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Melika Hinaje, Kévin Berger, Jean Lévêque, Bernard Davat. Superconducting coil fed by PEM fuel cell. *International Journal of Hydrogen Energy*, 2013, 38 (16), pp. 6773-6779. 10.1016/j.ijhydene.2013.03.151 . hal-00827214

HAL Id: hal-00827214

<https://hal.science/hal-00827214>

Submitted on 29 May 2013

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Superconducting Coil fed by PEM Fuel Cell

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Abstract- Fuel cells are electrochemical energy converters which allow transformation of the chemical energy of a fuel to electricity through oxido-reduction reaction. The voltage of an elementary cell is usually near 1 V in open circuit and around 0.6 V in nominal conditions of power generation. Fuel cells are then by essence low voltage sources , so that for most practical applications, power management is carried out by electronic converters, allowing in particular to rise the voltage to usual application levels.

In this paper, we propose to take advantage of this low voltage for a specific application stack such as superconducting coils power supply. At present, such applications are dealt with the use of specific electronic power supplies, exhibiting in most cases a huge volume and/or a low energy yield.

Keywords- PEMFC; superconductivity; superconducting coil; critical current density; controlled current source; short-circuited fuel cell.

1. Introduction

Fuel cells are complex systems which can be considered as low voltage electrical source. Preliminary investigations led in GREEN (Groupe de Recherche en Electrotechnique et Electronique de Nancy) with a single membrane fuel cell, either short-circuited or hybridized by discharged supercapacitors could evidence the behaviour as a current source [1], in which the current is directly controlled by the hydrogen flow. This operation mode forces the cell voltage to be far below the threshold recommended by the cell manufacturer. The paper is aimed at investigating this operation mode which allows the production of current of a very high quality, i.e. without oscillations and under a very low voltage to feed superconducting coils [2-3].

1.1 A short introduction to superconducting wires

In 1911 Kammerling Omnes accidentally discovered superconductivity. In a study of a sample of mercury at low temperatures, its abrupt overview of resistivity drop to 4.15 K. The second signature was discovered in 1933 by Meissner and Ochenfelf, it is the perfect diamagnetism.

Since these first discoveries, many materials have been found to be superconductors. Nevertheless, it was not until the early 60s, for use in electrical engineering, low temperature superconductor NbTi was discovered by Matthias Kunzler, but at low temperature, 4.2 K. Then, at the end of 80s, were discovered by Muller Berdnoz the high critical temperature superconductors HTS, these can operate at the temperature of liquid nitrogen.

Superconductivity exists only under certain conditions of temperature, magnetic field and current density. The three critical parameters T_c , H_c , J_c , can be represented in a three-dimensional space as shown in Fig. 1, or they define a critical surface. Beneath the surface, the material is in the superconducting state and above, it is in the normal state. Another very interesting property of superconductors is their critical current density very high, it can reach 3000 A/mm^2 .

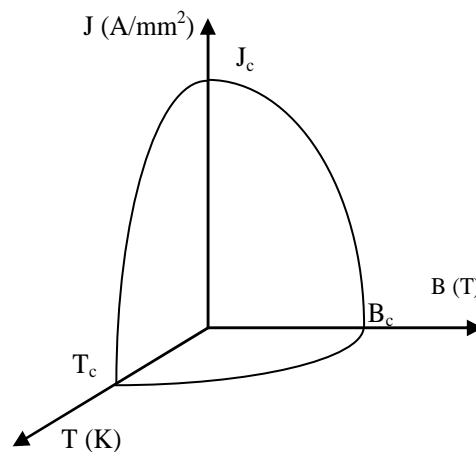


Fig. 1: Critical surface

After the discovery of the superconductivity the main problem is how to made superconducting wire? The first wire was made with NbTi [4]. For many reasons of electromagnetic and thermal stability, it is made of small filament of NbTi with a diameter lower than 20 micrometer in a cooper or alloy of copper matrix generally. The number of filament can be very high, in 90s some superconducting wire of 0.2 mm of diameter have more than 200 000 superconducting filament inside.

When the high temperature was discovered [5], it is more complicated to made wire because these superconductors are not

metallic but ceramic. So, we have two processes for these superconducting wires, either a classical techniques of powder in tube. This process is usual for BSCCO and MgB2 superconducting wire. In this case a wire is made of several filaments, less than hundred in a silver matrix. Neither the wire is made by classical chemical vapor deposition of superconductors on a substrate. These processes are user for YBCO superconducting wire. In this paper, we used a BSCCO superconducting wire made by Zenergy in Germany. These wires can be used in liquid nitrogen with good properties, but in fact their properties are better at lower temperature. Therefore, many applications use high temperature superconductors between 20 K. and 40 K.

For the superconductors, there are many constitutive laws, like Ohm's law for classical conductors, linking electrical field and current density in superconductors [6]. We shall present two laws: the Bean's model and a J^n law.

The Bean model is the simplest and is representative of the superconducting critical temperature low. In this model, the current in the superconductor can take only two possible values its critical current density or zero: $J=\pm J_c$ ou $J=0$.

The second model is better suited to high critical temperature superconductors. The law relating the current density of the electric field t is as follows:

$$\mathbf{e}(\mathbf{J}, \mathbf{B}, T) = E_c \left(\frac{\|\mathbf{j}(\mathbf{B}, T)\|}{J_c} \right)^n \frac{\mathbf{j}(\mathbf{B}, T)}{\|\mathbf{j}\|} \quad (1)$$

Where J_c is the critical current for an arbitrary value of the critical electrical field. This critical value of critical current density if not the same than in the previous definition and is called engineering critical current density. The value of the critical electrical field is generally chosen at 1 microvolt by meter.

Fig. 2 presents the behavior of the electric field versus the current density according to the considered models.

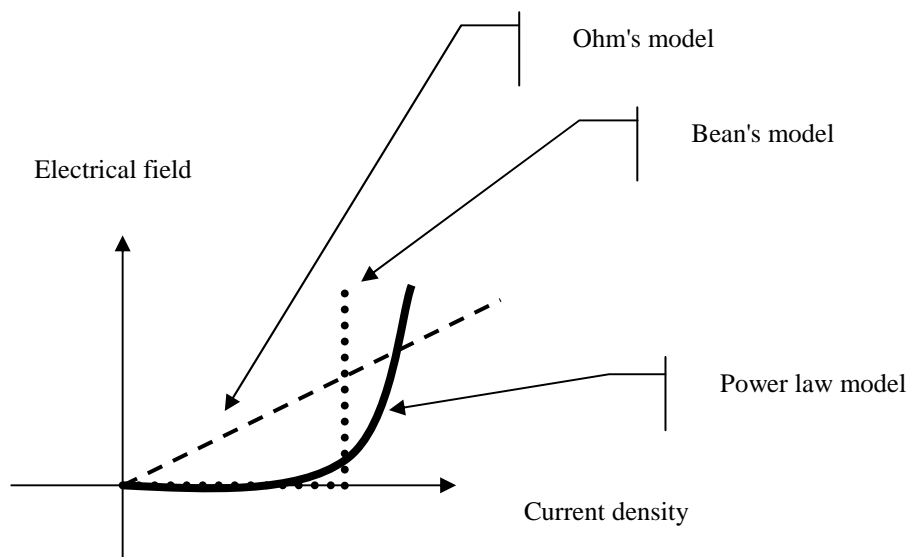


Fig. 2: Equivalent Ohm's law of superconductors

Characterization of superconducting materials is to find the relationship between the electric field and current density. The measuring principle is very simple and consists in measuring the voltage across a superconducting sample carrying current. For that we used of a specific power supply made by American Magnetics for superconducting applications. This power supply can reach 300A@±4V [7] and a nanovoltmeter 2182A/E from Keithley for the measurement of very low voltage across the superconducting sample.

Fig. 3 presents a sample of BSCCO superconducting tape used in the coil. Its electrical characterization is given for different applied magnetic field in Fig. 4.



Fig. 3: Sample of superconducting wire (BSCCO2212) and superconducting coil picture used in the experiment

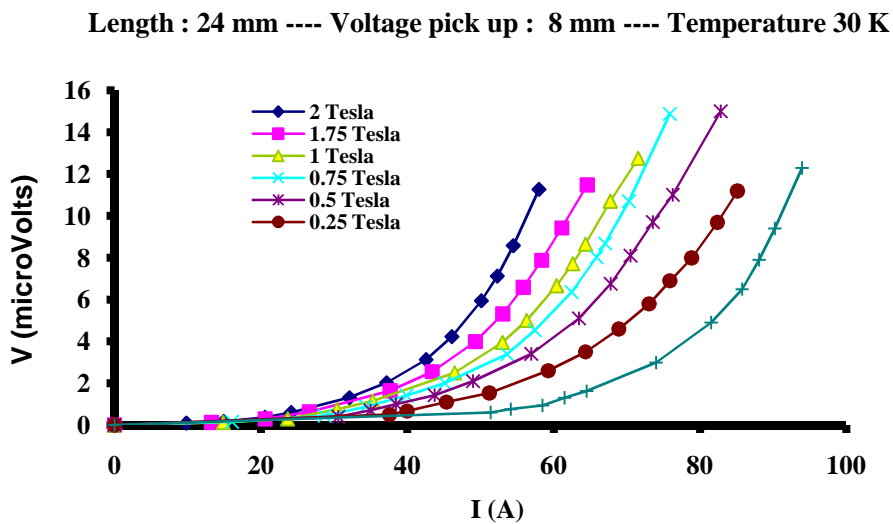


Fig. 4 Superconducting wire characterization

1.2 PEM Fuel cell characteristic

Membrane fuel cells consist of two electrode compartments separated by a polymer electrolyte membrane preventing from the transport of gas and electrons. As shown in Fig. 5, the two electrodes are stuck on the sides of the membrane, forming the Membrane-Electrode Assembly (MEA) of the individual cell. Protons generated by hydrogen oxidation migrate with water to the cathode through the membrane – which exhibits most often a high affinity to water - to the cathode, and take part in oxygen reduction to water. Fuel cells can be characterized by the variation of the available voltage with the delivered current density. This variation depends on several operating parameters, such as temperature [8] and pressure [9], reactant flow rates [10-11], membrane humidification [12], and also on the fuel cell design [13-14].

Fig. 6 presents a typical polarization curve of a single cell including the opened circuit voltage (OCV) and the working area [15]. The nominal operating point is about 0.6V at 0.4-0.8 A.cm⁻². According to electrical characteristics of superconducting coil, we interest in taking benefit on the last area of the polarization curve (concentration losses).

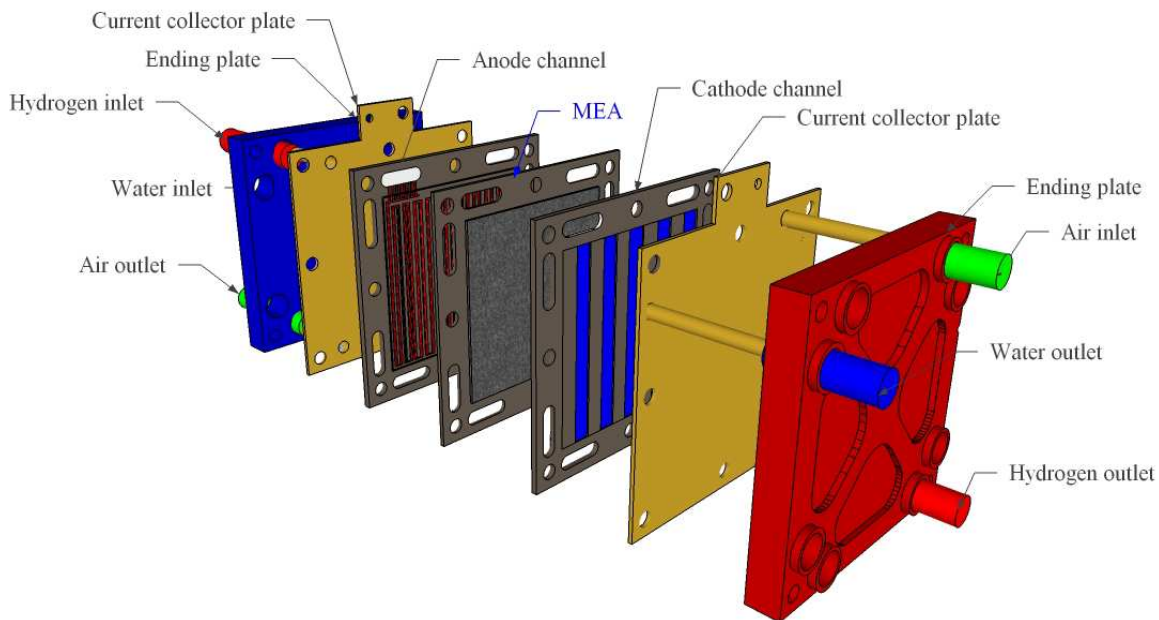


Fig. 5 Water cooled single PEM fuel cell

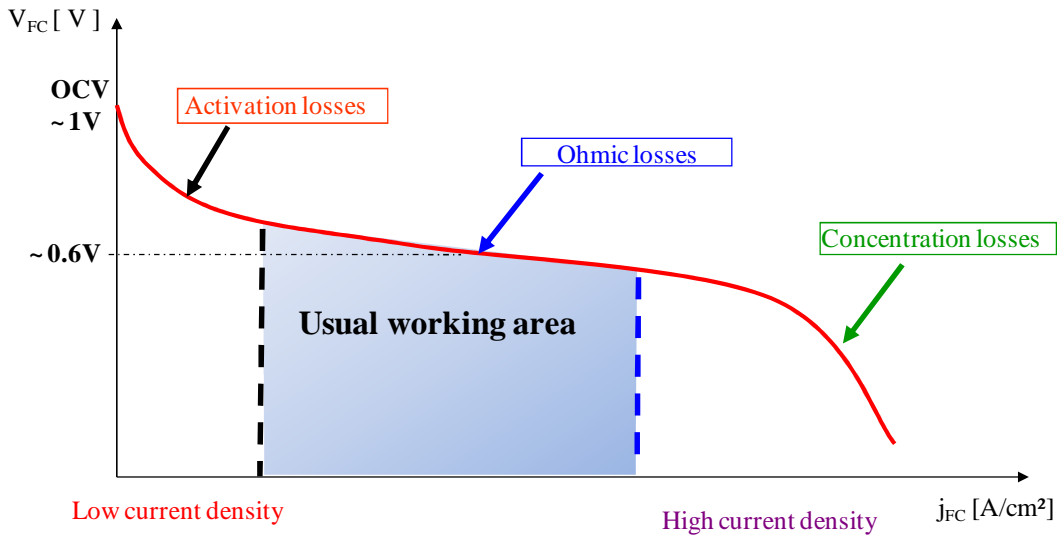


Fig. 6 : Single fuel cell polarization curve

2. EXPERIMENTATION OF A SINGLE PEM FUEL CELL CONNECTED TO A SUPERCONDUCTING COIL

2.1 Test Bench

The test bench is composed of a single fuel cell system (source) and a superconducting coil (load). The single fuel cell is a proton exchange membrane fuel cell of 100 cm² active area manufactured by UBZM (Germany). Pure dry hydrogen is supplied from cylinders at anode inlet and dry or humid air at cathode inlet.

A "real time" electronic card (dSPACE[®] DS1104 card) is used in combination with Matlab-Simulink[®] mathematical environment for all necessary control functions such as reference setting (inlet gas flows, outlet pressures, air humidity, and load current), measurement storage and conditioning, and safety shutdown. As it can be seen in Fig. 7, a cooling system keeps the fuel cell temperature constant. Air humidity can be regulated by a CEM-system (Controlled Evaporation and Mixing), this vaporizer system replace usual bubblers that are less accurate and above all do not allow humidity regulation.

Inlet gas flows are calculated versus a reference current I_{ref} , which can be set by an external signal (in case of an adapted flow supply), as follows:

$$\begin{cases} d_{H_2} = \frac{I_{ref}}{2F} \cdot \frac{RT_0}{P_0} \cdot \zeta_a \cdot 1000 \cdot 60 \\ d_{air} = \frac{I_{ref}}{4F} \cdot \frac{RT_0}{P_0} \cdot \frac{1}{0.21} \cdot \zeta_c \cdot 1000 \cdot 60 \end{cases} \quad [L \cdot \text{min}^{-1}], \quad (2)$$

with ζ_a , ζ_c anode and cathode stoichiometric coefficients, $T_0 = 273$ K and $P_0 = 1.013 \cdot 10^5$ Pa.

The operating conditions are set so as to obtain the single fuel cell voltage as low as possible (less than 0.3V) at a given current, which corresponds to an operation in the current source cell.

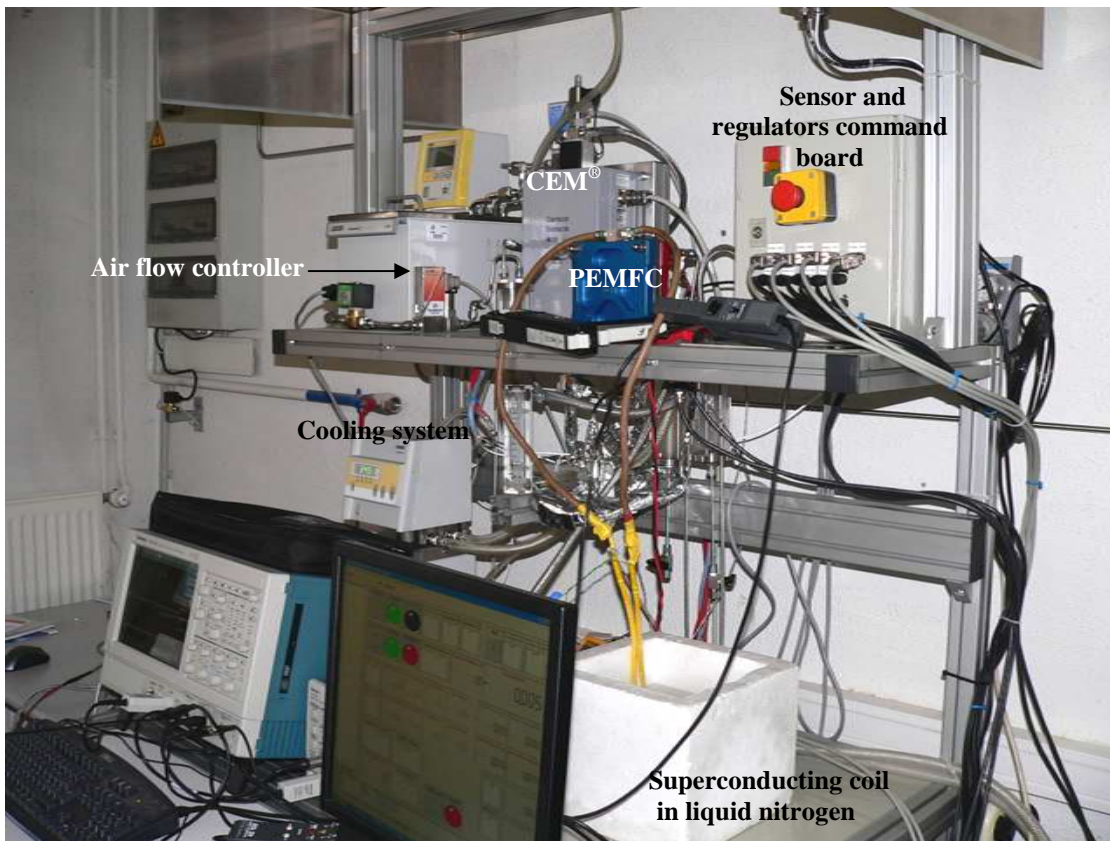


Fig. 7. Single cell test bench.

As we can see in Fig. 8, the superconducting coil is cooled by means of liquid nitrogen. As explained above, from now on, the resistance of the coil is null. Therefore, as soon as the single fuel cell will operate, this one will be short circuited. The aim is to make the fuel cell operate as a current source that is to say far below the threshold voltage as shown in Fig. 9. This particular operating mode has been studied in [1].

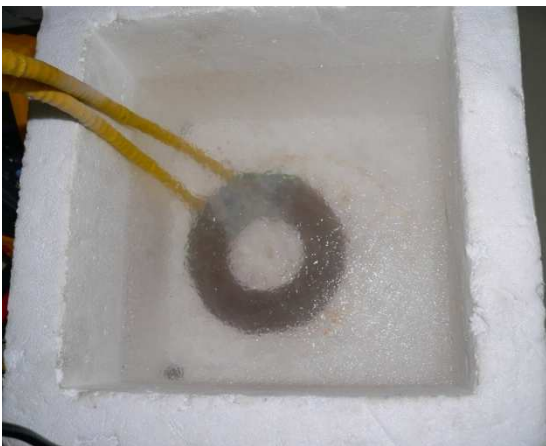


Fig. 8 Superconducting coil cooled in liquid nitrogen ($T = 77K$)

Table 1 : Characteristics of the coil and the wire

| Parameters | Value |
|-------------------------------|-------------------------|
| Thickness of the wire | 0.2 mm |
| Width of the wire | 4.0 mm |
| Critical current of the wire | 42 A@77K and self field |
| Number of turn of the coil | 208 |
| External diameter of coil | 115 mm |
| Internal diameter of the coil | 60 mm |
| Inductance of the coil | 4 mH |
| Critical current of the coil | 18 A@77K |

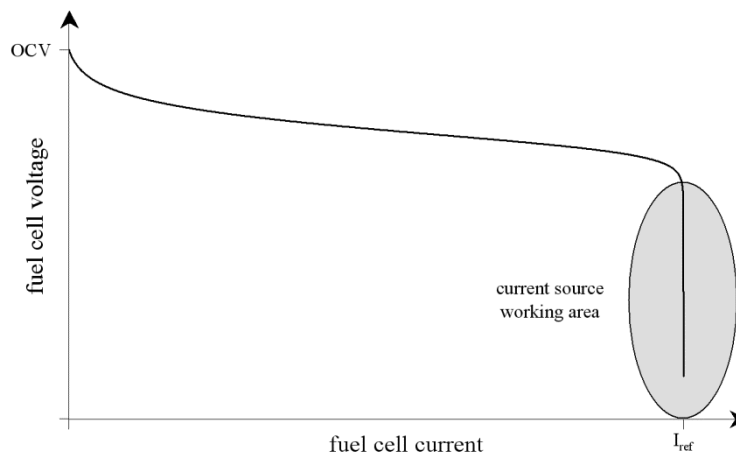


Fig. 9. Polarization curve including the area where the single cell runs as a current source controlled by hydrogen flow rate set by I_{ref} .

2.2 Fuel cell operating condition

First of all, some experiments will be led in order to set the optimum operating condition of the single fuel cell as current source. To this end, polarization curves are plotted for different values of air relative humidity and fuel cell temperature (Table 2 and Fig. 10).

Set the reference current at 10A and anode stoichiometric coefficient, ζ_a , at 1 mean that the fuel cell current cannot exceed 10A. In fact as a portion of the fuel is not consumed, the current is a little less than 10A as shown in Fig. 10.

At a given current, the fuel cell voltage has to be the smallest therefore it appears that the single cell has to be fed by dry air and its temperature regulated at 40°C.

Table 2 : Operating conditions

| Parameter | Symbol | Value | Unit |
|--|-------------|--------------------|------|
| Reference current (2) | I_{ref} | 10 | A |
| Anode stoichiometric coefficient (2) | ζ_a | 1 | |
| Cathode stoichiometric coefficient (2) | ζ_c | 6 | |
| Fuel cell temperature | T | 40-50 | °C |
| Anode relative humidity | RH_a | 0 % | - |
| Cathode relative humidity | RH_c | 0 - 62 % | - |
| Anode outlet pressure | p_a^{out} | $1.013 \cdot 10^5$ | Pa |
| Cathode outlet pressure | p_c^{out} | $1.013 \cdot 10^5$ | Pa |

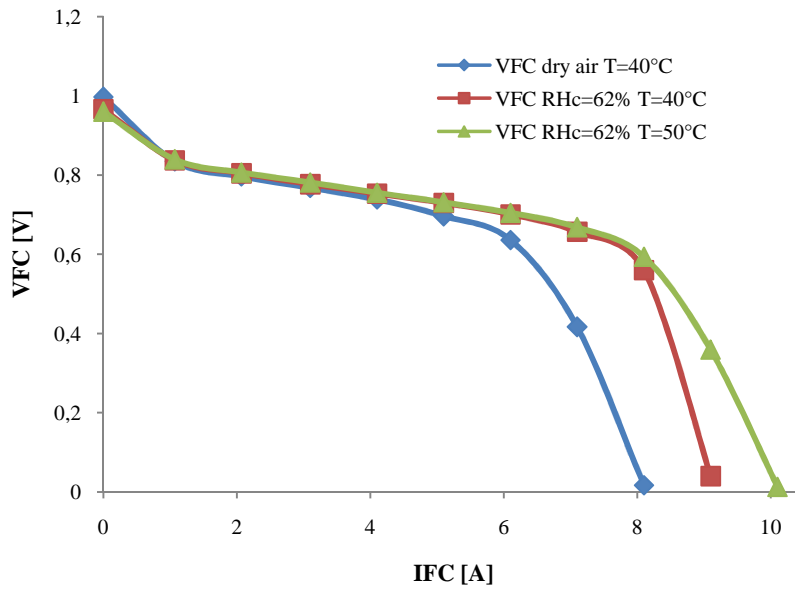


Fig. 10. Polarization curves at different operating conditions

2.3 Experimental results of Superconducting coil supplied by PEM single fuel cell

2.3.1 Superconducting coil characterization

Taking into account the results in the previous section for the operating conditions (Table 3), the single fuel cell is connected to the superconducting coil, which characteristics are given in Table 1.

Table 3 : Operating conditions of the fuel cell as a current source

| Parameter | Symbol | Value | Unit |
|--|-------------|--------------------|------|
| Reference current (2) | I_{ref} | 4 to 20 | A |
| Anode stoichiometric coefficient (2) | ζ_a | 1 | |
| Cathode stoichiometric coefficient (2) | ζ_c | 6 | |
| Fuel cell temperature | T | 40 | °C |
| Anode relative humidity | RH_a | 0 % | - |
| Cathode relative humidity | RH_c | 0 % | - |
| Anode outlet pressure | p_a^{out} | $1.013 \cdot 10^5$ | Pa |
| Cathode outlet pressure | p_c^{out} | $1.013 \cdot 10^5$ | Pa |

Fig. 11 presents the comparison of the superconducting coil characterization as it is fed by a specific power supply for superconducting coil (American Magnetics [7]) or by the single PEM fuel cell. We obtain the same results, the fuel cell operates as a current source as expected.

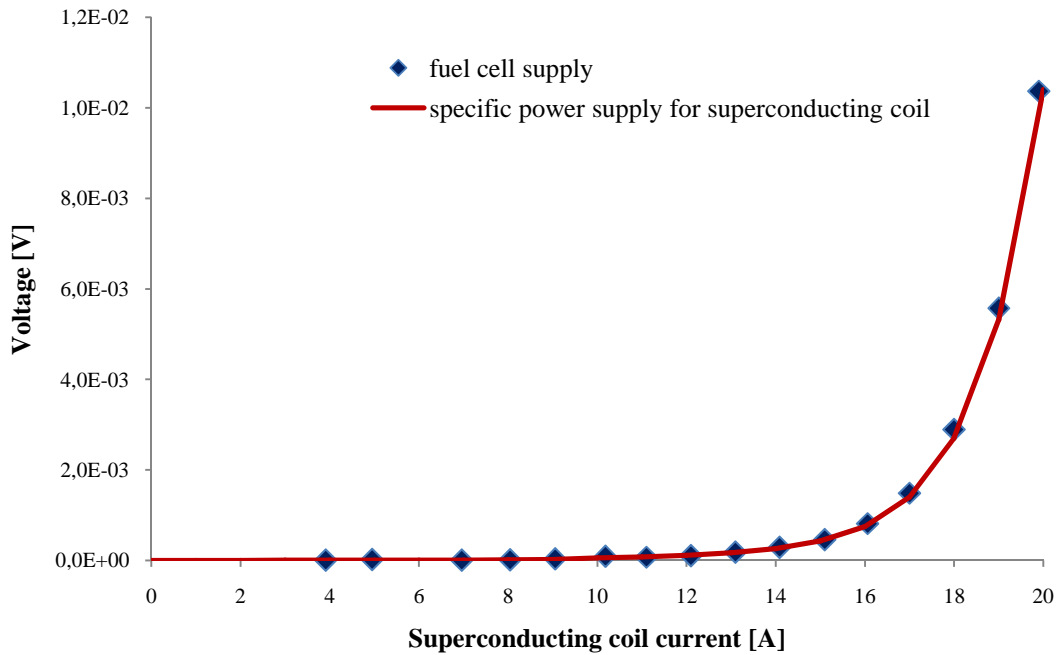


Fig. 11. Superconducting coil characterization using single PEM fuel cell

2.3.2 Single fuel cell polarization curve

In Fig. 12, the fuel cell voltage has been plotted for different current values. As it can be seen, the voltage does not exceed 0.1V at 20A, a smaller value can be expected as normally the fuel cell is short circuited (superconducting coil resistance is null).

It is due to the resistance of the wire, estimated at 4mΩ. Therefore, it underlines the importance of wires choice if using the fuel cell as a current source.

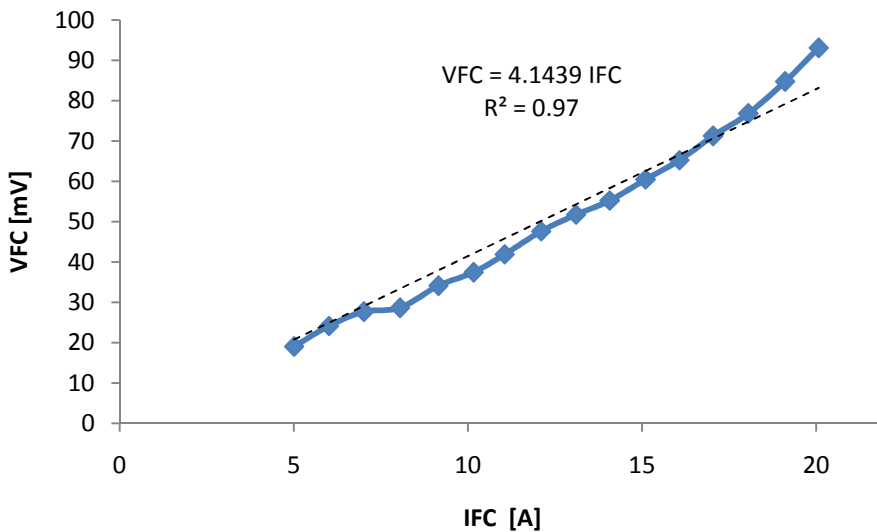


Fig. 12. PEM fuel cell voltage versus current

2.3.3 Single fuel cell transient behaviour

As studied in [1], the fuel cell current is controlled by hydrogen flow rate ($\zeta_a = 1$) through I_{ref} .

Fig. 13 presents the time variation of hydrogen flow rate (Ch.3) and current and voltage fuel cell waveforms (ch2. and ch4. respectively). A setpoint step of the hydrogen flow rate from $I_{ref} = 15A$ to $I_{ref} = 20A$ leads to a fuel cell current step from 15A to 20A. This new current setpoint is maintained since the hydrogen flow rate is regulated around $I_{ref} = 20A$.

A current profile is set through hydrogen flow rate by decreasing the reference current from 20A to 5A by step of 5A. Fuel cell current and voltage waveforms are given in Fig. 14. As it can be seen, the transient response is quite slow; this is mainly due to hydrogen flow controller, its regulation has to be improved. However, in the case of superconducting applications, it is not detrimental.

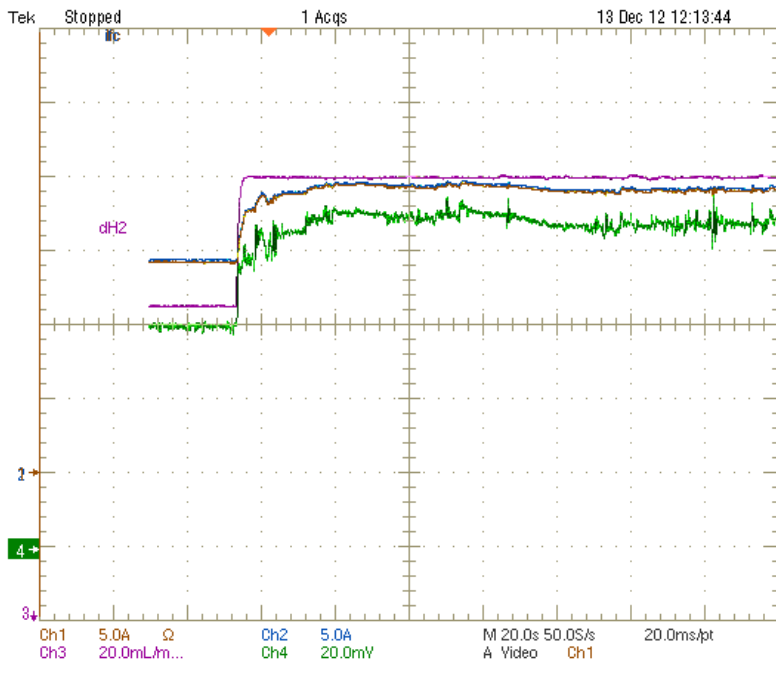


Fig. 13 . Current and voltage response to a setpoint step of the hydrogen flow rate from $I_{ref} = 15$ A to $I_{ref} = 20$ A (Ch. 2. Fuel cell current, Ch. 3. H₂ flow rate, Ch. 4. Fuel cell voltage)

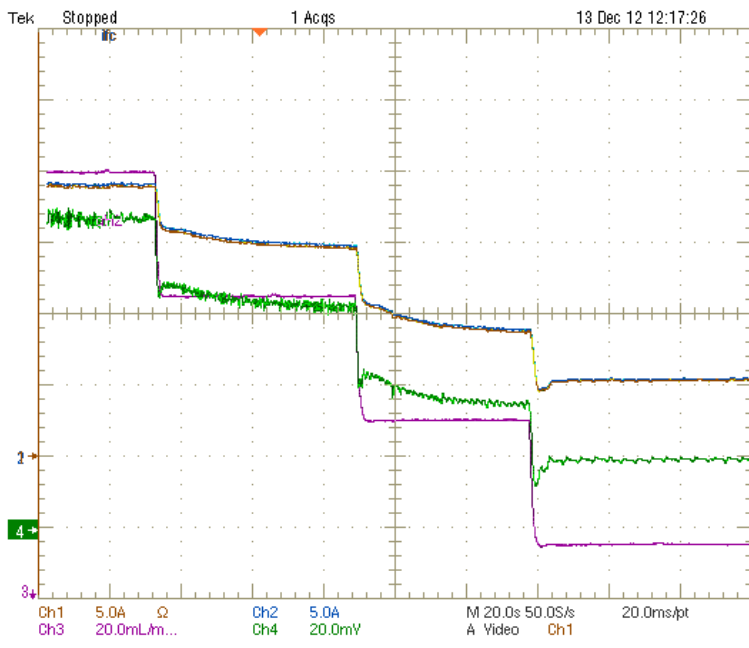


Fig. 14. Demonstration of the current controlled by hydrogen flow rate ($I_{ref} = 20-15-10-5$ A) (Ch. 2. Fuel cell current, Ch. 3. H₂ flow rate, Ch. 4. Fuel cell voltage).

3. CONCLUSIONS AND PROSPECTS

In this paper, we have demonstrated an original application of PEM fuel cell as current source for superconducting coil. Indeed, we take advantage of its low voltage and of the possibility to control its current by means of the hydrogen flow rate. Moreover superconducting coil fit to the slow dynamics of the PEM fuel cell.

This particular use of PEM fuel cell requires to operate in short-circuit and thus a study on the alteration of the fuel cell lifetime must be carried out, for instance concerning flooding and catalyst layers. As it was detailed, if the single fuel cell operates as current source, the hydrogen fed is totally consumed, so it can be expected that water condenses rapidly in the anode chamber because of the sharply decreasing gas flow rate. Flooding phenomenon is to become more significant near the outlet, resulting in locally reduced current density and possible washing out of the catalyst after long term runs. Examination of the current density distribution appears necessary to assess the feasibility of the technique.

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