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On-line monitoring of microbial fuel cells operated with pulse-width modulated electrical load

J. Coronado[a], B. Tartakovsky[b], M. Perrier[a,*]

[a] Departement de Génie Chimique, École Polytechnique Montréal, C.P. 6079 Succ., Centre-Ville Montréal, QC, Canada
[b] National Research Council of Canada, 6100 Royalmount Ave., Montreal, QC, Canada

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ABSTRACT

This study describes application of an equivalent circuit model (ECM) for on-line monitoring of microbial fuel cells (MFCs). ECM analytical solutions were derived for MFCs operated with pulse-width modulated electrical load connection at high and low frequencies. These analytical solutions were used to develop an on-line procedure for estimating MFC internal resistance, internal capacitance and open circuit voltage. The proposed parameter estimation and monitoring procedure was used to follow MFC startup performance as well as its performance at various organic loads. A comparison of ESM-based on-line estimations with conventional polarization tests confirmed feasibility of the proposed approach.

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1. Introduction

Microbial fuel cells (MFCs) represent a new type of a bioreactor capable of utilizing a broad variety of organic wastes for electricity production [1–3]. Biodegradation of organic matter in the MFC is accomplished by electricigenic (anodophilic) biofilm formed at the anode. The electricigenic microorganisms of the biofilm oxidize organic matter, transfer electrons to the anode and release protons. The electrons pass through an external electrical circuit and protons migrate to the cathode, where a catalytic reaction of oxygen reduction takes place.

Optimization of external electrical load is increasingly being considered for maximizing MFC power output. Park and Ren [4] developed a hysteresis controller-based MFC energy harvesting system with potentiometers as hysteresis controllers. The proposed control strategy enabled real time maximum power point tracking and maximized MFC energy production. Real time maximization of power production in a stack of two MFCs using a multi-unit approach for optimizing electrical loads (external resistances) was demonstrated by Woodward et al. [5]. Moreover, a comparison of several real-time optimization approaches demonstrated that a simple perturbation–observation algorithm for external resistance adjustment could be successfully used for power output maximization [6]. More recently, improved performance of a MFC operated with intermittent connection/disconnection of electrical load has been demonstrated [7,8].

While MFC performance could be improved using model-free approaches described above, the knowledge of electrochemical characteristics such as internal resistance is instrumental in maximizing MFC power output. Typically, electrochemical characteristics of MFCs are estimated by means of electrochemical methods like polarization curves, cyclic voltammetry and electrochemical impedance spectroscopy [9]. These methods require MFC to be taken off-line (disconnected from the electrical load) to perform the measurements. With this regard, model-based approaches could offer an advantage of continuous and non-disruptive process monitoring. Recently, an equivalent circuit model was used to identify the optimal capacitance in a transformer-based MFC power management system [10]. A similar equivalent circuit model was used to describe dynamics of a MFC operated with periodic connection/disconnection of electrical load and perform frequency analysis of this system [11]. This work demonstrated that MFC power output could be maximized both under limiting or non-limiting organic load conditions, without changing the value of the external resistance connected to the MFC by intermittently connecting/disconnecting the electrical load.

Looking forward toward model-based MFC control to further improve MFC power output, it might be necessary to develop means

* Corresponding author. Fax: +1 514 340 4159.
E-mail address: Michel.Perrier@polymtl.ca (M. Perrier).

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for on-line monitoring of key MFC parameters. The study described below employs a simple equivalent circuit model (ECM) to develop a parameter estimation procedure and apply it for real-time MFC monitoring.

2. Experimental

2.1. MFC design and operation

Two membrane-less 50 mL air-cathode MFCs (MFC-1 and MFC-2) were constructed using nylon plates as described elsewhere [7]. The MFCs were equipped with carbon felt anodes (SGL Canada, Kitchener, ON, Canada) and manganese oxide air cathodes (Electric Fuel Ltd, Bet Shemesh, Israel). The electrodes were separated by a nylon cloth. MFC-1 contained two 10 cm × 5 cm carbon felt anodes with a total thickness of 10 mm and two cathodes (one on each side) with a total surface area of 100 cm^2, while MFC-2 had one 10 cm × 5 cm carbon felt anode with a thickness of 5 mm and one 50 cm^2 cathode.

The MFCs were inoculated with a mixture of anaerobic sludge and an effluent from an operating MFC. The MFCs were maintained at 25 °C and were continuously fed with sodium acetate and trace metal solutions using a syringe pump and a peristaltic pump, respectively. An influent acetate concentration varied between 425 mg L^{-1} and 1700 mg L^{-1} by changing flow rate of the acetate stock solution, while maintaining a total flow rate of 150–160 mL d^{-1} corresponding to a hydraulic retention time of 8 h. A detailed description of MFC design, stock solution composition, and operating conditions can be found elsewhere [7].

2.2. Pulse-width modulated connection of external resistance

In the pulse width modulated (PWM) mode of MFC operation, the external electrical load is controlled by continually switching on and off an electronic power switching device (R-PWM mode). R-PWM mode can be characterized by the duty cycle (D), which is defined as the ratio of the cycle part during which the switch is closed (on-part of the cycle) to the cycle length. D is commonly expressed as percentage of cycle time:

$$D = \frac{t_{on}}{t_{on} + t_{off}} \times 100\% \qquad (1)$$

where t_{on} is the on-part of the cycle (switch is closed) and t_{off} is the off-part of the cycle (switch is open). Consequently, cycle length (T) is defined as $T = t_{on} + t_{off}$.

In the experiments, pulse-width modulated connection of the external resistor (R_{ext}) to MFC terminals was achieved by adding an electronic switch (IRF540, International Rectifier, El Sequndo, CA, USA) to the external electrical circuit. The electronic switch is denoted as SW in Fig. 1 with the corresponding switch resistance shown as R_{SW}. The switch was computer-controlled using a Labjack U3-LV data acquisition board (LabJack Corp., Lakewood, CO, USA). The data acquisition board was also used to record MFC voltage at a maximum rate of 22,500 acquisitions per second.

To account for the electronic switch resistance, the data acquisition board measured MFC output voltage (U_{MFC}) and voltage over the switch (U_{sw}), as shown in Fig. 1. Voltage over the resistive load (U_{Load}) was calculated as the difference between U_{MFC} and U_{sw} ($\underline{U_{Load}} = U_{MFC} - U_{sw}$). Electric current was calculated as $I = U_{Load}/R_{Load}$ $I = \frac{\underline{U_{Load}}}{R_{Load}}$ by applying Ohm's law over the external load resistance ($\underline{R_{Load}}$). Also, R_{sw} value was estimated by dividing the voltage over the switch by the current. In the following discussion, R_{ext} denotes the sum of the external load connected to the circuit and the switch resistance, i.e. $R_{ext} = R_{Load} + R_{sw}$ with a corresponding external voltage U_{ext}, as follows from the diagram shown in Fig. 1.

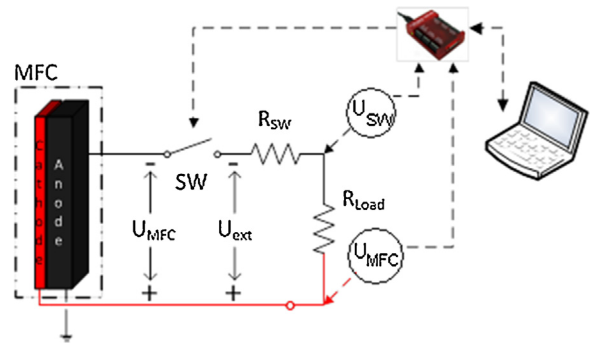

Fig. 1. Schematic diagram of the electrical circuit used in all tests. Notations: SW is the electronic switch, R_{SW} is the switch resistance, U_{sw} is the corresponding voltage measured by the data acquisition board, R_{Load} is the electrical load connected to MFC, U_{MFC} is the MFC voltage, and U_{ext} is the voltage corresponding to total external resistance $R_{ext} = R_{Load} + R_{sw}$.

2.3. Numerical methods

All computer simulations were carried out using *Matlab R2010a* (Mathworks, Natick, MA, USA). Parameter estimation was carried out using *fmincon* function of Matlab. The root mean square error between the model outputs and measured values of U_{MFC} was minimized using data of five on/off cycles obtained during both low and high frequency MFC operation. At an R-PWM frequency of 0.1 Hz this corresponded to 637 data points. At a frequency of 100 Hz, 1000 data points were used to estimate model parameters. On-line parameter estimations were carried out using a program written in Visual Basic V6 (Microsoft Corp, Redmond, WA, USA).

3. Results and discussion

3.1. Equivalent circuit model

In this study, dynamics of MFC output voltage was modeled using an equivalent circuit model, which consists of two resistors (R_1 and R_2), one capacitor (C), and an internal power source, as shown in Fig. 2.

The following first order differential equation can be written to describe voltage dynamics over the internal capacitance C shown in Fig. 2:

$$\frac{dU_c(t)}{dt} = \frac{U_{oc}}{C(R_1 + R_{ext})} - \frac{R_1 + R_2 + R_{ext}}{R_2 C(R_1 + R_{ext})} U_c(t) \qquad (2)$$

where $U_c(t)$ is the voltage at the internal capacitor, R_{ext} is the external resistance, and U_{oc} is the apparent open circuit voltage.

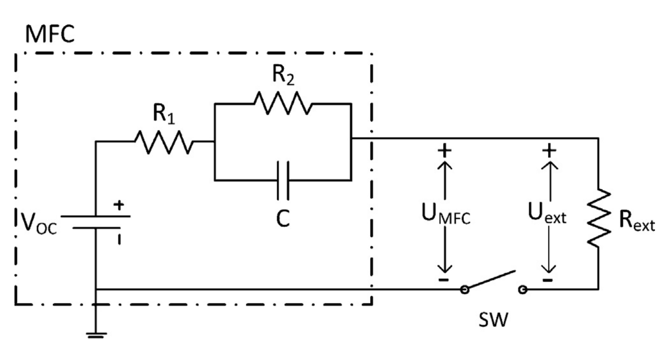

Fig. 2. MFC Equivalent Circuit Model consisting of two internal resistances R_1 and R_2 and internal capacitance C. Also shown are total external resistance (R_{ext}) and electronic switch (SW).

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