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# A tri-generation system based on polymer electrolyte fuel cell and desiccant wheel – Part A: Fuel cell system modelling and partial load analysis

Behzad Najafi, Stefano De Antonellis, Manuel Intini, Matteo Zago, Fabio Rinaldi, Andrea Casalegno *

*Department of Energy, Politecnico di Milano, Via Lambruschini 4, 20156 Milano, Italy*

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ABSTRACT

Polymer Electrolyte Membrane Fuel Cell (PEMFC) based systems have recently received increasing attention as a viable alternative for meeting the residential electrical and thermal demands. However, as the intermittent demand profiles of a building can only be addressed by a tri-generative unit which can operate at partial loads, the variation of performance of the system at partial loads might affect its corresponding potential benefits significantly. Nonetheless, no previous study has been carried out on assessing the performance of this type of tri-generative systems in such conditions. The present paper is the first of a two part study dedicated to the investigation of the performance of a tri-generative system in which a PEMFC based system is coupled with a desiccant wheel unit. This study is focused on evaluating the performance of the PEMFC subsystem while operating at partial loads. Accordingly, a detailed mathematical model of the fuel cell subsystem is first developed and validated using the experimental data obtained from the plant's and the fuel cell stack's manufacturer. Next, in order to increase the performance of the plant, two modifications have been proposed and the resulting performance at partial load have been determined. The obtained results demonstrate that applying both modifications results in increasing the electrical efficiency of the plant by 5.5%. It is also shown that, while operating at partial loads, the electrical efficiency of the plant does not significantly change; the fact which corresponds to the trade-off between the increment in the gross electrical efficiency and the lower slope of decrement in the auxiliary losses. The obtained results are suitable to be employed to assess the performance of the overall tri-generative system, conducted in the second part of the study, while meeting intermittent load profiles.



## 1. Introduction

Low temperature Polymer Electrolyte Membrane Fuel Cell (PEMFC) systems, owing to their higher performance and lower emissions, have received increasing attention in the recent years as a viable alternative for meeting the electrical and thermal needs of buildings. Operational PEMFC systems have demonstrated superior performance to combustion-based generation technologies at scales from 5 kW to 2 MW, a range that includes the electrical requirements of the most of the buildings [1,2].

However, fuel cells systems are far from being flexible and partial load control may affect potential benefits significantly. In addition, exploiting cogenerated heat as primary source for thermally driven cooling process is a hard task since PEMFC rejected heat temperature is relatively low, up to 65–70 °C. Therefore, a tri-generation system based on PEMFC requires a proper technology, design and reasonably accurate simulation tools. Accordingly, part A of the present study is focused on developing a proper model of the PEMFC based system and analysing its behaviour at partial load, while Part B is focused on analysing the performance of the overall system.

Most of the previous studies have been devoted to developing models and simulating the performance of different pilot plants. Ferguson et al. [1] developed a steady-state model of a generic PEMFC cogeneration plant and studied the effect of operating strategy and fuel cell sizing on the performance of the system. Radulescu et al. [3] performed an experimental and theoretical analysis on five different PEMFC based cogeneration plants installed in France. Ersoz et al. [4] investigated the performance of different hydrocarbon reforming approaches for PEMFC based cogeneration plants. Calise et al. [5] analysed an innovative

* Corresponding author.
*E-mail address:* andrea.casalegno@polimi.it (A. Casalegno).

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**Nomenclature**

*Acronyms*

| | |
|---|---|
| CHP | combined heat and power |
| DEC | desiccant evaporative cooling |
| GDL | Gas Diffusion Layer |
| HS | heat sink |
| LMTD | logarithmic mean temperature difference |
| MEA | membrane electrode assembly |
| OHM | ohmic |
| PEMFC | proton exchange membrane fuel cell |
| PES | primary energy saving |
| PrOX | Preferential Oxidation |
| SMR | Steam Methane Reforming |
| ST | storage tank |
| TER | thermal to electric ratio |
| WGS | Water Gas Shift |
| WKO | water knock out |
| W/O | without |

*Symbols*

| | |
|---|---|
| $C$ | cooling energy (MW h) |
| $E_{ID}$ | ideal voltage (V) |
| $E_a$ | activation energy (kJ mol$^{-1}$) |
| $F$ | fuel consumption (MW h) |
| $f$ | friction factor |
| $\Delta H_{298K}$ | 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 |
| $Nu$ | Nusselt number |
| $P_x$ | partial pressure of species $x$ |
| $P$ | power (kW) |
| $Pr$ | Prandtl number |
| $Q$ | thermal energy (MW h) |
| $\dot{Q}$ | time rate of heat transfer (kW) |
| $r$ | rate of reaction (mol l$^{-1}$ s$^{-1}$) |
| $R$ | universal gas constant (kJ kmol$^{-1}$ K$^{-1}$) |
| $Re$ | Reynolds number |
| $T$ | temperature (K) |
| $V$ | voltage (V) |
| $W$ | electrical energy (MW h) |

*Subscripts*

| | |
|---|---|
| $A$ | anode |
| AHU | air handling unit |
| $b$ | boiler |
| $C$ | cathode |
| cogen | cogeneration |
| el | electrical |
| th | thermal |
| tri | tri-generation |

*Greek symbols*

| | |
|---|---|
| $\eta_A$ | anodic voltage loss |
| $\eta_C$ | cathodic voltage loss |
| $\eta_{el}$ | electrical efficiency |
| $\eta_I$ | first law efficiency |
| $\eta_{th}$ | thermal efficiency |
| $\lambda_{H2}$ | anodic stoichiometric ratio |

poly-generation system based on solar heating and cooling and PEMFC technologies. Obara and Tanno [6] performed a study on PEMFC/engine combined generation plants. Obara [7] also studied the $CO_2$ emission characteristics of the same system. Nagata et al. [8] performed a quantitative analysis on $CO_2$ emissions reductions through introduction of stationary-type PEMFC systems in Japan. Hwang et al. [9] studied the implementation of a heat recovery unit for a PEMFC system; they also developed an efficient thermal control strategy for the plant.

Jovan et al. [10] performed an assessment on the actual energetic flows, and consequent electrical efficiency of a case-study PEMFC system. Najafi et al. [11,12] performed a sensitivity analysis on the steady state and long term performance of an High Temperature PEMFC based CHP system. The same authors performed another analysis [13] to evaluate the performance of the same system under partialization and power to heat shifting strategies. Hubert et al. [14] carried out a steady state modelling and optimization of a small heat and power PEMFC system, which is a part of EPACOP project installed in France. In this study, decreasing the natural gas consumption and increasing the heat recovery were considered as objective functions. Being a non conventional power generation technology, economic assessment of fuel cell based systems is of considerable importance [15,16]. Contreras et al. [17] performed an energetic and economic study on the utilisation of PEMFC based cogeneration systems in rural sector of Venezuela. Kamarudin et al. [18] carried out a profound study on economic evaluation of PEMFC systems. Guizzi et al. [19] performed an economic and energy performance assessment of a cogeneration system based on fuel cell designed for data centres.

Nižetić et al. [20] carried out a Levelised Cost of Energy (LCOE) analysis on an HT-PEM fuel cell based system supplying energy demand of a household in a Mediterranean climate. Niknam et al. [21] conducted an optimization and optimal planning study on a PEM fuel cell based combined heat, power and hydrogen production unit. Similar studies have also been carried out on tri-generation systems employing other types of fuel cells including solid oxide fuel cells (SOFCs). Ranjbar et al. [22] performed and energetic and exergetic assessment of a trigeneraton system based on SOFC technology. Joneydi Shariatzadeh et al. [23] performed an economic optimization study on a similar unit fed by biogas.

In the present work, a mathematical model of *Sidera30*, a natural gas fed residential micro cogeneration system manufactured by "ICI Caldaie", is first developed and different strategies are next proposed and implemented in order to facilitate addressing the intermittent loads.

Using the real geometries of the plant and employing kinetic models of the utilised catalysts, detailed mathematical models for the fuel processor reactors have been developed. The reactors models are subsequently validated using experimental data obtained from the plant. In order simulate the behaviour of the PEMFC stack, a detailed mathematical model has also been developed and validated using the experimental data provided by the manufacturer [24].

In the next step, the performance indices of the plant at normal operation are determined and two modifications for improving plant performance are proposed and applied. The obtained performance indices while applying the modifications are next determined and compared with the original ones.