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Predictive modelling and adaptive long-term performance optimization of an HT-PEM fuel cell based micro combined heat and power (CHP) plant

Alireza Haghighat Mamaghani, Behzad Najafi *, Andrea Casalegno, Fabio Rinaldi

Dipartimento di Energia, Politecnico di Milano, Via Lambruschini 4, 20156 Milano, Italy

HIGHLIGHTS

- Adaptive long-term performance optimization of an HT-PEM fuel cell based CHP plant is studied.
- The impact of degradation, within the fuel cell and reformer, on the system's performance is considered.
- At each interval, a set of optimal points each of which is a trade-off between the objectives is obtained.
- Electrical and thermal generation and the net electrical efficiency were selected as objective functions.
- Performance of the system operated at normal condition vs optimized condition was compared.

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ABSTRACT

In fuel cell based combined heat and power (CHP) plants, degradation within the fuel cell stack and the steam methane reformer significantly affects the generated electrical and thermal power. As a consequence, incorporating system's degradation within the model of the plant could be of great importance in order to estimate the resulting variations in the electrical and thermal power generation and taking appropriate measures to mitigate such deviations. To this end, in the present article, a multi-objective optimization approach has been proposed and employed to find the optimal operating parameters of an HT-PEM fuel cell based micro-CHP system within the first 15,000 h of operation while considering the impact of degradation. Two different optimization procedures with the following objective functions have been applied: (I) net electrical efficiency and thermal generation; and (II) net electrical efficiency and electrical power generation. Steam to carbon ratio, auxiliary to process fuel ratio, fuel partialization level and anodic stoichiometric ratio are the design parameters. Based on the results of optimization procedure I, the highest achievable net electrical efficiency at the beginning of operation is 32.75% which, due to degradation, considerably declines to 29.51% in the last time interval. Moreover, in all time steps, optimal solutions cover a wide domain of thermal generation which assures the capability of the system to easily cope with the thermal demand of the user. On the other hand, optimization procedure II displays a steady decrease in both electrical efficiency and electrical generation through time which indicates the adverse effect of degradation on these two performance indices. Finally, it has been found that, using optimization procedure I, the cumulative average electrical efficiency of the plant improved from 26.03% at normal operation to 27.56% at optimized condition. Furthermore, it was determined that by employing the optimal points obtained in optimization procedure II, the average cumulative electrical power generation is increased from 25.4 kW (at normal operation) to 26.8 kW. It is noteworthy that, the study not only provides some insights into the long-term performance of such system, but can be more importantly perceived as a guideline to adaptively optimize the operating conditions of the system in order to alleviate the degradation's effect and to guarantee optimal performance of the system throughout its lifetime.

1. Introduction

In the past decade, scarcity of primary energy sources and stringent environmental legislations concerning the emissions of

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* Corresponding author.
E-mail addresses: alireza.haghighat@mail.polimi.it (A. Haghighat Mamaghani), behzad.najafi@polimi.it (B. Najafi), andrea.casalegno@polimi.it (A. Casalegno), fabio.rinaldi@polimi.it (F. Rinaldi).

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Nomenclature

Acronyms

aux/proc	auxiliary to process flow rate ratio
CHP	combined heat and power
GDL	gas diffusion layer
HT-PEM	high temperature proton exchange membrane
MEA	membrane electrode assembly
OHM	ohmic
PBI	polybenzimidazole
S/C	steam to carbon ratio
SMR	steam methane reforming
WGS	water gas shift
WKO	water knock out

Symbols

E_{ID}	ideal voltage (V)
E_a	activation energy (kJ/mol)
f	friction factor
ΔH_{298K}	standard enthalpy of reaction (kJ kmol^{-1})
I	current (A)
k	rate coefficient
K	equilibrium constant
LHV	low heating value (kJ kg^{-1})
$\dot{m}$	mass flow rate (kg s^{-1})
N	number of cells
P	power (kW)
r	rate of reaction (mol lit^{-1} s^{-1})
R	universal gas constant (kJ kmol^{-1} K^{-1})
T	temperature (K)
V	voltage (V)

Subscripts

A	anode
B	burner
C	cathode
el	electrical

Greek symbols

η_A	anodic voltage loss
η_C	cathodic voltage loss
η_{el}	electrical efficiency
λ_{H_2}	anodic stoichiometric ratio

contaminants have set the focus on developing new technologies for more environmentally benign and more efficient power production systems [1,2]. One of the most acknowledged approaches in combating the aforementioned challenges is the usage of fuel cell technology in order to cater the electricity and heat demand of domestic dwellings which is responsible for a large part of total energy consumption in Europe [3]. Among different available technologies, fuel cells can be taken into account as one of the most encouraging options for future low-energy building concept. Fuel cell based micro-combined heat and power (micro-CHP) systems can reach higher electrical efficiencies in comparison with micro-CHPs based on heat engines while they also offer lower heat-to-power ratio.

Proton exchange membrane (PEM) fuel cell is amongst the most developed technologies for CHP applications and it covers around 90% of the fuel cell based CHP plants [4]. In this regard, many works have been dedicated to modelling and simulation, performance evaluation, and optimization of fuel cell based CHP plants [5–7]. Guizzi and Manno [8] carried out energetic and economic analyses on a cogeneration system based on a PEM fuel cell which was able to achieve net electrical and thermal efficiency of 41.93% and 64.16% respectively at rated conditions. In another study, Jannelli et al. [9] compared the performance of three cogeneration systems based on LT-PEM and HT-PEM fuel cells. The results showed that systems based on the HT-PEM fuel cell achieve electrical efficiency and first law efficiency up to 40% and 79% respectively. Zuliani and Taccani [10] analyzed the performance of a 1 kW HT-PEM based cogeneration system and reported that at design load, the system can reach electrical efficiency of 26% and the total efficiency of 78% while offering a simpler balance of plant compared to a LT-PEM based system. Kang et al. [11] applied a model of a 20 kW PEM fuel cell based system in ASPEN HYSYS to investigate the impacts of main operating parameters on the electrical and thermal efficiency of the plant. The simulation data reveal that the fuel delivery rate and air-fuel ratio supplied into the burner are crucial factors to obtain the desired electrical power and an acceptable CO concentration level. In another research, Napoli et al. [12] performed a techno-economic analysis on PEMFC and SOFC based micro CHP systems and concluded that for both cases, the investment cost is the main obstacle to compete with the conventional technologies. A thermo-economic analysis on an HT-PEM fuel cell based CHP systems showed that the average per-unit cost (PUC) of electrical power is 15–19,000/kWe, while the average PUC of electrical and heat recovery power is 7000–9000/kW [13]. Herdem et al. [14] carried out a parametric study on a methanol reformate gas fuelled HT-PEM fuel cell based system and demonstrated that the effect of CO molar ratio on the fuel cell performance declines with fuel cell temperature. The fuel cell voltage diminishes around 78% with an increment in current density from 0.1 A/cm^2 to 1 A/cm^2 for 160 °C fuel cell temperature and 0.9% CO molar ratio in the reformate gas. One of the approaches to increase the net electrical efficiency of the system is to harness the generated heat within the plant via organic Rankine cycle (ORC) and convert it to electrical power [15]. For this purpose, Perna et al. [16] integrated an HT-PEM fuel cell system with an ORC unit and compared the performance of the plant with and without the ORC unit. The obtained results revealed that the integration with an ORC unit can significantly boost the electrical production by 10%. Wu et al. [17] studied the performance of a polybenzimidazole (PBI) based HT-PEM fuel cell stack under air-breathing conditions. Their results suggested that a peak power density of 220.5 mW cm^{-2} at 200 °C can be achieved without employing any water management, which is comparable to those achieved with LT-PEM units.

Almost all fuel cell technologies suffer from degradation over time which results in performance deterioration and extra cost for replacement or repairing of the components. This issue is of particular importance and has been widely underscored in the case of fuel cell based CHP plants given the severe degradation in fuel cell stack. As a consequence, a number of studies have been focused on novel approaches for modelling the degradation and optimizing the operating conditions of the stack to alleviate the negative effect of degradation and elongate the system's lifetime. Pohl et al. [18] proposed a novel method for modelling the degradation within HT-PEM fuel cells using dual time scale simulations with shorter simulation time by approximately 73% compared to conventional simulation approaches. In another research, Zhang et al. [19] conducted an optimization on the operating temperature of HT-PEM fuel cell and based on their experimental results, the optimal operating temperature window is between 160 °C and 180 °C by compromising among the cell performance, CO tolerance

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