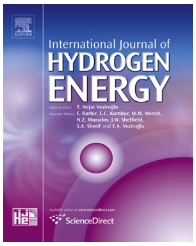
Available online at www.sciencedirect.com

ScienceDirect

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



Sensitivity analysis of stack power uncertainty in a PEMFC-based powertrain for aircraft application

G. Correa [a,*], F. Borello [b], M. Santarelli [c]

[a] Centro de Investigaciones y Transferencia de Catamarca (CITCA), CONICET-UNCA, Facultad de Ciencias Exactas y Naturales (UNCa), Maipú 662 – 4700, San Fernando del Valle de Catamarca, Argentina

[b] Politecnico di Torino, Departmant of Mechanical and Aerospace Engineering, Corso Duca degli Abruzzi 24, 10129 Torino, Italy

[c] Politecnico di Torino, Department of Energy, Corso Duca degli Abruzzi 24, 10129 Torino, Italy

ARTICLE INFO

Article history:
Received 31 March 2015
Received in revised form
15 May 2015
Accepted 19 May 2015
Available online xxx

Keywords:
PEM fuel cell
Sensor reliability
Sensitivity analysis
Aircraft power system
Dynamic model

ABSTRACT

Experimental data concerning the reliability of fuel cell systems (FCS) in aviation are still unavailable to technical community, while assessing reliability of a component or a whole system represents a fundamental aspect that allows a new technology to be introduced in a high safety system such as an aircraft. The main aim of this paper is to show a method to estimate the reliability of an aircraft power system based on a hydrogen fuel cell, mainly for design purposes. The method is based on a high-order adaptive response surface technique, coupled with a dynamic model of the aircraft power system, and it is applied to the failure event represented by an incorrect power supply due to the failure of sensors of the control system of the powertrain. The most important advantage of the proposed method is the low computational effort it requires. The result is a ranking of the most critical sensors to be considered in the design phase of the power system and demonstrate that accurate temperature sensors and sensor calibration are of dramatic importance for the control of the stack power, in case of powertrain based on PEM fuel cell systems.

Introduction

In parallel with the increasing interest in renewable fuels, high efficiency powertrain technologies start to be considered, such as fuel cell technologies. The high efficiency and environmental advantages of fuel-cell technology have generated an increasing interest in the aviation community. So far, the use of fuel-cell systems for propulsion of manned aircraft has been adequately demonstrated only in three projects: Boeing fuel-cell demonstrator airplane [1], the Antares DLR-H2 fuel-cell aircraft project [2], and the ENFICA-FC project [3].

Among the various types of Fuel Cells, the PEMFC technology has found widespread use, especially in vehicular application [4]. Instead, only two fuel cell technologies could be considered for aviation applications: PEMFC and SOFC,

---

Abbreviations: act, Activation; an, Anode; Amb, Ambient; ca, Cathode; CDF, Probability distribution function; conc, Concentration; HEX, Heat Exchanger; FC, Fuel cell; MC, Monte Carlo; Mem, Membrane; ohm, Ohmic; RSM, Response surface method; st, Stack; WC, Water cooling (deionizer water).

* Corresponding author. Tel.: +54 93513337718.
E-mail address: correa.gabriel@conicet.gov.ar (G. Correa).

http://dx.doi.org/10.1016/j.ijhydene.2015.05.133

Please cite this article in press as: Correa G, et al., Sensitivity analysis of stack power uncertainty in a PEMFC-based powertrain for aircraft application, International Journal of Hydrogen Energy (2015), http://dx.doi.org/10.1016/j.ijhydene.2015.05.133

Notations

A	Area, $[m^2]$
A_c	Cell active surface, $[cm^2]$
c_v	Water concentration, $[mol/cm^3]$
D	Diffusion coefficient, $[cm^2/s]$
E_0	Open Circuit Voltage, [volts]
C,Cp	Specific heat, [J/(kg K)]
F	Faraday number, [C/mol]
G	Mass flow rate, [kg/s]
g	Gibbs free energy, [W]
h	Mass specific enthalpy of the mass flow, [J/kg]
i	Current density, $[A/cm^2]$
I	Current, [A]
l	Electrode perpendicular distance
m	Total mass, [kg]
N_v	Net water flow $[mol/(s\ cm^2)]$
n_c	Number of cells in series in the PEMFC stack
n_d	drag coefficient [-]
P	Pressure, [bar]
P^{sat}	Saturation pressure, [bar]
R	Universal gas constant, [J/(mol °K)]
R_a	Propeller radius, [m]
S_{HEX}	Frontal surface of the heat exchanger, $[m^2]$
r	Resistance, $[\Omega\ m^2]$
T_r	Propeller thrust, [kg]
T	Temperature, [°K]
t_m	Membrane thickness, [cm]
V_c	Cell voltage, [V]
V_∞	Onset flow velocity, [m/s]
x_i	mole fraction of constituent i [-]
Wel	Electric power produced by the stack, [W]
Greek letters	
α^{el}	electrode transfer coefficients [-]
Φ	Heat transfer, [W]
η	over-voltage, [V]
ρ	Air density, $[kg/m^3]$

while the AFC systems have been used for space, but issues with poisoning by CO and CO_2 would eliminate applicability for general aviation. The MCFC technology [5,6] is the less suitable for transport application due to its low power density and the adoption of the electrolyte in molten phase; they are instead the cells with the higher rate of installation worldwide in the stationary applications, mainly at the level of power plants, with also the largest size power plant so far in operation (58.8 MW in Korea, produced by Posco energy).

Some of the key advantages and some disadvantages of PEMFC systems over the other competitive types of FCs can be specified as follows [7,8]: They provide high power density, high chemical-to-electrical energy conversion efficiency, and fast and easy start-up and operated a low temperature. The disadvantages are: they are very sensitive to impurities of hydrogen, need humidification units of reactive gases and use very expensive catalyst (platinum) and membrane (solid polymer).

In the early phases of the introduction of a new technology in highly controlled systems, information about the elements that most affect the reliability is critical for the designer. Unfortunately the reliability of new technologies is rarely known, because of an insufficient pool of data, both in terms of quantity and representativeness. In particular, for new device such as fuel cells, the failures data are always very difficult to obtain, due to the prolonged test periods required [9].

Some authors that works in fault detection and diagnosis found that some common fault sources of improper operation and control of fuel cell systems are sensors system (spurious o mal function) [10–13].

Several authors such as Mawardi and Pitchumani [14], Placca et al. [15] and Noorkami et al. [16] have worked on the study of uncertainties with the idea of assessing the effects on the performance of the fuel cell.

Mawardi and Pitchumani [14] develops a sampling-based stochastic model to elucidate the effects of uncertainty in operating cell temperature, anode pressure, and cathode pressure on the variation of power density. A one-dimensional non isothermal model is used to simulate the fuel cell operation for each sample. Based on the stochastic convergence analysis, a sample size of 100 was selected.

Noorkami et al. [16] estimate the expected level of uncertainty in polarization performance based on a given uncertainty in the temperature of the system (spatial and temporal). A simple lumped mathematical model is used to describe PEMFC performance under temperature uncertainty. An analytical approach gives a measure of the sensitivity of performance to temperature at different nominal operating temperatures and electrical loadings. The uncertainty assessment method used in this work is a direct Monte Carlo simulation.

The work of Placca et al. [15] focuses on the statistical analysis of the output voltage of a semi-empirical proton exchange membrane fuel cell model, introducing a degradation rate on the cell active area. The statistical analysis is performed by a quadratic response surface method and ANOVA with 1000 samples. The authors are able to define sensitivities and statistical description of the output, however the implemented statistical method requires great computational effort for models that require high number of variables.

In this work the authors present a method of failure analysis of fuel cell-based powertrain in case of aircraft application that can be used during the design phase. The method is general enough to be applied to different performance parameters of the targeted system, and to different sources of failure (here described as uncertainty in the performance of a component).

The novelties of the presented work are twofold: first of all the problem is analyzed from the point of view of the fault of sensors; this is due to the fact that the motivations of the work is to provide a tool to define the required equipment of the fuel cell system in an aeronautical application, where safety is often achieved by redundancies. Sensitivities can provide a useful measure of the relative importance of each sensor.

The second innovative aspect of the work is the used probabilistic method: an adaptive response surface is used to accurately predict the model outcome and to be processed by estimation methods (Monte Carlo, FORM, SORM or any other method). The method is able to evaluate the most suitable form for the response surface and this allows an easier

Please cite this article in press as: Correa G, et al., Sensitivity analysis of stack power uncertainty in a PEMFC-based powertrain for aircraft application, International Journal of Hydrogen Energy (2015), http://dx.doi.org/10.1016/j.ijhydene.2015.05.133