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Microbial fuel cell energy harvesting using synchronous flyback converter

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HIGHLIGHTS

- Novel MFC energy harvesting scheme using a synchronous flyback converter.
- Improved harvesting efficiency using transformer based synchronous converter.
- Non-inverting hysteresis controller for adaptive harvesting with fewer components.

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ABSTRACT

Microbial Fuel Cells (MFCs) use biodegradable substrates, such as wastewater and marine sediments to generate electrical energy. To harvest more energy from an MFC, power electronic converters have recently been used to replace resistors or charge pumps, because they have superior controllability on MFC's operating point and higher efficiency in energy storage for different applications. Conventional diode-based energy harvesters suffer from low efficiency because of the energy losses through the diode. Replacing the diode with a MOSFET can reduce the conduction loss, but it requires an isolated gate signal to control the floating secondary MOSFET, which makes the control circuitry complex. This study presents a new MFC energy harvesting regime using a synchronous flyback converter, which implements a transformer-based harvester with much simpler configuration and improves harvesting efficiency by 37.6% compared to a diode based boost converter, from 33.5% to 46.1%. The proposed harvester was able to store 2.27 J in the output capacitor out of 4.91 J generated energy from the MFC, while the boost converter can capture 1.67 J from 4.95 J.

1. Introduction

Microbial fuel cell (MFC) is an emerging technology that uses microorganisms to generate electrical energy from biodegradable substrates, such as municipal and industrial wastewater as well as marine sediments. The oxidation of organic substrates by microbial extracellular electron transfer results in electron transfer to the anode electrode, and current is generated when the electrons further flow to the cathode through the external circuit connection [1–3]. The power output from MFC systems has been improved significantly due to the development of new materials and reactor configurations, and in some areas such as remote sensing, the MFC has been considered as a viable power source [4–8].

One of the main challenges facing MFC technology is how to make power generation more efficient. Because the output power of an MFC is low and difficult to use directly [9,10], advanced power conversion techniques need to be developed to maximize energy harvest [11–13]. The harvesters that have been studied in recent years largely fall into two categories: passive and active harvesters.

Passive harvesters extract energy with passive electrical components, such as resistors, capacitors, and charge pumps. A resistor is the simplest energy extraction device and has been widely used [14–16]. It is well known that the extracted power is maximum when $R_{ext} = R_{int}$, but it should be noted that all of the extracted energy will be dissipated as heat instead of being used or stored. A supercapacitor is a better option than the resistor because it actually stores the energy instead of burning it. Different combinations have been used, but they share the idea of connecting the capacitors directly to the MFCs [4,5,7,17]. The problem is that the operating point of the MFC changes when the capacitor voltage changes

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as the energy balance varies. Therefore, it is practically impossible to maintain the operating point at the maximum power point (MPP) with direct connection of capacitors, where an MFC reactor can generate the maximum power possible for a given condition. A charge pump is a more advanced solution than directly-connected capacitors [4,7,18], because it consists of capacitors and switches that can increase the output voltage from a low input voltage and maintain it at a certain fixed level. Although charge pumps do contain active components, their controllability is insufficient to meet specific MFC requirements. Moreover, the availability of off-the-shelf charge pumps for MFCs is very limited, and their current level is low (e.g., <500 μA) to avoid the input voltage drop, which makes the harvesting efficiency low [19].

Active harvesters use power electronics converters and actively control the operating point and the energy extraction of an MFC. Active energy extraction is the most effective way to harvest the energy from low-power sources including MFCs [18,20–22]. The energy can be stored in a capacitor and the MFC voltage is controlled at any operating point, e.g., MPP. Power electronics converters using semiconductor devices switching at high frequency can provide far better controllability on power flow than passive components, which results in significantly improved energy extraction efficiency. For example, a diode-based boost converter operating in MPP can harvest 76 times more energy than the charge pump that is commonly used in MFC studies [19]. It also is beneficial to implement a controller that tracks the varying MPP [13]. If a double-layered scheme is used, the improved harvesting efficiency, increased capacity, and regulated output voltage can be simultaneously achieved [23]. Although the active harvesting approach has challenges such as complex circuitry and control, and higher loss and power consumption of the control system, the benefits in performance and efficiency outweigh the disadvantages. The elements of power converters, such as inductance, duty ratio, and the switching frequency, that affect the energy extraction were investigated in Ref. [24].

The boost converter is one of the widely used power converters for MFC energy harvesting because of its simple structure and the need to increase the output voltage of the MFC [20–22,25]. A conceptual boost converter schematic is shown in Fig. 1. When the switch Q_1 is closed and the switch Q_2 is open, the current will flow through the inductor L. The voltage will be generated across the inductor according to the basic inductance–current voltage relation

$$V_L(t) = L\frac{\mathrm{d}i_L(t)}{\mathrm{d}t} \tag{1}$$

where V_L is the voltage across the inductor L, and i_L is the current passing through it. Then the switches Q_1 and Q_2 should open and close, respectively, to forward the energy stored in the inductor to the load. During this time the current will start to flow through the switch Q_2 to charge the capacitor and the charging voltage will be given as

$$V_C = V_{\mathrm{in}} + V_L \tag{2}$$

where V_L is the inductor voltage achieved on the first time period. When all of the energy in the inductor is discharged, Q_1 and Q_2 should close and open to start the energy extraction. Switching between these two modes in high frequency will allow the energy to be extracted and stored in the capacitor with a boosted voltage.

For the simplest configuration, a diode is used for Q_2. A diode conducts or blocks the current path according to the bias voltage across it (forward- and reverse-biased). However, unlike the resistors, the diode has a fixed voltage drop (V_F, generally 0.4–0.7 V regardless of the current magnitude) when it is forward-biased and conducting. Hence, the loss of the diode is given as

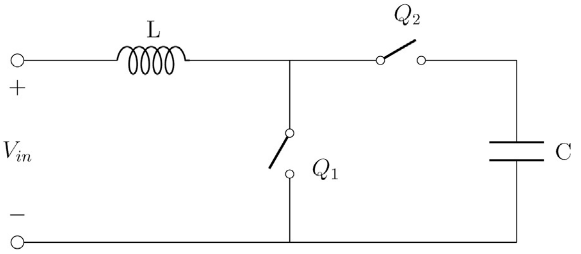

Fig. 1. Schematic diagram of boost converter.

$$P_D = V_F I_L \tag{3}$$

and it is very high considering the low power output of MFC [19], which is a critical drawback of the diode-based boost converter. To avoid the high loss of the diode, a synchronous boost converter can be used [25]. The synchronous boost converter replaces the diode with a MOSFET, and it reduces the overall loss significantly due to the MOSFET's low on-resistance (order of mΩ for low-power MOSFETs). However, the problem of using the synchronous boost converter is that the MOSFET will become a floating switch, which, unlike the diode, requires an isolated source to turn it on and off. Transformers have been used to drive the MOSFET in the synchronous boost converter, but the circuitry and control becomes quite complex.

In this study, a synchronous flyback converter was applied to MFC energy harvesting to simplify the control circuitry and improve the efficiency. The flyback converter is a viable alternative of the boost converter, because its energy transfer transformer can readily be used to drive the secondary floating switch. Hence, the synchronous flyback converter will be more efficient by eliminating the diode and using the main transformer for the gating signal as well as power transfer. Its energy harvesting performance at the MPP was compared to that of the boost converter.

2. Methods and materials

2.1. Microbial fuel cell

A two-chamber cube-shaped MFC was used in the study. A cation exchange membrane (CMI-7000, Membranes International, NJ) was used to separate the anode and cathode chamber, and each chamber's empty volume was 150 mL. Graphite brushes and carbon cloth were used as the anode and cathode material, respectively. Anolyte was acetate-based medium containing 1.25 g CH_3COONa, 0.31 g NH_4Cl, 0.13 g KCl, 3.32 g $NaH_2PO_4 \cdot 2H_2O$, 10.32 g $Na_2HPO_4 \cdot 12H_2O$, 12.5 mL mineral solution, and 5 mL vitamin solution per liter [26,27]. Phosphate buffered potassium ferricyanide solution (50 mM) was used as the catholyte to minimize the cathode effects on system performance. The reactor was initially operated in fed-batch mode until repeatable voltage was obtained, then they were switched to continuous-flow operation by recirculating anolyte with a 1000 mL reservoir at a flow rate of 45 mL min^{-1} and recirculating catholyte with another reservoir at a flow rate of 114 mL min^{-1}, respectively [19,31].

2.2. Synchronous flyback converter

The flyback converter is derived from the boost converter, but uses a transformer to store energy instead of the inductor in the boost converter. The transformer also offers voltage boost and