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Using Fuel cell as a Power Supply for Superconducting Coil

M. Hinaje, K. Berger, J. Lévêque and B. Davat, *Member, IEEE*

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 such as superconducting coils power supply. The solution proposed here for the generation of the perfectly direct current relies upon a fuel cell fed by hydrogen from cylinders, for which safety cautions have to be taken, but operation of superconducting coils, which have to be cooled with liquid nitrogen or helium or by specific cooling gases represents by itself a really safety-demanding process, which could easily accommodate the presence of a PEM fuel cell. The main advantages to be taken from fuel cells operated at very low voltages are autonomy – no supply connected on the grid, ensured continuous operation, together with the electrical quality of the current generated, i.e. free.

Index Terms—Current control, Power supply, Proton exchange membrane Fuel cell, Superconducting coil.

I. INTRODUCTION

The first demonstration of fuel cell (FC) was conducted by Sir William Grove in 1839 [1]. The research on fuel cell was very active in 1960 where fuel cells were developed for the NASA's space program. Technology at that time let the Alkaline Fuel Cell (AFC) be the best choice of electrical source on the space shuttle. The first Proton Exchange Membrane Fuel Cell (PEMFC) was developed during this program. The breakthrough of DuPont on Nafion® membrane

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in late of 1960 made the PEMFC more suitable for real world application [2]. The researches on fuel cells have been increased rapidly since 1997 by the awareness of the energy and environmental problems. Various types of fuel cell are available, but PEMFC is seemed to be the most practical among the low temperature types. The applications of the PEMFC ranges from small portable devices to stationary power supplies for resident or industrial use [3, 4].

Fuel cells are then by essence low DC 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.

Besides fuel cells are generators of electric power little suitable to sudden variations of current, principally because of the fairly slow response of the gas flow rate controllers. This slow dynamics renders necessary to associate a buffer component e.g. batteries or supercapacitor, whose function is to supply the charge with energy for the transient periods. Additionally the buffer component can be used as a complementary source or to ensure partial energy recovery – fuel cells are usually no reversible energy converters.

In this paper, we propose to do without these additionally devices by taking advantage of the natural low voltage of the fuel cell, without however the slow dynamics is a drawback.. Indeed, as we will see PEMFC's characteristics might be of a great interest for electrical supply of superconducting coils.

First of all, an introduction of PEMFC will be done as well as so called fuel cell system. Then, a potential application of fuel cell as controlled current source supply for superconducting coil will be highlighted. Finally, some prospects will be issued.

II. INTRODUCING THE PROTON EXCHANGE MEMBRANE FUEL CELL

What makes PEM fuel cell interesting among others is the use of hydrogen as fuel. Since, hydrogen is a gas that can be created from water by electrolysis process; there is no risk of shortage. The electrolysis process let water molecules adsorb energy from electricity and detach into hydrogen and oxygen gases. The PEMFC operating is based on the reverse process. As long as reactants are supplied to electrodes, the fuel cell feeds the load.

A. Operating principle

Membrane fuel cells consist of two electrode compartments separated by a polymer electrolyte membrane preventing from the transport of gas and electrons. The two electrodes are stuck

on the sides of the membrane, forming the Membrane-Electrode Assembly (MEA) of the individual cell, as presented in Fig. 1. Protons generated by hydrogen oxidation (1) 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 (2) to water. Fuel cells can be characterized by the variation of the available voltage with the delivered current density as shown in Fig. 2.

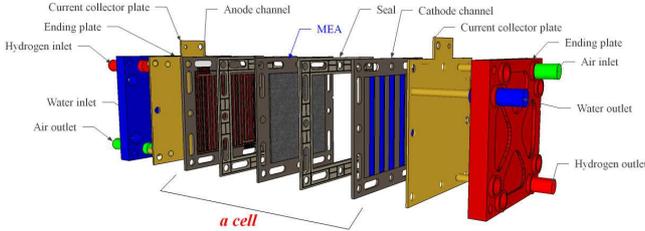


Fig. 1. Sketch of a PEM single fuel cell cooled by water



The consumption of reactants (molar flux, $N_{i,\text{cons}}$) increases in proportion with the fuel cell current, I_{FC} , as well as with the number of cells, N_{cell} , in the stack. The same applies for water production resulting from redox reaction

$$N_{\text{H}_2,\text{cons}} = \zeta_a N_{\text{cell}} \frac{I_{\text{FC}}}{2F} \quad (3)$$

$$N_{\text{O}_2,\text{cons}} = \zeta_c N_{\text{cell}} \frac{I_{\text{FC}}}{4F} \quad (4)$$

$$N_{\text{H}_2\text{O},\text{prod}} = N_{\text{cell}} \frac{I_{\text{FC}}}{2F} \quad (5)$$

Typical voltage of a cell at 0.5-0.6 A.cm⁻² is of the order of 0.6V. Higher voltages can be obtained in fuel cell systems by connecting in series a number of individual cells which form the fuel cell stack. The maximum fuel cell current depends on the active area of a fuel cell electrode that is to say the area is able to produce electricity from the supplied fuel. Bigger is the active area higher is the maximum current. For instance, assume that the whole MEA area of a 100 cm² PEMFC is active, it means that the fuel cell can reach about 50A. The cell voltage V_{FC} is the result of Open Circuit Voltage (OCV) minus the losses due to irreversibilities.

$$V_{\text{FC}} = \text{OCV} - \eta_{\text{act}} - \eta_{\text{ohm}} - \eta_{\text{conc}} \quad (6)$$

A voltage proportion is lost in driving the chemical reaction that transfers the electrons. This voltage drop also called activation overvoltage denoted η_{act} in Fig. 2, is highly non-linear open circuit voltage. Activation losses are caused by the slowness of the reactions taking place on the surface of the electrodes.

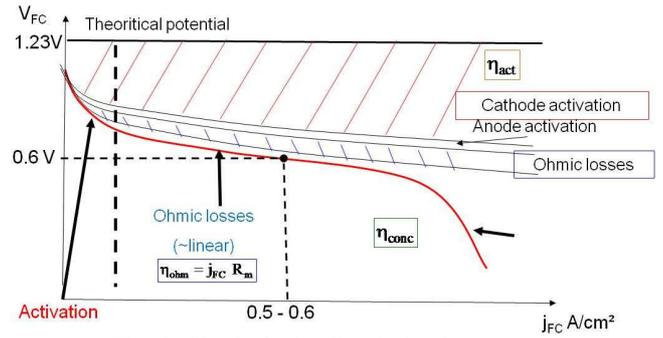


Fig. 2. Single fuel cell polarization curve

The straight part located in the middle of the curve corresponds to ohmic losses, η_{ohm} , and are mainly due to the membrane resistance, R_m . However, it has to be underlined that the membrane resistance depends on the fuel cell current, it is linked to the proton conductivity of the membrane. Concentration losses, η_{conc} , become significant at high current when the slow rate of the reactants transport is unable to meet the high demanded current. This voltage drop is caused by the slow rate of mass transport (diffusion limitation) that leads to the depletion of reactants in the vicinity of active reaction sites and the overaccumulation of reactants product which prevent the reactants from reaching the reactant sites.

B. Fuel cell system

Fig. 3 presents an example of a fuel cell system fed by dry hydrogen from cylinder and humidified air. Set point of reactant flow rates are imposed by means of Flow Controllers (FC). There are normally closed electromagnetic valves at the each inlet gas that ensure the shutdown of reactant supply in case of default and normally open valves at the outlets. Condensers can be used to collect water coming from unconsumed gas. In some fuel cell system, to avoid waste, unconsumed hydrogen is recovered and fed back to inlet. However, in doing so, the system is not only more expensive but also more complex. There is also an alternative in the regulation of fuel cell temperature, in some other systems, fuel cells are cooled by air.

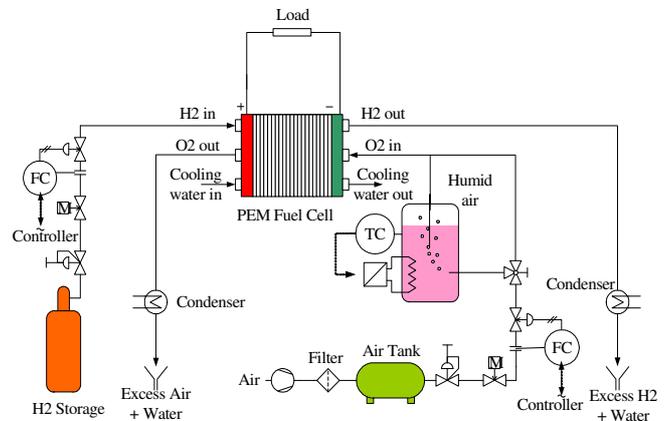


Fig. 3. PEM fuel cell system

The reactant flow rate is set according to (7)

$$\begin{cases} d_{H_2} = N_{cell} \frac{I_{ref}}{2F} \cdot \frac{RT_0}{P_0} \cdot \zeta_a \cdot 1000 \cdot 60 \\ d_{air} = N_{cell} \frac{I_{ref}}{4F} \cdot \frac{RT_0}{P_0} \cdot \frac{1}{0.21} \cdot \zeta_c \cdot 1000 \cdot 60 \end{cases} \quad [L \cdot min^{-1}] \quad (7)$$

Where N_{cell} is the number of cells of the stack, I_{ref} the demanded fuel cell current and ζ_a , ζ_c the anode and cathode stoichiometric coefficients respectively $T_0 = 273$ K and $P_0 = 1.013 \cdot 10^5$ Pa.

The fuel cell performance depends on several operating parameters such as fuel cell temperature, supply gas (or stoichiometric coefficients), relative humidity and operating pressure.

Some experimental results presented in Fig. 4 to Fig. 6 point out the influence of operating conditions on single fuel cell performances.

C. Influence of operating conditions

1) Influence of reactant flow rates

The experiment was led on the single fuel cell fed by humidified air and dry hydrogen from cylinders. The fuel cell is cooled by water and its active area is 100 cm^2 .

As it can be seen in Fig. 4, the decrease of hydrogen flow rate does not make any difference on the voltage fuel cell. On the contrary, as air flow rate decreases, the fuel cell voltage decreases until air supply becomes insufficient ($\zeta_c=1.1$) for the demanded current which leads to a strong drop of the voltage (Fig. 5).

This phenomenon is called air starvation. Since the fuel cell is not overfed, air does not reach the entire active region and the reduction reaction does not occurs uniformly in the cell [5].

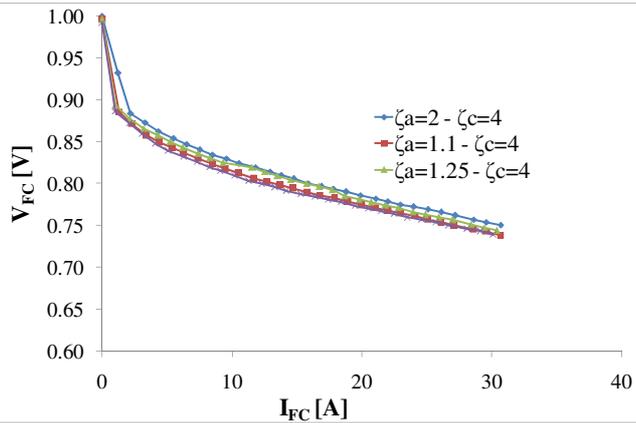


Fig. 4. Single fuel cell polarization curves versus hydrogen flow rate.

2) Humidification and Fuel cell temperature

Among the losses, a significant portion comes from the membrane resistance. Its value depends on the water content of the membrane and the temperature. As it can be seen in Fig. 6, the conductivity is improved as the membrane is well humidified (and heated) [6-11]. Since the membrane is

humidified using the air supply. Air starvation leads also to the humidification decrease and thus to voltage drop.

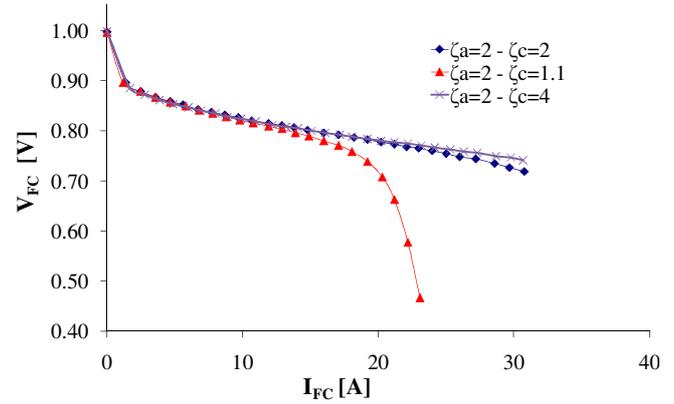


Fig. 5. Single fuel cell polarization curves versus air flow rate

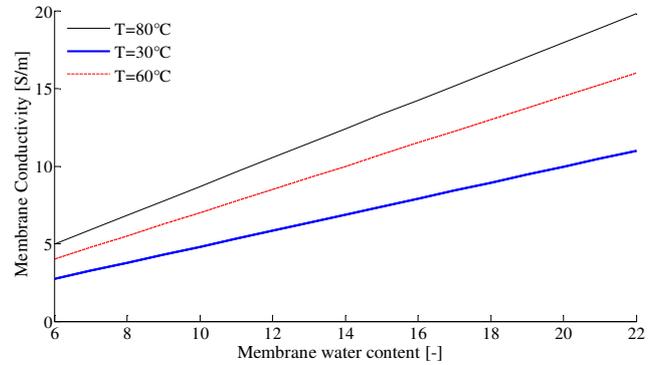


Fig. 6. Variation of membrane conductivity according to temperature and water content.

III. FUEL CELL OPERATING AS A CONTROLLED CURRENT SOURCE

A. Fuel cell current controlled by hydrogen flow rate

In a previous paper [12], it has been highlighted the potential use of a single PEM fuel cell as a current source controlled by hydrogen flow rate ($\zeta_a = 1$) through I_{ref} (7). In this case, the single fuel cell is short-circuited and runs in the operating conditions given in Table I. As the fuel cell voltage is near zero, the fuel cell operating point is located in the last part of the polarization curve that is to say diffusion limitation. Fig. 7 presents the time variation of hydrogen flow rate (Ch.3) and current and voltage fuel cell waveforms (ch1. and ch2. respectively). A setpoint step of the hydrogen flow rate from $I_{ref} = 20$ A to $I_{ref} = 40$ A leads to a fuel cell current step from 20A to 40A. This new current setpoint is maintained since the hydrogen flow rate is regulated around $I_{ref} = 20$ A. Then, the current decreases to 20 A by decreasing the reference current that is to say the hydrogen flow rate. 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.

TABLE I
FUEL CELL OPERATING CONDITIONS

Symbol	Quantity	Value ^a
ζ_a	Anode stoichiometric coefficient (7)	1
ζ_c	Cathode stoichiometric coefficient (7)	6
I_{ref}	Reference current (7)	20A - 40A
T	Fuel cell temperature	40°C
RH_a	Anode relative humidity	0 %
RH_c	Cathode relative humidity	65 %
P_a	Anode pressure	1 atm
P_c	Cathode pressure	1 atm

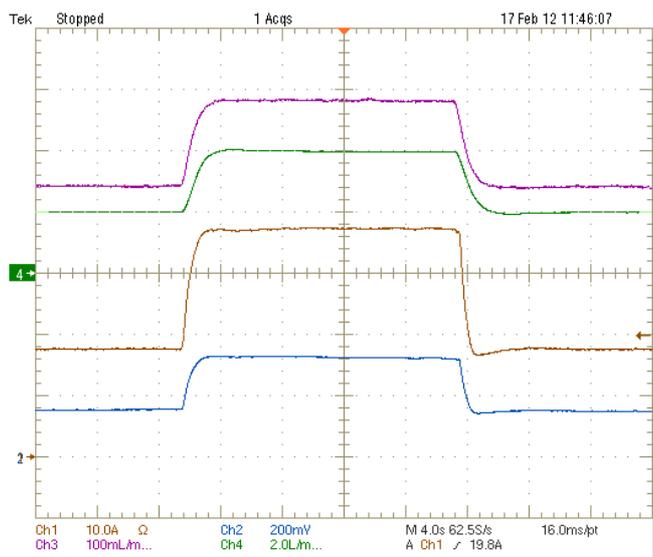


Fig. 7. Demonstration of the current controlled by hydrogen flow rate ($I_{ref} = 20A - 40A - 20A$) (Ch. 1. Fuel cell current, Ch. 2. Fuel cell voltage, Ch. 3. H_2 flow rate, Ch. 4. air flow rate).

B. Operation condition setting

Once we have proved that the fuel cell is able to run as a current source controlled by hydrogen flow rate. This one is connected to a superconducting coil which characteristic is given in Table II.

But first of all, some experiments have been led in order to set the optimum operating condition of the single fuel cell as current source. To this end, polarization curves were plotted for different values of air relative humidity and fuel cell temperature (Table II **Erreur ! Source du renvoi introuvable.** and Fig. 8).

Set the reference current at 10 A and anode stoichiometric coefficient, ζ_a , at 1 mean that the fuel cell current cannot exceed 10A. In fact as some fuel does not reach the catalyst sites this one is not consumed and so, the current is a little less than 10 A as shown in Fig. 8.

Taking into account 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.

IV. SUPPLY OF A SUPERCONDUCTING COIL

A. Test bench

The test bench is composed of a single fuel cell system as presented in Fig. 3. Usually, air is humidified by means of a bubble which inconvenient is not accurate and above all does

not allow regulation, that are the reasons why this device has been replaced by a CEM-system (Controlled Evaporation and Mixing). The single fuel cell is a proton exchange membrane fuel cell of 100 cm² active area manufactured by UBZM (Germany) connected to a superconducting coil (Table II and Fig. 10). This coil has already been characterized in the liquid nitrogen by an improved method [13]

There are flow controllers (FC) at each side of the fuel cell. The set point flow rates are imposed by means of a "real time" electronic card (dSPACE® DS1104 card) used in combination with Matlab-Simulink® software according to (7).

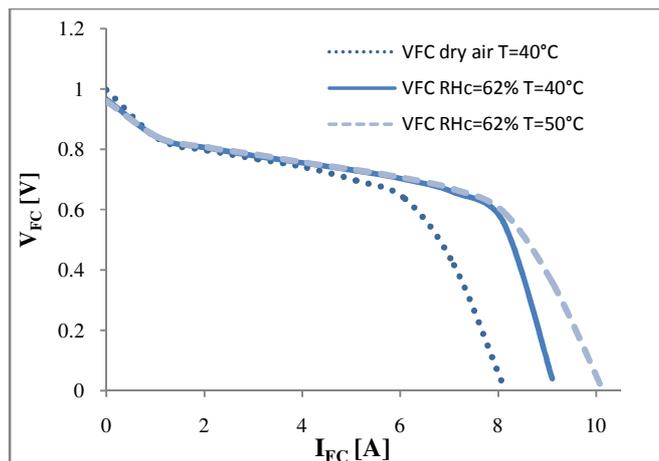


Fig. 8. Polarization curves while varying the temperature and the relative humidity of inlet air.

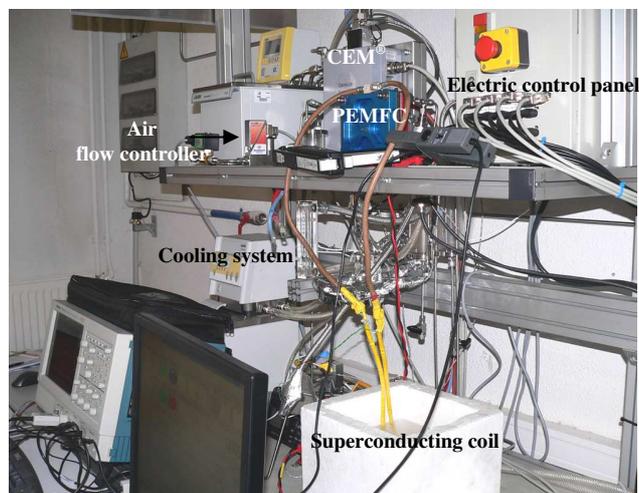


Fig. 9. Test bench of a single PEM fuel cell connected to a superconducting coil cooled by nitrogen.

TABLE II
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 @ 77 K 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 @ 77 K



Fig. 10. Sample of superconducting wire (BSCCO2212) and superconducting coil used in the experiment (on the right side)

B. Experimental results

Fig. 11 presents the comparison of the superconducting coil characterization as it is fed by a specific power supply for superconducting coil (American Magnetics [14]) or by the single PEM fuel cell, the same results are obtained. As expected the fuel cell operates as a current source. The fuel cell voltage does not exceed 0.1 V at 20 A (Fig. 12). A smaller value can be expected as normally the fuel cell runs as it is short circuited. 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.

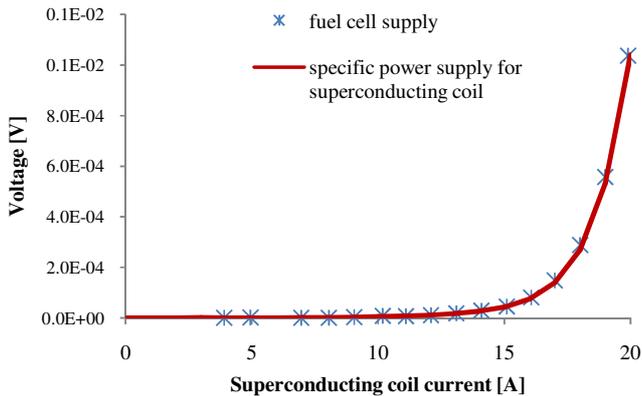


Fig. 11. Superconducting coil characterization using single PEM fuel cell

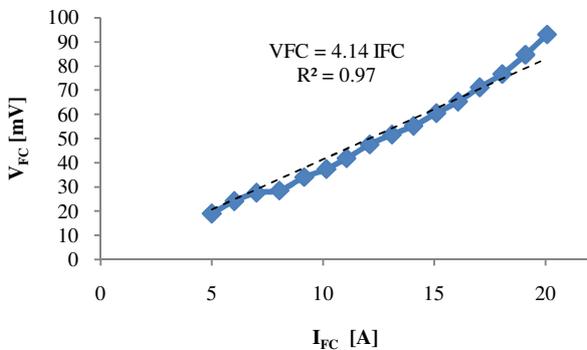


Fig. 12. Fuel cell voltage versus current during the superconducting coil supply.

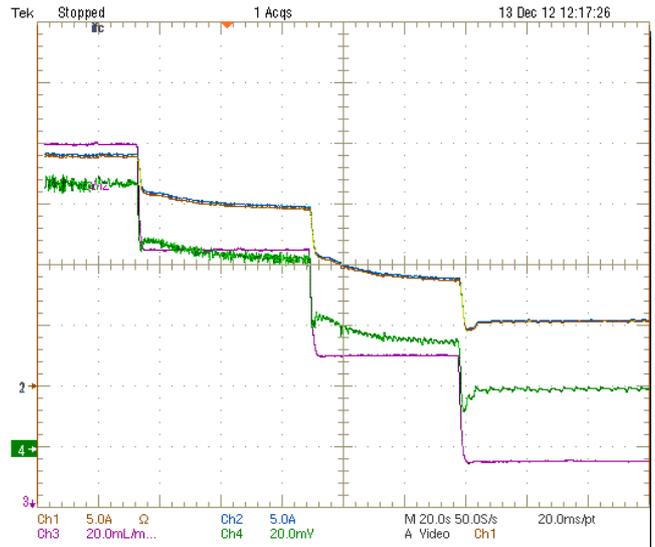


Fig. 13. Demonstration of the current controlled by hydrogen flow rate ($I_{ref} = 20-15-10-5A$) (Ch. 2. Fuel cell current, Ch. 3. H_2 flow rate, Ch. 4. Fuel cell voltage).

Fig. 13 presents the current profile set through hydrogen flow rate by decreasing the reference current from 20 A to 5 A by step of 5A. A setpoint step of the hydrogen flow rate from $I_{ref} = 15 A$ to $I_{ref} = 20 A$ leads to a fuel cell current step from 15 A to 20 A. This new current setpoint remains constant since the hydrogen flow rate is regulated around $I_{ref} = 20 A$. Because of the time constant of the hydrogen flow controller, the transient response is quite slow, its regulation has still to be improved.

V. CONCLUSION

In this paper, a new supply for superconducting coil has been presented. Taking benefit of the natural low voltage of single fuel cell and of the possibility to control its current by means of the hydrogen flow rate, a superconducting coil has been characterized. Although the fuel cell system transient response is quite slow, it is suitable to superconducting coil.

This particular application of PEM fuel cell requires to operate well below the threshold voltage close to short-circuit, thus a study on the alteration of the fuel cell lifetime must be carried out. Examination of the current density distribution appears necessary to assess the feasibility of the technique. Additional experiment has also to be done by supplying a more inductive superconducting coil at higher current and fuel cell current ripple has to be estimated.

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