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Fault-tolerant model predictive control of a direct methanol-fuel cell system with actuator faults

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ABSTRACT

This paper investigates fault tolerant model predictive control (MPC) of a direct methanol fuel cell (DMFC) system with several faults in the methanol feeding pump. An active FTMPC strategy with a hierarchal structural design is developed. The focus here is on fault detection and isolation (FDI) and the implementation of fault-tolerant strategies within the control algorithm. To this end, a model-based FDI scheme with virtual sensors is first developed by means of the real-time diagnosis of fault occurrence during operation. Thereby, several faults in the methanol pump are characterized and the information integrated into the MPC algorithm in each fault case. Strategies are presented to reconfigure the active fault-tolerant MPC to keep the DMFC system stable in case of a feeding failure. Moreover, economic, stability and lifetime characteristics are also integrated into the active fault-tolerant MPC. The proposed FDI and FTMPC scheme is tested experimentally in a DMFC test rig with a 5-cell DMFC stack to demonstrate the effectiveness and robustness of the designed approach. Several fault scenarios with the FTMPC are shown. Particularly in the case of fuel cells, fault tolerance is necessary to meet the goals of long-lasting system stability and efficiency.

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1. Introduction

Complex systems are widely used in the modern world. The number of such systems continues to increase in certain industries on the back of new developments in the process engineering fields. Developing effective control strategies for these systems is a demanding task. In the 1970s, a new control method was developed, namely *'Model Predictive Control'* (MPC). Central to this method is the use of an internal model as part of the controller. By minimizing a cost function of the model-based prediction and real measurement of the control output, control values for the optimal trajectory of the process variables are generated. Initially, it was only used in the context of oil refining and chemical processes (Qin & Badgwell, 1997). Nowadays, MPC is widely applied in different industrial sectors and the number of control systems with embedded MPC continues to increase (Dittmar & Pfeiffer, 2004, 2006).

Fuel cells supply power by means of an electro-chemical process, with no combustion taking place. There are many different types of fuel cells but in this paper, the focus will be on direct methanol fuel cells (DMFCs). The main components of DMFCs are bipolar plates and the membrane electrolyte assembly (MEA), which is the electro-chemical heart of the fuel cell. To operate a DMFC with optimal performance, many aggregates and sensors are required. The control algorithm should offer a long operation time and good performance in achieving the goals of low emissions and high efficiency. Many control strategies have been advanced in the literature, from PID-control (Behrendt, Bajcinca, Zenith, & Krewer, 2012; Wilhelm, 2010; Wilhelm, Blum, Janßen, Mergel, & Stolten, 2010; Zenith & Krewer, 2010), to neuronal networks (Chang, Hsu, Wang, & Chen, 2012), to fuzzy control (Liping, Dong, & Minxiu, 2013; Yang, Feng, & Zhang, 2014; Zhang & Yan, 2011), to MPCs (Behrendt et al., 2012; Yang et al., 2014) or some hybrid configurations of these (Chang et al., 2012; Yang et al., 2014). With the MPC algorithm, there are many advantages of dealing with these requirements. With DMFC systems, there are numerous control and manipulated values that must satisfy particular specifications. One advantage is that the limits of control variables and manipulated variables are integrated into the control algorithm. With online calculation, constraints can be kept in range. Moreover, redundant manipulated values to control a given process value and long downtime periods or time delays are also important for DMFC systems. Many studies outline

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DMFCs under normal circumstances, but only a small proportion address fault conditions. In a bid to contribute to filling this gap, this paper reports on a fault-tolerant algorithm intended to enable a continuous, stable DMFC in the case of a fault and against the backdrop of long-term degradation. This algorithm is referred to as *'fault-tolerant control'* (FTC). More recently, due to the advantages of the MPC algorithm, it has received increasing attention in the field of FTC research. Both algorithms can be combined. The first argument in favor of handling the FTC with MPC was presented by Maciejowski (Maciejowski, 1997a, b, 2002) and is called *'Fault Tolerant Model Predictive Control'* (FTMPC). This method will be used in this paper. With an FTMPC, stability, safety, robustness and long-term performance can be placed in the hands of the user. The first approaches with fuel cells, especially PEMFCs in FTC, are outlined in (Puig, Feroldi, Serra, Quevedo, & Riera, 2008; Rotondo, Puig, & Nejjari, 2015; Vengerskiy, 2015).

For the purposes of this paper, an MPC is used to control a DMFC system. The critical faulty component in the system is the fuel pump, which supplies it with methanol. Several faults can occur in a methanol pump. With a robust MPC design, it can be shown that the main control variable, which is affected by this fault in the methanol concentration, can be held stable between its boundaries in case of a fault scenario arising. Later, the fault of the pump may become too large, meaning that boundaries have been reached. The FTMPC algorithm is built up on a top-down basis, without modifying the general MPC algorithm. In order to rectify a fault in the system's methanol pump, the FTMPC should achieve stable control. The main control objective is that the methanol concentration of the DMFC system should be stable in case of the occurrence of faults. Given the system efficiency, other process values are allowed to differ from the setpoint values. Therefore, the capability of redundant manipulated values to control the methanol concentration is revealed. It is also shown that with the FTMPC, the DMFC system is not only stable, but is shown to be capable of being kept in a state of optimal efficiency. The FTMPC controller is tested with a 5-cell DMFC stack in a DMFC test rig.

This paper has the following structure: in Section 2, the non-linear model of a DMFC system with differential equations is presented. In Section 3, the robust model predictive controller design is defined. Section 4 introduces the fault-tolerant MPC diagnosis unit. Initially, it is shown why an MPC algorithm is useful, especially for a DMFC system. Faults that can occur within the methanol pump and scenarios of possible effects on the DMFC system are shown in Section 5. In Section 6, the reconfigurable FTMPC design for every scenario is presented. Section 7 shows the used experimental setup for the validation of the constructed FTMPC design. Section 8 closes the paper with the experimental results of all scenarios. Finally, some concluding remarks are outlined in Section 9. All nomenclatures are shown in Table 1.

Table 1
Nomenclature.

Nomenclature	
MPC	Model Predictive Control
DMFC	Direct Methanol Fuel Cell
FDI	Fault Detection and Isolation
FTC	Fault Tolerant Control
FTMPC	Fault Tolerant Model Predictive Control
FS	Fault Scenario
PTFC	Passive Fault Tolerant Control
AFTC	Active Fault Tolerant Control
PFTMPC	Passive Fault Tolerant Model Predictive Control
AFTMPC	Active Fault Tolerant Model Predictive Control
MEA	Membrane Electrolyte Assembly
CV	Control Variable
MV	Manipulated Variable
PEMFC	Proton Exchange Membrane Fuel Cell
Q	Output Error Weighting (MPC)
R	Control Action Change Weighting (MPC)
EI	Embedded Integrator
FC	Feedback Compensation
J	Threshold
r	Residual

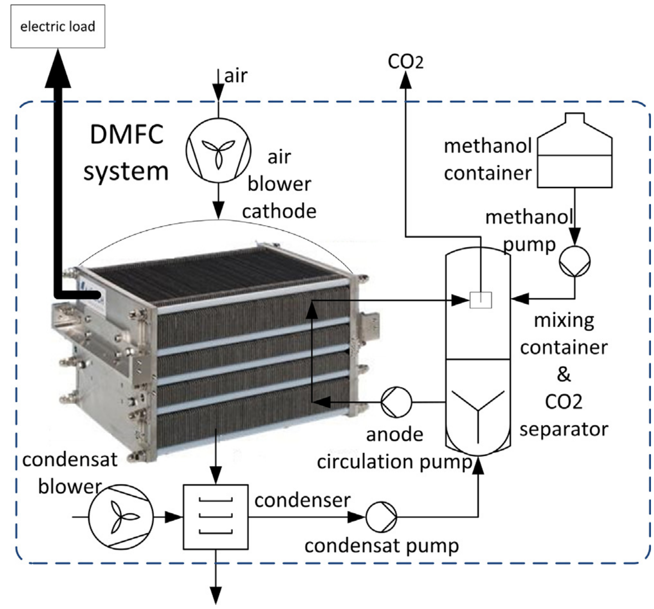

Fig. 1. DFMC system.

2. Model of direct methanol-fuel cell system

The most important objective that the MPC presents is to build an accurate model of the physical system that represents the core MPC algorithm. The characteristics of a DMFC system are non-linear. There are three manipulated variables that correspond to the DMFC: the electrical current density j_{el} (mA/cm^2), the volume flow $\dot{V}_{cathode}$ (ml/cm^2 min) of air on the cathode side and the volume flow $\dot{V}_{\mathrm{MeOH}}$ (ml/min) of methanol entering the system. The input vector is stated as follows:

$$u = \left[j_{el}, \dot{V}_{cathode}, \dot{V}_{\mathrm{MeOH}}\right]^T. \tag{1}$$

A schematic illustration of the entire system is presented in Fig. 1. The non-linear model of the DMFC system used for the FTMPC in this paper is derived and modified from previous work conducted at the Forschungszentrum Jülich (FZJ) by Schulze Lohoff and Verhülsdonk (Schulze Lohoff, 2013; Verhülsdonk, 2015).

The DMFC system is non-linear system illustrated in a state-space Eq. (2):

$$\begin{aligned} \dot{x} &= f(x, u) \\ y &= g(x, u). \end{aligned} \tag{2}$$

The DMFC system responds with process and state values. There are four state variables in total, which are represented in the following vector:

$$x = \left[T_{Stack}, c_{\mathrm{MeOH}}, u_{1\_cell}, u_{2\_cell}\right]^T. \tag{3}$$

The methanol concentration of the anode methanol–water mix c_{MeOH} (mol/l), the temperature of the entire DMFC stack T_{Stack}(°C) and the two internal state variables with no physical interpretation, which comes from a voltage overshoot in the case of variation of the stack current density j_{el}, are described in Eq. (14). The output vector of the DMFC system represents the methanol concentration, as well as the temperature, of the DMFC stack. They have already been represented through the state vector of the system and therefore have not been changed. Moreover, the cell voltage of a single cell, u_{cell}(V), is also part of the output vector. It is as follows:

$$y = \left[T_{Stack}, c_{\mathrm{MeOH}}, u_{cell}\right]^T. \tag{4}$$

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