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Application of a two-level rolling horizon optimization scheme to a solid-oxide fuel cell and compressed air energy storage plant for the optimal supply of zero-emissions peaking power

Jake Nease[a], Nina Monteiro[b], Thomas A. Adams II[a,*]

[a] *Department of Chemical Engineering, McMaster University, 1280 Main Street West, Hamilton, Ontario, Canada*
[b] *Engenharia Química, Universidade Federal do Paraná, Avenida Coronel Francisco Heráclito dos Santos, Jardim das Américas, Curitiba, Brazil*

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ABSTRACT

We present a new two-level rolling horizon optimization framework applied to a zero-emissions coal-fueled solid-oxide fuel cell power plant with compressed air energy storage for peaking applications. Simulations are performed where the scaled hourly demand for the year 2014 from the Ontario, Canada market is met as closely as possible. It was found that the proposed two-level strategy, by slowly adjusting the SOFC stack power upstream of the storage section, can improve load-following performance by 86% compared to the single-level optimization method proposed previously. A performance analysis indicates that the proposed approach uses the available storage volume to almost its maximum potential, with little improvement possible without changing the system itself. Further improvement to load-following is possible by increasing storage volumes, but with diminishing returns. Using an economically-focused objective function can improve annual revenue generation by as much as 6.5%, but not without a significant drop-off in load-following performance.

1. Introduction

Due to pressure from governmental regulations, the constant knowledge of waning resources, and the rapidly improving technologies for generating reliable electricity from renewable resources, classic power plants utilizing fossil fuels such as coal and natural gas (NG) are being eschewed in favour of more environmentally friendly alternatives, particularly in North America. In fact, it is projected that by 2035 the United States and Canada will each generate approximately 10% (US Energy Information Administration, 2014) and 16% (National Energy Board, 2016) of their power from non-hydroelectric renewable resources, respectively. However, a current prohibitive feature of renewable resources is that they are typically intermittent in nature (variable and unpredictable wind/cloud patterns, day/night cycles, *etc.*), which makes them unsuitable for use in a bulk supply scenario, which requires high reliability and consistency. Although it is possible to use large-scale intermittent energy storage techniques such as pumped hydro storage (Beevers et al., 2015), compressed air energy storage (CAES) (Sun et al., 2015), molten salt loops (Srivastava et al., 2016), material phase changes (Zanganeh et al., 2014) and others in order to levelized the power supply from intermittent renewables, the high variability of renewables coupled with the limited capacity of energy storage techniques make for significantly difficult planning and operability concerns. These problems are further exacerbated by the low capacities of renewables and round-trip efficiency losses in potential energy storage systems, both of which must be improved before renewable energy sources will be capable of fully displacing fossil fuel-based power.

While the paradigm in energy sources for electricity generation moves to renewables, the use of fossil fuels still constitutes a major portion of the power generated worldwide. In fact, it is estimated that the United States will still supply approximately 34% of its electricity demand through the consumption of coal (US Energy Information Administration, 2014). Furthermore, at its current usage rate it is estimated that North America possesses sufficient reserves for over 250 years of domestic coal consumption (BP Energy, 2014). This large supply of coal, combined with the forecasted importance of it as a future resource, provides an opportunity and challenge to use make the most efficient usage of this resource as possible.

Solid oxide fuel cells (SOFCs) can be used to generate reliable "peaking" electric power at the bulk scale with minimal environ-

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* Corresponding author at: 1280 Main Street West, Hamilton, Ontario, L8S 4L7, Canada.
E-mail address: tadams@mcmaster.ca (T.A. Adams II).

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Nomenclature

Abbreviations

CAES	Compressed air energy storage
CCS	Carbon capture and sequestration
EOS	Equation of state
GT	Gas turbine
HHV	Higher-heating value
HRSG	Heat recovery and steam generation
IESO	Independent electricity systems operator
RHO	Rolling horizon optimization
SOFC	Solid oxide fuel cell
SSE	Sum of squared error

Mathematical Symbols

E	Power produced by SOFC/CAES plant (via optimization)
$\bar{E}$	Actual power produced at each time step
$\dot{E}$	Initial guess for E for proceeding simulation step
P	Pressure in CAES storage (via optimization)
$\bar{P}$	Actual pressure recorded in CAES storage at each time step
$\dot{P}$	Initial guess for P for proceeding simulation step
n	Number of moles in CAES storage (via optimization)
$\bar{n}$	Actual number of moles in cavern at each time step
$\dot{n}$	Initial guess for n for proceeding simulation step
$\Re$	Total revenue
D	Demand
F	Molar flow rate of cathode exhaust
N	RHO forecasting horizon
R	Universal gas constant
V	Volume
a	Model coefficient
$f(\cdots)$	SOFC/CAES reduced model
δ	Binary charge/discharge decision variable
$\dot{\delta}$	Initial guess for δ for proceeding simulation step
ω	Price of electricity
ψ	User-defined economic/load-following weight factor
Φ	Economic/load-following objective function
BL	Base load
S	Cathode exhaust diversion parameter
ν	Molar volume
Δ	Time step length
a_{SRK}, b_{SRK}	SRK model coefficients

Subscripts

i	First-stage simulation/control time step
ι	Second-stage simulation/control time step
t	First-stage RHO calculation time horizon step
τ	Second-stage RHO calculation time horizon step
m	Reduced model identifier
k	Reduced model variable identifier
a, b, c	Reduced model order/coefficient identifiers
max	Maximum allowable value
min	Minimum allowable value

mental impact when appropriate carbon capture strategies are used (Adams and Barton, 2009; EG&G Technical Services, 2004; Williams et al., 2005). To do this, SOFCs fueled by coal (Nease and Adams, 2014a) (Ming, 2007), or natural gas (NG) (Nease and Adams, 2013) can be integrated with compressed air energy storage (CAES) in order to exploit some process synergies that enable the system to meet an ever-changing electricity demand through the day despite having no direct CO_2 emissions. The electric power can be generated at a competitive market price, even without government subsidies, once the SOFC technology reaches maturity. Furthermore, detailed life cycle analyses have shown that these proposed SOFC plants have significantly lower environmental impacts than other state of the art options such as the NG combined cycle (NGCC) (Nease and Adams, 2015a) or supercritical pulverized coal (SCPC) (Nease and Adams, 2015b) process.

In the SOFC/CAES system, the SOFCs produce power at a constant, steady rate, and the CAES system either stores or releases compressed air in different amounts that can change hourly or even more frequently. The goal is to adjust the amount stored or released throughout the day in order to change the total net electricity production needed to meet the demand. However, because the SOFC output is limited and the CAES storage capacity is finite, the power demand cannot always be met every hour of every day, week, and month. Therefore, an operating policy is required which must decide how well to match the production and demand at any given time. For example, the original proof-of-concept used a naïve (or "greedy") operating policy, which was to always store or release energy at any given moment such that power demand at that moment would be met exactly. Although this worked sometimes, it also led to significant "large misses" when the CAES storage volume reached minimum or maximum capacity, leading to all flexibility in the system being lost instantaneously (Nease and Adams, 2014a; Ming, 2007; Nease and Adams, 2013). The concept of real-time optimization (Chachuat et al., 2009; De Souza et al., 2010; Zanin et al., 2010; Zhao et al., 2013) being used in chemical plants and even with small SOFC experimental setups (Bunin et al., 2012) led to the eventual development of a rolling horizon optimization (RHO) technique that uses forecasts of future demand to optimally plan the next series of control moves based on the operating and storage constraints of the SOFC/CAES system (Nease and Adams, 2014b). With this approach, the system would predict a potential problem and then avoid it by scheduling a series of "small misses" over time in order to prevent a more serious large miss. Although this method improves the day-to-day performance and peak-following capability of the SOFC/CAES plant, it does not solve the problem of seasonal changes in demand, such as a generally higher demand (up to 30% more) during the summer and winter months compared to autumn and spring.

Therefore, to better solve this problem, we present a new, expanded version of the RHO concept by formulating a two-stage RHO methodology that exploits the modular nature of the upstream SOFC stacks by turning some of them on or off safely, infrequently, and in incremental amounts. This leads to a modular step increase or decrease in the steady-state output of the plant, and thus the baseload can be optimally selected in order to track seasonal changes in demand as closely as possible. This allows for the CAES storage volume to be much more efficiently utilized, and significantly improves season-to-season and overall annual load-following performance. To demonstrate, this concept is applied to a SOFC/CAES plant with zero direct CO_2 emissions using gasified coal as a fuel source, showing for the first time that it is possible to use coal for clean, reliable and efficient electrical peaking power at the 100 megawatt scale over the entire year.

2. The process and simulation models

2.1. SOFC/CAES plant layout

The integrated SOFC/CAES system used for this work is shown in Fig. 1, which was studied in a prior work using the "greedy" operational strategy (Nease and Adams, 2014a) but has not been examined using a RHO framework. This system is capable of pro-