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Operating strategies to minimize degradation in fuel cell gas turbine hybrids

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HIGHLIGHTS

- Cell degradation was simulated for a standalone atmospheric stack and a hybrid system.
- Five control strategies were developed to mitigate degradation effects.
- Long term performances were compared.
- Fuel cell life could be extended by an order of magnitude in a hybrid system.

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ABSTRACT

The hybridization of Solid Oxide Fuel Cell (SOFC) and gas turbine technologies provides an increase in system efficiency and economic performance. The latter aspect is significantly affected by fuel cell degradation, due to several mechanisms. However, hybrid systems allow different control strategies to minimize degradation effects on system performance and their impact on economic feasibility.

A real-time distributed model of a SOFC was used to simulate fuel cell degradation in the cases of a standalone stack and a hybrid configuration, in the latter of which the numerical model is normally coupled with the hybrid system hardware components of the National Energy Technology Laboratory (NETL) hyper facility. The results showed how in a hybrid system it is possible, with an appropriate strategy, to maintain constant voltage even if the cell is degrading, reducing degradation rate during time. At constant power demand, fuel cell life could be significantly extended using the operating strategies allowed by coupling with a turbine (an order of magnitude longer than a standalone fuel cell), maintaining high system efficiency despite fuel cell degradation.

1. Introduction

Extensive on-going research on high temperature fuel cells such as Solid Oxide Fuel Cells (SOFCs) has proven these devices to be a promising technology for energy conversion. Their high fuel-to-electricity efficiency, up to 50%, the reduced CO_2 emissions and negligible NO_x and SO_x emissions, together with a very low noise level, make SOFCs attractive for stationary power production. Due to the significant amount of high quality generated heat, in co-generation systems the total efficiency could reach 85% [1].

Coupling the SOFC with a bottoming gas turbine cycle to recover the available heat can lead to significantly higher electrical efficiency and increase the system flexibility [2–5]. The turbine recovers the waste heat from the fuel cell and the unutilized fuel enhancing the power production and the global efficiency as high as 60% on coal (through gasification) and above 70% on natural gas [4,5]. On the other hand, the compressor is used to pressurize the fuel cell and pre-heat the cathode stream at no additional cost, further improving fuel cell performance.

SOFC high operating temperature (between 600 and 900 °C) is favorable not only in terms of efficiency, but also in terms of fuel flexibility, since internal methane reforming and water-gas-shift reactions are possible [6]. However, temperature fluctuations, thermal stresses, and presence of impurities in the fuel can induce severe performance degradation over time, limiting the economic feasibility of this technology. Thermal cycles and different thermal properties of the materials that constitute the cell can cause electrolyte cracking and electrodes delamination, segregation, and detachment [7,8]. Fuel contaminants can block the fuel channels or react with the catalyst, provoking in both cases an increment in polarization and a reduction in power output [9,10]. Carbon

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Nomenclature

ASR	area specific resistance $[\Omega\cdot m^2]$
CF	cash flow [$]
FU	fuel utilization
LHV	low heating value [kJ/kg]
LSM	lanthanum strontium manganite
NPV	net present value [$]
PBP	payback period [yr]
PID	proportional integrative derivative
SOFC	Solid Oxide Fuel Cell
TCI	total capital investment [$]
TPB	triple phase boundary
YSZ	yttria-stabilized zirconia
A	area $[m^2]$
C_f	fuel consumption [kg]
c_p	specific heat [J/kg·K]
E_{el}	electricity production [kW·h]
F	Faraday's constant [C/mol]
G	Gibbs free energy [kJ]
h	specific enthalpy variation from reference condition (298 K) [kJ/kg]
i	current density $[A/cm^2]$
i_0	exchange current density $[A/cm^2]$
k	thermal conductivity [W/m·K]
L	fuel cell length [m]
$\dot{m}$	mass flow rate [kg/s]
n	number of electrons transfer per reaction
$\dot{n}$	molar flow rate [mol/s]
P	turbine power [kW]
p	partial pressure [atm]
$\dot{Q}$	transferred heat [kW]
q_{gen}	specific generated heat [W/m]
R_g	ideal gas constant [J/mol·K]
r	internal rate
r_d	degradation rate [%/kh]
T	temperature [K] or [°C]
V	voltage, overpotential [V]
x	molar fraction
α	charge transfer coefficient
η_{GT}	gas turbine efficiency
ν	stoichiometric coefficient
ρ	density $[kg/m^3]$
act	activation
dif	diffusion
ohm	ohmic

deposition, sulfur and chromium poisoning of the electrodes are also causes of performance degradation and limited fuel cell life [10,11].

The influence of stack operating conditions on degradation was widely investigated in the open literature [12,13]. Hagen et al. experimentally observed that high current density and low temperature accelerate cell degradation [12]. Nakajo et al. employed a detailed, semi-empirical model of several degradation mechanisms to evaluate the SOFC lifetime at different operating conditions, and concluded that lower power density and higher temperature promoted lower degradation [13]. Both of these studies suggested that the control of stack current density and temperature could mitigate degradation phenomena. Moreover, fuel utilization control was considered fundamental to avoid anode re-oxidation [13,14].

The effects of cell degradation on the performance of a fuel cell gas turbine hybrid system have not been deeply considered so far. A preliminary lifetime assessment showed the potential of systems hybridization to extend fuel cell life [15]. Those promising results were the motivation for the more extensive study presented in this paper. In this work, five different operating strategies were tested on an atmospheric SOFC stack and an SOFC gas turbine hybrid system, with the goal of minimizing degradation effects on system performance. The lifetime comparison could be the starting point for a future economic analysis to determine the benefit of a hybrid system and the optimal operative strategy along plant life. This analysis will be used in the framework of the European project "BioHypp", which aims to build and test a real fuel cell gas turbine hybrid plant.

2. Background

Due to the currently very high cost of fuel cell stacks, numerical models play a valuable role for the study of SOFCs and SOFC hybrids in terms of dynamics and control. In particular, numerical studies on hybrid systems demonstrated high performance at both full- and part-load conditions, and improved system flexibility during transients compared to standalone fuel cells [16]. Evaluating optimal control strategies was also the objective of many efforts: components matching [17], temperatures control [18,19], and load following [20,21] are some examples. In particular, a distinction can be made between dynamic and supervisory controls, the latter often based on optimization approaches. In the open literature, mainly low-level controls are applied to SOFC systems.

The main goals that a control strategy should accomplish could be considered: good load following, sufficiently high efficiency in off-design conditions, and long components lifetime, i.e. reduced components degradation. To address these requirements, parameters such as fuel cell temperature and fuel flow have been considered in the literature as key control variables [22–26]. Among low-level controls, a combination of PIs and feedforward controllers was proposed by Ferrari in order to limit temperature and fuel utilization oscillations in the system and achieve fast response during load variations [22]. The control strategy included the control of SOFC power, fuel utilization, fuel cell temperature, and gas turbine power. Different control architectures were evaluated to avoid fuel starvation and excessive temperature variations during load following [23–25]. Aguiar et al. proposed a two-loop control system where a master (supervisory) controller fixed air and fuel flows according with the power demand and a PID controller adjusted the airflow around the value imposed by the master controller in order to keep constant outlet gas temperature [26].

Multi-variable model predictive control has been used to minimize thermal stresses in a SOFC and improve lifetime [27–29]. Model predictive control was also employed successfully as supervisory control in an SOFC hybrid system, where the MPC manipulated the set-point of lower level PIDs [30]. Huang et al. showed that smooth control and better performance can be obtained by using MPC [31]. Supervisory control systems were often applied to PEM fuel cells to improve performance and durability [32–34].

The regulation of current, temperature, and fuel utilization during the cell operating life is expected to influence cell degradation evolution, hence fuel cell lifetime [12,13]. An optimization framework have been employed so far to minimize degradation effects

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