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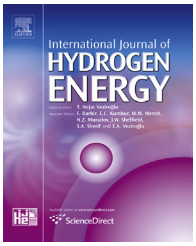

Fault Tolerant Control Strategy applied to PEMFC water management

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ABSTRACT

In this paper, a Fault Tolerant Control Strategy (FTCS) dedicated to PEMFC (Polymer Electrolyte Membrane Fuel Cell) water management is implemented and validated online on a real PEMFC system. Thanks to coupling a Fault Detection and Isolation (FDI), an adjustable controller and a reconfiguration mechanism, FTCS allows addressing the important challenge of Fuel Cell (FC) reliability improvement. Only few works have already been conducted on FTCS applied to FC actuators faults, and none of them on FC water management faults. In this work, a neural-based diagnosis tool is computed online as FDI component and is coupled to a self-tuning PID controller. This diagnosis tool shows low computational time and high detection performance. The self-tuning PID controller shows robustness against noise measurements and model uncertainties. Its low computational cost makes it a suitable control method for real-time FTCS. Performed on a PEMFC system, the FTCS shows promising results on fault diagnosis and performance recovery.

Introduction

Fuel cells (FC) are electro-chemical converters turning hydrogen into electricity and heat, with water as a byproduct. Indeed, when produced from renewable resources by electrolysis, hydrogen has a carbon free use cycle and allows reducing greenhouse gas emissions. As an energy vector, it can be stored in different forms, directly consumed as a fuel in internal combustion engines or considered as an energy source to generate electricity. Several technologies of FC exist, among them Proton Exchange Membrane FC (PEMFC). Thanks to its fast and easy start-up, its high power density and low temperature operation, PEMFCs are perfect candidates for both stationary and transport applications. However, performance, safety and reliability of PEMFCs have to be improved to extend their large-scale commercialization. Because FC is multi-physics in nature, and FC systems require numerous ancillaries, many faults can occur as sensors and actuators

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Nomenclature

RH	relative humidity, %
T	temperature, °C
P	outlet gas pressure, kPa
$\dot{m}$	mass flow rate, sccm
I	load current, A
V	measured voltage, V
$\hat{V}$	voltage estimated by neural network, V
ΔP	measured cathodic pressure drop, kPa
$\widehat{\Delta P}$	cathodic pressure drop estimated by neural network, kPa
J	cost function
s_V	voltage acceptance threshold, %
$s_{\Delta P}$	cathodic pressure drop acceptance threshold, kPa

Greek letters

λ	gas excess ratio
θ	neural network weight matrix
φ	neural network activation function
ε_V	relative error between simulated and measured voltage, %
$\varepsilon_{\Delta P}$	error between simulated and measured cathodic pressure drop, kPa

Subscripts

a	anode
c	cathode
cell	fuel cell
air	air
set	setpoint

Controller parameters

u	manipulated variable
y	controller output
y_{set}	controller setpoint
e	trajectory tracking error
n_y	number of past outputs required
n_u	number of past inputs required
k_c, τ_i, τ_d	PID controller parameters

failures, or improper operating conditions. The safety and the reliability of the system require a high tolerance to these malfunctions.

In the best-case scenario, these malfunctions lead to performance losses. At worst, system failures, irreversible degradations and premature ageing can occur. Basics classical controllers are not able to manage these faults. Their weaknesses induce productivity, performance and reliability losses due to control loop inefficiency. A control strategy which tolerates system faults by maintaining suitable operating conditions is then needed. In this context, fault tolerant control strategies (FTCS) allow to fulfill industrial expectations despite of these possible faults. FTCS is highly developed to control safety-critical systems, and increasingly to satisfy industrial expectations. FTCS avoids incidents, maintains stability, ensures safety, reliability and system efficiency despite of possible faults [1]. FTCS could be an efficient way to improve FC availability and also FC lifetime, that are not yet fully optimal for industrial applications.

FTCS can be sorted into 2 types: passive and active FTCS, respectively PFTCS and AFTCS. The PFTCS design relies on a controller expected to be robust against some specific presumed faults. These faults, assumed to be known *a priori*, are only taken into account during controller synthesis. Controller parameters will not be adjusted anymore after this stage and its tolerance is limited to these expected faults. Regarding PFTCS, neither FDI tools nor reconfiguration mechanisms are needed. On the contrary, AFTCS typically includes a Fault Detection and Isolation tool (FDI), which diagnoses the fault thanks to physical (additional hardware sensors) or analytical (soft sensors) redundancy. The fault diagnosis result is sent to a reconfiguration mechanism. This tool determines the remedial actions to be started or calculates the appropriate parameters to reconfigure the controller. The previous FDI tool allows setting up the appropriate response to each specific fault.

Both passive and active FTCS have advantages and limitations, as exposed in Ref. [2]. Because of FDI tool implementation requires redundancy an active FTCS is more complex to develop than a passive strategy. Furthermore, the AFTCS effectiveness strongly depends on FDI tool efficiency. However, even if PFTCS is simpler to implement and to perform, its tolerance to faults declines as the number of expected faults increases. Besides, from performance point of view, PFTCS is designed to be robust against a list of predefined faults without any consideration about the optimal performance for any of these faults conditions. Basically, AFTCS components are: a diagnosis tool, a reconfiguration mechanism and an adjustable controller. Because these components involved really different fields and approaches, the development of these tools were conducted separately and independently. For FC applications, each AFTCS components have already been tested and validated separately, making AFTCS implementation easier to carry out.

FC diagnosis tools can be sorted in two main categories: model-based and non-model-based approaches. In literature, many FC diagnosis tools have been investigated.

A complete study on non-model-based approaches has been conducted in Ref. [3], describing the three types of approaches: artificial intelligence, statistical and signal processing methods.

Model-based methods are often residual-based, they involve the instantaneous remoteness between the real FC behavior and the expected optimal and healthy behavior. A model describing a healthy FC system behavior is identified and the residue between this model and the collected experimental data is calculated. The residue analysis allows detecting and isolating faults. There are as many FC models as residual-based diagnosis methods. As examples, the models can be Artificial Neural Networks (ANN), equivalent circuits or based on physical equations. A thorough survey of model-based diagnosis is done in an overview [4].

In addition to an FC stack or a single cell, an FC system requires a various number of ancillaries to operate (Fig. 1). These ancillaries include hydrogen storage, gas flow controllers, gas humidification systems, temperature and pressure