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Controlling for peak power extraction from microbial fuel cells can increase stack voltage and avoid cell reversal

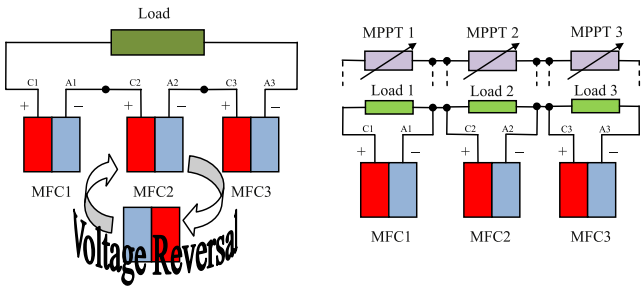
Hitesh C. Boghani [a], George Papaharalabos [b], Iain Michie [a], Katrin R. Fradler [a], Richard M. Dinsdale [a], Alan J. Guwy [a], Ioannis Ieropoulos [b, 1], John Greenman [b], Giuliano C. Premier [a, *]

[a] Sustainable Environment Research Centre (SERC), Faculty of Computing, Engineering and Science, University of South Wales, Llantwit Rd, Pontypridd, Mid-Glamorgan CF37 1DL, UK
[b] Bristol Robotics Laboratory, University of the West of England and University of Bristol, Bristol BS16 1QY, UK

HIGHLIGHTS

- It is possible to avoid voltage reversal in stacked MFCs despite feed imbalance.
- We applied MPPT along with hybrid connectivity to prevent voltage reversal.
- MPPT improved stack performance compared to series/parallel connectivity alone.
- The strategy is transferable between significantly different MFC systems.

GRAPHICAL ABSTRACT



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ABSTRACT

Microbial fuel cells (MFCs) are bioelectrochemical systems which can degrade organic materials and are increasingly seen as potential contributors to low carbon technologies, particularly in energy recovery from and treatment of wastewaters. The theoretical maximum open circuit voltage from MFCs lies in the region of 1.1 V, but is reduced substantially by overvoltage losses. Practical use of the power requires stacking or other means to increase voltage. Series stacking of MFCs with typically encountered variability in operating conditions and performance raises the risk of cell reversal, which diminishes overall power performance. A novel strategy of MFC subsystem series connectivity along with maximum power point tracking (MPPT) generates increased power from individual MFCs whilst eliminating cell reversal. MFCs fed with lower concentrations of substrate experienced voltage reversal when connected in normal series connection with one common load, but when MFCs and loads together were connected in series, the underperforming cell is effectively bypassed and maximum power is made available. It is concluded that stack voltage may be increased and cell reversal avoided using the hybrid connectivity along with MPPT. This approach may be suitable for stacked MFC operations in the event that large scale arrays/modules are deployed in treating real wastewaters.

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1. Introduction

Microbial fuel cells (MFCs) are a promising technology, capable of generating electricity whilst degrading/oxidising organic substances such as food processing wastes, at their anodes. Such COD

* Corresponding author. Tel.: +44 (0)1443 482333; fax: +44 (0)1443 482169.
E-mail addresses: ioannis.ieropoulos@brl.ac.uk (I. Ieropoulos), iano.premier@southwales.ac.uk (G.C. Premier).
[1] Tel.: +44 (0) 1173286318; fax: +44 (0) 1173283960.

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removal is catalysed by electrogenic bacteria, which use the anode as an electron acceptor and produce a current flow with the aid of (typically) an oxygen reduction reaction at the cathode electrode. Although these bioelectrochemical devices can develop theoretical open circuit voltages of 1.1 V (at NTP, pH 7 and acetate concentration of 5 mM) [1], the highest open circuit voltages achieved are *circa* 0.8 V. When operated under load, MFCs are able to generate working voltages of approximately 0.5 V [2].

The voltage generated from individual MFCs is insufficient for most practical applications such as powering electronics or charging batteries, and so they would benefit from stacking in series to increase the voltage. Many researchers have stacked MFCs in this way e.g. Aelterman et al. [3] stacked 6 individual MFCs to boost the voltage and were able to persistently extract power. But at high current levels, towards the maximum power available from the MFCs, the voltage from some of the MFCs diverged and reversed. This cell reversal behaviour has been observed by several researchers, as in the work of Taniguchi et al. [4] whilst investigating proton exchange membrane (PEM) fuel cells. They attributed the cause of this cell reversal to fuel starvation, including during start-up. Oh and Logan [5] confirmed that fuel starvation could have the same effect in MFC systems. Cell reversal should be avoided as it causes serially connected stacks of MFCs to underperform, as power is lost within the stack in sustaining the voltage of the reversed cell(s). When serially wired, MFCs should be operating with similar and sufficient substrate concentration, whilst having fully enriched electrogenic biofilms on their anodes and with active cathodes, they may thus be expected to produce comparable electrical and ionic currents to each other and voltage reversal should not occur during the stack operation [6]. An imbalance in the organic strength of substrate supplied to stacked MFC cells is likely to occur in practice and in circumstances where volumetric throughput is important, such as in wastewater treatment applications; it is even more likely as MFCs will tend to be hydraulically connected in series and substrate will be progressively consumed as it passes through the system [6–8].

Application of a bank of capacitors for charge accumulation from MFCs electrically connected in series has allowed energy harvesting from MFCs to perform useful tasks as evidenced in Ref. [9]. Kim et al. [2] demonstrated that cell reversal could be avoided by providing a bank of capacitors arrangement in such a way that they would be charged by MFCs connected in parallel and then discharged simultaneously in series across a load. However, the impedance of an MFC varies with changes in substrate concentration, operating temperature, buffer concentration, pH, biofilm ecology and structure, all of which might be expected to dynamically vary during reactor operation [10–12] e.g. wastewater treatment. The state of the system is therefore seldom likely to be static. An MFC could be operated to match its real-time impedance as in Refs. [13,14], which could be coupled to the charging and discharging of capacitors by suitable control of current sourcing. Therefore, we present a novel study which seeks to determine if controlling the current sourced from individual MFCs whilst simultaneously connected in series can avoid cell reversal and maximise the power they generate.

2. Materials and methods

2.1. Tubular MFC (t-MFC) construction and operation

Three independent tubular MFCs (t-MFC1, t-MFC2 and t-MFC3) with approx. 220 mL anodic volume were constructed and enriched, as previously described [15] and operated in a temperature controlled chamber at 30 ± 2 °C with 40 mM acetate in their anodes. Polarisation curves were determined for the t-MFCs by stepwise reducing the electrical load from 5 kΩ to 5 Ω using a resistor box and power was normalised to the empty bed volume of the anode.

When beginning each set of experiments, t-MFC1 and t-MFC3 were provided with 2 mM sodium acetate as substrate whereas t-MFC2 was fed 0.5 mM sodium acetate unless otherwise specified, to instigate substrate imbalance, which is plausible in practice. Substrate was provided with 50 mM phosphate buffer and nutrients as previously described [15]. All t-MFCs were operated in batch mode at ambient temperatures of 30 ± 2 °C according to the experimental set-up elaborated below and until the substrate was apparently depleted.

CASE-1: The MFCs were connected in series, connecting anodes to cathodes. The stack of MFCs was connected to a static load of 150 Ω as shown in Fig. 1a.
CASE-2: Each MFC was connected to the maximum power point load of 50 Ω (static) determined a *priori* using power curves (power *vs.* current). The MFCs and associated loads were then connected in series as shown in Fig. 1b. During CASE-1 and CASE-2 experiments, the voltage drop across the individual MFC loads and the stack voltage was sampled at 30 s intervals using a PC equipped with LabVIEW™ and NI USB-6218 (National Instruments, Newbury, UK).
CASE-3: As shown in Fig. 1c, each MFC was connected to a maximum power point tracking (MPPT) device which controlled the current sourced from each MFC. Boolean logic based hill climbing control [16] was implemented by varying the load in response to the gradient of the power curve and of its rate of change. Additionally, logic increased the load in steps *if* (conditional) MFC voltage < 0.1 V. A digital potentiometer (Intersil® X9C102, Farnell UK Ltd., Leeds) was used as the load to control the current *via* a PC equipped with LabVIEW™ and NI USB-6218. The implementation of the LabVIEW™ algorithm is presented in Supplementary information S1. The current sourced from the MFCs was regulated using digital potentiometers and thus actuated the MPPT. The voltage drops across these potentiometric loads and across the entire stack were digitally sampled at intervals of 150 s.

2.2. Small-scale MFCs (s-MFCs) construction and operation

The small 6.25 mL MFCs (Fig. 5), are of a well-established MFC design in the literature [17] and were first introduced in the EcoBot-III project. It is built entirely from Nanocure RC25 terracotta resin. The internal volume of the anode is 6.25 mL with a projected surface area of 20 mm × 30 mm and the cathode is open-to-air. s-MFCs were operated at ambient temperature (22 ± 3 °C) and supplied with fresh urine. Polarisation curves were determined for the s-MFCs in a similar manner to that for the t-MFCs, with loads ranging from 30 kΩ to 4 Ω.

s-MFC1 and s-MFC3 were fed with neat urine (as organic substrate) and s-MFC2 was provided with 1:1 diluted urine with distilled water. s-MFCs were connected in the same configuration as the experiments employing t-MFCs. However, in CASE-1 a static load of 8 kΩ was used to match the overall internal resistance of the s-MFCs; In CASE-2, static loads of 2 kΩ were used for s-MFC1 and s-MFC3, and 4 kΩ static load for s-MFC2 and; In CASE-3, a digital potentiometer (Intersil® X9C103, Farnell UK Ltd., Leeds) was used such that it suited the range of current evident from the power curve obtained from the s-MFCs.

2.3. Prolonged voltage reversal and its effect on biofilms/ecology

Acetate concentrations of 0.5 mM (t-MFC1), 0.5 mM (t-MFC2) and 2 mM (t-MFC3) were respectively fed in batch to each of the t-

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