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Mathematical model for the analysis of structure and optimal operational parameters of a solid oxide fuel cell generator

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HIGHLIGHTS

- Potential markets for ethanol-fueled solid oxide fuel cell power systems in Brazil are analyzed.
- A simulation model of this kind of power system is formulated.
- The model is run with different system configurations to identify the optimal one.
- Operation with pure ethanol or, in alternative, with anodic recirculation proves to be the best operating conditions.

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ABSTRACT

Solid oxide fuel cells are globally recognized as a very promising technology in the area of highly efficient electricity generation with a low environmental impact. This technology can be advantageously implemented in many situations in Brazil and it is well suited to the use of ethanol as a primary energy source, an important feature given the highly developed Brazilian ethanol industry. In this perspective, a simplified mathematical model is developed for a fuel cell and its balance of plant, in order to identify the optimal system structure and the most convenient values for the operational parameters, with the aim of maximizing the global electric efficiency. In this way it is discovered the best operational configuration for the desired application, which is the distributed generation in the concession area of the electricity distribution company Elektro. The data regarding this configuration are required for the continuation of the research project, i.e. the development of a prototype, a cost analysis of the developed system and a detailed perspective of the market opportunities in Brazil.

1. Introduction

The field of new energy converters has recently been the target of intense research activities, with the main goal of improving systems' energy efficiency, while facing the challenges related pollutant emissions reduction. In this scenario, one of the most promising technologies is the Fuel Cell (FC). Fuel cells are electric energy generators characterized by their high efficiency (about 50% based on the net energy produced [1]) and very low pollutant emissions. The electric energy generation results from direct conversion of the fuel's chemical energy through electrochemical reactions. In addition to the fuel cells themselves, arranged in stacks, electric generation systems based on FCs require various auxiliary devices, collectively called Balance of Plant (BoP) of the fuel cell stack.

One type of FC that attracts great interest in the scientific community is the Solid Oxide Fuel Cell (SOFC), which uses a solid ceramic electrolyte capable of conducting oxygen ions (O^{2-}) from the cathode to the anode [1]. The operating temperature varies between 650 °C and 1000 °C. The fuel can be hydrogen, biogas or simple hydrocarbons, which can decompose to CO and H_2 inside the SOFC anode, or synthesis gas obtained through previous

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chemical treatment of complex hydrocarbons. Two important advantages of this kind of FC are the capacity to work with fuels other than pure hydrogen and the high temperature of the heat generated as a byproduct of the electric energy production. Due to their peculiar characteristics, SOFCs are particularly well suited to use in high efficiency stationary Combined Heat and Power (CHP) systems, with power ranging from 500 W up to several MW. In fact, the energetic performance of fuel cell based generation systems is approximately a constant function of the produced power.

One of the most interesting applications of low power SOFCs is in micro-CHPs (combined heat and electric power generators characterized by nominal electric power lower than 50 kW, according to the European Union's definition [2]). This is a technological area where relevant development efforts are concentrated, particularly aiming to obtain more efficient, sustainable and stable national electric generation grids, by means of the widespread use of high efficiency micro-CHP units in a distributed generation scheme, as evidenced in the literature [3]. However, to reach a true beneficial effect, it is vitally important that these micro-CHP units have an efficiency similar to that observed in modern centralized generation systems. This requirement cannot be easily satisfied using conventional technologies, but it can be reached using FC systems, which present high efficiencies even when working at low power levels. As a consequence, fuel cell systems are potential candidates for massive diffusion of micro-CHP systems. In this area, SOFC technology seems to be particularly promising [4], offering the previously mentioned advantages over other types of FCs. During the last ten years, the research in this field has been intense, leading to the creation of several prototypes and pre-commercial products. Several installation programs were initiated in order to demonstrate the technology [5,6], and some companies are in the first commercialization stage of SOFC-based methane-fueled micro-CHPs, introduced in the market as substitutes for the traditional domestic heaters, widely used for residential applications. Given the proposed application, these devices are usually designed in a way to maximize global efficiency (sum of thermal and electrical efficiencies) and to assure enough thermal power, treating the electric energy just like as a useful byproduct of heat production.

2. Potential markets in Brazil

In Brazil, energy generation and its use have peculiar profiles, very different from the ones that characterize most other economically important countries on the global scale. One important characteristic is the high percentage of electric energy that is produced through renewable sources (89%), mainly hydropower and biomass, with a small wind power contribution [7]. Another important aspect is the minimal use of energy for residential heating, limited to small areas of the country and only for few days a year. Moreover, the country presents the need for a considerable expansion of the energy production, transmission and distribution infrastructure, to support the country's economic growth and extend the availability of electrical power in remote areas. To tackle this last issue, a federal program was launched: between 2003 and 2013 more than 3 million new electric connections were implemented, with an investment of R$ 20 billion [8]. Despite this investment, some areas of the country still lack a connection to the national transmission grid, and a substantial growth of demand is expected. Therefore, it is probable that the country's power supply needs will grow even more in the next years, requiring additional grid reinforcement or alternative solutions such as distributed generation. Finally, Brazil possesses an important bioethanol production capacity and distribution infrastructure [7], well established in every Brazilian state, including both large industries and small family-operated agro-industries. The primary energy generation from sugar cane products showed steep growth in the last years and in 2009 surpassed the hydroelectric energy generation in the country.

Given this scenario, the use of SOFC micro-CHP systems would also present some peculiarities, such as the use of ethanol as fuel, instead of methane, and the operation essentially dedicated to electric production, even though some areas of the country present periods of cold weather, when the residential cogeneration of electricity and heat could be interesting. There are many situations in Brazil where the use of SOFC systems could bring environmental and economic benefits. A first application is the substitution of generators characterized by high environmental impact (in most cases internal combustion engines). These are currently used in some specific cases, including the generation of power when the electric energy reaches its peak in demand (and as a consequence the cost is higher), or the supply of electricity to remote places not connected to the national transmission grid, or even the strengthening of load covering capacities in small groups of grid users distant from the main company grid that do not present a regular consumption high enough to justify the installation of new higher capacity cables. It would be possible to replace the above mentioned generators with SOFC systems, maintaining the same service and infrastructure quality, but markedly increasing generation efficiency and at the same time reducing pollutant emissions. The Brazilian market for peak-hour additional generation capacity is estimated to lie between 3 and 10 GW [9]. Until recently, the energy generated to meet this peak-hour demand was produced through the use of internal combustion engines, but an increase in the price of diesel and a drop in the electricity peak price have made this solution less economically viable. On the other hand, ethanol-fueled SOFC systems could offer better economic performance, due to this type of equipment's higher electric efficiency. Furthermore, the electric energy demand projected for the next years can be used to evaluate the potential market size for distributed generation. The expected increase in Brazilian electricity demand between 2012 and 2022 has been estimated around 275 TWh, including grid supplied power and autoproduction (industrial cogeneration and distributed generation) [10]. This value represents an increase of approximately 55% whit respect to the current figures. Admitting that a large part of this considerable demand increase will be satisfied using conventional methods (namely, expansion of centralized generation and power transmission grids), the potential market for distributed generation in Brazil is still very important, especially considering that the size of the country implies high costs of transmission lines. For example, the current cost of a 345 kV line can be evaluated around 584,000 R$ km^{-1} [11]. As a consequence, in several cases the cost of the lines required to connect remote locations to the national transmission grid, or to increase the power capacity of existing connections, can make the dissemination of distributed generators with higher cost per installed kW economically viable. In this scenario, ethanol-fueled SOFC micro-CHPs could offer unique advantages over other technologies, namely the possibility to generate energy on demand using a renewable energy source. In addition to what was stated up to now in this section, it should be noted that, even though centralized electric generation in Brazil basically relies on renewable sources, its environmental impact is not negligible. Being mostly of hydro-electrical origin, it involves a considerable production of methane and carbon dioxide from organic material decomposition in water reservoirs [12]; in fact, the extension of water accumulation lakes can be used to quantify the environmental impact of these plants [13]. Moreover, since it is centralized, this kind of generation requires a big transmission and distribution infrastructure that presents high financial and environmental costs, and creates relevant losses in efficiency. As a consequence, the use