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Control of microbial fuel cell voltage using a gain scheduling control strategy

Hitesh C. Boghani, Iain Michie, Richard M. Dinsdale, Alan J. Guwy, Giuliano C. Premier*

Sustainable Environment Research Centre (SERC), Faculty of Computing, Engineering and Science, University of South Wales, Pontypridd, Mid-Glamorgan, CF37 1DL, UK

HIGHLIGHTS

- Control of microbial fuel cell (MFC) voltage is demonstrated.
- Gain scheduling allows control over the operating range.
- Control is transferable between similar MFCs.
- Control strategy is parsimonious and hence practical.

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ABSTRACT

Recent microbial fuel cell (MFC) research frequently addresses matters associated with scale and deployability. Modularisation is often needed to reduce ohmic losses with increasing volume. Series/parallel is then often an obvious strategy to enhance power quality during operation, to make best use of generated electricity. Hence, voltage reversal resulting from power and voltage mismatch between cells become virtually unavoidable. Control MFC voltages could be used to stabilise MFC stacks. Here, nonlinear MFCs are controlled using simple gain scheduled Proportional + Integral actions. Parsimonious control may be necessary for implementation in MFC arrays, so minimising costs. Controller parameterisation used several linearised models over the dynamic operating range of the MFCs. Controller gains were then scheduled according to the operating conditions. A digital potentiometer was used to actuate the control, varying the current sourced from the MFC. The results show that the controller was able to control MFC voltages, rejecting the disturbances. It was shown that the controller was transferable between MFCs with different power performances. This study demonstrates that the control of MFCs can be achieved with relatively simple digital approaches, plausibly implementable using low cost microcontrollers, and likely to be useful in the effective deployment of MFCs in large scale arrays.

1. Introduction

The microbial fuel cell (MFC) is historically, the base implementation for the emerging low carbon technological field of bioelectrochemical systems (BES), which include a variety of applications. MFCs can generate electricity by consuming organic contaminants present in substrates such as wastewaters. The substrate degradation is catalysed by a group of electrogenic anode respiring bacteria present at the anode of a MFC. MFCs have been presented as an alternative wastewater treatment technology, where they have potential to replace the aerobic treatment [1]. While such a transition may yet require an order of magnitude improvement in their power density, the reducing power they generate can be used for processes and products of higher value than electricity generation [2]. Current MFC configurations would typically require many cells to be electrically connected in order to provide substantial operating volume, as the losses incurred with scale are highly significant [3]. At large scales, it is likely that MFCs would need to be deployed in arrays, or by some other means, reducing apparent ohmic losses. Power management is therefore a requisite component of any implementation of MFCs and likely in other BES also.

* Corresponding author.
E-mail addresses: hitesh.boghani@southwales.ac.uk (H.C. Boghani), iain.michie@southwales.ac.uk (I. Michie), richard.dinsdale@southwales.ac.uk (R.M. Dinsdale), alan.guwy@southwales.ac.uk (A.J. Guwy), iano.premier@southwales.ac.uk (G.C. Premier).

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Voltage reversal is a considerable obstacle in the operation of MFCs in series stack [4–7]. Several studies have focused on this issue; and to prevent it several strategies have been considered [4,8–10]. Several researchers have used the technique of charging a bank of capacitors to boost voltage and harvest energy while avoiding voltage reversal from MFCs [10,11]. Boghani et al. [4] used bridging connections in a series stack of MFCs where the affected MFC could essentially be bypassed, although practical viability of such an arrangement is yet to be assessed, as there would be loss of power in bridging connections. Recently, An et al. [8] also showed a similar approach to [4] to tackle the voltage reversal issue in the MFC stack but instead of bridging the connections between the adjacent serially connected MFCs, they included a threshold loading (resistor). Also, to generate MFCs and likely in other BES also form, several researchers have considered DC–DC converters, low power energy harvesters and AC converters [12–17]. However, MFC voltage can vary dramatically due to environmental and operating conditions which can affect their efficiencies and performance. Control of MFCs is desirable as it is expected that it can be beneficial in improving the performance of stacked cells by improving disturbance rejection and increasing relative stability in a power management system. More specifically, several MFCs in a stack may not present the same performance in terms of cell potentials and power production and so an imbalance in current between connected cells may result. The weaker MFC(s) may be driven by those with higher performance. A well designed controller should be able to present all of the interconnected MFCs at defined and sustainable voltage level, which can then be beneficial in the management of a MFC stack.

Comprehensive knowledge of the state of a process can be advantageous in its control. However, large volumetric capacity systems are expected to contain many MFC cells, each producing relatively small amounts of power [18]. Therefore, the cost of any microprocessor based control, and importantly its energy consumption, need to be minimised. It is expected that very low cost micro-controllers could be integrated with a small subset of MFCs; using energy saving mechanisms such reverting to *sleep mode* for most of the time and waking at each sample instance only to sample the voltages, determine control actions and communicate between cells and a hierarchical overseer. This implies simplicity in the control algorithm, minimising machine cycles to perform the control functions. Two term (PI; proportional + integral) control in association with *a priory* parameterised black box models of the process may suffice. MFCs and other BES exhibit some complex and nonlinear characteristics, which have previously been discussed; furthermore, the possibility of piecewise linearization of process models has also been proposed as a practical approach [19]. A very large literature exists on control strategies for nonlinear systems, several e.g. Refs. [20–22] receiving specific attention, or collected in texts such as [23]. The ubiquitous linear three term (PID) controller in its digital implementation can readily be applied to many nonlinear time varying processes by employing adaptive control techniques such as gain scheduling, model reference adaptive control and self-tuning approaches [24,25]. Of these, gain scheduling is arguably the parsimonious method of choice to rapidly adapt controller tuning to the prevailing operating conditions in a mildly time invariant system [26–29], provided the temporal variations can be accommodated as disturbances by the control strategy.

Control of MFC and MEC has been considered previously but to-date these have been mainly limited to simulations of theoretical studies [30,31]. The control of MFC voltage has not to our knowledge, yet been demonstrated. The study presented here demonstrates the plausible control of MFC voltage over its working range, with the perceived benefit that cell potentials could be matched to avoid disparities in arrays of MFCs. The study uses a deliberately parsimonious and therefore applicable approach employing a PI controller in which the controller parameterisation (gain vector) is adapted over the working range of the MFC, by so-called gain scheduling. A tubular MFC was modelled using a system identification black box approach with a piecewise linearised set of models determined offline at incremental steps over the working range of the MFC voltage. These models were then used to parameterize the controller to achieve a specified performance, and the controller gain was scheduled depending on the value of instantaneous cell voltage. A digital potentiometer was used as the actuator and the means of current sourcing, but in real application it is anticipated that it would be replaced with suitable energy harvester electronics or high impedance devices dissipating less energy.

2. Materials and methods

2.1. MFC construction and operation

Two cation exchange membranes (CMI7000S, Membrane International Inc., NJ, USA) were formed into tubes over the structural support of mesh tubes (RN2530, Industrial Netting, MN, USA). The cathodes were made by coating 0.5 mg cm^{-2} Pt on one face and PTFE on the other face of the carbon cloth (CCP40, Fuel Cell Earth LLC, MA, USA). Hydrogel (CAM1033H, Camcare gels, Cambridgeshire, UK) was pasted lightly onto the membrane tube to maintain continuity in the ionic path. The cathode was pressed against the membrane tube by applying an external distributed force using a split mesh tube. Six helical anodes were built using nylon formers to support the laying of 0.5 cm wide strips of carbon cloth into helical channels. The MFC was inoculated as previously described in Ref. [32]. The MFCs were fed with standard media [32] with 40 mM sodium acetate and the media was re-circulated from a bottle with flow rate of approximately 3 mL min^{-1} and operated at room temperature of 22 ± 3 °C during the periods of acclimatisation/enrichment of the anodes, model identification process and dynamic testing of the control strategy.

During the controller testing phase investigating the dynamics of the controlled MFC (lasting less than 1 h), anode potential was monitored vs. Ag/AgCl electrode (Saturated KCl, +0.210 V vs. NHE, BASi, UK). For the disturbance rejection performance testing of the MFC under control, conducted over an extended period (over 24 h), six MFCs were supplied with 2 mM sodium acetate as substrate, re-circulated through the MFCs and a reservoir (2 L) resulting in total liquid anolyte capacity of 5 L, circulated through the six MFCs. MFC1 and MFC2 were hydraulically independent (hydraulically in parallel to each other) and MFC3 to MFC6 were connected hydraulically in series to each other. A total of three MFC systems, identified as MFC1, MFC2 and MFC(3–6) were fed from the same 2 L reservoir (Fig. S1 in Supplementary Information). The MFCs that were not under control (i.e. acting as a reference for comparison) were connected separately to 33 Ω external loads, advantageously estimated heuristically on the basis of peak power impedance matching, obtained from several power curves (data not shown). Furthermore, Fig. 4b indicates the variation in external loading as a result of depleting substrate and the resulting control action. The initial external load can be seen to be close to 33 Ω at the start, which supported the selection of this as a static external load.

2.2. MFC model identification

The MFCs were all subjected to incrementing step changes in electrical load as inputs disturbances over the operating range of cell voltages (as listed in Table S1, S2 and S3 in the Supplementary Information) as previously described for MFCs of different design [19], however a digital potentiometer, which was controlled