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PEM single fuel cell as a dedicated power source for high-inductive superconducting coils

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A B S T R A C T

In practice, the voltage of a hydrogen–oxygen fuel cell is around 1 V at open circuit and from 0.6 V to 0.7 V at full rated load and it can be considered as a low-voltage energy source. Moreover, preliminary investigations undertaken on a single proton exchange membrane fuel cell (PEMFC) highlighted its behavior as a DC current source, that can be directly controlled by the H_2 flow rate when the operating point is at very low voltage. In this paper, we present an innovative application of PEMFC that relies on taking advantage of both low voltage level and current source operating mode to feed a high inductive superconducting coil. Such a coil has no resistance and among others, is very sensitive to current ripples. Thus, specific power supplies are designed to feed them but they exhibit in most cases a huge volume and/or a low energy yield. Connecting a superconducting coil to a PEMFC implies to operate in short-circuit, which is an unusual use of PEMFC. To this end, requirements of such an application are defined, by making use of a PEMFC electrical model based on a 1D analog representation of mass transport phenomena. This model, that enables to take into account the influence of gas supply conditions, notably diffusion limit operation, is directly implemented in a standard simulation software used in electrical engineering. Then, simulation results and experimental results obtained by supplying a 10 H superconducting coil cooled by liquid helium by means of a single 100 cm^2 PEMFC are compared and discussed.

Introduction

Polymer electrolyte membrane (PEM) fuel cells are by essence low voltage sources. Indeed, the voltage of a single cell is usually near 1 V at open circuit and around 0.6 V at rated conditions of power generation. Thus for power applications, PEMFC composed of several cells connected in series, also called stack, and electronic converters, allowing in particular to rise the voltage to usual application levels are used. Hinaje et al. [1] have led theoretical and experimental investigations in GREEN laboratory (Groupe de Recherche en Electrotechnique et Electronique de Nancy) with a single PEM fuel cell (PEMFC), either short-circuited or hybridized by discharged supercapacitors, and brought out the electrical behavior as a current source, in which the current is directly controlled by the H_2 flow rate according to Faraday's law (NB: for usual FC applications, H_2 is overfed in comparison to the current generated). The basic principle is schemed in Fig. 1: at very low voltage operation, close to short-circuit conditions, the cell

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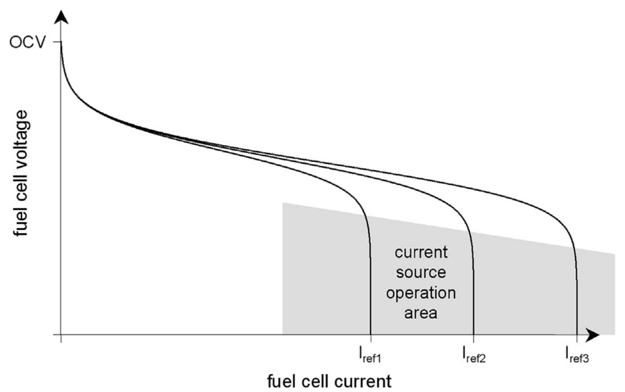

Fig. 1 – Representation of the area where FC operates as a current source controlled by H_2 flow rate set by I_{ref}.

operating point is located in the limit diffusion area that corresponds, in electrical theory, to an ideal current source. This particular behavior of the PEM cell can be of great interest for specific applications requiring a DC current supply under a nearly zero voltage.

In this paper, we propose an innovative application that takes great advantage of both PEMFC low voltage and current source behavior: the electrical supply for high-inductive superconducting coils. Hinaje et al. [2] have already experimented, in GREEN laboratory, the use of a fuel cell for supplying current to a superconducting coil. However, the experiment was led on a low inductance superconducting coil, i.e. 4 mH, which is not representative of the requirements and problems met with big superconducting coils, as a possible negative voltage across the fuel cell due to a significant value of $L \times dI/dt$. In this work, a superconducting coil of L = 10 H is supplied by a current, *I*, produced by a single FC, what has never been achieved before.

At present, specific electronic power supplies are used to supply superconducting coils and in most of cases they have a huge volume and/or a low energy yield. Indeed, the supply has to respect several constraints such as no current ripples that generate electrical losses in the superconductor material that can cause the accidental loss of the superconductor state, also called quench phenomenon, or even lead to its destruction. Moreover it has to be able to deliver several kA. A disadvantage of such electronic supplies is the generation of harmonic noise onto the industrial grid, and the increase in current to its nominal level has to be achieved carefully. Contrary to those electronic supplies, FCs operating at very low voltages are autonomous (no supply connected to the grid), ensured continuous operation (no risk of power failure due to the grid), together with the electrical quality of the current generated, i.e. free harmonic oscillations. Another advantage not least, to increase the current, the active area of the electrochemical generator has only to be enhanced, either by connecting single cells in parallel, or by using a single cell with an active area corresponding to the desired current level, whereas high current electronic power supplies lead to heavy, bulky and expensive equipments. Obviously, the proposed solution for the perfectly direct current generation relies upon a PEMFC fed by H_2 from cylinders, for which safety cautions have to be taken. But taking into account the operation of superconducting coils that have to be cooled with liquid nitrogen or helium or by specific cooling, represents by itself a really safety-demanding process, which could easily accommodate the presence of a PEMFC. At last, recent works carried out on a single PEMFC by Bonnet et al. [3] in LRGP laboratory (Laboratoire Réactions et Génie des Procédés) have shown that operating far below the threshold FC voltage (given by the cell manufacturer) does not lead to additional aging in comparison to usual operating conditions.

In the first part, a PEMFC dynamic model based on an analog formulation of transport partial differential equations (PDE), and its implementation in an electrical engineering simulation software (as Saber®) are presented. The model details are given in Ref. [4]. Then, we demonstrate that this model is suitable to simulate the behavior of a single PEMFC operating as a controlled current source by means of H_2 flow rate. In the second part, theoretical principles and experimental results of the association of a power superconducting coil and a single FC are presented and discussed. The electrical structure is first described, as well as the experimental bench. Then, simulation investigation and requirements that enable safe FC operation when supplying a huge inductive coil are realized. Finally, the theoretical principles are validated through different experiments led on a 100 cm^2 single PEMFC feeding a 10 H superconducting coil as a load.

Model of a PEM single fuel cell operating as a controlled current source

Governing equations

In previous work led by Noiying et al. [4], a PEMFC electrochemical model based on electrical analogy of mass transport phenomena in gas diffusion layers (GDL) and membrane was established. This PDE model is implemented in simulation software commonly used in electrical engineering to design systems (e.g. Saber®, in present case). As a result, even if it can be considered of circuit type, and contrary to most circuit models found in the literature such as those presented in Refs. [5–10], it naturally includes large signal description, space-dependent parameters in each element of the cell (that is to say local partial pressures in GDL, and water content in the membrane), and also influence of operating conditions (such as FC temperature, gas flow rates, anode and cathode pressures, relative humidity). In this work, our aim is to use it for simulating PEMFC operation as an electrical current source controlled by H_2 flow rate to determine requirements for supplying current to a power superconducting coil.

As presented in Fig. 2, a PEM single cell is composed at each part of the membrane by a catalyst layer (CL) and a GDL [11]. The fuel cell is supplied with hydrogen at anode and oxygen usually from air at cathode, each reactant can be humidified, to either side of a proton exchange membrane coated with platinum-based electrode layers. Protons, H^+, resulting from hydrogen oxidation pass from the anode to cathode side through the membrane while electrons, e^-, must flow through an external load, thereby creating electrical current. H^+ then recombine with the electrons and oxygen on the cathode side, forming liquid water as the primary reaction product. The

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