

Intelligent Systems Reference Library

Volume 161

Series Editors

Janusz Kacprzyk, Polish Academy of Sciences, Warsaw, Poland

Lakhmi C. Jain, Faculty of Engineering and Information Technology, Centre for Artificial Intelligence, University of Technology, Sydney, NSW, Australia;
Faculty of Science, Technology and Mathematics, University of Canberra, Canberra, ACT, Australia;
KES International, Shoreham-by-Sea, UK;
Liverpool Hope University, Liverpool, UK

The aim of this series is to publish a Reference Library, including novel advances and developments in all aspects of Intelligent Systems in an easily accessible and well structured form. The series includes reference works, handbooks, compendia, textbooks, well-structured monographs, dictionaries, and encyclopedias. It contains well integrated knowledge and current information in the field of Intelligent Systems. The series covers the theory, applications, and design methods of Intelligent Systems. Virtually all disciplines such as engineering, computer science, avionics, business, e-commerce, environment, healthcare, physics and life science are included. The list of topics spans all the areas of modern intelligent systems such as: Ambient intelligence, Computational intelligence, Social intelligence, Computational neuroscience, Artificial life, Virtual society, Cognitive systems, DNA and immunity-based systems, e-Learning and teaching, Human-centred computing and Machine ethics, Intelligent control, Intelligent data analysis, Knowledge-based paradigms, Knowledge management, Intelligent agents, Intelligent decision making, Intelligent network security, Interactive entertainment, Learning paradigms, Recommender systems, Robotics and Mechatronics including human-machine teaming, Self-organizing and adaptive systems, Soft computing including Neural systems, Fuzzy systems, Evolutionary computing and the Fusion of these paradigms, Perception and Vision, Web intelligence and Multimedia.

**** Indexing:** The books of this series are submitted to ISI Web of Science, SCOPUS, DBLP and Springerlink.

More information about this series at <http://www.springer.com/series/8578>

Ravi Patel · Dipankar Deb ·
Rajeeb Dey · Valentina E. Balas

Adaptive and Intelligent Control of Microbial Fuel Cells

Ravi Patel
University of Auckland
Auckland, New Zealand

Rajeeb Dey
Department of Electrical Engineering
National Institute of Technology
Silchar, India

Dipankar Deb
Institute of Infrastructure Technology
Research and Management
Ahmedabad, Gujarat, India

Valentina E. Balas
“Aurel Vlaicu” University of Arad
Arad, Romania

ISSN 1868-4394 ISSN 1868-4408 (electronic)
Intelligent Systems Reference Library
ISBN 978-3-030-18067-6 ISBN 978-3-030-18068-3 (eBook)
<https://doi.org/10.1007/978-3-030-18068-3>

© Springer Nature Switzerland AG 2020

This work is subject to copyright. All rights are reserved by the Publisher, whether the whole or part of the material is concerned, specifically the rights of translation, reprinting, reuse of illustrations, recitation, broadcasting, reproduction on microfilms or in any other physical way, and transmission or information storage and retrieval, electronic adaptation, computer software, or by similar or dissimilar methodology now known or hereafter developed.

The use of general descriptive names, registered names, trademarks, service marks, etc. in this publication does not imply, even in the absence of a specific statement, that such names are exempt from the relevant protective laws and regulations and therefore free for general use.

The publisher, the authors and the editors are safe to assume that the advice and information in this book are believed to be true and accurate at the date of publication. Neither the publisher nor the authors or the editors give a warranty, expressed or implied, with respect to the material contained herein or for any errors or omissions that may have been made. The publisher remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.

This Springer imprint is published by the registered company Springer Nature Switzerland AG
The registered company address is: Gewerbestrasse 11, 6330 Cham, Switzerland

Preface

Renewable and clean energy is a fundamental need of the human society today. At the same time, a third of the world population lacks adequate and cost-effective sanitation. Microbial Fuel Cells (MFCs) attempt to address both these needs by directly converting organic content to electricity from bacteria. It is now well known that electricity can be made using biodegradable material without even adding any special chemicals, simply by using bacteria already present in the wastewater with an anode compartment. The bacteria of a specifically designed fuel cell free of oxygen, attach to the anode. Because of lack of oxygen, they must transfer the electrons to the cathode rather than to oxygen. Then the electrons, oxygen, and protons combine to provide clean water. The electrodes, when at different potentials, create a fuel cell with influent food or “fuel” that is continuously used up by the bacteria.

This book provides basic information about fuel cells, and specifically MFCs, and the materials and the construction of such cells, all from the perspective of a control engineer in ensuring a regulated output from the cell. The book provides basic information about different modeling strategies applicable in MFCs, including outlines of statistical models, and more details with respect to engineering models. Mathematical models for single compartment MFCs with single microbial population and also dual microbial populations are described. Additionally, mathematical modeling for dual chamber MFCs is also presented. All these models are developed in a way that identifies the uncertain parameters and is appropriate for controller formulation such that the equivalent model is a control-oriented parametrized model appropriate for further control and estimation action.

The developed MFC model for single population is then individually analyzed for two types of inputs: (a) dilution rate and (b) influent concentration, with respect to the equilibrium points and the stability of those equilibrium points. A robust controller design for norm bounded uncertainty is studied for this single population MFC using Linearity Matrix Inequality (LMI) criterion.

Adaptive control methodologies are dealt with in detail in literature in the last half a century. However, in the context of MFCs, the authors felt the need to provide the basic formulations of the specific types of adaptive control

methodologies with appropriate example that is relevant to the specific dynamical equations of the MFCs studied in this book. We also formulate, in detail, the dynamical equations representing single compartment MFCs containing single and dual populations, while systematically presenting the adaptive control methodologies most appropriate to the specific types of MFCs. An intelligent control method like the exact linearization method is presented for the more complicated MFC setup with dual chambers consisting of separate dynamical equations representing the anode and cathode chambers, but with a single population.

We have described a laboratory-level setup of five similar MFC setups with two-compartment configuration with cow dung slurry as the substrate. Using system identification techniques, the transfer function models of the cathode and anode compartments are developed, which is then controlled using two different MRAC techniques in the final chapter.

In summary, this book presents a systematic description of adaptive and intelligent control of different types of MFCs that span nonlinear control techniques like backstepping control, linear and robust control methods using linear matrix inequality, and estimation and adaptive update of uncertain parameters using adaptive control techniques. It is hoped that this book will facilitate a researcher to delve into the fundamentals of MFCs and position the researcher to develop and engineer the advanced control methods so as to be able to make a well-presented handout for the formulation of new knowledge in this upcoming field of renewable energy.

The authors acknowledge the support received from Dr. Meenu Chhabra, Assistant Professor, Indian Institute of Technology Jodhpur and Dr. Sourav Das, Assistant Professor, Institute of Infrastructure Technology Research and Management, Ahmedabad, in developing the laboratory-level MFC setups which enabled validation of the control methodologies developed in this book.

Auckland, New Zealand
Ahmedabad, India
Silchar, India
Arad, Romania

Ravi Patel
Dipankar Deb
Rajeeb Dey
Valentina E. Balas

Contents

1	Introduction	1
1.1	Fuel Cell	1
1.2	Microbial Fuel Cell	3
1.3	Construction and Materials	3
1.4	Scope and Outline of the Book	5
	References	8
2	Mathematical Modelling	11
2.1	Engineering Based Modeling of MFCs	11
2.2	Mathematical Modelling of MFCs	14
2.2.1	Single-Population Single Chamber MFC	16
2.2.2	Two-Population Single Chamber Microbial Fuel Cell	18
2.2.3	Two Chamber Single-Population Microbial Fuel Cell	20
2.3	Control-Oriented Parametrized Models	22
2.3.1	Single-Population Single Chamber MFC	23
2.3.2	Two-Population Single Chamber MFC	24
2.3.3	Single-Population Two Chamber MFC	25
	References	27
3	Model Analysis of Single Population Single Chamber MFC	29
3.1	Introduction	29
3.2	SPSC MFC Model with Dilution Rate as Input	33
3.2.1	Equilibrium of the System	34
3.2.2	Stability of Equilibrium Points	34
3.3	SPSC MFC Model with Influent Concentration as Input	36
3.3.1	Equilibrium Points of the System	37
3.3.2	Stability of the Equilibrium Points	37
	References	40

4	Robust Control Design of SPSC Microbial Fuel Cell with Norm Bounded Uncertainty	41
4.1	Introduction	41
4.2	Brief Overview of LMI	43
4.2.1	Some Control Problems in LMI Framework	45
4.2.2	LMI Solvers	47
4.3	Linear MFC Model with Uncertain Dilution Rate	47
4.4	Controller Design	48
	References	51
5	Introduction to Adaptive Control	53
5.1	Introduction	53
5.2	Indirect Adaptive Control	54
5.3	Direct Adaptive Control	56
5.4	Model Reference Adaptive Control	58
5.5	Adaptive Backstepping Control	60
	References	64
6	Adaptive Control of Single Population Single Chamber MFC	67
6.1	Introduction	67
6.2	Backstepping Control Scheme	68
6.3	Adaptive Backstepping Control Scheme	71
6.3.1	Adaptive Controller Design	72
6.3.2	Adaptive Update Laws	73
6.3.3	Stability Performance Analysis	73
	References	78
7	Adaptive Control of Single Chamber Two-Population MFC	81
7.1	Introduction	81
7.2	Adaptive Control Design	82
7.3	Simulation Results	85
	References	89
8	Exact Linearization of Two Chamber Microbial Fuel Cell	91
8.1	Exact Input-Output Linearization	91
8.2	Exact Linearization Control of Anode Chamber's Dynamics	93
8.3	Exact Linearization Control of Cathode Chamber Dynamics	94
	References	98
9	Microbial Fuel Cell Laboratory Setup	99
9.1	Materials	99
9.2	Procedure and Operation	101

- 9.3 Experimental Results 103
- 9.4 System Identification 104
- References 107
- 10 Model Reference Adaptive Control of Microbial Fuel Cells 109**
 - 10.1 Model Reference Adaptive Control Using MIT Rule 109
 - 10.2 Simulation Results 111
 - 10.3 Model Reference Adaptive Control 114
 - 10.4 Performance Evaluation and Simulation Results 117
 - References 121

About the Authors

Ravi Patel is currently a Research Scholar at the University of Auckland, New Zealand. He holds Master of Technology in Electrical Engineering from Institute of Infrastructure Technology, Research and Management, Ahmedabad, India. He holds B.E. degree from LDRP Institute of Technology & Research, Gandhinagar, India. He is a Student Member of IEEE and Asian Control Association. His research interest includes Adaptive Control, Nonlinear Control, and Renewable Energy and Microbial Fuel Cell and its control applications.

Dipankar Deb is a Professor and Department Coordinator in the Department of Electrical Engineering at Institute of Infrastructure Technology, Research and Management, Ahmedabad, India. He holds B.E. degree from National Institute of Technology, Karnataka, M.S. degree in Electrical and Computer Engineering from University of Florida, Gainesville, and Ph.D. degree in Electrical Engineering. He is a Senior Member of IEEE. He has filed and published 6 US patents and 25 Indian patents, apart from 50 research articles in International Journals and Conferences. He has authored and edited five books with Springer. He has wide experience both in Academia and Industry both in the US and in India. His research interest includes Adaptive Control, Active Flow Control, Renewable Energy, Smart Infrastructure, and Bio-medical Control Applications.

Rajeeb Dey is currently an Assistant Professor in the Department of Electrical Engineering at National Institute of Technology, Silchar, India. He holds M.Tech degree in Control System Engineering, from Indian Institute of Technology, Kharagpur, India and Ph.D. degree also in Control System Engineering from Jadavpur University, Kolkata, India. He is a Senior Member of IEEE Control System Society, Member Institution of Engineers (India), and Life Member of System Society of India. His research interest includes Design of Robust Control, Optimization based on LMI techniques, Time-Delay Systems, Intelligent Control, Decentralized Control and Control applications, and Bio-medical Control Applications.

Valentina E. Balas is currently a Professor in the Department of Automatics and Applied Software at the Faculty of Engineering, University “Aurel Vlaicu” Arad (Romania). She holds a Ph.D. in Applied Electronics and Telecommunications from Polytechnic University of Timisoara. She is author of more than 160 research papers in refereed journals and International Conferences. Her research interests are in Intelligent Systems, Fuzzy Control, Soft Computing, Smart Sensors, Information Fusion, Modeling, and Simulation. She is the Editor-in-Chief to International Journal of Advanced Intelligence Paradigms (IJAIP), member in Editorial Board member of several national and international journals, and is evaluator expert for national and international projects. Dr. Balas participated in many international conferences as General Chair, Organizer, Session Chair, and member in International Program Committee. She was a mentor for many student teams in Microsoft (Imagine Cup), Google, and IEEE competitions in the last years. She is a member of EUSFLAT, ACM and a Senior Member IEEE, member in TC—Fuzzy Systems (IEEE CIS), member in TC—Emergent Technologies (IEEE CIS), member in TC—Soft Computing (IEEE SMCS), and also a member in IFAC—TC 3.2 Computational Intelligence in Control. Dr. Balas Is Vice-president (Awards) of IFSA International Fuzzy Systems Association Council and Joint Secretary of the Governing Council of Forum for Interdisciplinary Mathematics (FIM)—A Multidisciplinary Academic Body, India.

Acronyms

1-D	One-Dimensional
2-D	Two-Dimensional
3-D	Three-Dimensional
CEM	Cation Exchange Membrane
DC	Dual Chamber
FC	Fuel Cell
LMI	Linear Matrix Inequality
MFC	Microbial Fuel Cell
MIT	Massachusetts Institute of Technology
MPC	Model Predictive Control
MRAC	Model Reference Adaptive Control
ODE	Ordinary Differential Equation
PD	Proportional & Derivative
PDE	Partial Differential Equation
PEM	Proton Exchange Membrane
PI	Proportional & Integral
PID	Proportional Integral & Derivative
SC	Single Chamber
SISO	Single Input Single Output
SPSC	Single Population Single Chamber

List of Figures

Fig. 1.1	Basic construction of FC.	2
Fig. 1.2	Basic construction of two chamber MFC	4
Fig. 1.3	Control development of existing MFC models	6
Fig. 1.4	Experimental development of MFC model and its control strategies.	7
Fig. 2.1	Mathematical modeling approaches.	12
Fig. 2.2	Types of microbial fuel cells.	12
Fig. 2.3	SC MFC with PEM	16
Fig. 2.4	SC two-population MFC without PEM.	18
Fig. 2.5	Two chamber single-population MFC.	21
Fig. 3.1	Schematic diagram of the quadruple tank system	32
Fig. 3.2	Substrate concentration in nonlinear model with different inputs	35
Fig. 3.3	Biomass concentration in nonlinear model with different inputs	35
Fig. 3.4	Substrate concentration in linear model with different inputs	36
Fig. 3.5	Biomass concentration in linear model with different inputs	36
Fig. 3.6	Pole-zero plot of open-loop transfer function	38
Fig. 3.7	Bode plot of open-loop transfer function	39
Fig. 3.8	Comparison of substrate concentration	39
Fig. 3.9	Comparison of biomass concentration.	39
Fig. 4.1	Uncertain dilution rate with time	42
Fig. 4.2	Effect of dilution rate on substrate and biomass concentration.	42
Fig. 4.3	Performance comparison at $f = 0.05$ Hz.	50
Fig. 4.4	Performance comparison at $f = 0.1$ Hz.	50
Fig. 5.1	Basic adaptive control configuration	54
Fig. 5.2	Basic configuration of indirect adaptive control	54
Fig. 5.3	Basic configuration of direct adaptive control.	56

Fig. 5.4	Schematic diagram of model reference adaptive control scheme	59
Fig. 6.1	Flow of the MFC operation with control system.	68
Fig. 6.2	Adaptive controller scheme for MFC	71
Fig. 6.3	Performance of substrate concentration (Desired)	75
Fig. 6.4	Performance of biomass concentration	75
Fig. 6.5	Tracking error comparison	76
Fig. 6.6	Parameters estimations	76
Fig. 6.7	Parameter errors	76
Fig. 6.8	Anode voltage.	77
Fig. 6.9	Cathode voltage	77
Fig. 6.10	MFC voltage.	77
Fig. 7.1	Adaptive controller for MFC system.	82
Fig. 7.2	Substrate concentration with nominal parameters and adaptive control	86
Fig. 7.3	Influent substrate concentration, $u(t)$ as determined by adaptive controller	87
Fig. 7.4	Convergence of error signals	87
Fig. 7.5	Parameter estimation signals	87
Fig. 7.6	Convergence of parameter errors	88
Fig. 7.7	Parameter θ_1 , estimation and error with uncertainty at $t = 25$ days.	88
Fig. 8.1	Basic schematic diagram of exact input-output linearization control.	92
Fig. 8.2	An integrated block diagram of exact linearization control	96
Fig. 8.3	Anode chamber controlled output (substrate concentration)	96
Fig. 8.4	Anode chamber control input (dilution rate D_1)	97
Fig. 8.5	Cathode chamber controlled output (substrate concentration)	97
Fig. 8.6	Cathode chamber control input (dilution rate D_2)	97
Fig. 9.1	Stainless steel mesh and activated carbon cloth	100
Fig. 9.2	MFC laboratory setup	102
Fig. 9.3	Overview of experimental process of MFC.	103
Fig. 9.4	MFCs output voltage (Experiment round 1)	104
Fig. 9.5	MFCs output voltage (Experiment round 2)	104
Fig. 9.6	MFCs output voltage (Experiment round 3)	104
Fig. 9.7	System identification process flow	106
Fig. 10.1	Block diagram of MRAC using MIT rule.	110
Fig. 10.2	Anode chamber performance without control action.	111
Fig. 10.3	Cathode chamber performance without control action.	112
Fig. 10.4	Anode chamber performance with MRAC using MIT rule	112
Fig. 10.5	Cathode chamber performance with MRAC using MIT rule	112
Fig. 10.6	Control Signal from adaptive control	113

Fig. 10.7	Convergence of error signal	113
Fig. 10.8	Variation in control parameters of both the chambers.	113
Fig. 10.9	Basic configuration of MRAC scheme for anode and cathode chambers.	115
Fig. 10.10	Performance of anode states	118
Fig. 10.11	Performance of cathode states.	119
Fig. 10.12	Convergence of anode state errors	119
Fig. 10.13	Convergence of cathode state errors	119
Fig. 10.14	Anode input signals	120
Fig. 10.15	Cathode input signals	120

List of Tables

Table 2.1	Equations representing different types of MFCs models [14]	14
Table 2.2	Modeling categorization of MFCs	15
Table 2.3	Nominal values: single species anode based MFC [12]	18
Table 2.4	Nominal values: multi-population SC MFC [8]	20
Table 2.5	Nominal values of dual chamber MFC [7].	23
Table 6.1	Control techniques developed for MFCs [1]	68
Table 7.1	Controller gains and constants	86
Table 7.2	Nominal and range of parameters.	86
Table 9.1	Materials list for the MFC setup	100
Table 9.2	Anode and cathode media	101
Table 9.3	Output voltages with different Inputs from MFC setups.	105
Table 9.4	Estimation of MFC model	107