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Advanced control approach for hybrid systems based on solid oxide fuel cells

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HIGHLIGHTS

- Advanced new control system for SOFC based hybrid plants.
- Proportional–Integral approach with feed-forward technology.
- Good control of fuel cell temperature.
- All critical properties maintained inside safe conditions.

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ABSTRACT

This paper shows a new advanced control approach for operations in hybrid systems equipped with solid oxide fuel cell technology. This new tool, which combines feed-forward and standard proportional–integral techniques, controls the system during load changes avoiding failures and stress conditions detrimental to component life. This approach was selected to combine simplicity and good control performance. Moreover, the new approach presented in this paper eliminates the need for mass flow rate meters and other expensive probes, as usually required for a commercial plant. Compared to previous works, better performance is achieved in controlling fuel cell temperature (maximum gradient significantly lower than 3 K/min), reducing the pressure gap between cathode and anode sides (at least a 30% decrease during transient operations), and generating a higher safe margin (at least a 10% increase) for the Steam-to-Carbon Ratio.

This new control system was developed and optimized using a hybrid system transient model implemented, validated and tested within previous works. The plant, comprising the coupling of a tubular solid oxide fuel cell stack with a microturbine, is equipped with a bypass valve able to connect the compressor outlet with the turbine inlet duct for rotational speed control. Following model development and tuning activities, several operative conditions were considered to show the new control system increased performance compared to previous tools (the same hybrid system model was used with the new control approach). Special attention was devoted to electrical load steps and ramps considering significant changes in ambient conditions.

1. Introduction

Hybrid systems, consisting of a solid oxide fuel cell (SOFC) combined with a microturbine (mGT), are expected to have a significant role due to widespread distributed generation paradigm [1–4] and hydrogen economy [5–7]. More specifically, high performance aspects in small-size systems (ultra-high efficiency [8,9], ultra-low emissions [10], fuel flexibility [11,12] and co-generative applications [13,14]) of these innovative plants are essential in terms of environmental and energy demand [15,16].

Despite the important results obtained for SOFC hybrid systems through both theoretical [17–19] and experimental [8,20,21] tools, only one prototype, developed by Siemens-Westinghouse [22], reached performance levels close to the expectations. This low rate of success for these kinds of plants is due to the high cost of components [7,23] and technical problems related to system integration [7,24,25]. An important technical issue not completely settled concerns the control system because SOFC hybrid plants are subject to several additional constraints as opposed to standard mGT plants [26]. More specifically, in addition to turbine constraints (maximum rotational speed, surge line and maximum thermal stress for components [27]), other risk situations must

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Nomenclature

Acronyms
AC Ambient Conditions
DOE Department Of Energy
DS DeSulfurizer
FC Fuel Cell
FF Feed-Forward
HS Hybrid System
mGT micro Gas Turbine
NETL National Energy Technology Laboratory
PI Proportional–Integral controller
REC RECuperator
SOFC Solid Oxide Fuel Cell
TPG Thermochemical Power Group

Variables
Coeff power sharing-out coefficient (–)
diff_p anode-cathode differential pressure (Pa)
eff plant net efficiency (–)
FO valve Fractional Opening (–)
LHV Low Heating Value (J/kg)
Kp surge margin (–)
K_p proportional coefficient for a PI controller (–)
i electrical current density (A/m^2)
m mass flow rate (kg/s)
n molar flow rate (mol/s)
N rotational speed (rpm)
p pressure (Pa)
P power (W)
RH Relative Humidity (%)
STCR Steam-To-Carbon Ratio (–)
T temperature (K)
Ta ambient temperature (K)
TIT Turbine Inlet Temperature (K)
U_f fuel utilization factor (–)
XMA mass fraction (–)

Greek symbols
β compression ratio
τ_I integral coefficient for a PI controller (–)

Subscripts
ar anodic recirculation
aux auxiliaries
cath cathodic
dp design point
f fuel
FC Fuel Cell
in inlet
mGT micro Gas Turbine
out outlet
s.l. surge line

be addressed [26,28], including (I) excessive temperature or (II) thermal gradient in the fuel cell, (III) excessive pressure difference between cathodic and anodic sides and (IV) too low Steam-To-Carbon Ratio (STCR) in the SOFC anodic side. These constraints must be considered not only for steady-state conditions, but also during time-dependent operations [29], such as load variations, ambient temperature changes and start-up/shutdown phases [30]. More specifically, several challenges must be overcome to couple the very fast response of the mGT system (low mechanical inertia of the turbine shaft) with the slow thermal variations of the SOFC stack [31] (high thermal capacitance of fuel cell materials), while the different volume values of SOFC sides generate different time-dependent performance in terms of pressurization/depressurization delays (an important aspect to take into account in order to prevent excessive cathode/anode pressure difference during transient operations [25]). Moreover, the fluid dynamic and chemical responses of the anodic side, important aspects to avoid low STCR values, are usually not in line with the transient behaviour necessary to prevent other failures [32–34].

Although in the last ten years several works [29,33,35–37] have been carried out on these control issues, the problem is not completely solved due to the large number of constraints to be considered and aspects related to costs that have not been completely optimized. For instance, even if some papers [33,36,37] presented effective control systems for SOFC hybrid plants, thermal stress on the fuel cell was not always prevented (significant thermal gradient: higher than 3 K/min [38] especially for large load steps) and expensive probes were used (e.g. mass flow rate meters in [33,35]). Moreover, the cathode/anode pressure difference was carefully considered only in [33], while other control systems showing interesting result neglected the constraints of this important property (see [26] for experimental aspects). Also the time-dependent aspects related to anodic recirculation were often neglected (considering constant recirculation ratios [38]) or based on very simple approaches [37]. Since the importance of anodic circuit response is essential in preventing failures (e.g. low STCR), it is imperative to develop a transient model of the anodic devices (e.g. an anodic ejector [26,39]) to study a reliable control system for the entire plant [33].

This work focused on the development of an advanced control system for SOFC hybrid plants. So, the control strategy presented in [33] was improved considering the coupling of Proportional–Integral (PI) controllers with feed-forward approaches to prevent thermal stress in the fuel cell and to reduce the peak values of cathode/anode pressure difference and STCR. Since the thermal capacitance of the stack is very high, the PI controller necessary to maintain constant stack temperature must be a very slow response device (as done in [33]) to avoid unstable behaviour. However, this approach cannot prevent significant thermal gradients (higher than 3 K/min) in the fuel cell (responsible of serious stress on ceramic material) because the new rotational speed set-point is generated only after an excessive temperature oscillation. On the other hand, the coupling with feed-forward technique (in a system equipped with load variation smoothing devices: a battery package or an electrical grid) can obtain the new rotational speed with the requested time performance and without instability problems. Moreover, this is a simple approach (in comparison with multiple-input and multiple-output controllers), which can combine possible corrective actions for disturbances (e.g. variations of ambient conditions) with less oscillations in plant critical properties. Even if the same basis shown in [33] was maintained (e.g. the mGT speed control was carried out with a compressor/turbine bypass valve), the results obtained with a Matlab®-Simulink® transient model shows better performance in terms of thermal and mechanical stress on the components. The Matlab® version used in this work is the R2010a (7.10.0.499), which is coupled with version 7.5 of the Simulink® tool.

This work demonstrates improved control performance, over previous works [29,32,33,41], which can prevent failures and increase component life, also broadening the types of transient