Journal of Power Sources 395 (2018) 98–105

Contents lists available at ScienceDirect

Journal of Power Sources

journal homepage: www.elsevier.com/locate/jpowsour

Scaling up benthic microbial fuel cells using flyback converters

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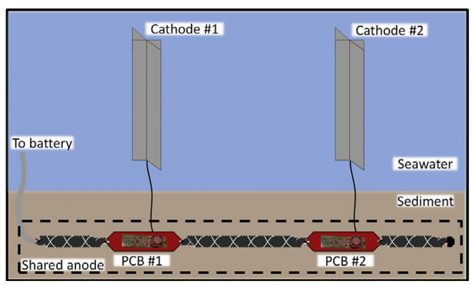
HIGHLIGHTS

- Scalable energy harvesting strategy for linear benthic microbial fuel cells.
- Scaling achieved using multiple power management systems on a single shared anode.
- Power management system buried alongside the shared anode.
- Voltage boosted from 0.4 V to 12 V with a 77% power efficiency.
- 20 m of anode tested in field-relevant conditions operating for two months.

GRAPHICAL ABSTRACT



ARTICLE INFO

Keywords:
Benthic microbial fuel cells
BMFC
Power management system
Flyback converter

ABSTRACT

Benthic microbial fuel cells (BMFCs) are alternative energy sources that can power sensors underwater. However, their use underwater is limited by low conversion efficiencies of the low-voltage energy to higher voltages required by modern electronics. Additionally, BMFC systems detailed in the literature are incompatible with the deployment difficulties associated with underwater sensing. In this work, we present an optimal underwater scaling strategy combined with an integrated power management system. We successfully demonstrate the modular scale-up of BMFCs using in-line flyback converters that held the BMFC input voltage at an optimal cell potential of 0.35–0.5 V while directly increasing output voltage to 12 V. Two flyback converters could operate successfully on a single shared anode, delivering 16 mW of the BMFC power directly to a 12 V rechargeable battery at 77% efficiency. We show that the internal resistance of the BMFC and effective resistance of the power management system determine the transition from start up to stable BMFC operation for up to seventy days. These combined factors have not been demonstrated previously. Such a system allows for a broad range of BMFC underwater array configurations that are critical to the future integration of BMFCs with seafloor systems and sensors.

1. Introduction

One low-tech, low maintenance approach to generating power by harnessing redox gradients that exist in sediments is via microbial fuel cell technology; we refer to these systems as benthic microbial fuel cells (BMFC) [1]. Redox gradients naturally occur in aquatic environments as the difference in redox potential between the aerobic zone and the anaerobic zone within the sediment. Typically, an excess of oxygen drives the redox potential to positive oxidizing values in the aerobic zone. In this environment, a BMFC cathode would accept electrons via the oxygen reduction reaction (ORR) [2–4]:

$$O_2 + 4H^+ + 4e^- \rightarrow 2H_2O \quad (1)$$

The reaction described by equation (1) can also be catalyzed by specialized bacteria forming cathodic biofilms and subsequently sustainable biocathodes [5–8]. However, when oxygen is depleted, often

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https://doi.org/10.1016/j.jpowsour.2018.05.042
Received 8 November 2017; Received in revised form 9 May 2018; Accepted 10 May 2018
0378-7753/ Published by Elsevier B.V.

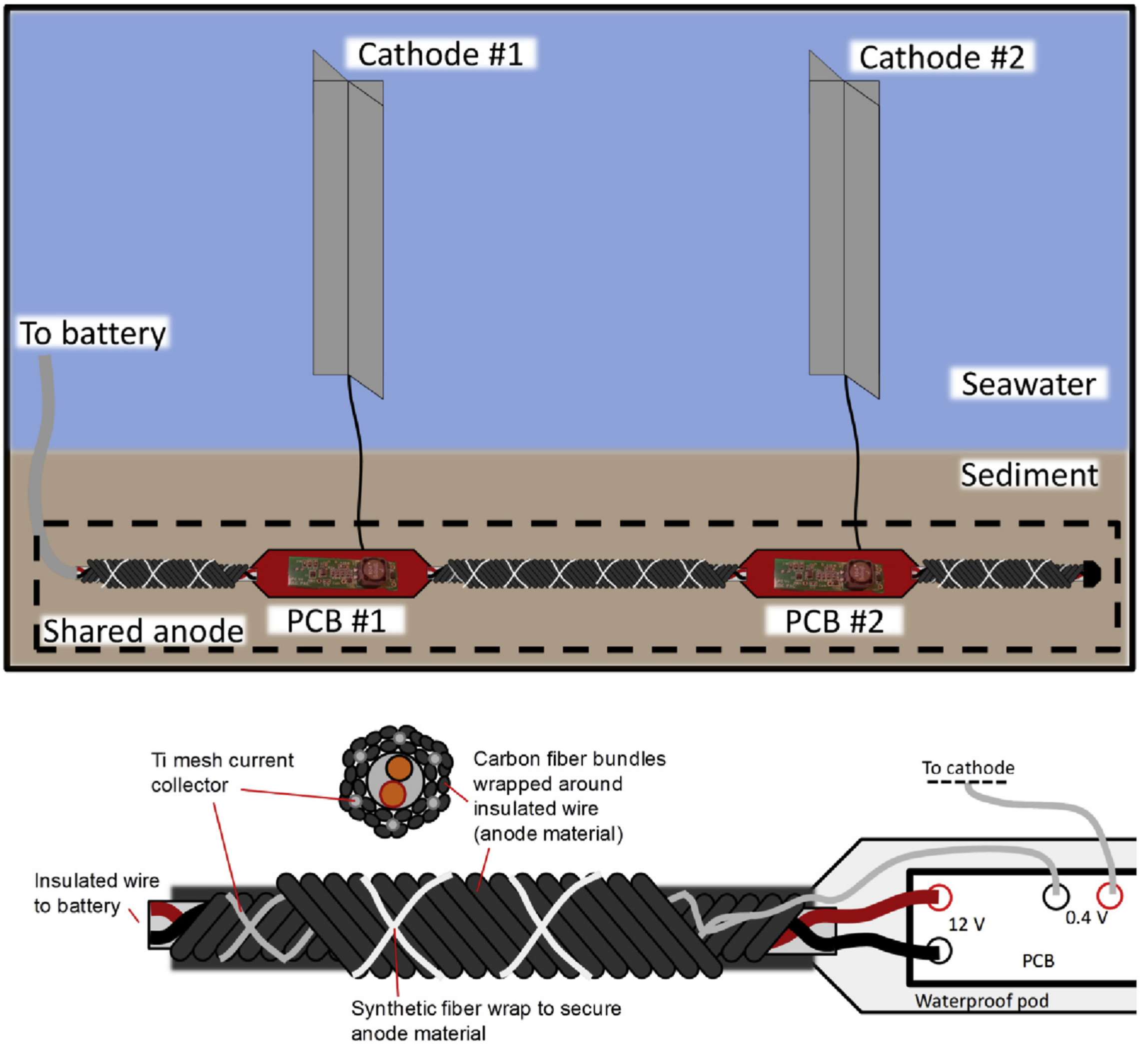

Fig. 1. Diagram of the of the BMFC system showing the main components and connections. Not drawn to scale.

several centimeters into the sediment, anaerobic microbial respiration procceses drive the redox potential to negative, reducing values [9,10]. The BMFC anode therefore operates through microbial metabolisms oxidizing organic carbon ultimately to carbon dioxide, protons, and electrons:

$$Organic\ Carbon + H_2O \rightarrow CO_2 + H^+ + e^- \quad (2)$$

The microbial community generates by-products that contain the electrons described by equation (2), which can be oxidized at the anode [5,11–17]. Microorganisms on the anodes and cathodes of BMFC utilize extracellular electron transfer to reach the electrodes. Extracellular electron transfer provides the fundamental basis by which BMFCs operate [18–22]. BMFCs utilize the aerobic (cathode) and anaerobic (anode) biofilms colonizing each electrode to generate power. Because the biofilms are naturally-forming and are sustained through natural processes such as tidal movement to bring in replacement nutrients, the BMFC power is considered an alternative, sustainable, and renewable energy.

BMFCs suffer from a scaling issue that arises from an operating cell voltage of 0.4–0.5 V. As power increases, the internal resistance of the BMFC inversely decreases. For a 1 W BMFC operating at 0.4 V, the internal resistance is expected to be 0.16 Ω, which is practically unattainable due to the resistivity of electrode materials. Thus, BMFCs must be stacked in series to increase the total cell voltage or in parallel to meet the low internal resistance required. It has been demonstrated that they scale poorly when directly connected in the series and parallel configuration [23]. Power management systems (PMS) have avoided the issue by introducing a two-stage design, placing an intermediate charge storage (usually a capacitor) that bridges the incompatible electrical load with the low voltage BMFC [24–27]. Further, PMS are separated into two categories: 1) PMS that are self-starting with all charge derived from the BMFC and 2) PMS that maintain an already charged battery. Both have their advantages in application. The difficulty with current designs of PMS is that in practice, after combination, they rarely scale effectively with the BMFCs intended for integration.

Effective scaling with BMFCs takes into consideration the physical aspects of the BMFC in addition to the electrical aspects. These physical aspects include the size of the BMFC, the location of the PMS relative to the BMFC, and the ease of deployment of the integrated system (BMFC + PMS). These factors are overlooked in laboratory studies where the BMFC is conveniently located nearby. However, when considering how to integrate multi-BMFC arrays hundreds of meters away, the PMS must be designed with this in mind. For example, we recently demonstrated the challenges of deploying a 210 m, multi-stranded BMFC linear array that operated a seafloor magnetometer [28]. This system utilized the PMS described here to connect multiple BMFCs in parallel using flyback converters.

PMS that utilize flyback conversion in discontinuous conduction mode take advantage of the flexibility to choose the operating region of the BMFC and boost the voltage across a single transformer [29]. On the primary-side of the transformer, the circuit design focuses on operating