Applied Energy xxx (2017) xxx–xxx

Contents lists available at ScienceDirect

Applied Energy

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

A model-based diagnostic technique to enhance faults isolability in Solid Oxide Fuel Cell systems

Pierpaolo Polverino *, Marco Sorrentino, Cesare Pianese

Università degli Studi di Salerno, via Giovanni Paolo II 132, 84084 Fisciano, SA, Italy

HIGHLIGHTS

- A model-based diagnostic technique is proposed to improve fault isolation.;
- A Solid Oxide Fuel Cell Anode-Off Gas Recycling system is considered.;
- Isolated system component sub-models are used to solve fault clustering issues.;
- The technique is tested in simulation environment on four faults at system level.;
- The algorithm proved its diagnostic capabilities in each analysed condition.

ARTICLE INFO

Article history:
Received 21 January 2017
Received in revised form 14 April 2017
Accepted 6 May 2017
Available online xxxx

Keywords:
Solid Oxide Fuel Cell
Fault detection
Fault isolation
Model-based diagnosis
Fault simulation
Diagnostic technique

ABSTRACT

This work illustrates an innovative diagnostic technique able to improve fault isolability in Solid Oxide Fuel Cell (SOFC) energy conversion systems. On-board sensor reduction may induce fault clustering and, thus, hinder univocal fault isolation. According to the proposed technique, isolated system component sub-models, fed with faulty inputs, can be used to solve this issue. These models provide a set of redundant residuals, which react only if the related component is under faulty state. The technique is characterized and tested in simulated environment on an SOFC Anode Off-Gas Recycling (AOGR) system. Hydrogen external leakage, fuel and air heat exchangers efficiency reduction and recirculation unit malfunction are addressed and implemented in the complete system model. This latter is used to simulate system variables in both nominal and faulty conditions and compute residuals for fault detection and isolation. The sub-models are then used to introduce further residuals, and their behaviour is investigated at different fault magnitudes. The analysis is firstly performed in an ideal case scenario, considering the fault isolability that can be theoretically achieved. Then, practical application of the diagnostic algorithm is discussed, considering quantitative residuals deviation and properly analysing the effects of feeding the sub-models with inputs provided by both faulty and nominal models. The achieved results confirm the capability of the proposed approach to univocally isolate the considered faults in all the investigated conditions. Moreover, the analysis of the real case scenario proved the proposed algorithm suitable also for real applications.

1. Introduction

Nowadays, Solid Oxide Fuel Cells (SOFCs) represent one of the most suitable alternatives to conventional energy production systems (e.g. internal combustion engines based on fossil fuels) for cogeneration and Auxiliary Power Unit (APU) uses [1]. However, SOFC mass-market deployment is mainly hindered by their high production costs and limited durability [2]. To overcome these issues, advanced control and diagnostic algorithms can be applied, since the use of proper diagnostic strategies can efficiently detect and isolate malfunctions at both stack and system levels [3]. Combining the diagnostic inference with suitable control strategies, appropriate counteractions can be implemented to prevent performance losses and abrupt system failure [4], thus reducing maintenance costs and improving system lifetime. This latter can also be increased using prognostic algorithms, able to perform online Remaining Useful Life (RUL) forecast by means of degradation mechanisms modelling [5] and proper use of control rules and diagnosis results [6].

Fuel cell manufacturing companies are mainly focusing on the improvement of overall system efficiency through advanced sys-

* Corresponding author.
E-mail address: ppolverino@unisa.it (P. Polverino).

http://dx.doi.org/10.1016/j.apenergy.2017.05.069

Nomenclature

Acronyms

AOGR	Anode Off-Gas Recycling
APU	Auxiliary Power Unit
CHP	Combined Heat and Power
FTA	Fault Tree Analysis
FSM	Fault Signature Matrix
GT	Gas Turbine
LCA	Life Cycle Assessment
LNG	Liquid Natural Gas
RF	Random Forest
RNN	Recurrent Neural Network
RUL	Remaining Useful Life
SOEC	Solid Oxide Electrolyser Cell
SOFC	Solid Oxide Fuel Cell
SOM	Self Organization Map
SVM	Support Vector Machine
TCPG	Triple Combined-cycle Power Generation
VARS	Vapour Absorption Refrigerator System

tem configurations. Among those investigated, Anode Off-Gas Recycling (AOGR) has been singled-out as one of the most promising configurations, which is able to improve efficiency by increasing fuel utilization [7]. Nevertheless, such configuration implies the introduction of a recirculation unit and related balance of plant, with a consequent increase in system complexity and cost. In order to reduce this latter, manufacturers are also trying to decrease the number of sensors the system is equipped with. However, the reduction in available sensors may hinder the effectiveness of on-board diagnosis, since the source of key information is diminished [8]. For this reasons, it is clear the need for advanced diagnostic algorithms, able to use in a more efficient way the available measurements and boost information extraction with limited available equipment.

The present paper illustrates an innovative solution to the sensors reduction issue, by means of isolated sub-model analysis. The proposed technique allows achieving optimal fault detection and isolation at system component level, even though a reduced number of sensors is used. The main contribution given by the present paper to the available literature consists in the proposed diagnostic methodology, which uses in a more suitable way sensors measurements and system components models to amplify the available information and thus increase diagnostic redundancy.

In the following sections, an overview of the current State-of-the-Art concerning SOFC system applications and diagnosis is presented, to highlight the originality and innovations of the present manuscript. Then, a brief introduction to model-based diagnosis is given, followed by the description of the proposed technique by means of a theoretical example. Afterwards, the technique is firstly applied to an SOFC AOGR system, then its efficacy is verified through simulation tests. As first step, the approach is qualitatively investigated in an ideal case, and then its performance are examined in a realistic scenario, introducing practical application limitations. In this latter case, quantitative analysis of the diagnostic results is performed, highlighting the changes with respect to the ideal case.

2. State-of-the-Art analysis on SOFCs applications and diagnosis

2.1. Solid Oxide Fuel Cells applications overview

Several studies available in the literature investigate the use of SOFCs for Combined Heat and Power (CHP) production [9,10], as APUs for ships [11,12] and trucks [13–15], combined with Gas Turbines (GT) [16,17] as well as for fuel production (e.g. as electrolysers) [18,19].

Concerning CHP systems, Ellamla et al. [9] detailed in their review on worldwide systems deployment that, at the end of 2014, almost 100,000 units have been installed in Japan and around 1000 units in South Korea and Europe, respectively, with SOFCs covering about 10% of the total amount. Their robustness with respect to load dynamics was proved by Hanke et al. [20], who tested SOFC stacks under power cycling operation and observed no acceleration in the degradation rate compared to constant operation. This advantage, associated to high energy conversion efficiency (and thus low fuel consumption with respect to other fuel cell technologies), make SOFC systems appealing from both a technical and economic point of view. Indeed, Napoli et al. [21] and Pellegrino et al. [22] observed that, although SOFCs shows high investment costs, they ensure high yearly savings, at different configurations and load scenarios. On the same line, Facci et al. [10] performed a techno-economic analysis of an SOFC-based power plant for the combined generation of cooling, heat and electric power. Different configurations have been considered, each one with a specific control strategy and optimal design, confirming in all cases a cost reduction with respect to separate energy production systems.

In the work of Strezza et al. [11], a Life Cycle Assessment (LCA) method has been applied to a 20 kW electric SOFC system operating as an APU, proving better environmental performances with respect to conventional power systems (i.e. engines). Also Diaz-de Baldasano et al. [12] demonstrated the reduction in pollutant emissions, combining a new designed SOFC system with diesel generators for ship uses. Venkataraman et al. [13] developed a model of an SOFC APU coupled with a Vapour Absorption Refrigerator System (VARS) for truck refrigeration, showing the feasibility of such an application for small trucks, with a theoretical increase in the SOFC system efficiency up to 80% and a significant reduction in the main engine load. In addition, the works of Kendall et al. [14] and Recheberg et al. [15] remarked the advantage of using SOFCs for truck applications. The former focuses on the use of downsized microtubular SOFC stacks running on Liquid Natural Gas (LNG), to improve system robustness and achieve faster dynamic response, whereas the latter investigates heavy duty truck idling reduction by means of SOFCs as APUs running on diesel fuel.

The coupling of SOFCs with GTs has also proved being effective. He et al. [16] illustrated that, through the development of a suitable control strategy, substantial increase in system efficiency and power management can be achieved. The work of Larosa et al. [23] details, through a simulation study, the feasibility of developing a hybrid system made of an SOFC and a micro GT, whereas Santin et al. [24] performed a thermo-economic analysis to investigate the main advantages related to an SOFC-GT hybrid system with different fuels and plant configurations. Obara [25] accomplished a numerical investigation on the electric stabilization of a 1.4 MW SOFC-based power plant (made of an SOFC, a GT and a steam turbine) combined with a large scale photovoltaic plant. In the work of Zaccaria et al. [26], a 1-D real time model of an