. 3: Comparison of dynamic fuel cell stack model to experimental stack data.

The structure of such a model is illustrated in Fig. 2. Both the cathode and anode are divided into three consecutive manifolds, interconnected with nozzles. The model dynamics are described by the transient mass balances driven by the ongoing chemical reactions as well as convective and diffusive transport of species (hydrogen, oxygen, nitrogen, water). Water vapor and nitrogen are exchanged through the membrane between the center manifold of cathode and anode. The membrane humidity is described through a transient water mass balance to account for transient drying and wetting of the membrane. This phenomenon is responsible for the characteristic transient voltage response of PEM fuel cells. The internal thermodynamic states and their derived quantities are then used in an electrochemical model to describe the relation between current and voltage.

In the literature there is a multitude of models with a structure similar to the one described above. Each of them has its own characteristics and advantages, however, the great challenge lies in the parametrization of the fuel cell model to replicate an actual physical fuel cell. This is due to the large number of parameters along with the highly non-linear and numerically stiff model structure. Currently, at the Christian Doppler Laboratory for Innovative Control and Monitoring of Automotive Powertrain Systems at Vienna University of Technology [cdl2020] a new approach is being developed that allows to parametrize the fuel cell model solely based on experimental data recorded on the fuel cell stack. The approach comprises both the methodology to actually adapt all parameters to match the model with the data as well as mathematically profound guidelines on how to dynamically excite the fuel cell in order to be able get all parameters correctly. The latter is known under the term dynamic design of experiments, [Ritz2018b]. Fig. 3 illustrates the dynamic accuracy that can be achieved by using the proposed approach.

4. MODEL BASED FUEL CELL CONTROL

The main component of a PEMFC is the gas conditioning system, which controls the inlet gas temperatures, anode and cathode pressures, relative humidity and mass flow of the gases at the inlets of the PEMFC stack.

In highly dynamic PEMFC operation the main challenge in the design of PEMFC controllers lies in the control and decoupling of the pressures on the anode and cathode sides and decoupling pressures and mass flows, respectively. Temperature and humidity dynamics are rarely considered, however, they play an important role in the operation of the FC stack.

In Fig. 4 the performance of a conventional cathode gas conditioning control system is shown:

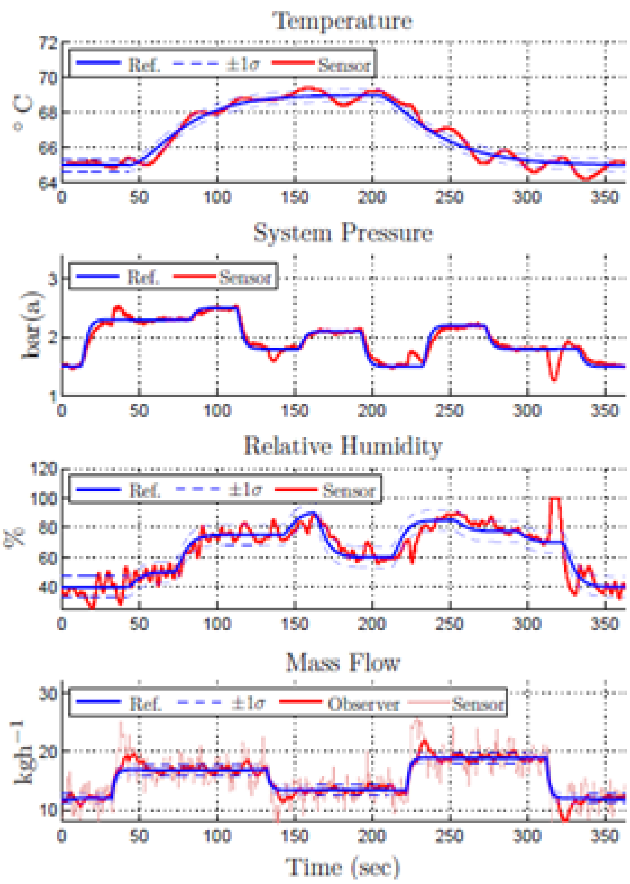

Fig. 4: Performance of fuel cell gas conditioning using conventional control

It can be seen clearly, how the strong nonlinear coupling between the thermodynamic states leads to undesired oscillations. Even more, system states can quickly reach levels which are dangerous for the fuel cell operation: As an example, consider the sharp system pressure drop at t=320 s, accompanied by a relative humidity of 100% at the cathode inlet. In [Kan2016] a novel nonlinear model-based control concept for a highly dynamic operation of PEMFC stacks is presented, which simultaneously controls and decouples the inlet gas temperature, stack pressure, relative humidity and gas mass flow. This represents a nonlinear control problem with multiple inputs and multiple outputs (MIMO). To this end the method of exact input-output linearisation is employed. To achieve robust decoupling, the differential flatness of the system is exploited, see Fig. 6.

Fig. 5 from [Kan2017] demonstrates, how control performance of the FC stack can be significantly improved through the proposed model-based control concept. Oscillations are greatly avoided while the system is still able to accurately track the given reference trajectories for the thermodynamic states. Through decoupling the previously existing excessive overshoots e.g. of relative humidity are also gone.

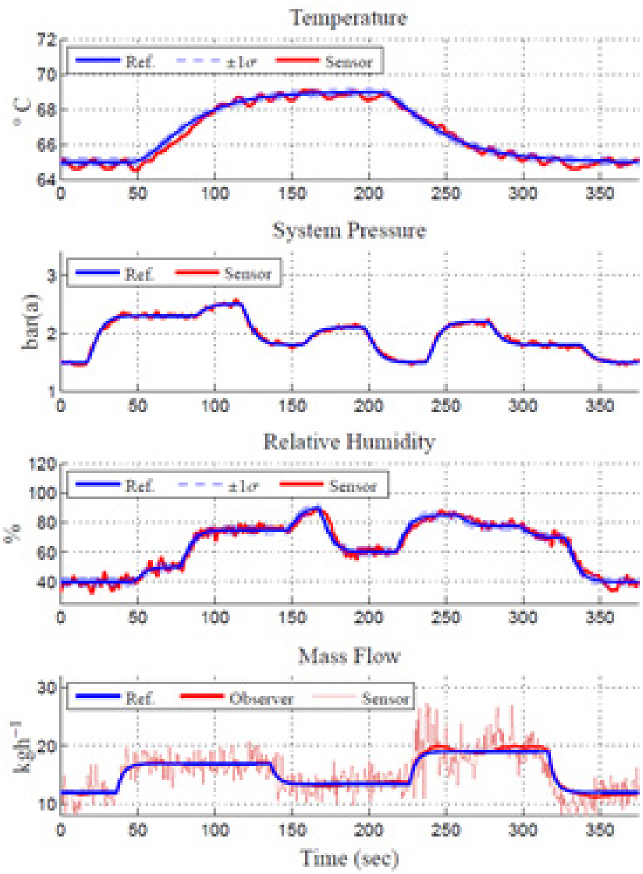

Fig. 5: Performance of fuel cell gas conditioning using nonlinear model-based control

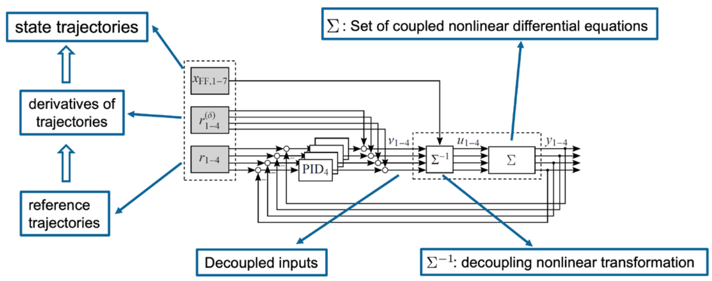

Fig. 6: Nonlinear model based control concept for a highly dynamic fuel cell stack operation

5. OUTLOOK

The conventional way of controlling fuel cell operation is by using reference values for its stoichiometries, pressures or voltage, all provided by expert knowledge or from some sort of offline optimization. It is done so by linking these quantities to the functional output of the fuel cell, which is electrical power. This approach works fine as long as there are only little dynamic transients in the load demand trajectory to be expected.

It is exactly during strong transients when violations of internal constraints happen which adversely affect the lifetime of the fuel cell. Typical constraint violations comprise exceeding maximum pressures of cathode and anode, exceeding maximum membrane difference pressure as well as oxygen and hydrogen starvation.

In [Fon2014], differential flatness is used to control the oxygen stoichiometry and cathode pressure. Feedback linearization has been used to track an optimal reference of the oxygen excess ratio for the air supply subsystem of a fuel cell as seen in [Liu2018]. However, controlling the fuel cell in a vehicular operation with a set of reference values for the pressures and stoichiometries is not realistic as the trajectories of the mentioned quantities are generally not known. Instead, it is more plausible to think of it as a constantly changing demand of power that has to be supplied by the fuel cell. The control scheme of choice is the Model Predictive Control (MPC). Model predictive control is an advanced method of process control that is used to control a process through optimization over a receding time window while satisfying a set of constraints. It is widely used in the process industries in chemical plants and oil refineries and is now gradually advancing to the automotive industry and power electronics where significantly faster execution times are required.

One of the main strengths of MPC is its ability to explicitly handle constraints, which, in the context of fuel cell control, directly translates to safety limits and degradation avoidance imposed to the control system. Current research activities are focused towards using MPC with linear and nonlinear fuel cell stack models. The primary control goal should be to satisfy the power demand given by the superordinate control authority. However, at the same time the MPC should maximise efficiency and minimise the degradation. It can do so by integrating the physical insights provided by the fuel cell model in terms of predictions of its internal states. In a similar manner, various diagnostics functions could be used to adapt the way the MPC drives the fuel cell, leading to the concept of fault tolerant control.

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