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Integral Backstepping Control of Two Compartment Microbial Fuel Cell

JES

Journal of Electrical Systems

Abstract: - Microbial fuel cells (MFCs) are a promising alternative to generate electricity from wastewater. MFCs need an efficient control system to get the optimal output voltage. The present study proposes an integral backstepping controller for the two-compartment microbial fuel cell. The complex higher-order transfer function of MFC is reduced using the approximation method. The effectiveness of the proposed controller is validated in MATLAB/Simulink simulation environment. The performance of the proposed controller is compared with the classical PID controller. The proposed controller's performance outweighs the PID controller.

Keywords: Microbial fuel cells (MFCs), Backstepping Control, PID controller, Waste water treatment, Renewable energy

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I.   INTRODUCTION

Global industrial growth at a rapid pace has increased demand for energy supplies among growing populations. Over time, technologies for renewable energy have developed [1]. It's interesting to note that these technologies are independent of the finite fuel sources. Energy and environmental problems are effectively resolved by extracting energy from organic or inorganic waste. Massive energy availability is crucial for powering equipment, and batteries or fuel cells are required for remote or in unsupervised particular applications. Extended power sources like fuel cells are useful for equipment that will be deployed over an extended period of time or put in isolated areas [2][3]. Unlike batteries, fuel cells may generate energy constantly if they receive an adequate supply of external fuel. Micro-organisms act as bio-catalytic elements in microbial fuel cells (MFCs), also known as bio-fuel cells, which are promising pollutant removal units that employ chemical energy to produce electrical energy through substrate oxidation [3]. Industrial expansion has led to a significant increase in water pollution. Over time, wastewater treatment has gained attention; nevertheless, most of these solutions are ineffective, costly, and non-sustainable. With the use of affordable electrolytes, electrodes, and urine, MFCs can clean wastewater with zero or positive energy [4]. The endurance of MFCs' cells makes them appealing options for long-term power supply in a range of applications, including remote sensing and extended research [5].

MFC technology still needs more research because it is just at the laboratory phase and is yet to undergo major commercialization. Because MFC can produce bioelectricity from waste water unlike to conventional waste water treatment technologies has higher conversion efficiency.

Under specific assumptions and factors, a limited number of mathematical models of MFCs have been developed and evaluated. The efficacy of the linear control strategies previously created for MFCs might be influenced by parametric ambiguities. Proportional Integral (PI) base non parametric MFC was developed using system identification tool.PI control techniques have several benefits like easy to develop and implement, cost effective etc. When uncertainties and disturbances are present, the performance of such a PI controller is significantly impacted. Various control mechanisms are used for MFCs in order to ensure optimal performance under controlled situations [1].

In this paper, back stepping control strategy has been designed for two chamber MFC.The performance of proposed controller is compared with classical PI controller. Lyapunov stability is validated and proved for two chamber MFC.The rest of the paper is organized in six sections. In section II , overview of the microbial fuel

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cells is discussed. The control problem is formulated in Section III. In Section IV, an integral backstepping control is proposed. The simulation study has been carried out in Section V. Finally, the conclusions are presented in Section VI.

II.   Overview of Microbial Fuel Cell (MFC)
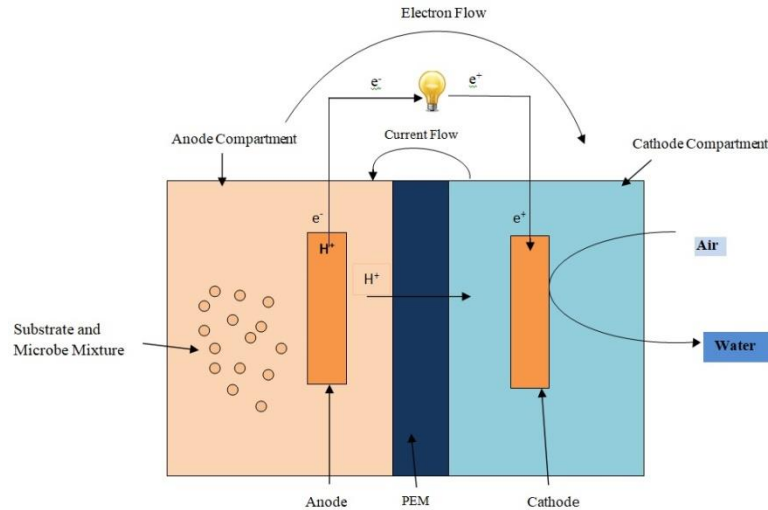
Fig. 1 Basic construction of MFC

A two-chamber MFC's fundamental construction and related parts are shown in Fig. 1.Basic components of MFC can be described as below.

1) Anode: Anode material has to be chemically stable, biologically compatible, conductive, inert, and nontoxic[6][7]. These properties of anode material are mostly responsible for the biofilm formation to electron transmission from anode compartment to the anode surface[7]. Graphite plates are the most accessible materials to use as anode since they are cheaper and have a clear surface area. The electrode materials impact the performance in terms of electron mobility and electrochemical efficiency [7]. The electrodes must be affordable, sustainable, easily accessible, and able to deliver the highest power density for commercial purposes.

2) Cathode: System performance is primarily affected by the cathode material, which is chosen for its operation close to the open circuit voltage potential [7][8]. Catalytic properties, significant mechanical strength, and high electrical and ionic conductivity are essential characteristics of cathode materials [7]. The most common oxidizers used in MFCs include hydrogen phosphate, oxygen, hydrogen peroxide, manganese dioxide or copper chloride. The impacts of various cathode and anode materials on system performance are examined and illustrated in [9-11]

3) Substrate: MFC's principal objective is to produce power and reduction in pollution from waste water[7]. The most significant biological ingredient influencing the production of energy is the substrate. Performance of MFC varies by the nature and amount of the substrate used for oxidation, which are generally microorganisms. The functionality of MFC with different substrate is explained in [17-24]

4) Membrane: Anode and Cathode is separated by membrane. Proton exchange membranes (PEMs) normally allow ions to flow while restricts entry of substrate and oxygen[7]. The development of different types of membranes and how it affects MFC performance are discussed in [20-29]. Ion exchange membranes have significant effects on stability and performance, which has created rapid demand.

5) Mediator: The indirect process includes the use of an outside mediator to help transfer of electron from bacteria to Anode[7]. The results of utilizing various mediators to improve MFC performance have been published in [30-36]

2.1   *Charge Balance and Mass Balance of Anode/Cathode*

The chemical reaction in both compartments is explained by[7]

$(CH_2O)_2 + 2H_2O \longrightarrow 2CO_2 + 8H^+ + 8e^-$ (1)

$O_2 + 4e^- + 2H_2O \longrightarrow 4OH^-$ (2)
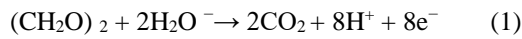
At Anode charge & mass balance substrate, carbon dioxide, positive ions and active biomass of microorganisms are given by

$V_a \dfrac{dCac}{dt} = Qa\ (C^{in}_{AC} - C_{AC}) - A_m\ r_1,$ (3)

$V_a \dfrac{dCco2}{dt} = Qa\ (C^{in}_{co2} - C_{co2}) + 2A_m\ r_1$ (4)

$V_a \dfrac{dCH}{dt} = Qa\ (C^{in}_{H} - C_{H}) + 8A_m\ r_1$ (5)

$V_a \dfrac{dX}{dt} = Qa\ \dfrac{(Xin - X)}{fx} + + AmYr1 - VaKd\ X$ (6)

$C_{cap,a} \dfrac{d\eta a}{dt} = 3600\, icell - 8Fr1$ (7)

In the anode chamber, the chemical reaction rate, r_1 is defined as[7]

$r_1 = K1^0 \exp\left(\dfrac{\alpha f}{RT}\eta_a\right)\dfrac{CAC}{CAc + KAC}$ (8)

Where the anode is denoted by the subscript '*a*' and influent is denoted in the equations by the superscript '*in*', the forward rate constant related to anode reaction at standard condition is denoted by $K1^0$, the surface area of membrane and wash-out fractional parameter respectively are represented by *Am* and *fx*, the universal gas constant, operational temperature, capacitance at anode, and current density of MFC are denoted as *R, T, Ccap* and *icell* respectively, and the coefficient of charge transfer at anode is denoted by α

The equations of charge balance, and mass balance of oxygen, negative hydroxyl ions and positive ions represented by

$V_a \dfrac{dCO2}{dt} = Qc\ (C^{in}_{O2} - C_{O2}) - A_m\ r_2$ (9)

$V_c \dfrac{dCoH}{dt} = Qc\ (C^{in}_{OH} - C_{OH}) - 4\, A_m\ r_2$ (10)

$V_c \dfrac{dCM}{dt} = Qc\ (C^{in}_{M} - C_{M}) + A_m\ N_m$ (11)

$C_{cap,c} \dfrac{d\eta c}{dt} = 3600\, icell - 4Fr2$ (12)

In the cathode chamber, the chemical reaction rate, r2 is defined as

$r_2 = K2^0 \exp\left(\dfrac{(\beta - 1)F}{RT}\eta_c\right)\dfrac{CO2}{CO2 + KO2}$ (13)

The subscript, 'c' stands for the cathode, $K2^0$ and β are forward rate constant and cathode charge transfer coefficient respectively, *NM* is the *M+* ion flux moved from cathode chamber to anode via a membrane

III Formulation of Control Problem

A mathematical representation of a dynamic system in terms of transfer functions can be obtained by the system identification tool. The below system transfer function is taken from [7]. In [7], the experimental setup has been developed to get the input and output data. The inputs are concentrations substrates of the anode and chamber, and the output is the voltage. The system identification method has been used to get the transfer function of both chambers. Among all the combinations, the authors have selected the transfer functions with the best efficiency which is 92%. Therefore, those transfer functions are selected in this study,

The anode chamber transfer function is given by

$$T_a(s) = \frac{4.16 \times 10^4}{s^4 + 11.44\, s^3 + 60.71\, s^2 + 180.9\, s + 312.1} \qquad (14)$$

$$= \frac{4.16 \times 10^4}{(s + 1.39 \pm 3.39j)(s + 4.33 \pm 2.11j)} \qquad (15)$$

The cathode chamber transfer function is given by

$$T_c(s) = \frac{-94.97}{s^3 + 2.169\, s^2 + 4.09\, s + 4.819} \qquad (16)$$

$$= \frac{-94.97}{(s + 0.313 + 1.74j)(s + 1.52)} \qquad (17)$$

The pole-zero locations of the anode and cathode chamber transfer functions are illustrated in Figure. 2 and Figure. 3.
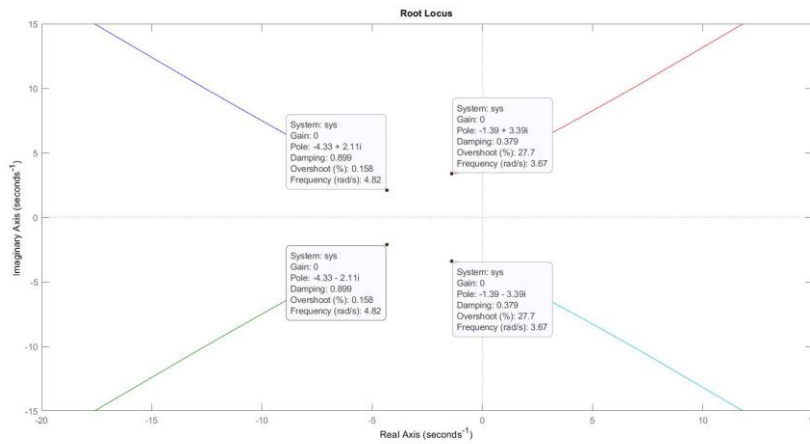

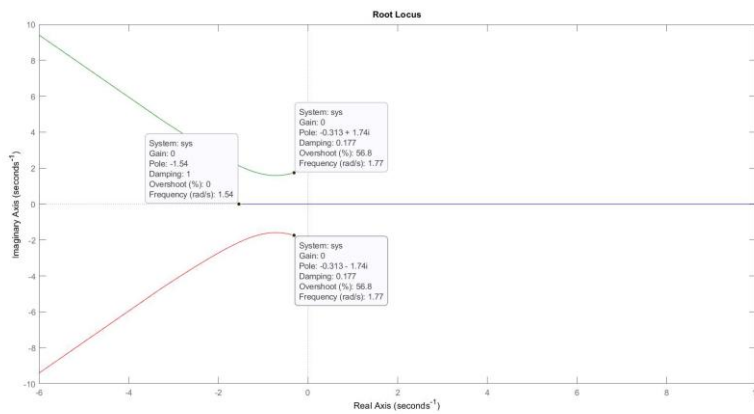**Fig. 2 Location of poles and zeros for anode**

Fig. 3 Location of poles and zeros for cathode

The above transfer functions are higher order transfer functions. It is obvious that the control system for higher order transfer functions is complex. Sometimes it is difficult to design a stable controller for higher order systems. Therefore, an approximation method is used to reduce the order of the above transfer functions.

The approximated transfer function of anode chamber is defined by

$$T_a(s) = \frac{0.224\,e^4}{s^2+2.78\,s+13.42} \qquad (18)$$

The approximated transfer function of cathode chamber is defined by

$$T_c(s) = \frac{-61.89}{s^2+0.626\,s+3.125} \qquad (19)$$

3.1   State Space Equation for MFC

In this subsection, the transfer function to state space equations conversion method is discussed. For example, the transfer function of the nominal system is

$$\frac{y}{r} = \frac{b1}{s2 + a1s + a2} \qquad (20)$$

where y and r are output and input respectively. a_1, a_2 and b_1 are constants.

Simplifying the above equation and converting into state equation, it is defined as

$$\ddot{y}+a_1\dot{y}+a_2y+b_1y=b_1r \qquad (21)$$

Let's assume system states x_1 and x_2

$$x_1 = y$$

$$x_2 = \frac{dy}{dt}=\dot{y}$$

The derivative of the system states are

$$\dot{x}_1 = \dot{y} = x_2 \;\&\; \dot{x}_2 = \ddot{y}$$

From equation (20)(21), the system states are

$$\dot{x}_1 = \dot{x}_2$$

$$\dot{x}_2 = b_1r - a_1x_2 - a_2x_1$$

From the above method, anode and cathode chamber equations are defined as

For Anode

$$\dot{x}_1 = x_2 \text{ and } \dot{x}_2 = 0.224*10^4r - 2.78\ x_2 - 13.42\ x_1 \qquad (22)$$

For Cathode

$$\dot{x}_1 = x2 \text{ and } \dot{x}_2 = -61.89r - 0.626\ x_2 - 3:125x_1 \qquad (23)$$

The integral back stepping controller is proposed using above state space equation in next section

IV.Design of Back Stepping Controller

Integral Backstepping would be helpful when uncertainties are not modeled as normally happens. The control objective is to develop an efficacious scheme to track desired response [37][38]. Generalized mathematical equations for applying a integral back stepping algorithm are as follows

$$\dot{x}_1 = x_2 \text{ and } \dot{x}_2 = a + bu \qquad (24)$$

where a and b are the parameters or constant terms of the system

Tracking errors e_1 and e_2 are defined as

$e_1 = x_{1d} - x_1, \ e_2 = x_{2d} - x_2$ (25)

where x_{1d} is desired tracking path. x_{2d} is the virtual control which is defined as

$x_{2d} = c_1e_1 + \dot{x}_{1d} + \lambda\chi$ (26)

such that $\chi = \int e_1(\tau)d\tau$ shows the integral action

Using (25), we get

$\dot{e}_1 = \dot{x}_{1d} - \dot{x}_1 = \dot{x}_{1d} - x_2 = -c_1e_1 - \lambda\chi + e_2$ (27)

$\dot{e}_2 = \dot{x}_{2d} - \dot{x}_2 = c_1\dot{e}_1 + \ddot{x}_{1d} + \lambda e_1 - bu - a$ (28)

Substituting the values of (26) in (27) and re-writing the derivative of the error $\dot{e}_2$ we get

$\dot{e}_2 = -c_1^2 e_1 - c_1\lambda\chi + c_1e_2 + \ddot{x}_{1d} + \lambda e_1 - bu - a$ (29)

To ensure that $\dot{e}_2 = -c_2e_2 - e_1$,($c_2 > 0$) , we choose a control law u given by

$u = \frac{1}{b}[(1-c_1^2+\lambda) \ e1 + (c_1+c_2) \ e2 - c_1\lambda\chi + \ddot{x}_{1d}] - \frac{a}{b}$ (30)

To check the system stability, we can construct a positive definite Lyapunov function as follows

$V = \frac{1}{2}\lambda\chi^2 + \frac{1}{2}e_1^2 + \frac{1}{2}e_2^2$ (31)

By taking differentiation of V, we obtain

$\dot{V} = -c_1e_1^2 - c_2e_2^2 < 0$ (32)

where c_1, c_2 and λ are positive constants.

From (31) we can say that the MFC with integral back stepping control will be stable

based on the Lyapunov theory

From equation (29), the control input is obtained for anode and cathode by adding below

a, b and r

Anode:

$a = -2.78x_2 - 13.42x_1, \ b=0.224 \times 10^4, r=u$

Chosen controller parameters: $c_1 = 0.001$, $c_2 = 0.09$ and $\lambda = 100$

Cathode:

$-0.6262X_2 - 3.125X_1, \ b=-61.89, \ r = u$

Chosen controller parameters: $c_1 = 2.75$, $c_2 = 0.09$ and $u = 1.85$.
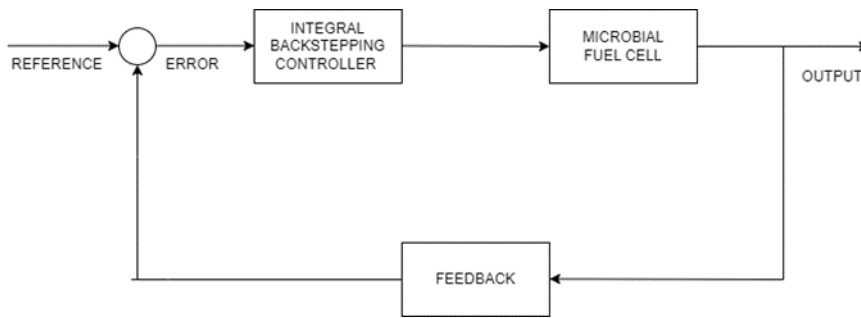
<div align="center">V Simulation Result</div>

Fig. 4 Block Diagram for Integral Back stepping control

The schematic of integral backstepping control is illustrated in Figure 4. The simulation has been carried out in MATLAB/Simulink in this paper. Both anode and cathode chambers have been simulated. The performance of the proposed integral back-stepping controller is compared with that of the classical PID controller. The rationale behind choosing the classical PID controller is that it is well-known and widely used. Most industries are using PID controllers due to their simplicity. It is worth mentioning that the PID controller gains have been tuned using the PID tuner application in Simulink.

The output of the anode chamber is shown in Fig5. It can be observed that the proposed integral backstepping control provides better tracking performance compared with the classical PID controller. It is also observed that the settling time is less in the case of the proposed controller.
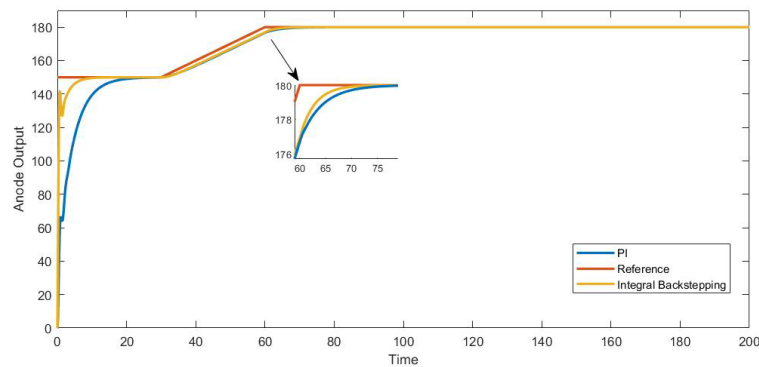

Fig. 5 Anode Chamber output

The output of the cathode chamber is shown in Fig.6. It can be observed that the pro-posed integral backstepping control provides better tracking performance compared with the classical PID controller. It is also observed that the performance of the PID controller is oscillating, whereas the proposed controller provides a smooth response.
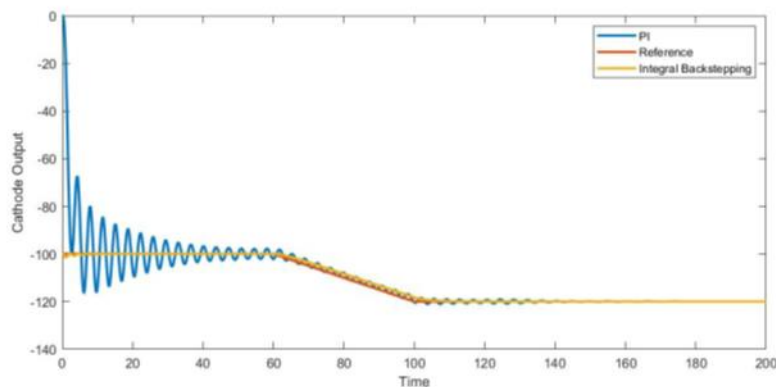

Fig. 6 Cathode Chamber Output

VI. Conclusion

Microbial fuel cells are a promising alternative to generate electricity from wastewater. It is necessary to get constant and reliable power from the MFCs. Therefore, this study is focused on the nonlinear control methods to get the constant output voltage from the MFC. In this study, the integral backstepping controller has been proposed. The efficacy of the controllers was tested using the MATLAB/Simulink simulation test bench. The performance of the proposed controller is compared with that of the classical PID controller. The simulation results confirm that the proposed controller outperforms the classical PID controller for both anode and cathode chambers. The settling time and other performance, such as transient performance, are far better than those of the classical PID controller.

REFERNCES

[1] Patel R, D.Deb "Nonlinear Adptive control of Micro Bial Fuel Cell with two species in a single chamber," *Journal of Power Source 434 (2019) 226739.*

[2] M.Rahimnejad, A.Adhami,"Microbial fuel Cell as new technology for Bioelectricity generation: A review 2015" pp.745-756

[3] P chaudhury , U.S.P Uday,N.Mahata,et.al.Performance Improvement of Microbial fuel Cells for waste water treatment along with value edition: a review on past achievement and recent perspective ,Renew,Sustain.Rev.79 (May)2017)372-379

[4] P.Hu.,Y.Ouyang,L.Wu,L.shen,P.Christrie,"Effect of water management on arsenic and cadmium speciation and accumulation in upland rice cultivar" J Environ sci (china)27 (c) 2015 225-231

[5] R.Kumar ,L.Singh, A.W Zularisam,D.Mohd Fadhil, Exoelectrogens in microbial fuel cells towards bioelectricity generation A review Int.J.Energy Res.39(8)(2015)1048-1067

[6] R.Patel, D.Deb" Control-Oriented Parameterized Models for Microbial Fuel Cells" 978-1-5090-4874-8/17/$31.00c 2017 IEEE

[7] Patel R, Deb D, Dey R., Balas V."Adaptive and Intellegent control of Microbial Fuel Cells. Intellegent Reference System Library Book series Springer.https://doi.org/10.1007/978-3-030-18068-3.

[8] Logan, B., Hamelers, B., Rozendal, R., Schrãuder, U., Keller, J., Freguia, S.: Microbial fuel cells: methodology and technology. Environ. Sci. Technol. 40, 5181–5192 (2006)

[9] Dumitru, A., Scott, K.: Anode materials for microbial fuel cells. Microb. Electrochem. Fuel Cells, 117–152 (2016)

[10] Yamashita,T.,Yokoyama, H.: Molybdenum anode: a novel electrode for enhanced power generation in microbial fuel cells, identified via extensive screening of metal electrodes. Biotechnol Biofuels **11**(39), 1–13 (2018)

[11] Mustakeem, M.: Electrode materials for microbial fuel cells: nanomaterial approach. Mater Renew. Sustain. Energy **4**(22), 1–11 (2015)

[12] Gezginci, M., Uysal, Y.: The Effect of different substrate sources used in microbial fuel cells on microbial community. JSM Environ. Sci. Ecol. **4**(3) (2016)

[13] Pandey, P., Shinde, V.N., Deopurkar, R.L., Kale, S.P., Patil, S.A., Pant, D.: Recent advances in the use of different substrates in microbial fuel cells toward wastewater treatment and simultaneous energy recovery. Appl. Energy **168**, 706–723 (2016)

[14] Rezaei, F., Richard, T.L., Brennan, R.A., Logan, B.E.: Substrate-enhanced microbial fuel cells for improved remote power generation from sediment-based systems. Environ. Sci. Technol.41 (11), 4053–4058 (2007)

[15] Chae, K.J., Choi,M.J., Lee, J.W., Kim, K.Y., Kim, I.S.: Effect of different substrates on the performance, bacterial diversity, and bacterial viability in microbial fuel cells. Bioresour. Technol.100 (14), 3518–3525 (2009)

[16] Zhao, Y.G., Zhang, Y., She, Z., Shi, Y., Wang, M., Gao, M., Guo, L.: Effect of substrate conversion on performance of microbial fuel cells and anodic microbial communities. Environ. Eng. Sci. vpl. 34(9), 666–674 (2017)

[17] Wu,W.,Yang, F., Liu,X., Bai, L.: Influence of substrate on electricity generation of Shewanella loihica PV-4 in

microbial fuel cells. Microb. Cell Factories 13(1), 1–6 (2014)

[18] Mokhtarian, N., Rahimnejad, M., Najafpour, G.D., Daud, W.R.W., Ghoreyshi, A.A.: Effect of different substrate on performance of microbial fuel cell. African J. Biotechnol. 11(14),3363–3369 (2012)

[19] Garba, N., Saadu, L., Balarabe, M.: An overview of the substrates used in microbial fuel cells.Greener J. BioChem. Biotechnol. 4(2), 7–26 (2017)

[20] Scott, K.:Membranes and separators for microbial fuel cells.Microb. Electrochem. Fuel Cells,153–178 (2016)

[21] Leon, J.X., Daud, W.R.W., Ghasemi, M., Liew, K.B., Ismail, M.: Ion exchange membranes as separators in microbial fuel cells for bioenergy conversion: a comprehensive review. Renew.Sustain. Energy Rev. **28**, 575–587 (2013)

[22] Chouler, J., Bentley, I., Vaz, F., Fee, O., A, Cameron PJ, Di Lorenzo M.: Exploring the use of cost-effective membrane materials forMicrobial Fuel Cell based sensors. Electrochimica Acta **231**, 319–326 (2017)

[23] Das, S., Dutta, K., Rana, D.: Polymer electrolyte membranes for microbial fuel cells: a review.Polymer Rev., 1–20 (2018)

[24] Ghassemi, Z., Slaughter, G.: Biological fuel cells and membranes. Membranes **7**(1), 1–12 (2017)

[25] Rahimnejad, M., Bakeri, G., Najafpour, G., Ghasemi, M., Oh, S.: A review on the effect of proton exchange membranes in microbial fuel cells. Biofuel Res. J. **1**, 7–15 (2014)

[26] Dharmadhikari, S., Ghosh, P., Ramachandran, M.: Synthesis of proton exchange membranes for dual-chambered microbial fuel cells. J. Serbian Chem. Soc. **83**(5), 611–623 (2018)

[27] Zhang, X., Cheng, S., Huang, X., Logan, B.E.: Improved performance of single-chamber microbial fuel cells through control ofmembrane deformation. Biosens. Bioelectron. **25**, 1825–1828 (2010)

[28] Christgen, B., Scott, K., Dolfing, J., Head, I.M., Curtis, T.P.: An Evaluation of the performance and economics of membranes and separators in single chamber microbial fuel cells treating domestic wastewater. PLOS ONE **10**(8) (2015)

[29] Mishra, B., Awasthi, S., Rajak, R.: A review on electrical behavior of different substrates, electrodes and membranes in microbial fuel cell. World Academy Sci. Eng. Technol. Int. J.Energy Power Eng. **11**(9), 1023–1027 (2017)

[30] Lohar, S., Patil,V., Patil,D.: Role of mediators inmicrobial fuel cell for generation of electricity and waste water treatment. Int. J. Chem. Sci. Appl. 6(1), 6–11 (2015)

[31] Park, D., Zeikus, J.G.: Electricity generation in microbial fuel cells using neutral red as an electronophore. Appl. Environ. Microbiol. 66(4), 1292–1297 (2000)

[32] Lin, C.W., Wu, C.H., Chiu, Y.H., Tsai, S.L.: Effects of different mediators on electricity generation and microbial structure of a toluene powered microbial fuel cell. Fuel 125, 30–35(2014)

[33] Sund, C.J.,McMasters, S., Crittenden, S.R.: Effect of electron mediators on current generation and fermentation in a microbial fuel cell. Appl. Microbiol. Biotechnol. 76, 561–568 (2007)

[34] Rossi, R., Cavina, M., Setti, L.: Characterization of electron transfer mechanism in mediated microbial fuel cell by entrapped electron mediator in saccharomyces cerevisiae. Chem. Eng. Trans. 49, 559–564 (2016)

[35] Adebule, A.P., Aderiye, B.I, Adebayo, A.A.: Improving bioelectricity generation of microbial fuel cell (MFC) with mediators using kitchen waste as substrate. Ann. Appl. Microbiol. Biotechnol. J. 2(1), 1–5 (2018)

[36] Yifeng, Z., Liping, H., Jingwen,C., Xianliang, Q.,Xiyun, C.: Electricity generation inmicrobial fuel cells: using humic acids as a mediator. J. Biotechnol. 136, 474–475 (2008)

[37] R.Patel,D.Deb," Parametrized control-oriented mathematical model and adaptive backstepping control of a single chamber single population microbial fuel cell" Journal of Power Sources Volume 396, 31 August 2018, Pages 599-605

[38] R.Patel, D.Deb," Adaptive Backstepping Control Scheme with Integral Action for Quanser 2-DOF Helicopter"978-1-5090-6367-3/17/$31.00 ©2017 IEEE