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Fault Analysis, Detection and Estimation for a Microgrid via H_2/H_∞ *LPV* Observers

Marcelo M. Morato[a,*], Daniel J. Regner[a], Paulo R.C. Mendes[a], Julio E. Normey-Rico[a], Carlos Bordons[b]

[a] *Universidade Federal de Santa Catarina, Florianópolis, Brazil*
[b] *Departamento de Ingeniería de Sistemas y Automática, Universidad de Sevilla, Sevilla, Spain*

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ABSTRACT

This works addresses the problem of Fault Detection and Diagnosis and provides a solution based on the use of multiple Linear Parameter Varying (*LPV*) extended-state observers coupled with simple search algorithm. This methodology is applied to a Grid-Connected Hybrid Power Plant, with different renewable sources, such as photovoltaic panels, wind power generation and the use of biomass. This plant might present different possible faults, that can lead it not to comply to its operational constraints, such as communication problems, valve malfunctions, vapor leakages and others. All these possible faults are carefully categorized based on empirical information from real plants in Brazil. The Fault Detection and Diagnosis (*FDD*) system designed aims to estimate and categorize these faults and, to do so, the proposed *LPV* observers are derived from *LMI* computation of the mixed H_2/H_∞ norm minimization, in such a way to reduce the effect of noise and external disturbances upon the fault estimation. Through high-fidelity simulations, the benefits of the presented method is discussed.

1. Introduction

Efficient energy generation is of uttermost importance in terms of the search for an *eco-friendly* development and a sustainable future. Much is discussed about the use of renewable sources, but it is important to remark that, although these seem very appealing, they are intermittent, difficult to predict (specially solar irradiance curves), heavily dependent on the weather conditions and to deal with them is a defying factor for system safety and technical-economical network management.

The integration of renewable sources to power systems can be a good alternative to avoid greenhouse emissions and environmental impact, but the open issue to be investigated is how can these sources be integrated without losing efficiency and dispatchability of energy plants.

In recent years, the Control Systems community has given certain attention to this question of prime importance. The concept of microgrids – a set of generators, loads and storage units that operate together, in isolated mode, or connected to the main grid, proposed in [1] – has been given attention, as it facilitates the modelling and control of hybrid plants, as well as the model integration of renewable sources to energy systems. This methodology is applied in [2,3], for example.

Also, the optimal control of these hybrid generation microgrids, that include renewable and non-renewable sources, in order to maximize the use of *renewables* and economic profit while complying to operational demands, has been treated, specially, with Model Predictive Control (*MPC*) based control schemes. This has been seen in a diverse set of works: Ref. [4] presents an *MPC*-controlled hydrogen-based domestic microgrid; Ref. [5,6] also deal with optimal generation for renewable microgrids; Ref. [7] presents an *MPC*-based framework for distributed energy management; Ref. [8] shows an *MPC* structure for energy management of experimental microgrids, coupled with hydrogen storage systems; the work shown in [9] presents an economical *MPC* applied for the optimal production timing and power, considering biomass dispatch of an olive oil mill.

Still on this matter, the case studied herein is a hybrid energy producer based on a sugarcane processing plant, considering biomass, *biogas*, solar and wind power energy as primary energy sources. This specific power system was firstly presented in [10] and further detailed in [11]. Then, in [12], a model-based predictive controller was designed and some other advanced control techniques, considering disturbance forecasting, were implemented in [13,14].

Nonetheless, the discussion of the effect of faults on this energy system is yet to be researched. Real instrumented systems present

* Corresponding author.
E-mail address: marcelomnzm@gmail.com (M.M. Morato).

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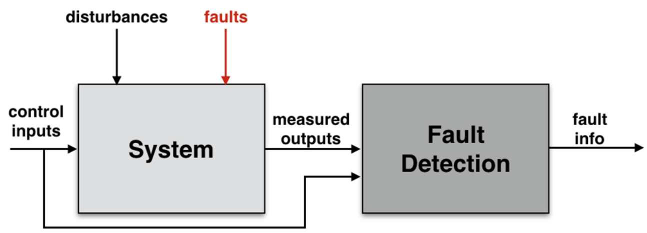

Fig. 1. Fault detection system.

evermore an increase on complexity and become more vulnerable to faults. This is also very true for energy systems and power microgrids. Possible faults on these systems may lead these plants not to comply to their operational constraints, which might result in economic deprivation and in a lack of the available power to the external network. To ensure sufficient measures of reliability and safety, fault detection methodologies have been sought. A fault detection system is represented in Fig. 1.

A deep discussion about how can process control enhance the safety and reliability of energy systems, altogether with sustainability (social, economic and environmental) goals, is presented in [15]. Nonetheless, up to the authors' knowledge, only a few works have tried to deal with the issue of Fault Detection of microgrids at a higher control level, working in parallel to the energy generation planning layer. This is, dealing with the design of systems that detect, diagnose and quantify the state of the whole controlled plant, if it is healthy or faulty. An adaptative, statistical method for fault identification in power systems has been firstly seen in [16]. A categorization algorithm for possible faults in a microgrid has been seen in [17]. The issue of fault location has been dealt with in [18], for a direct current power system. A fault detection methodology for *DC* power systems has been presented in [19], considering the analysis of transient behaviour. Still, in [20], the issue of high impedance fault detection is studied, considering complex electrical distribution networks. A good review of *FDD* applications for renewable systems has been seen in [21]. The work [22] has tried to deal with this issue, as it presents a Fault Detection and Diagnosis (*FDD*) for wind turbines using available information of a supervisory (*SCADA*) system. Some other works should also be mentioned, although being focused on the fault detection of individual energy subsystem (at a lower control level, with a more limited scope): Ref. [23] presents a monitoring and fault diagnosis system for wind power systems; Ref. [24], presents the detection of fault on photovoltaic panels, with a power losses analysis approach; Ref. [25] detects and classifies faults on steam turbines using neuro-fuzzy methods; Ref. [26] presents the handling of faults for a wind system.

The detection of faults on these studied hybrid energy systems can elevate internal system stability, safety and also enable the better management of energy. If a controller has accurate and timely knowledge about faulty situations, an active Fault Tolerant Control (*FTC*) scheme can be designed, as discussed in [27], to overcome the fault outcomes so that the energy production can be immune to faults, offering increased process availability, avoiding breakdowns from simple fault events.

An accurate Fault Detection and Diagnosis system is, then, of most importance for an *FTC* in order to provide it with timely information on the condition, subsystem (location), magnitude and type of fault event that occurs on the controlled plant (in this case, microgrid). In terms of *FDD* systems, some works opt for nonlinear model-based approaches, as those in [28–31]. Anyhow, a great deal of works suppose Linear Time Invariant (*LTI*) system characteristics and resort to parity-space and residual analysis, as those seen in [32–34].

This usual *LTI* model-based *FDD* design method pre- sents some troubles when dealing with operational point changes, as (false) fault alarms may appear. One key issue that has to be noticed is that most of the cited studies (both nonlinear and *LTI*) make use of the redundant availability of sensors in order to determine if the system is healthy or not. This issue can be overlapped, for instance, with the use of observer-based *FDD*, as it has been deeply discussed in [35]. Thus, from the beginning of the 2000s, works have proposed gain-scheduled *FDD* design to extend the scope of the linear *FDD* methods to nonlinear systems. A natural idea is to extend *LTI* system models to Linear Parameter Varying (*LPV*) ones. Such models can be used to accurately describe some complex nonlinear plants, as demonstrated [36,37]. *LPV* systems can be understood as a representation form for dynamical systems with bounded parameter variations. In comparison to the *LTI* state-space representation, they present matrices that are dependent on known, bounded scheduling parameters.

An *LPV*-based fault estimation system can, in an autonomous way, re-adjust and schedule itself depending on the observed plant's operating point, according to the sche- duling parameter. Choosing an *LPV* system representation is an interesting option, as it represents something in between the full nonlinear designs and *LTI* methods based on a fixed operating condition, since most of the conveniencies of *LTI* synthesis are present and, still, good performance and stability conditions can be guaranteed over a broader operating set.

In terms of *LPV* design, the Control Systems community has given attention, mostly to controller synthesis, as in [38,39], although literature on *LPV*-based *FDD* is still slightly limited. Anyhow, the *LPV*-based observer design method to estimate faults is quite advantageous, as they can present good results with somewhat easy implementation and not needing any additional sensors. This work opts for this kind of approach.

A few of these recent *LPV-FDD* works have presented strong results, that also include some experimental validation. These are: the paper [40] shows the application of model-based *LPV FDD* to an industrial benchmark; An *FTC* strategy for actuator faults on helicopters is seen in [41]; An adaptive fault estimation scheme is also applied to helicopter models in [42]; Recently, [43] showed fault estimation for discrete *LPV* systems, with the use of switched observers; In [44], where a method is presented for the synthesis of *FDD* filters based on an *LMI* solution for polytopic *LPV* systems and in [45], where an *LMI*-based pole-placement robust *LPV* estimator is presented.

1.1. Studied Problem

Given the presented context, the following novel discussion is the main purpose of this work: how to analyse, detect, diagnose faults on hybrid energy generation plants with a broader view, focusing on all possible faults on all subsystems from a higher (supervisory) level, without any additional sensors? This paper discusses the use of *LPV*-based *FDD* to detect and estimate these faults, that usually stand for actuator malfunctions, gain decresce upon boilers and turbines due to accumulated dirt and many others.

1.2. Main Contributions

This article aims to unravel a solid framework on how to detect and diagnose faults on a hybrid power plant. The main contributions are listed next:

(i) First of all, based on real data, this work tries to mangle out all the possible faults that might occur on the studied microgrid, categorizing and sorting them out in terms of magnitude, location, type, reason and effect. Then, the faults are modelled as different multiplicative factors;
(ii) Secondly, a bank of *LPV* observers is designed to detect and diagnose each of these faults, considering a mixed H_2/H_∞ synthesis. Also, a simple search algorithm is presented in order to categorize the estimated faults. With the aid of a high-fidelity simulation model, results are delivered to enlighten the effectiveness of the proposed approach.