Microbial fuel cells for energy harvesting: electrical characterization and modeling

A. Capitaine^{1,2}, T. Chailloux¹, G. Pillonnet¹ and B. Allard²

¹ Univ. Grenoble Alpes, F-38000 Grenoble, France CEA, LETI, MINATEC Campus, F-38054 Grenoble, France

² Laboratoire Ampère, UMR CNRS Université de Lyon, INSA de Lyon

ABSTRACT –Microbial fuel cell (MFC) is a promising energy harvester for supplying sensors on seafloor where solar, thermal and vibration sources are inadequate. Extensive researches focused improvement of MFC biological and electrochemical capabilities while the electrical perspectives are poorly addressed in literature. In order to promote MFC as energy scavenger, this paper explains the methods used to electrically characterize MFCs and the way to model its steady state and dynamic operation modes close to the maximum power point (MPP). The method is applied to a benthic MCF delivering 22μ W at 0.29V optimal voltage. This work is a crucial step to efficiently apprehend the elaboration of an electrical harvesting interface.

Keywords—energy harvesting ; microbial fuel cell

1. INTRODUCTION

Harvesting energy in the surrounding environment is an advantageous alternative to conventional batteries for powering autonomously remote sensors in addition to processing in an eco-friendly way. Besides, solar, thermal gradient and mechanical vibrations are widely used as energy scavengers. Less analyzed in literature, the microbial fuel cell (MFC) studied in this paper is an emerging technology that exploits catalysis properties of bacteria into a couple of redox reactions, to convert chemical energy into electrical energy. The field of application is large regarding the wide range of organic substrates that can be used (organic rich sediment, compost, waste water) [1]. It is worth noting that they can be deployed in regions where any other energy harvesters would be inappropriate (seafloors, sewage works).

The MFC is relatively mature but the generated power is low (typically 10µW/cm²) and its voltage is not directly usable (typically less than 0.6V) to power continuously low-power sensor node. These main limitations come from the redox potential value involved in the MFC process and the slow bacteria activity. So far, the related researchers have focused their work on optimizing the MFC electrochemical properties (electrode material and design, bacteria selection) in order to maximize the power density [1]. However, only few of them study the MFC from an electrical point of view [2] i.e. how to characterize, model and efficiently extract the available electrical power from the MFC? An assumption would be that the field is widely covered by environment science researchers rather than researchers in power electrical field. Yet, actively capturing the energy with a power management unit is an essential step and can enhance tremendously the harvested power, particularly working at MPP where the MFC delivers the highest possible power.

In order to elaborate an efficient harvesting circuit, it is crucial to electrically model the MFC. That is the focus of this

paper. In literature, several characterization methods were already adopted that focused the MFC electrochemical properties [3]. First, polarization curve (PC), which is the most extensively used technique for estimating static electrical performances. Second, electrochemical impedance spectroscopy (EIS), which is used to find the small signal circuit model in the desired frequency range at a certain polarization point.

In this paper, both methods were performed on an *in-situ* benthic MFC and two equivalent circuits were deduced: a DC one analyzing the static response of the MFC close to MPP and an AC one analyzing its dynamic response when polarized close to MPP.

2. MFC ELABORATION



Fig. 1. Schematic diagram of the in-situ microbial fuel cell.

A schematic diagram of the MFC is shown in Fig. 1. Bacteria catalyze the oxidation of the organic substrate at the Anode A while oxygen is reduced at the Cathode C, inducing a transfer of electrons from A to C and thus energy generation [1]. Sediment collected at Gaou beach near Toulon was chosen as the anaerobic bacterial medium in which a 20-cm² graphite felt anode was buried. A 20-cm² graphite felt cathode was placed in water in which minerals were added to emulate the sea water characteristics. A pumping system was used to model the sea waves and favor the oxygen reduction. This setup has been settled in collaboration with B. Erable [4].

3. STATIC MODELISATION

3.1. Static measurements

First, the MFC static behavior was evaluated by tracing its PC using a potentiostat (Biologic VMP3). In Fig. 2, the blue

curve shows the MFC voltage, U_{CA} vs. the flowing current, I_{CA}. Each point was determined after 3h of stabilization, so that it can be considered as the real static characterization of the MFC (unlike most of the PCs obtained in literature using Cyclic Voltammetry [3]). The open-circuit voltage V_{OC} is 0.5 V, confirming the need for a voltage-boost harvesting interface to power sensors. The red curve shows the calculated power U_{CA}×I_{CA} vs. I_{CA}. MPP is achieved at U_{MPP}=0.29 V. At this point, the harvested energy is 22µW corresponding to a power density of 1.1 µW/cm².



Fig.2. Blue line: polarization curve of the MFC measured by varying progressively the MFC output voltage (0.1 V every 3h once the induced output current is stable). Green dashed line: polarization curve close to MPP modelled by a thevenin electrical model. Red line: output power.

3.2. Static electrical model

The solar, thermal or bio fuel-cell harvester is often modeled by a Thevenin equivalent circuit when operating close to MPP (Fig. 3) [5]. The polarization curve around MPP shown in Fig. 2 can be roughly represented by a straight line (dashed line in Fig. 2) defined with $U_m = 0.6$ V and $R_m = 3.8$ k Ω .



Fig.3. Thevenin electrical circuit equivalent to the MFC close to MPP.

Identifying these two parameters is a crucial step to determine the value of R_h and maximize the power extraction from the MFC. In fact, the power received by a harvester interface is expressed in (1).

$$P_h = U_h I_h = \frac{R_h}{(R_h + R_m)^2} U_m^2 = k U_m^2$$
(1)

Where k is the coupling coefficient between the harvester and harvesting interface. The harvested power is optimized when k is maximized, i.e. R_h is equal to R_m . Then, the electrical interface (e.g. boost converter) has to present an input impedance equal to the MFC output impedance R_m .

4. DYNAMIC MODELISATION

4.1. Dynamic measurements

The MFC dynamic behavior was determined analyzing its current response to a small sinusoidal signal perturbation around the polarization voltage, V_{MPP} . The impedances of both electrodes have been measured to decouple the characteristics of each (interesting to see for instance which one is limiting the MFC performances). For convenience, Fig. 4 gathers the results in a Bode diagram of the total MFC impedance.

4.2. Dynamic electrical model

A dynamic analysis can be very valuable to anticipate the

MFC behavior when facing a switching power converter. The model is more detailed than the one seen previously and is determined using the previous EIS results. It can be divided into two symmetrical models, one representing the anode, the other one the cathode (Fig. 5). The capacitive component represents the double layer charging along the electrode surface, the resistive ones the charge transfer resistance across the electrode surface and the charge flow resistance in the electrodes and the electrolyte. The constant phase element (CPE) is attributed to the diffusion effect, and eventually the inductive component is characterized in the high frequency range and can be due to connection artifacts. The model parameters are calculated to fit with impedance measurements (Fig. 4). It is interesting to note that the sum of all the resistances matches with the static equivalent resistance R_m .



Fig.4. Bode diagrams (a) Impedance modulus vs. frequency : Measurement (black line) and Equivalent model (red line). (b) Impedance phase vs. frequency : Measurement (black line) and Equivalent model (red line)



Fig.5. Dynamic electrical circuit equivalent to the MFC close to MPP

5. CONCLUSION

Benthic MFC static and dynamic models could be deduced from appropriate characterizations. This work is a crucial step to design a suitable electric interface dedicated to benthic MFC characteristics, in order to harvest its energy in an optimized way. The dynamic model is particularly interesting to evaluate the association of the MFC to an electrical switching converter.

6. References

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