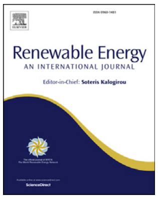
Renewable Energy xxx (2016) 1–9

Contents lists available at ScienceDirect

Renewable Energy

journal homepage: www.elsevier.com/locate/renene



A model-based framework for fault estimation and accommodation applied to distributed energy resources

James T. Allen, Nael H. El-Farra*

Department of Chemical Engineering, University of California, Davis, CA 95616, USA

A R T I C L E I N F O

Article history:
Received 24 February 2016
Received in revised form
30 April 2016
Accepted 2 May 2016
Available online xxx

Keywords:
Fault estimation
Fault accommodation
Model-based control
Sampled-data systems
Distributed energy resources

A B S T R A C T

This paper presents the development and approach of a model-based fault identification and accommodation framework applied to sampled-data controlled distributed energy resources subject to control actuator faults. The main objective of the proposed approach is to handle faults that degrade stability as well as performance, while remaining robust to false alarms. The proposed method allows for dual fault detection and estimation, through the use of an embedded system model that minimizes the residual between the estimated and sampled states at each sampling period by adjusting a fault parameter in the embedded model over a past horizon. The resulting fault parameter estimate is then used by the control system to find an optimal fault accommodation strategy by minimizing a predefined performance metric whilst ensuring closed-loop stability. The developed fault accommodation framework is then applied to a simulated model of a solid oxide fuel cell subject to both stability and performance degrading faults in the control actuators. A discussion of some of the practical implementation issues associated with the developed framework is also included.

1. Introduction

Distributed energy resources (DERs) are composed of modular energy generation units including, for example, micro-turbines, fuel cells, renewable energy systems, battery storage and other such technologies deployed close to the point of consumption. The modular nature of DERs allows them to be integrated with existing grid infrastructure or implemented in a stand-alone manner. DERs offer advantages over conventional grid electricity by offering end users a diversified fuel supply; higher power reliability, quality, and efficiency; lower emissions and greater flexibility to respond to changing energy needs. While DERs have aided in the integration of sustainable energy resources into the power grid, they also pose fundamental challenges, including fluctuations in generation from intermittent availability of renewable resources as well as the resulting increased communication between generation and loads.

These and other challenges have been the subject of a significant and growing body of research work on the control of DERs (e.g., [1–6]). Important contributions in this direction include the use of conventional and model-based feedback control algorithms to regulate various types of grid-connected DERs in order to enhance power system stability (e.g., [7–10]), mitigate power quality problems (e.g., [11]) and improve the continuity of electricity supply (e.g., [12]), the development of various distributed control and coordination architectures using multi-agent systems (e.g., [13,14]) and predictive control approaches (e.g., [15,16]).

While control is necessary to ensure that the load demand is met and that economical operation of each DER is maintained, the stability and performance of smart grid DERs have not been rigorously assessed in the presence of faults or failures at the local and network levels. This is an important problem given the fact that the distributed power market is driven by the need for reliable high-quality power, and the fact that local faults and disruptions in power flow can have a substantial impact, especially in situations when DERs are integrated to support grid operations. The timely identification and mitigation of faults at the local level before they cascade through the network are important capabilities that ensure autonomous control and protection, which when coupled with proper supervisory oversight enable distributed energy generation to provide highly reliable services under all

---

* Corresponding author.
E-mail address: nhelfarra@ucdavis.edu (N.H. El-Farra).

http://dx.doi.org/10.1016/j.renene.2016.05.002

Please cite this article in press as: J.T. Allen, N.H. El-Farra, A model-based framework for fault estimation and accommodation applied to distributed energy resources, Renewable Energy (2016), http://dx.doi.org/10.1016/j.renene.2016.05.002

disturbance and fault scenarios. In this context, fault-tolerant control is an important tool for reducing performance deterioration in the face of faults and uncertainties in the system components, such as actuators and sensors, resulting in increased reliability of the network.

In prior work ([17]), fault-tolerant control has been studied in the context of a small-scale network of solid oxide fuel cells (SOFCs), where the focus has been on the detection and handling of destabilizing failure events at the local level without supervisory oversight. Local monitoring of the health status of each DER took place through use of a time-varying alarm threshold on a properly designed observer-based output residual. Exploiting the inherent actuator redundancy in SOFCs, three stabilizing controller configurations were designed, and a methodology for active switching between them in the event of a threshold breach was developed. The main contribution was the characterization of a stability region within which each controller configuration could operate. However, the faults considered in that work were limited to total failure events, thus negating the need for fault isolation or estimation. The proposed stability-based scheme also was not designed to detect faults that only degrade performance but do not compromise stability, and this can lead to sub-optimal performance.

Motivated by these considerations, this paper presents a framework for local actuator fault-tolerant control that accounts for both performance and stability degrading faults, while optimizing suitable performance metrics and maintaining closed-loop stability. The developed framework is realized through an integrated approach that brings together model-based control, data-based fault estimation and performance-based fault accommodation. The rest of the paper is organized as follows. A SOFC system is initially introduced in Section 2 to motivate the development and application of the proposed framework. This model system is used to design a local model-based state feedback controller that operates on sampled data and characterize its stability properties in the presence of faults. A fault estimation scheme that provides an estimate of the fault magnitude by solving a data-based moving horizon optimization problem is then introduced in Section 3. A performance index suitable for sampled-data systems is then introduced in Section 4 and used to develop a performance-based fault accommodation strategy that alters model and control parameters to minimize post-fault performance losses while maintaining closed-loop stability. Practical implementation issues, such as the need to minimize false alarms, are discussed and guidelines for dealing with these issues are presented. Finally, simulation results are presented in Section 5.

2. Preliminaries

2.1. Motivating example: a solid oxide fuel cell

Due to their modular and stable nature SOFCs are of particular interest when it comes to decentralized distributed energy generation. A SOFC consists of two porous electrodes, an anode and a cathode, in contact with a solid metal oxide electrolyte between them. Hydrogen is fed along the surface of the anode where it releases electrons that migrate externally towards the cathode. The electrons combine with oxygen fed along the surface of the cathode to form oxide ions. These ions diffuse through the electrolyte towards the anode where they combine with the hydrogen ions to produce water and power. Under standard modeling assumptions (see [18]), the following dynamic model of the SOFC stack can be obtained from first principles:

$$
\begin{aligned}
\dot{p}_{H_2} &= \frac{T_s}{\tau^*_{H_2} T^* K_{H_2}}\left(q^{in}_{H_2} - K_{H_2}p_{H_2} - 2K_rI\right)\\
\dot{p}_{O_2} &= \frac{T_s}{\tau^*_{O_2} T^* K_{O_2}}\left(q^{in}_{O_2} - K_{O_2}p_{O_2} - K_rI\right)\\
\dot{p}_{H_2O} &= \frac{T_s}{\tau^*_{H_2O} T^* K_{H_2O}}\left(q^{in}_{O_2} - K_{H_2O}p_{H_2O} + 2K_rI\right)\\
\dot{T}_s &= \frac{1}{m_sC_{ps}}\Bigg[\sum q^{in}_i \int_{T_{ref}}^{T_{in}} C_{p,i}(T)dT\\
&\qquad - \sum q^{out}_i \int_{T_{ref}}^{T_s} C_{p,i}(T)dT - 2K_rI\Delta\widehat{H}^o_r - V_sI\Bigg]\\
V_s &= N_0\Delta E - r_0 \exp\left[\alpha\left(\frac{1}{T_s} - \frac{1}{T_0}\right)\right]I\\
\Delta E &= \left[\Delta E_0 + \frac{RT}{2F}\ln\left(\frac{p_{H_2}p^{(0.5)}_{O_2}}{p_{H_2O}}\right)\right]
\end{aligned}
\tag{1}
$$

For the component mass balances, p_i is the partial pressure of component i, T_s is the stack temperature, τ_i is the time constant for component i, described by $\frac{V}{K_iRT^*}$ with V being the volume component i is contained in, K_i is the valve molar constant for component i, R is the gas constant, $\tau^*_i = \tau_i\big|_{T_s=T^*}$, and T^* is the operating temperature. q^{in}_i, p_i are the inlet flow rate and partial pressure of component i, respectively, $K_r = N_0/(4F)$, where N_0 is the number of cells in the stack and F is Faraday's constant. Lastly I is the load current. As for the energy balance, m_s and C_{ps} are the mass and heat capacity of the stack, T_{ref} and T_0 are the reference and feed temperatures, $C_{p,i}$ is the heat capacity of component i, q^{out}_i is the outlet flow rate of gas i, $\Delta\widehat{H}^o_r$ is the specific heat of reaction, V_s is the stack voltage, r_0 is the internal resistance, α is the resistance slope, and ΔE_0 is the standard cell potential.

2.2. Control problem formulation with fault modeling

The SOFC system modeled in Eq. (1) has three potential manipulated variables. Previous work has exploited this fact to implement multiple control configuration in the case of actuator failure (see [17]). However, here the focus will be on the accommodation of faults through model manipulation, and the main control configuration will be the one utilizing the hydrogen gas flow rate as the manipulated variable (this should be assumed unless otherwise noted). A similar approach can be used if other manipulated variables are chosen instead (the oxygen flow rate or the feed temperature).

The problem formulation is the same as in [17], where the controller design is based on the linearized system model about the desired operating set-point, where the time evolution of the system is given by:

$$\dot{x} = Ax + B\theta u \tag{2}$$

$$\dot{\widehat{x}} = \widehat{A}\widehat{x} + \widehat{B}\widehat{\theta}u \tag{3}$$

$$u = K\widehat{x} \tag{4}$$

where $x = \left[p'_{H_2}\ p'_{O_2}\ p'_{H_2O}\ T'_s\right]^T$ is the state vector of deviation variables from the desired steady state operation point ($x_{ss} = [0.3973\ 0.3142\ 0.2951\ 1162.8]^T$), $\widehat{x}$ is the model state which provides an estimate of x, $\widehat{A}, \widehat{B}$ are constant model matrices that approximate the linearized system matrices, A, and B allowing for consideration of plant-model mismatch (see Eq. (5) for the values of the nominal system state matrices). The effect of faults is captured through θ which, in general, is a diagonal matrix whose diagonal

Please cite this article in press as: J.T. Allen, N.H. El-Farra, A model-based framework for fault estimation and accommodation applied to distributed energy resources, Renewable Energy (2016), http://dx.doi.org/10.1016/j.renene.2016.05.002