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Optimal operating point for energy harvesting from microbial fuel cell with finite initial energy

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HIGHLIGHTS

- Maximum power operating point may not be best for finite amount of initial energy.
- An operating point that optimizes the power level and efficiency was developed.
- Much more energy can be harvested than that of maximum power operating point.

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ABSTRACT

It is well known that maximum attainable power is generated at a certain operating point from renewable energy resources. As can be seen in the microbial fuel cells (MFCs) and thermoelectric generators (TEGs), a linear output voltage current characteristic will form a convex output power pattern, where the maximum power operating point (MPP) can be analytically derived. Although operation at the MPP has been widely used from the instantaneous power standpoint, it would not be an optimal operating point in terms of energy extraction if the energy resource has a finite amount of initial energy and follows a quadratic loss model. In this paper, an optimal operating point that simultaneously optimized the harvested power level and conversion efficiency to maximize the energy extraction from an MFC with a finite initial energy was developed. At the proposed optimal operating point, an MFC generated less power, but internal loss was considerably less compared to that of the MPP, which entailed harvesting more energy from the initial energy in the reactor. The proposed energy harvesting scheme can achieve much higher electricity generation efficiency from an MFC that contains a finite amount of energy.

1. Introduction

1.1. MFC model

Energy harvesting from Microbial Fuel Cells (MFCs) has been extensively investigated during the recent years. Electrochemically active bacteria (EAB), such as *Geobacter*, *Shewanella*, and *Pseudomonas* spp., are known to generate electricity from bio-degradable substrates [1–3]. These microorganisms produce electrons while they oxidize an electron donor such as glucose, acetate, fatty acids, and wastewater organic carbon [4–6]. The electrons flow through an external circuit from anode to cathode and are used to form water at the proton exchange membrane at the cathode. The power density from such MFCs has been improved up to recently reported 6.9 W/m^2 [7].

The electrical equivalent circuit has been used to describe the electricity generation from the MFC systems and operational characteristics, such as steady-state conditions, charging/discharging dynamics, and frequency responses [8–10]. Methods to identify the parameters associated with the equivalent circuit have also been proposed [11–14]. Fig. 1 shows the typical electrical equivalent circuit models for MFCs. As can be seen in the equivalent circuit in Fig. 1b, the capacitor models the dynamic change of MFC voltage and current. Once the transient is attenuated and the reactor operates in a steady state generating electricity consistently, it can be modeled with the simple equivalent circuit in Fig. 1a, especially in the ohmic region where the energy harvesters typically operate [9,11,14,15]. Due to the voltage drop across the internal resistor, the output voltage decreases linearly as the load current increases, which makes an MFC a weak voltage source with a convex output power curve.

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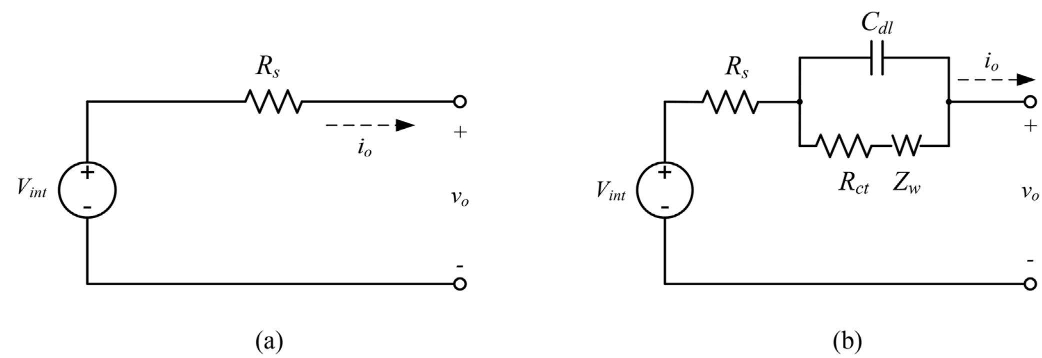

Fig. 1. Typical MFC equivalent circuits. (a) Simplest steady-state equivalent circuit. (b) Randles equivalent circuit with Warburg diffusion element. R_s, R_{ct}, C_{dl}, and Z_w denotes the ohmic resistance, charge transfer resistance, double-layer capacitance, and Warburg diffusion element, respectively.

1.2. Biochemical energy in MFC reactor

Batch-fed MFCs are an attempt to control nutrient availability by providing regular doses of a designated electron donor. Microorganisms, including EABs, use different metabolisms that work to oxidize chemicals, e.g., organic electron donors such as acetate, releasing metabolic energy in the form of electrons. When captured with the potential difference between anode and cathode, as occurs in MFCs, the electrons released from the oxidation of the electron donors can be used to generate electrical power. This MFC set-up is very commonly used in the literature and yet is susceptible to the effects of limiting nutrients, even though the reactor is regularly supplied with an electron donor; the building cytotoxic effects of increasing waste products; and the complex metabolic needs of some EABs.

Batch-fed MFCs represent closed systems and are susceptible to decreasing nutrient concentrations and increasing concentrations of metabolic wastes over time. How these changing parameters impact the long-term operation of batch-type MFCs is largely unknown. Mixed inoculum batch-type MFCs have the additional challenge of needing to nutritionally support several potential EABs within a given reactor, noting that mixed species EABs will have different nutritional requirements including a variety of electron donors. Finally, mixed species EABs can produce waste products of varying cytotoxicity. Over time, the end result can be the creation of a chemically heterogeneous environment with undefined effects on the productivity and sustainability of power.

1.3. Electrical power extraction and loss mechanism

It is well known that some energy resources such as fuel cells and thermoelectric generators (TEGs) have an operating point that generates the maximum power, which is called maximum power operating point (MPP). It can be analytically shown that the maximum power occurs when the output voltage is equal to half of the internal thermodynamic voltage, also known as open-circuit voltage (OCV), or when the external resistance is same as the internal resistance. The output power at the MPP is given as

$$P_{\max} = \frac{V_{\text{int}}^2}{4R_s} \tag{1}$$

where V_{int} and R_s is the internal thermodynamic voltage and internal resistance, respectively. The operation at MPP has been widely used to generate from various renewable energy resources including wind turbines and photovoltaic panels. Many renewable energy management systems, including MFCs, operate at the MPP which requires tracking to adjust for MPP variations. Operation at the MPP will not only extract the largest amount of power that the source can provide in a given condition, but will also harvest the largest amount of energy at the output for a given time T.

$$E = \int_0^T P(t)dt \tag{2}$$

Therefore, it makes sense to run a renewable generator system at the MPP if the energy comes in the form of instantaneous power, e.g., wind or solar irradiation. Because of the uncertainty in knowing the total amount of attainable energy or the duration of extraction, it would be the best approach to extract the maximum as it is available.

However, it would be a different situation if an energy management system tries to extract and convert a finite amount of energy from a renewable energy source. For example, a batch-fed MFC reactor has a finite source of metabolic and chemical energy that can be converted into electricity. Any conversion of energy between different forms incorporates loss. In MFC's case, it occurs when the voltage drops as the electrons flow out of the reactor and it changes as load current varies. Although it is true that the operation at the MPP will extract the maximum power instantaneously, it will not harvest the maximum possible energy from the initially stored energy because of the conversion efficiency.

The internal resistance explains the voltage drop at the MFC output terminals, and it also models the internal power loss.

$$P_{loss} = i_o^2 R_s \tag{3}$$

where P_{loss} is the power that is dissipated in the internal resistance R_s. It can be seen that the amount of power loss from the thermodynamic source increases quadratically proportional to the output current as output voltage linearly drops, which is why the MPP exists. The steady-state output power can be given as follows.

$$P_o = P_{\text{int}} - P_{loss} = V_{\text{int}} i_o - i_o^2 R_s \tag{4}$$

The energy conversion efficiency of an MFC reactor linearly decreases as the output current increases. Suppose a load resistor R_o is connected at the MFC output terminals. The conversion efficiency can be determined as

$$\eta = \frac{P_o}{P_o + P_{loss}} = \frac{i_o^2 R_o}{i_o^2 R_o + i_o^2 R_s} = \frac{R_o}{R_o + R_s}. \tag{5}$$

The efficiency at MPP is 0.5, meaning the system loses 50% of internally stored energy during the conversion process.

Fig. 2 shows a computer simulation for an MFC reactor with 1 V V_{int} and 100 Ω R_s. It is assumed that the reactor contains 1 J of initial energy. As discussed, the MPP occurs when the output resistance R_o is 100 Ω, same as R_s, where the output current is 5 mA.

$$i_o = \frac{V_{\text{int}}}{R_s + R_o} \tag{6}$$

The maximum power is 2.5 mW from (1). Two more operating points around MPP were simulated: 185.71 Ω (0.35 A) and 53.85 Ω (0.65 A). As can be seen in Fig. 2b, the power loss is proportional to the square of output current and the generation efficiency decreases linearly as load