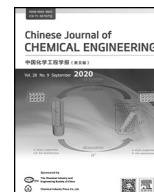




Contents lists available at ScienceDirect

Chinese Journal of Chemical Engineering

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

Article

Dynamic analysis and split range control for maximization of operating range of continuous microbial fuel cell

Ashish Yewale, Ravi Methekar *, Shailesh Agrawal

Department of Chemical Engineering, Visvesvaraya National Institute of Technology, South Ambazari Road, Nagpur 440010, India



ARTICLE INFO

Article history:

Received 3 September 2019

Received in revised form 12 June 2020

Accepted 21 June 2020

Available online 27 June 2020

Keywords:

CMFC

Modeling

Variable Volume

Split Range Controller

ABSTRACT

Human development is inherently connected with availability of water and energy. Energy production requires water, whereas water treatment needs energy. On the other hand, microbial fuel cell has capability to produce energy and water simultaneously from waste water or organic matter. In this paper, first principle-based model of variable volume microbial fuel cell is simulated. Hydraulic retention time is selected as the manipulated variable using the study of steady state and dynamic responses. Classical PI and model predictive control strategies are developed for controlling the produced power from the cell, and its performance is tested for servo problem. Settling time for positive and negative set points is found to be 126 and 889 h in case of classical PI and 120 and 750 h in case of linear MPC, respectively along with large increase (three times order of magnitude) in working volume for negative set point. These control challenges are overcome by using split range controller with variable and constant volume microbial fuel cells. The settling time for negative set point is found to be 49 and 21 h for classical PI and linear MPC schemes, respectively, which is significantly lower than using only variable volume microbial fuel cell. Also, there is no increase in the working volume of the constant volume microbial fuel cell. Hence, operating range of the microbial fuel cell is enhanced using split range controller.

© 2020 The Chemical Industry and Engineering Society of China, and Chemical Industry Press Co., Ltd. All rights reserved.

1. Introduction

Human development is inherently connected with availability of water and energy. Energy production requires water, whereas water treatment needs energy [1]. In this regard, microbial fuel cell (MFC) is such a technology where water and energy are produced. MFC converts chemical energy of wide range of organic waste into electrical energy with the help of microorganisms [2]. However, utilization of this technology for wellness of mankind at industrial scale is not commonly practiced till date [3,4]. To use this technology at industrial scale, some of the limitations such as scale up [5], small current production capacity [6], continuous operation for extended time periods, current instability and high internal resistance [7] need to be addressed. Profound understanding of process and its accurate mathematical representation can play a significant role in mitigating some of these issues and thus may help in well-being of mankind [8].

Available models [7–31] of the MFC in literature can be classified based on various criteria such as operational mode, number of chambers and presence of biofilm. The possible classification of available continuous models (concerned for this manuscript) is given in Fig. 1.

Steady state models [10,11] do not provide any information about dynamics of the system and hence cannot be used for performance

optimization and control design. Ismail and Habeeb, [17], Mardanpour *et al.* [18] developed the dynamic models of MFC considering impact of factors like bacterial growth, mass exchange within bulk and biofilm in temporal as well as spatial domain. As both, spatial and temporal domains were considered; their model resulted into partial differential equations. In general, partial differential equations require more computational effort to solve and hence cannot be used for optimization and control purpose. Esfandyari *et al.* [16] developed one dimensional continuous dual chamber biofilm model and used Nernst-Monod kinetics for growth rate of microorganisms in biofilm along with mass balances for key species such as substrate, CO₂ and protons. The model is computationally easy to solve yet captures required dynamics very well and can be used for optimization and control design purposes. Hence, model presented by Esfandyari *et al.* [16] is used in this paper and updated to accommodate variable volume.

MFC is a complex and a nonlinear system having many influencing factors (pH, temperature, biofilm thickness, microorganism's growth, variable working volume, diffusion and kinetics of reaction, external load, substrate concentration *etc.*) that affect its performance. It is thus, crucial to understand the impact of these factors on performance of MFC to ensure smooth operation for long duration. Oliveira *et al.* [13] studied the initial dynamics of the system with the help of parameters (half velocity rate constant, partition coefficient, cathodic and anodic transfer coefficient). Lin *et al.* [19] studied the impact of initial substrate concentration, dilution rate and external resistor on

* Corresponding author.

E-mail address: ravimethekar@che.vnit.ac.in (R. Methekar).

the performance of single chamber MFC and found optimal conditions for better performance. They also mentioned that little efforts had been undertaken to study of dynamics of continuous MFC (CMFC).

During prolonged operation of MFC, disturbance from various variables such as initial feed concentration, initial feed flow rate, voltage, external load, pH and temperature etc. may arise. However, to control the power from MFC different control strategies were developed. Significant amount of effort were devoted to develop maximum power point tracking (MPPT) control using voltage or current as the manipulated variable. Various techniques used for MPPT control are summarized as multiunit optimization [32], extremum seeking (ES) [33], hill climbing [34], ES along with neural network [35] or adaptive excitation [36]. Some researcher used only classical control [37], classical control augmented with fuzzy logic [38] or gain scheduling [39] controller. However, according to Recio-Garrido *et al.* [40] that there is a need of control studies to address the multi dynamic issues linked with electrical and biological nature of the MFC. Recently, Patel and Deb [41] presented adaptive back stepping controller with dilution rate as the manipulated variable. They linked the electrical dynamics with biological nature of the MFC; however their control development is complicated. Hence in this paper, a simple split range control strategy which will link electrical and biological nature of CMFC using hydraulic retention time (HRT), and inlet substrate flow rate as manipulated variables was developed. Split range control strategy required to have models of variable and constant volume CMFCs. For dynamic model, steady state and transient analysis of constant volume CMFC, readers may refer to Yewale *et al.* [42]. In this manuscript, dynamic model, steady state and transient analysis of variable volume CMFC are described.

First time in the literature, a comparison of constant and variable volume CMFC is carried out and operability window is defined. Novelty of this paper lies in the pioneering effort of integration of variable and constant volume CMFCs through split range control strategy. Using split range controller, the operating regime of the CMFC is enhanced with lower settling time of the controller for all the desired set points. Another novelty of this paper lies in pioneering effort to understand the dynamics of the variable volume CMFC.

2. First Principle-based Model of Variable Volume CMFC

The anode chamber was considered to be under the anaerobic condition, where lactate ($C_3H_6O_3$) solution of specific concentration was fed. Then lactate solution diffused from the bulk into the biofilm attached to the anode electrode. Lactate was oxidized in the biofilm by the pure biomass (*Shewanella oneidensis*) producing electrons and protons. The produced electrons passed through an external circuit via current collector to the cathode chamber producing power. At cathode electrode, a reduction reaction between transported electrons, migrated protons and oxygen molecule take place producing water as a by-product.

In this paper, the model developed by Esfandiyari *et al.* [16] is used, which accounts for (i) reactions (redox) occurring at anode and cathode electrodes, (ii) diffusion of species such as substrate, CO_2 and protons between biofilm and bulk of the liquid and (iii) movement of electrons to the cathode chamber through external circuit. Following assumptions were made while developing this model. CMFC is considered as controlled system and hence heat generated due to exothermic reaction is taken out by the coolant flow around the CMFC. It is assumed that the pH of the system is tightly controlled by an introduction of appropriate amount of buffer dosing in both the chambers.

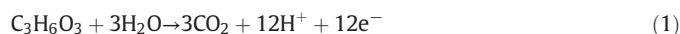
- 1) Bulk of the anode chamber is considered to be well mixed with a constant temperature and impact of pH was neglected.
- 2) Biomass stacked around the anode electrode.
- 3) Migration of only positive ions (protons) were considered through proton exchange membrane (PEM).
- 4) Operating conditions (temperature and pH) in the cathode chamber were kept constant.

- 5) The heat and mass losses through the body of chambers were neglected.
- 6) All the migrated protons and electrons reduce to water at the cathode electrode.

The model was modified to capture the additional phenomena like variable volume through the impact of inlet and outlet flow rates of substrate, diffusion of protons from biofilm to the bulk of liquid and migration to the cathode chamber through PEM.

2.1. Redox reaction modeling

The redox reactions taking place at anode and cathode electrode are given as:



Utilization of lactate in biofilm is modeled using Nernst-Monod kinetics given as:

$$\mu_s(t) = \mu_{\max} \frac{C_{bf,s}}{K_{bf,s} + C_{bf,s}} \left(\frac{1}{1 + \exp\left(\frac{-F}{RT} \eta_{act}\right)} \right) \gamma_a \quad (3)$$

2.2. Bulk of anode and cathode chamber modeling

The species like substrate, CO_2 and protons exchanges mass between the bulk of anode and biofilm using diffusion, which is represented as:

$$\frac{d(C_{bk,p}(t))}{dt} = \frac{1}{V_L(t)} \left(\frac{-A_{bf} D_p}{L_i} (C_{bk,p}(t) - C_{bf,p}(t)) \right) + \left(\frac{C_{bk,p, in} f_{lin}}{V_L(t)} \right) - \left(\frac{C_{bk,p} f_{out}}{V_L(t)} \right) \quad (4)$$

$$\frac{d(C_{bk,p}(t))}{dt} = \frac{1}{V_L(t)} \left(\frac{-A_{bf} D_p}{L_i} (C_{bk,p}(t) - C_{bf,p}(t)) \right) - \left(\frac{A_m D_m}{L_h A_m d_m} (C_{bk,p}(t) - C_{h,c}(t)) \right) \quad (5)$$

In the above equations, Eq. (4) represents the mass balance for substrate and CO_2 whereas Eq. (5) denotes mass balance for protons in the bulk of anode chamber. The first term in above equations represents the diffusion of species from bulk of anode to biofilm. Inlet and outlet mass rates are shown by second and third terms of Eq. (4). Second term in Eq. (5) denotes transfer of protons from bulk of anode to cathode chamber via PEM.

Volume of bulk liquid of the anode chamber is variable because of change in thickness of the biofilm as well as net change in the flow rate of the substrate from inlet to outlet, which is given as:

$$\frac{d(V_L(t))}{dt} = -A_{bf} \frac{dL(t)}{dt} + f_{lin} - f_{out} \quad (6)$$

Using Eq. (6), a variable volume microbial fuel cell can be converted to constant volume microbial fuel cell by equaling inlet and outlet flow rates.

Oxygen concentration in the bulk of the cathode chamber is modeled using oxygen transfer rate and uptake rate, given as:

$$\frac{d(C_{O_2}(t))}{dt} = k_L a (C_{O_2}^* - C_{O_2}(t)) - q_{O_2} C_{O_2} \quad (7)$$

2.3. Biofilm of anode chamber modeling

The active and inactive biomass present in the biofilm is defined on the volume fraction basis which is given as:

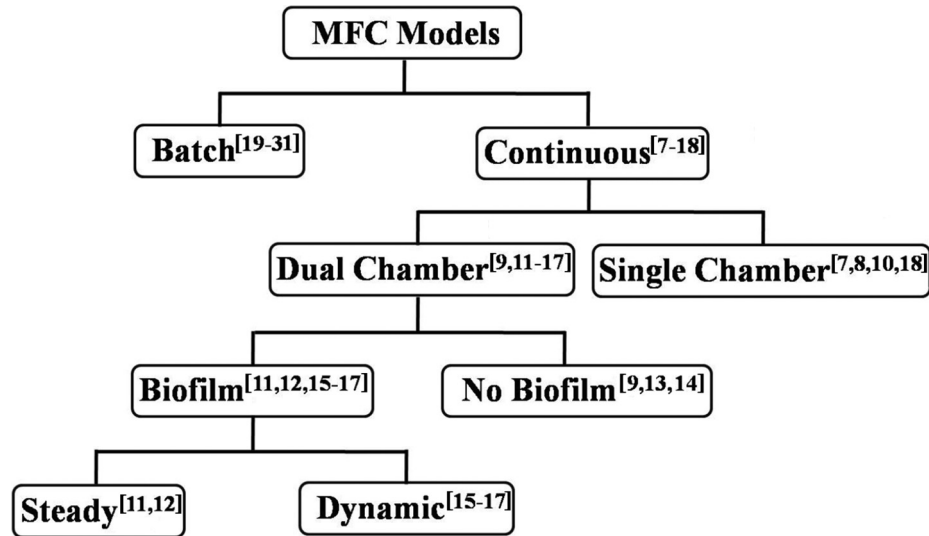


Fig. 1. Classification of continuous mode modeling efforts from literature of the MFC.

$$\gamma_a(t) + \gamma_i(t) = 1 \quad (8)$$

The thickness of the biofilm is dynamic, because of change in volume fraction of active and inactive biomass. This change occurs due to detachment of biomass, conversion of active biomass into inactive biomass, and growth of active biomass. The thickness of the biofilm is modeled as:

$$\frac{dL(t)}{dt} = Y_{la}\mu_s(t)L(t) + \delta(t) \quad (9)$$

$$\delta(t) = -\sigma_{det}L(t) \quad (10)$$

Change in volume fraction of the biomass is given as:

$$\frac{d(\gamma_a(t))}{dt} = -\sigma_{ina}\gamma_a(t) + \frac{\gamma_a(t)}{L(t)}\delta(t) - \frac{\gamma_a(t)}{L(t)}\frac{dL(t)}{dt} + Y_{la}\mu_s(t) \quad (11)$$

$$\frac{d(\gamma_i(t))}{dt} = \sigma_{ina}\gamma_a(t) + \frac{\gamma_i(t)}{L(t)}\delta(t) - \frac{\gamma_i(t)}{L(t)}\frac{dL(t)}{dt} \quad (12)$$

First term in Eqs. (11) and (12) is the conversion rate of active to inactive biomass as a function of inactivation coefficient (σ_{ina}). Rate of detachment of active and inactive biomass from the biofilm is represented by the second term in Eqs. (11) and (12). The third terms shown in above equations emerges due to implementation of chain rule because of dynamic volume. The last term on the right-hand side of Eq. (11) represents the multiplication rate of active biomass.

As mentioned above, three species (substrate, protons and CO_2) exchange mass with the bulk of the anode liquid and is given as:

$$\frac{d(C_{bf,p}(t))}{dt} = \frac{D_p}{L_1L(t)}(C_{bk,p}(t) - C_{bf,p}(t)) + \alpha\mu_s(t) - \frac{C_{bf,p}(t)}{L(t)}\frac{dL(t)}{dt} \quad (13)$$

The sign of α is negative for consumption and positive for production. First term in Eq. (13) represents diffusion of species from bulk of the anode chamber to biofilm. Second term represents the consumption or production of particular species inside the biofilm. The last term in above equation is a balance term arising due to dynamic volume.

2.4. Electrochemical model

The electrons produced by redox reaction move through external circuit of resistance (load) and produces power. The actual voltage of

the cell deviates from the equilibrium voltage because of series of irreversible losses. These losses are activation (η_{act}), ohmic (η_{ohm}) and concentration (η_{conc}) losses. Butler-Volmer equation is used to relate the impact of the substrate consumption and production of the species like protons, electrons and CO_2 on the current production capability of the MFC. For further details of this model, reader may refer to Esfandyari *et al.* [16] and Yewale *et al.* [42].

$$E_{output} = E_{thermo} - \eta_{act} - \eta_{ohm} - \eta_{conc} \quad (14)$$

2.5. Simulation and model validation

All the above equations were solved for specific time duration. First, using Eq. (14), current was obtained by fixing the voltage of the MFC. For solving the differential equations, solver *ode23tb* in MATLAB® was used. To avoid iterative procedure for voltage, the solution procedure given by Methkar *et al.* [43] is adopted. The data used for the base case is given in our earlier publication Yewale *et al.* [42].

The simulated model of the MFC was validated with the experimental data of Esfandyari *et al.* [16]. For validation results of this model along with numerical analysis of error, readers may refer Yewale *et al.* [42]. Only for validation purpose, inlet and outlet substrate flow rates were kept constant. However, for further analysis and control, the inlet and outlet flow rates were considered to be different. Hence the volume of CMFC will change called as variable volume CMFC.

3. Steady State and Dynamic Analysis

To carry out the steady state and dynamic analysis, power produced from the CMFC is considered as the output. According to physics of the system, various potential manipulated variables are inlet substrate flow rate, initial (feed) substrate concentration, HRT and voltage. In steady state analysis, each potential manipulated variable was changed one at a time, keeping the other variables and parameters of the system constant at the base case. Steady state data were collected by simulating the model. Step response methodology was used for carrying out dynamic analysis.

3.1. Steady state analysis

Steady state analysis for all four potential manipulated variables is shown in Fig. 2, where the base case value for manipulated variable is indicated by red color diamond data point.

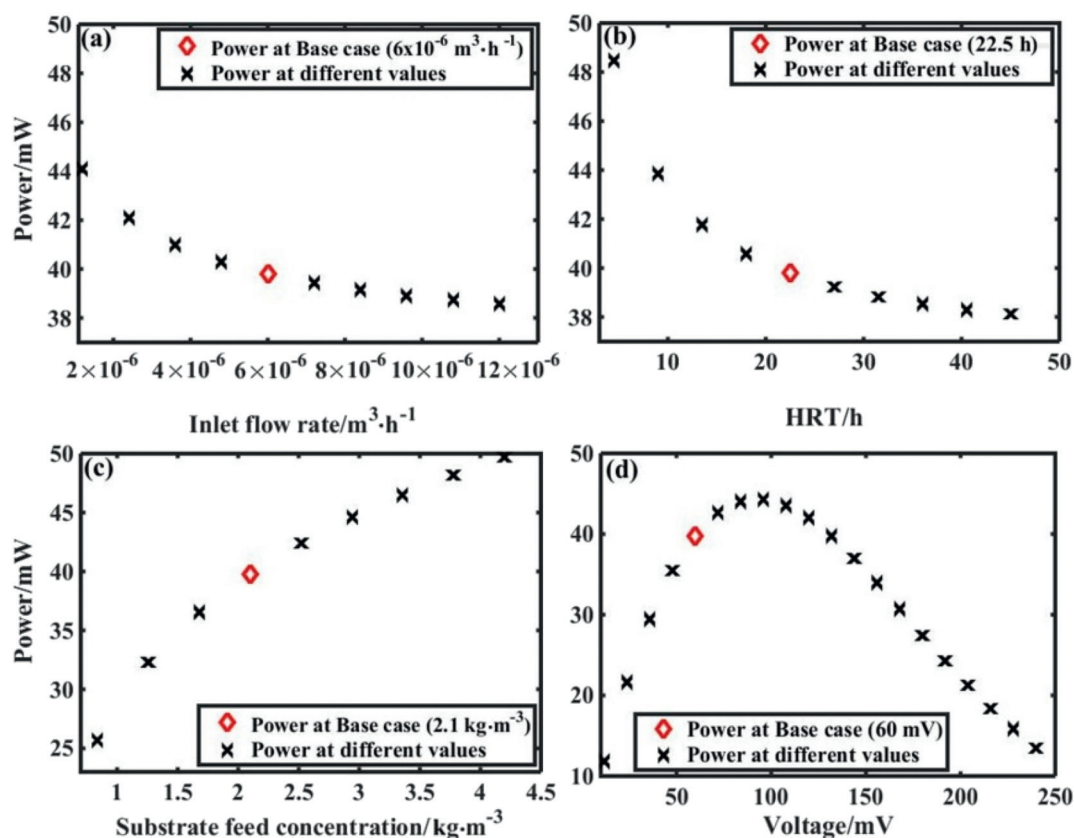


Fig. 2. Steady state responses of potential manipulated variables a) Inlet substrate flow rate b) Hydraulic retention time (HRT), c) Substrate feed concentration and d) voltage.

3.1.1. Inlet substrate flow rate

In this simulation, HRT was kept constant at the base case value of 22.5 h. If outlet flow rate was kept constant instead of HRT, the working volume would have increased or decreased continuously. In such cases, system (CMFC) may become open loop unstable, which is not a favourable situation for practical applications. Hence, while studying the steady state impact of inlet substrate flow rate on the power produced, HRT was kept constant.

Increased power was observed with a decreased input flow rate of substrate, and hence it was concluded that the power has inverse relationship with inlet substrate flow rate (Fig. 2(a)). As inlet substrate flow rate decreased, instantly working volume of the CMFC starts decreasing. To maintain constant HRT, outlet flow rate also decreased. Decrease in volume of the working fluid, resulted in increasing the concentration of the nutrients in the bulk of the liquid. More substrate diffuses into the biofilm, and hence availability of nutrients into the biofilm increased. Oxidation of more nutrients takes place by the available microbes, producing more protons and electrons, thus producing more power. A reverse phenomenon was observed with increased inlet substrate flow rate.

3.1.2. Hydraulic retention time

The relationship between hydraulic retention time and power is shown in Fig. 2(b) and observed to be an inverse relationship with power. Decrease in the value of HRT resulted in decrease in the working volume of CMFC, which leads to an increase in the substrate concentration in the bulk of CMFC. This increased concentration enables higher diffusion of substrate to the biofilm. Large amount of substrate available for oxidation to the microbes resulted in production of more protons and thus more power. A reverse phenomenon was observed with increased HRT value.

3.1.3. Inlet substrate concentration

Fig. 2(c) shows effect of change in initial substrate concentration with power. This figure shows that power of the CMFC increases monotonically with increase in the initial substrate concentration. Increase in the bulk substrate concentration, increases diffusion of substrate to the film. Hence, large amount of substrate was available to the microorganism for oxidation, which resulted in generating large number of protons and electrons. This increased generation of electrons, increases the power production when compared to the base case. An opposite effect was observed with decreased feed substrate concentration.

3.1.4. Voltage

Fig. 2(d) demonstrates a nonlinear relationship between voltage and produced power of the CMFC. This also demonstrates that there exists a maximum power in the steady state relation of power and voltage. This type of behavior is called as input multiplicity, where the steady state gain changes its direction at certain operating condition.

3.2. Dynamic analysis

Dynamic analysis was carried out for three manipulated variables viz i) HRT, ii) inlet substrate flow rate and iii) initial substrate concentration. Steady state analysis of cell voltage showed strong nonlinear relationship with input multiplicity. In general, a strong nonlinear control design is required for complex dynamics system [44]. For this paper, nonlinear controller development is out of scope and hence the voltage was neglected for further study. Dynamic analysis was carried out by providing a step change of particular magnitude in the chosen manipulated variable while keeping all other variables at their base case value. The step change was given in both the direction i.e. positive and negative from the base case value.

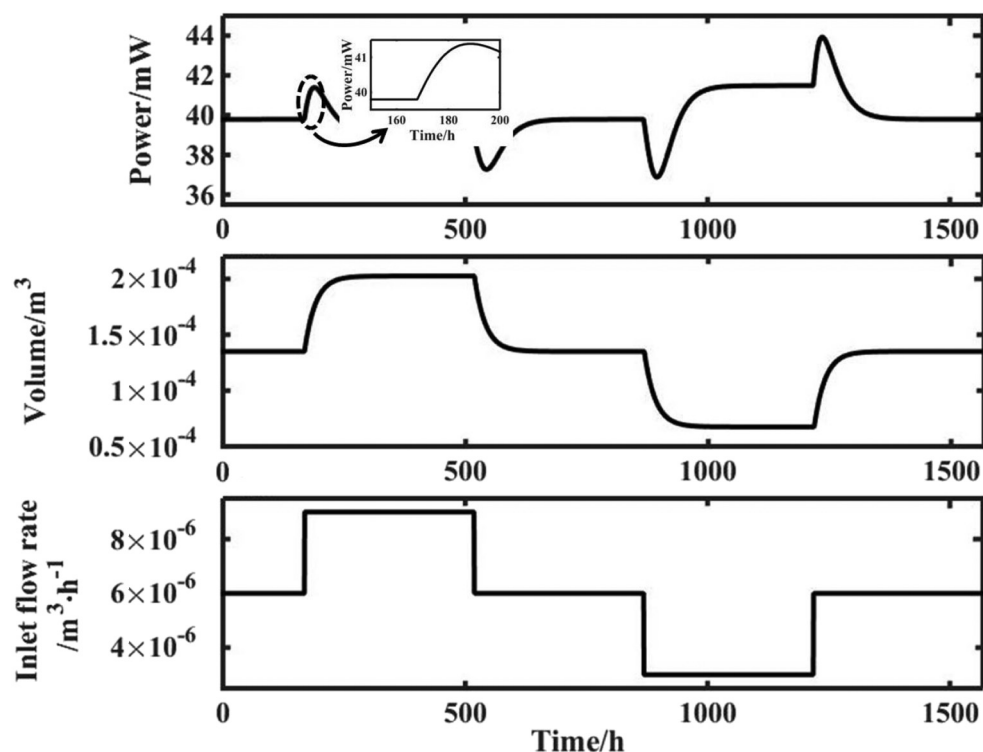


Fig. 3. Transient response of power for inlet substrate flow rate.

3.2.1. Transient response of inlet substrate flow rate

Fig. 3 shows the transient response of power with inlet substrate flow rate. When the inlet substrate flow rate was increased, a fast increase in the power (up to a time of 190 h) and then a relatively gradual decrease was observed. The initial increase in power was observed because of increased consumption of substrate in the biofilm.

Due to increase in inlet substrate flow rate (Fig. 4a), inflow of substrate increases instantly (Fig. 4b). Although working volume increases with inlet substrate flow rate, rate of substrate in was more compared to the rate of volume increase (Fig. 4c), and hence concentration of substrate increases in the bulk (Fig. 4d). Thus, diffusion of substrate increased in the biofilm (Fig. 4e), increasing the amount of substrate

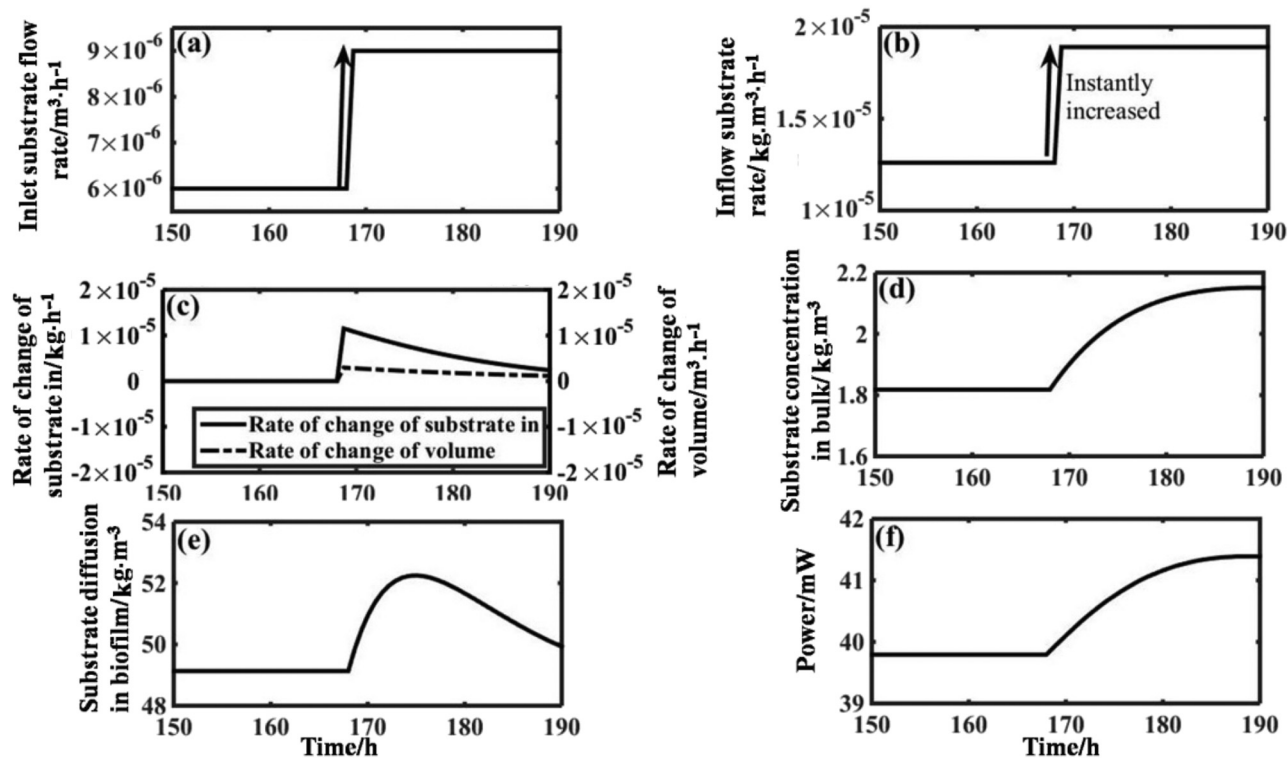


Fig. 4. Graphical representation of increase in power with increase in inlet substrate flow rate from the time instant of 150 to 190 h (initial increase in power).

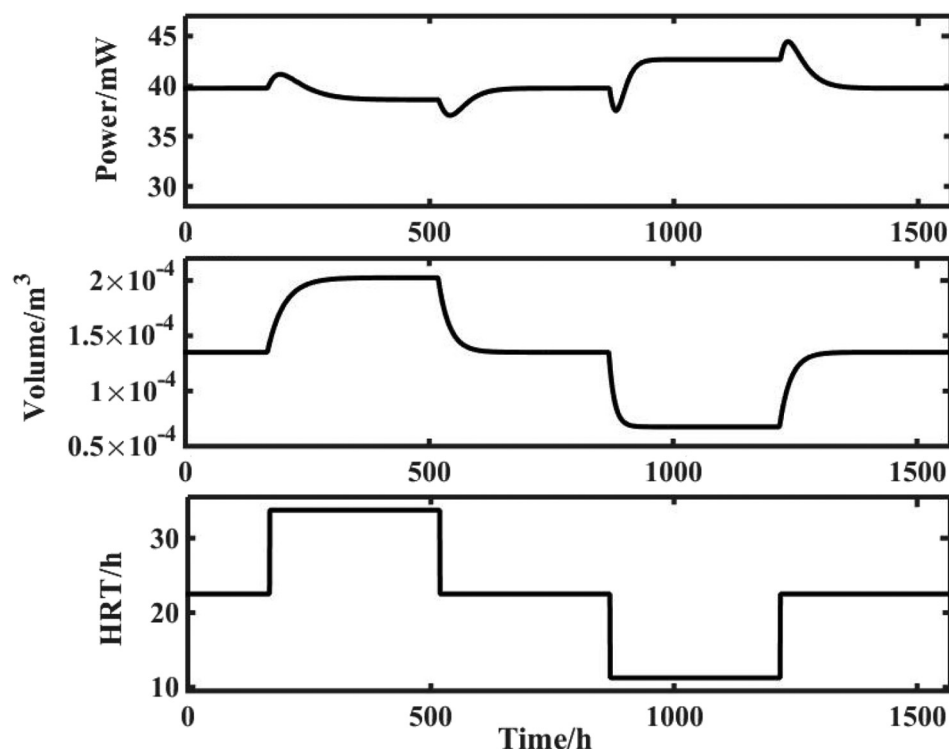


Fig. 5. Dynamic response of power with HRT.

available for the microbes. This resulted in higher production of electrons and protons. Hence, power produced from the cell increased during the initial period (Fig. 4f).

In later stage, outlet flow rate marched towards new steady state to maintain HRT. This resulted in reduction of substrate concentration in the bulk with an increased outlet flow rate and increased working volume. This decreases the concentration gradient between bulk and biofilm. Fewer nutrients were available for microbes and diffusion of protons dominates as compared to the production of protons. Hence drop in the power in latter stage of the step change was observed. The reverse phenomena were observed when the direction of step changed. The normalised steady state gain of power for positive and negative step change (50%) in initial substrate flow rate was found to be 3.80% and 8.50% respectively. The graphical representation of this explanation is given in Appendix A.

After providing a step change of known magnitude in both the directions, we observed inverse response in system as shown in Fig. 3. Due to increased inlet substrate flow rate, initially the rate of consumption of substrate was higher compared to the rate of diffusion of substrate inside the biofilm. Also, because of increased rate of substrate consumption, rate of proton production was higher compared to diffusion of proton. Hence initial increase in produced power was observed. At later stage, the outlet flow rate increased and attained a new steady state to maintain HRT (22.5 h). Due to this, the rate of diffusion is higher as compared to the rate of consumption and hence drop in power was observed. Time taken for overcoming the inverse response is 71 h and 73 h for positive and negative step change respectively.

3.2.2. Transient response of HRT

A step change of known magnitude in the value of HRT was given at the base case steady state value. As shown in Fig. 5, with 50% positive step change in the HRT, an initial increase and then gradual decrease in power was observed. As soon as the positive step change was given in HRT, outlet flow rate gets dropped significantly to compensate for the increased HRT value. Now outlet flow rate becomes small as

compared to inlet flow rate and hence the working volume increases. Because of increased working volume, concentration gradient of substrate between the bulk of liquid and biofilm increased, resulting in an increased diffusion from the bulk (As explained in Section 3.2.1), leading to increased power from the CMFC. Increase in working volume also increased the outlet flow rate from the earlier dropped value. At the new HRT value (33.75 h), the working volume started to reach a new steady state (different than the base case) value, and outlet flow rate also slowly started increasing towards the base value ($6 \times 10^{-6} \text{ m}^3 \cdot \text{h}^{-1}$). At this point, outlet flow rate approximately became equal to the inlet flow rate. Hence, rate of nutrients coming in the system and going out of the system became approximately equal. Because of this phenomenon, concentration of substrate in bulk of liquid and biofilm decreases, and settled towards the base case value. The production of protons in the biofilm decreased, which resulted in decreased power production from the CMFC in the later position of the step change in HRT. The opposite trends were observed when negative step change in the values of HRT was given. The normalised steady state gain of power using positive and negative step change (50%) in HRT was found to be 5.80% and 14.42%, respectively.

In the initial phase of step changes in HRT, a sudden decrease in outlet flow rate was observed keeping inlet flow rate at the base value. Because of this, substrate concentration gradient develops between the bulk and biofilm on the anode. This increases the rate of diffusion of substrate into the biofilm, however this rate is small compared to the rate of consumption of substrate inside the biofilm. Hence, we observed an initial increase in the power generation. In the later stage, rate of diffusion dominates the rate of consumption, and hence decrease in power was observed. Time required to overcome inverse response was 84 h and 32 h for positive and negative direction of step change respectively.

3.2.3. Transient response of initial substrate concentration

Fig. 6 demonstrates the transient response of power to the initial substrate concentrations. Increased initial substrate concentration resulted in increased bulk substrate concentration, leading to higher

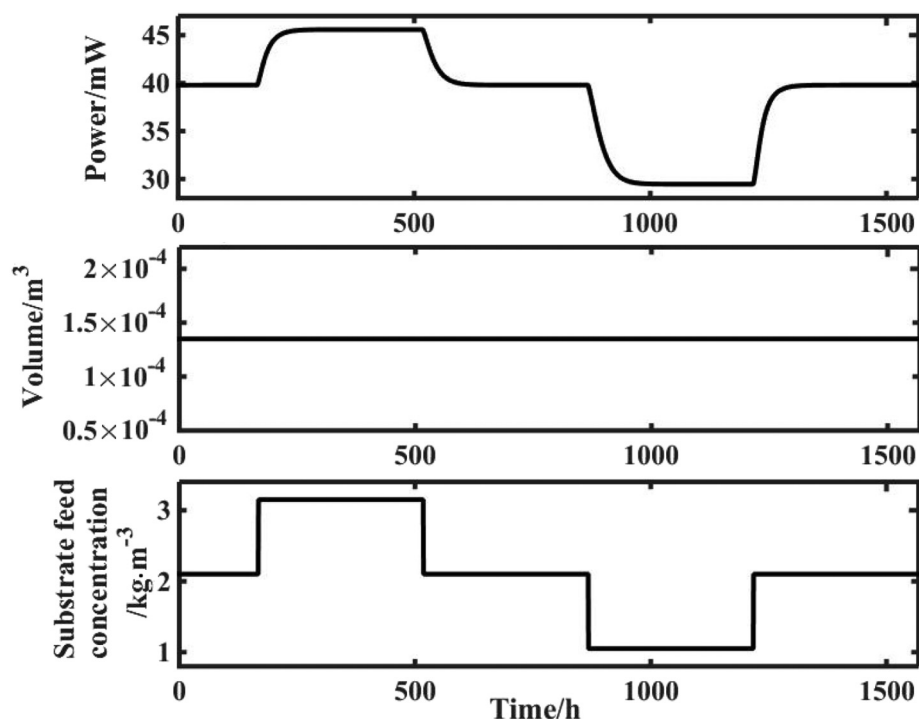


Fig. 6. Transient response of power for initial substrate concentration.

driving force for the diffusion of substrate into the biofilm. Thus, more substrate flows into the biofilm and hence more nutrients were available for oxidation to the microbes. Faster metabolism reaction produces more protons and electrons thereby producing more power. The opposite phenomena were observed, when direction of step changed. The normalised steady state gain of the power from initial substrate concentration for positive and negative step change (50%) from the base value was found to be 29.10% and 52%, respectively.

4. Selection of Manipulated Variable

Proper selection of manipulated variable was carried out using steady state as well as dynamic analysis. HRT, inlet substrate flow rate and initial substrate concentration can be manipulated using linear controller, as these variables showed a monotonic response with power of the CMFC. The normalised steady state gains for positive dynamic responses were 29.10%, 5.80% and 3.80% with initial substrate concentration, HRT and inlet substrate flow rate respectively. Initial substrate concentration was an ideal candidate for the control purpose because of higher gain. However, manipulation will be very difficult for control purpose. Hence, initial substrate concentration was not considered as the potential manipulated variable.

We observed that with an change in inlet substrate flow rate, working volume of the substrate in the bulk of liquid either increased to infinity (overflow of the cell) or decreased to zero (draining of the cell) without keeping HRT constant. Both of these cases are not favourable for continuous operation of the CMFC and steady state gain is also lower as compared to the HRT. Hence, inlet substrate flow rate was not selected as the manipulated variable. HRT showed inverse relationship and acceptable steady state gain with power. Hence, HRT was selected as the manipulated variable.

5. Development of Linear Controllers for Variable Volume CMFC

To have smooth and prolonged operation of the variable volume CMFC, a robust control strategy needs to be devised. In the proposed control approach, a control-oriented model was identified using input–output data. The input signal was in the form of pseudo random binary signal (PRBS) of HRT whereas power produced as the output from system. Skogestad's internal model control (SIMC) [45] rule was implemented to find the values of the tuning parameters for classical controller. A linear model predictive controller was also designed to enhance an efficiency of the operation of the CMFC. To test the efficacy of the proposed controllers, simulations for servo problems were carried out. In Section 5.1, 5.2, and 5.3, the procedure for model identification

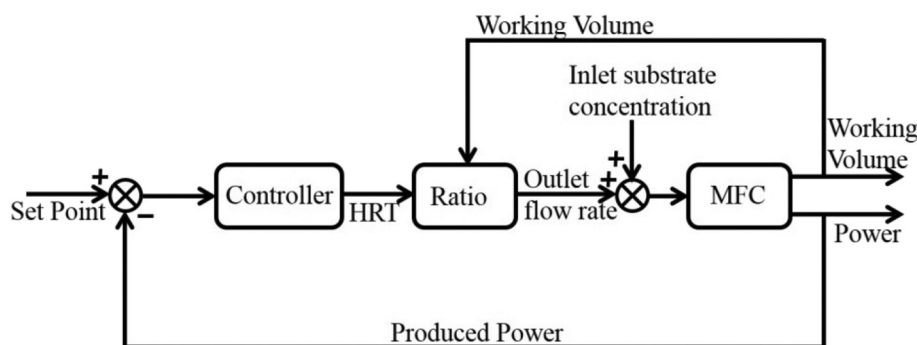


Fig. 7. Schematic diagram of proposed control strategies.

and design of controllers is presented. The schematic of the proposed control strategy is shown in the Fig. 7.

5.1. Control-oriented model identification and its validation

Control oriented model was identified using perturbed data obtained from simulated first principle-based model of the CMFC. A PRBS input signals of appropriate magnitude were given to the simulated model and output data were collected. From input–output data, a higher order state space model was identified using identification toolbox in MATLAB®. Then this model was reduced to a second order model using “*balred*” command in MATLAB®. Both of these models were validated using the input–output identification data (Fig.8).

The higher and second order control-oriented models were quantitatively compared with perturbation data. The models fit were found to be 80.74% and 78.39% respectively and thus acceptable for control design purpose.

5.2. Efficacy of the linear classical control strategy

A classical control in the form of proportional-integral (PI) was developed and implemented on the simulated model. The control-oriented model was used to find the tuning parameters of the controller. The SIMC tuning method for the second order process was used as given below:

$$K_c = (1/K_p) \times (\tau_1/\tau_c) \quad (15)$$

$$\tau_i = \min([\tau_1, 4\tau_c])$$

Because of nonlinearity present in the system, initial values of the tuning parameters were detuned and then PI controller was implemented on the system.

The proposed control scheme (classical PI control) was tested by controlling the power of the CMFC at various set points such as 48 and 37 mW. The measured value of power was subtracted from the desired set point and thus error was calculated. Using this error, value of manipulated variable was calculated by the PI controller and

subsequently fed to the CMFC model. The hard constraints on the input were imposed for maximum and minimum values to avoid emptying (zero) or overflowing of the CMFC. The performance of the proposed controller is demonstrated in Fig. 9.

Steady state value of power for base case was maintained at 38.73 mW whereas the first set point was given to controller is 48 mW. This set point was tracked by the controller in 126 h with initial inverse response and oscillatory behavior. The initial inverse behavior was observed to be around 49 h. As soon as the demand in the power increased, the manipulated variable (HRT) starts moving towards the lower value when compared to the value given before the set point. This was maintained by increasing the outlet flow rate from the cell. Increased outlet flow rate with constant inlet substrate flow rate resulted in decreased working volume. However, because of substantial high flow rate, most of nutrients exited without reaction and hence scarcity of nutrients faced by the microbes, resulting into dropping of power. Once, the outlet flow rate started to settle to a new steady state value and volume to a lower steady state value, the concentration increases in the bulk of CMFC. Thus, more diffusion of substrate from bulk of the CMFC into biofilm occurred. Hence availability of nutrients for microbes increased in biofilm leads to more power production.

The second set point was equal to steady state value of the base case. The settling time for this set point was around 156 h. Volume of the working fluid and the HRT settled to the base case values. The third set point was equal to 37 mW, lower than the base case value and the settling time for this set point was around 889 h. This is because of nonlinearity present in the system. As HRT demonstrated inverse relationship with power, it was expected to increase the HRT value for lower power demand. Because of an increase in HRT, working volume of the anode chamber increases and became three times to the base case value. This showed that for demanding lower power than the base case, cell size should be larger than the base case. The designed linear classical controller for the variable volume CMFC was facing two main challenges viz. 1) The settling time for lower set point than base case is very large i.e. 889 h. 2) The increase in working volume of the reactor is also very large i.e. three times more than the base case volume.

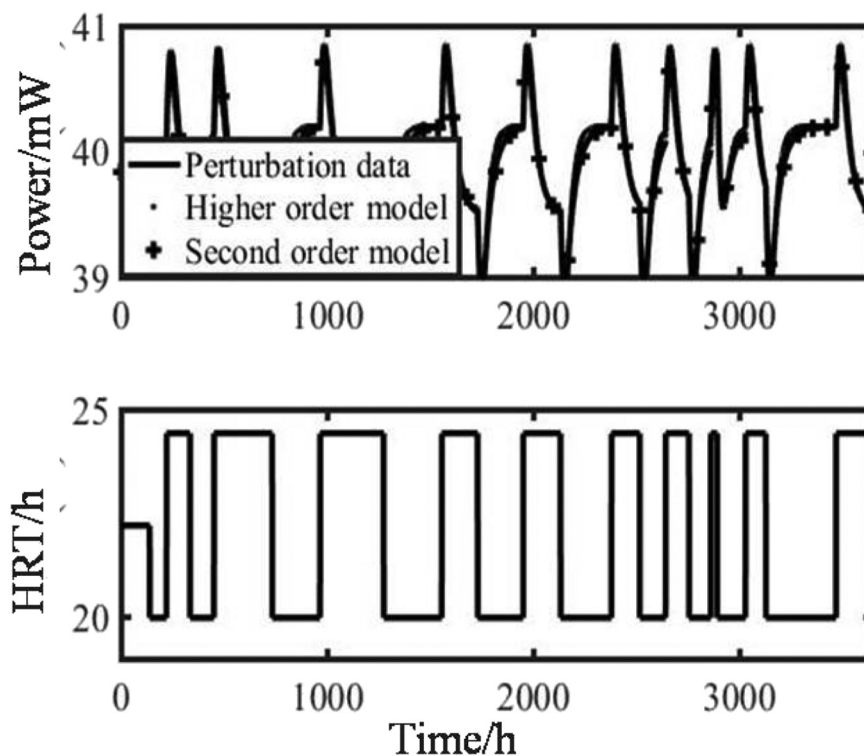


Fig. 8. Control-oriented model validation.

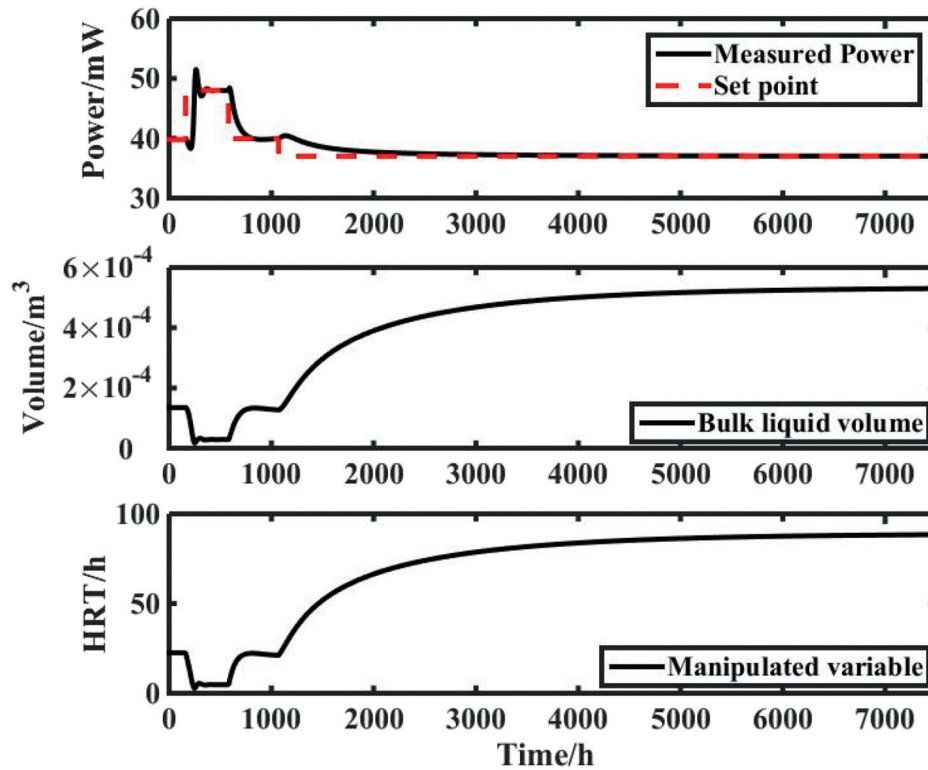


Fig. 9. Proposed classical controller performance for servo problem.

This will increase the capital cost of the CMFC. The solution for these challenges was tried to found out using more sophisticated linear controller framework in the form of model predictive controller. In the next sub-section, a detailed discussion for development of linear model predictive controller is given.

5.3. Efficacy of the linear model predictive control strategy

Model predictive control refers to the class of control algorithms which deal operational constraints and multi-variable interaction in a systematic way. The main idea of the model predictive control is to use a model of the system for predicting the future input moves for the controller. An open loop optimal control problem is solved over the finite horizon, at each sampling instant. Only the first input move is implemented and then with the new measurement, again an open loop optimal control problem is solved and the process is repeated.

For developing the model predictive controller, a linear discrete state space model was used, given as

$$x(k+1) = \Phi x(k) + \Gamma u(k) \quad (16)$$

$y(k) = Cx(k)$
The desired future set point trajectory at instant k is given by, $y_r(k+j|k) : j = 1, 2, \dots, p$ where p shows the prediction horizon. The model predictive control problem at the sampling instant k is defined as unconstrained optimization problem, where future input moves are calculated by minimizing the objective function J defined as [46,47].

$$J = \varepsilon(k)^T W_\infty \varepsilon(k) + \sum_{j=1}^p \varepsilon(k)^T W_e \varepsilon(k) + \sum_{j=0}^{q-1} \Delta u(k)^T W_{\Delta u} \Delta u(k) \quad (17)$$

Here, W_e represents positive definite error weighting matrix, $W_{\Delta u}$ represents positive semi-definite input move weighting matrix and

W_∞ represents the terminal weighting matrix. Where prediction control error and change in input moves represented as

$$R(k) = [y_r(k+1, k)^T \ y_r(k+2, k)^T \ \dots \ y_r(k+p, k)^T]^T \quad (18)$$

$$\varepsilon(k) = R(k) - \hat{y}(k)$$

$$\Delta u(k) = u(k) - u(k-1)$$

$$j = 1, \dots, q-1$$

The unconstrained MPC control using innovation bias formulation was re-cast as follows.

$$\min_{U_q(k)} \frac{1}{2} U_q(k)^T H U_q(k) + F(k)^T U_q(k) \quad (19)$$

where,

$$H = 2(S_u^T W_e S_u + \Delta U^T W_{\Delta U} \Delta U + \Gamma^T W_\infty \Gamma) \quad (20)$$

$$F(k) = -2[\xi^T(k) W_e S_u + (\Psi_0 u(k-1))^T W_{\Delta U} \Psi + (\Phi \hat{x} - \hat{x}_k) W_\infty \Gamma] \quad (21)$$

$$\xi(k) = R(k) - S_x \hat{x}(k|k-1) - S_e e_f(k) \quad (22)$$

$$W_e = \text{block diag} [w_e w_e w_e w_\infty]_{(pn \times pn)}$$

$$W_{\Delta U} = \text{block diag} [w_{\Delta U} w_{\Delta U} w_{\Delta U} w_{\Delta U}]_{(qm \times qm)}$$

$$S_x = \begin{bmatrix} c\Phi \\ c\Phi^2 \\ \dots \\ c\Phi^p \end{bmatrix} \quad (23)$$

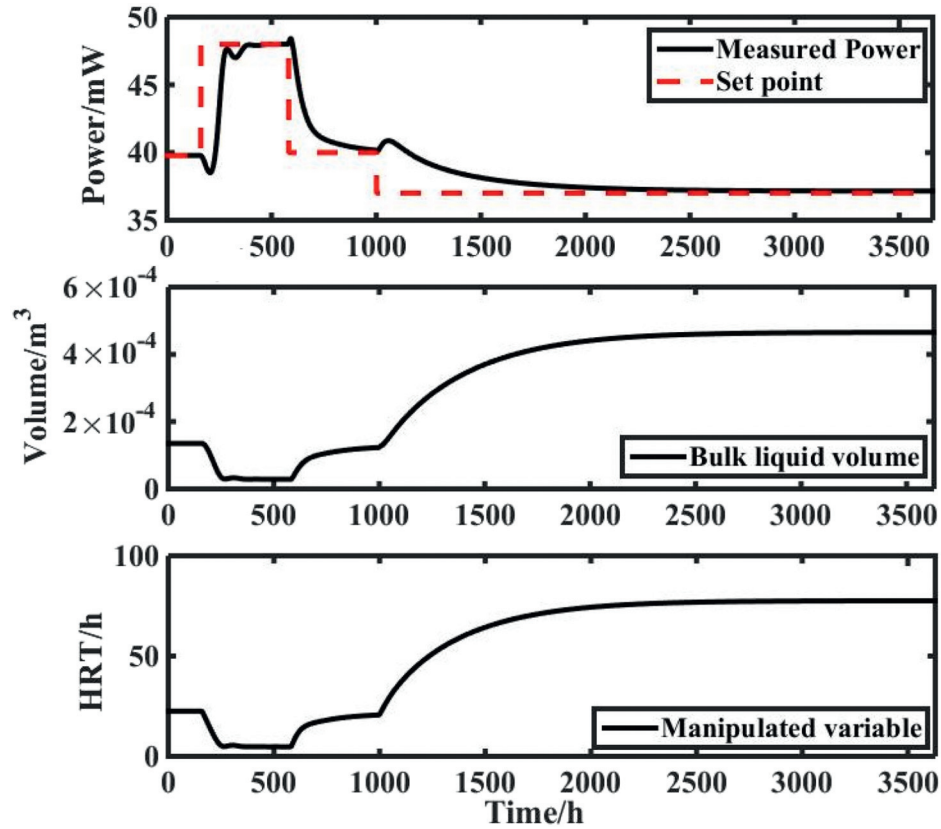


Fig. 10. Performance of linear MPC for variable volume CMFC.

$$S_u = \begin{bmatrix} c\Gamma_u & [0] & [0] & \dots & [0] \\ c\Phi\Gamma_u & c\Gamma_u & [0] & \dots & [0] \\ \dots & \dots & \dots & \dots & [0] \\ c\Phi^{p-1}\Gamma_u & c\Phi^{p-2}\Gamma_u & \dots & \dots & c\Gamma_u \end{bmatrix} \quad (24)$$

Here S_u referred as a dynamic matrix

$$\Delta U_p(k) = \begin{bmatrix} u(k, k) - u(k-1) \\ u(k + m|k) - u(k|k) \\ \dots \\ u(k + m_{q-1}|k) - u(k + m_{q-2}|k) \end{bmatrix} = \Psi U_q(k) - \Psi_0 U(k-1) \quad (25)$$

Where

$$\Psi = \begin{bmatrix} I_m & [0] & [0] & [0] \\ -I_m & I_m & [0] & [0] \\ \dots & \dots & \dots & \dots \\ [0] & \dots & -I_m & I_m \end{bmatrix}_{(qm \times qm)} ; \quad \Psi_0 = \begin{bmatrix} I_m \\ [0] \\ \dots \\ [0] \end{bmatrix}_{(qm \times qm)} \quad (26)$$

The unconstrained MPC problem can be solved analytically, as follows

$$\begin{aligned} [U_q(k)]_{opt} &= -H^{-1}F(k) \\ u_{opt}(k, k) &= \Psi_0^T [U_q(k)]_{opt} = -\Psi_0^T H^{-1}F(k) \end{aligned} \quad (27)$$

Only first input move is implemented at each sampling instant, and the entire procedure is repeated at each sampling instant with a new measurement, until the given set point have been tracked.

The efficacy of the linear MPC is tested on the developed variable volume CMFC, and shown in Fig. 10. It was observed that there was not significant improvement for first two set points when compared to classical PI controller; however, some improvement was observed for the third set point. The settling time for the third set point was found to be 750 h, which is less than the classical controller settling time. The linear MPC improved the performance of controller for third set point tracking in term of settling time; however, the problems associated with CMFC under the variable volume system were not addressed by the linear MPC.

Another class of controller i.e., non-linear controller will solve the first challenge of higher settling time; although the second challenge may not be addressed even with nonlinear controller. Hence in this manuscript, a split range controller in the framework of model predictive controller is proposed to address these two challenges from control design point of view and described in the next section.

6. Comparison of Constant and Variable Volume CMFC

In constant volume CMFC, volume of the anodic chamber is the summation of volume of working fluid and biofilm. The impact of variation of inlet and outlet flow rate was neglected as these flow rates were maintained at the same constant value. In variable volume CMFC, the inlet and outlet flow rates were not maintained at constant single value and hence working volume of the anodic chamber varies.

Steady state analysis of HRT with power in constant as well as variable volume of CMFC is shown in Fig. 11. This figure demonstrates that the power has inverse relationship with HRT as well as inlet substrate flow rate (at constant HRT) in case of variable volume CMFC.

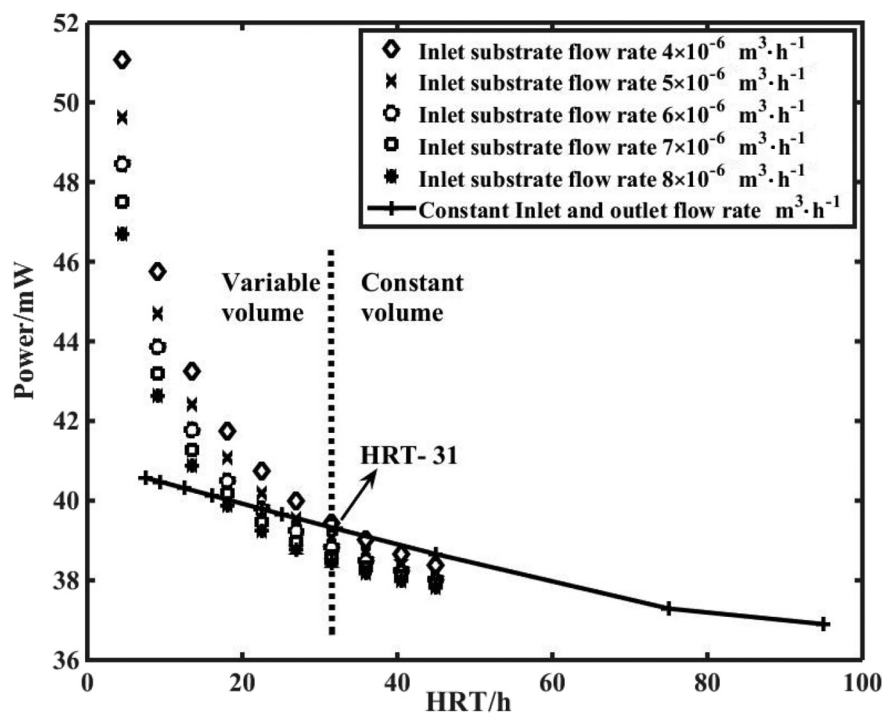


Fig. 11. Steady state operation comparison of constant and variable volume MFC.

Whereas direct relationship of power with inlet substrate flow rate and inverse relationship with HRT for constant volume CMFC.

Salient features of Fig. 11 are as follows:

- 1) At any given constant HRT values, higher power will be obtained at lower inlet substrate flow rate in case of variable volume CMFC.
- 2) The power produced per unit mass of substrate is five times higher in magnitude in case of variable volume CMFC as compared to the constant volume CMFC at same value of HRT. From this observation it was inferred that the operational cost (cost of substrate) for higher power is less in variable volume CMFC as compared to the constant volume CMFC.
- 3) At any constant given HRT, volume of the cell increases from a higher power to lower power
- 4) As the HRT increases, volume of the CMFC increases. In order to accommodate these increases in volume, larger volume CMFC needs to be fabricated, and capital cost will be higher.
- 5) Below the value of 31 h of HRT, variable volume CMFC always generate higher power as compared to the constant volume CMFC, whereas this advantage diminishes as HRT increases above 31 h.
- 6) To operate CMFC over entire operating range of HRT, a split range control strategy including variable volume (up to HRT of 31 h) and constant volume (more than HRT of 31 h) CMFC would be beneficial.

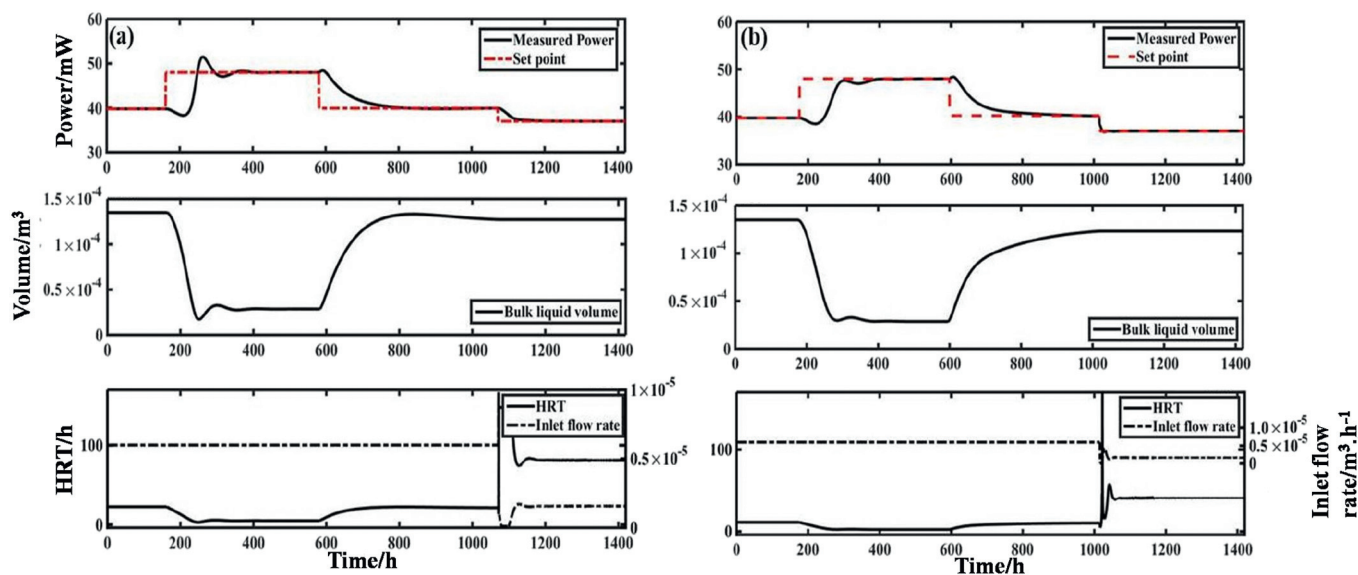


Fig. 12. Proposed split controller performance for servo problem a) IMC based PI and b) linear MPC.

7. Split Range Control Design

In the split range controller, the higher set points (greater than the base case value) were tracked using variable volume CMFC with HRT as the manipulated variable. Whereas the lower set point was tracked using constant volume CMFC with inlet substrate flow rate as the manipulated variable. The conversion of variable volume to constant volume is carried out by equalizing the outlet flow rate with the inlet flow rate of substrate. Practically this equalization can be easily achieved.

For split range controller, two control strategies were evaluated i.e., linear classical controller and MPC. Two PI controllers, one for each, i.e., variable volume CMFC (Section 5) and constant volume CMFC (design taken from Yewale et al. [42]) were designed. Similarly, one linear MPC for variable volume CMFC and other for constant volume CMFC were also designed. The entire operating range of the CMFC was divided using above described two manipulated variables. The performance of split range controllers for classical PI and MPC is demonstrated in Fig. 12 (a) and (b), respectively and comparison of controller performance criteria such as Integral Square of Error (ISE), Integral Control Effort (ICE), and Control Effort (CE) are presented in Table 1. As the controller and system for first two set points are same as described in Section 5, hence the performance of both the controllers were also same as described in Section 5. However, for the third set point, the entire system switches to the constant volume CMFC and inlet substrate flow rate now works as the manipulated variable. It was found that the settling time for the third set point is reduced to 49 h from 889 h (for variable volume CMFC) in case of classical control scheme. However, in case of linear MPC, the settling time for third set point was found to be 21 h and which is significantly lower than the classical control scheme for constant volume as well as linear MPC for variable volume CMFC. It was also observed that all the performance criteria were improved for split range controllers as compared to single PI and linear MPC controllers for variable volume CMFC for the last set point. As the last set point was tracked using constant volume CMFC, there was no increase in volume of the CMFC. Hence two challenges faced by the linear controller system with variable volume CMFC were overcome using split range control design.

8. Conclusions

Literature based fixed volume model of the CMFC was converted to variable volume by considering the impact of inlet and outlet flow rates of substrate. This model was also updated for the diffusion of protons to the cathode chamber through biofilm and bulk of the anode liquid. Selection of manipulated variable (HRT)

was systematically carried out using steady state and dynamic analysis.

The classical linear PI and MPC controllers were designed to control the power from CMFC. The efficacy of the designed controllers was tested for servo problem. It was found that the settling time for tracking higher set point from the base case was around 126 and 120 h for linear PI and MPC, respectively. However, the settling time for lower set point was found to be 889 and 750 h for linear PI and MPC along with increase in working volume of the anode chamber. The challenges of higher settling time and large increase in working volume of the CMFC were addressed using split range controller combining the variable and constant volume microbial fuel cells. The settling time for the lower set point was found to be 49 and 21 h for linear PI and MPC, which is significantly lower than using only single PI or linear MPC controller over the entire operating range of the variable volume fuel cell. As the third set point has been tracked using constant volume fuel cell, there is no increase in the working volume and hence capital cost required to compensate increase in volume was saved. Linear MPC demonstrated remarkable performance improvement over the classical PI controller for split range controller and hence use of linear MPC is recommended for split range controller for CMFC.

Nomenclature

A	surface area, m^2
b	Tafel coefficient, V
C	output matrix
c	concentration, $kg \cdot m^{-3}$
D	diffusion coefficient, $m^2 \cdot h^{-1}$
d	distance, m
E	voltage, V
F	Faraday constant, $C \cdot mol^{-1}$
f_l	volumetric flow rate, $m^3 \cdot h^{-1}$
i	current, mA
J	cost of objective function
K	conductivity, $s \cdot m^{-1}$
k_{La}	overall volumetric mass transfer coefficient, h^{-1}
L	biofilm thickness, m
n	No. of electron produced
Q	specific uptake rate, h^{-1}
R	Universal gas constant, $J \cdot mol^{-1} \cdot K^{-1}$
S_u	dynamic matrix
T	temperature, K
t	time, h
U	manipulated variable
Δu	change in input moves
V	volume of anode chamber, m^3
x	state variable
Y	bacterial yield
y	measured output
W_e	positive definite error weighting matrix
$W_{\Delta u}$	positive semi-definite input move weighting matrix
W_{∞}	terminal weighting matrix
r	input matrix
r	fraction of biomass
δ	detachment rate, $m \cdot h^{-1}$
ε	prediction control error
η	overpotential, V
μ	rate constant, h^{-1}
ξ	estimation error compensated set point trajectory
ρ	biomass density, $kg \cdot m^{-3}$
σ	biomass separation rate
Φ	state (or system) matrix

Table 1

Controller performance criteria for split range and single controllers: - The values with and without parenthesis represent for single and split range PI controller, whereas values in the square and curly bracket indicate single and split range linear MPC

Set point	Settling time/h	ISE $\times 10^{-4}$	ICE	Control effort $\times 10^{-4}$
48	126	0.1825	0.002	1.366
	[120]	[0.1806]	[0.001]	[0.641]
	(126)	(0.1825)	(0.002)	(1.366)
	{120}	{0.1806}	{0.001}	{0.641}
40	156	1.0531	0.0011	0.352
	[154]	[0.912]	[0.0003]	[0.259]
	(156)	(1.0531)	(0.0011)	(0.352)
	{154}	{0.912}	{0.0003}	{0.259}
37	49	0.0942	0.036	2.158
	[21]	[0.0423]	[0.0066]	[1.02]
	(889)	(0.8554)	(1.3)	(62.4)
	{750}	{0.764}	{0.951}	{0.51}

Superscripts

* saturation

Subscripts

0 initial condition

a active

act activation

aq aqueous solution

bf biofilm

bk bulk chamber

cell between electrodes

det detachment

H protons

h between electrode and membrane

i inactive

in inlet

ina inactivation

L bulk liquid

l sublayer

La lactate

M membrane

max maximum value

out outlet

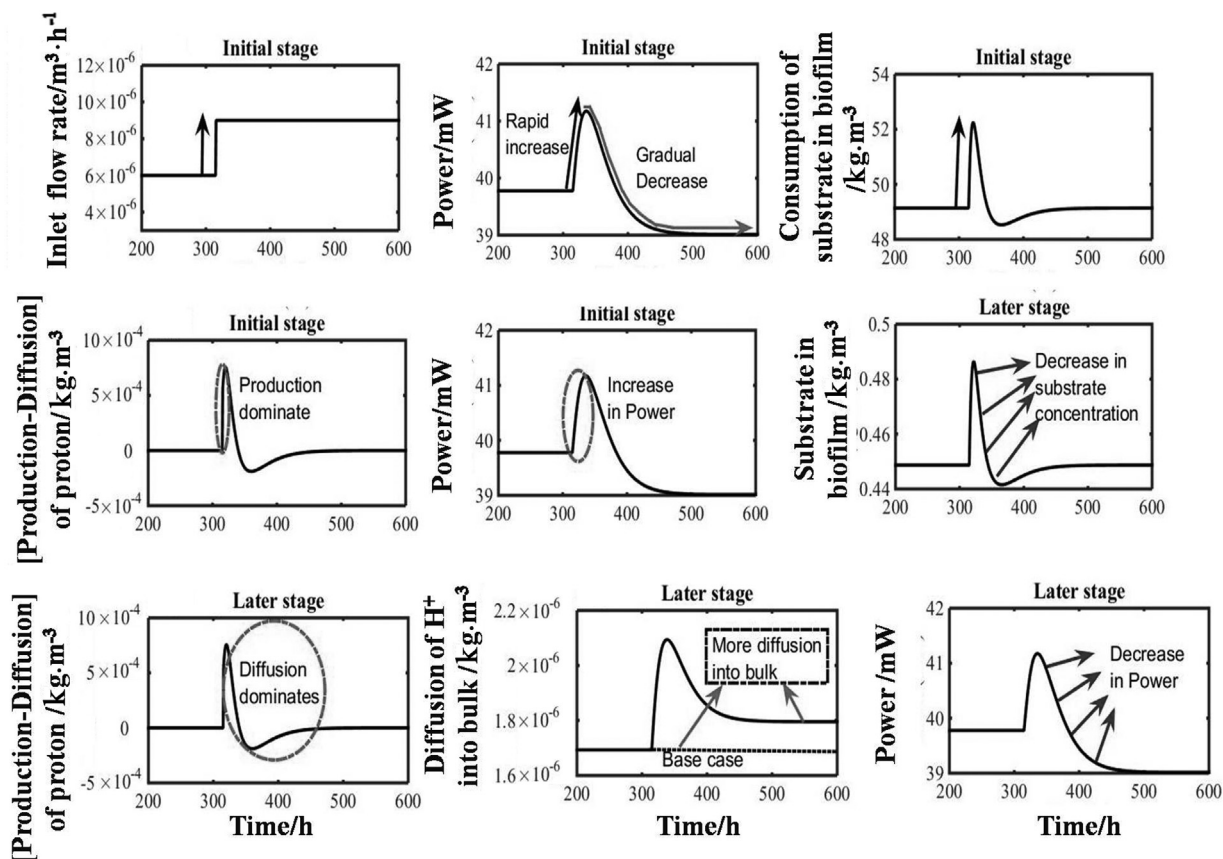
output output value

P species in the anode side of CMFC

ref reference

s substrate

thermo theoretical value

Appendix A**References**

- [1] C.J. Schuster-Wallace, M. Qadir, Z. Adeel, S.K. Dickin, Putting Water and Energy at the Heart of Sustainable Development, UHN-INWEH Reports, United Nations University, Canada, 2015, <http://inweh.unu.edu>.
- [2] V.B. Oliveira, M. Simões, L.F. Melo, A.M.F.R. Pinto, Overview on the developments of microbial fuel cells, *Biochem. Eng. J.* 17 (2013) 53–64.
- [3] V.M. Ortiz-Martínez, M.J. Salar-García, A.P. de los Ríos, F.J. Hernández-Fernández, J.A. Egea, L.J. Lozano, Development in microbial fuel cell modelling, *Chem. Eng. J.* 271 (2015) 50–60.
- [4] J. Chouler, G.A. Padgett, P.J. Cameron, K. Preuss, M.M. Titirici, I. Ieropoulos, M. Di Lorenzo, Towards effective small-scale microbial fuel cells for energy generation from urine, *Electrochim. Acta* 192 (2016) 89–98.
- [5] S. Choi, Micro scale microbial fuel cells: advances and challenges, *Biosens. Bioelectron.* 69 (2015) 8–25.
- [6] M. Zhou, H. Wang, D.J. Hassett, T. Gu, Recent advances in microbial fuel cells (MFCs) and microbial electrolysis cells (MECs) for wastewater treatment, bioenergy and bioproducts, *J. Chem. Technol. Biotechnol.* 88 (4) (2013) 508–518.

- [7] M.H. Do, H.H. Ngo, W.S. Guo, Y. Liu, S.W. Chang, D.D. Nguyen, L.D. Nghiem, B.J. Ni, Challenges in the application of microbial fuel cells to wastewater treatment and energy production: a mini review, *Sci. Total Environ.* 639 (2018) 910–920.
- [8] A.G. Capodaglio, D. Molognoni, A. Callegari, Formulation and preliminary application of an integrated model of microbial fuel cell process, *Proc. 29th Eur. Conf. Model. Simul. ECMS 8* (2015) 340–344.
- [9] Q. Wen, Y. Wu, D. Cao, L. Zhao, Q. Sun, Electricity generation and modeling of microbial fuel cell from continuous beer brewery wastewater, *Bioresour. Technol.* 100 (2009) 4171–4175.
- [10] Y. Zeng, Y.F. Choo, B.H. Kim, P. Wu, Modelling and simulation of two-chamber microbial fuel cell, *J. Power Source* 195 (2010) 79–89.
- [11] R.P. Pinto, B. Srinivasan, M.F. Manuel, B. Tartakovsky, A two-population bio-electrochemical model of a microbial fuel cell, *Bioresour. Technol.* 101 (2010) 5256–5265.
- [12] J.R. Kim, H.C. Boghani, N. Amini, K.F. Aguey-Zinsou, I. Michie, R.M. Dinsdale, A.J. Guwy, Z. X. Guo, G.C. Premier, Porous anodes with helical flow pathways in bioelectrochemical systems: the effects of fluid dynamics and operating regimes, *J. Power Sources* 213 (2012) 382–390.
- [13] V.B. Oliveira, M. Simões, L.F. Melo, A.M.F.R. Pinto, A 1D mathematical model for a microbial fuel cell, *Energy* 61 (2013) 463–471.
- [14] R. Shankar, P. Mondal, S. Chand, Modelling and simulation of double chamber microbial fuel cell: cell voltage, power density and temperature variation with process parameters, *Green* 3 (2013) 181–194.
- [15] D. Recio-Garrido, M. Perrier, B. Tartakovsky, Parameter Estimation of a Microbial Fuel Cell Process Control-oriented Model, 22nd Mediterr. Conf. Control Autom. MED, (2014) 918–923.
- [16] M. Esfandiyari, M.A. Fanaei, R. Gheshlaghi, M. Akhavan Mahdavi, Dynamic modeling of a continuous two-chamber microbial fuel cell with pure culture of *Shewanella*, *Int. J. Hydrog. Energy* 42 (2017) 21198–21202.
- [17] Z.Z. Ismail, A.A. Habeeb, Experimental and modeling study of simultaneous power generation and pharmaceutical wastewater treatment in microbial fuel cell based on mobilized biofilm bearers renew, *Energy* 101 (2016) 1256–1265.
- [18] M.M. Mardanpour, S. Yaghmaei, M. Kalantar, Modeling of micro-fluidic microbial fuel cells using quantitative bacterial transport parameters, *J. Power Sources* 342 (2017) 1017–1031.
- [19] H. Lin, S. Wu, J. Zhu, Modeling power generation and energy efficiencies in air cathode microbial fuel cells based on Freter equations, *App. Sci.* 8 (10) (2018) 1983.
- [20] X. Zhang, A. Halme, Modelling of a microbial fuel cell process, *Biotechnol. Lett.* 17 (1995) 809–814.
- [21] A. Kato, C.I. Torres, B.E. Rittmann, Conduction based modeling of the biofilm anode of a microbial fuel cell, *Biotechnol. Bioeng.* 98 (2007) 1171–1182.
- [22] C. Picioreanu, I.M. Head, K.P. Katuri, M.C.M. van Loosdrecht, K. Scott, A computational model for biofilm-based microbial fuel cells, *Water Res.* 41 (2007) 2921–2940.
- [23] C. Picioreanu, K.P. Katuri, I.M. Head, M.C.M. Van Loosdrecht, K. Scott, Mathematical model for microbial fuel cells with anodic biofilms and anaerobic digestion, *Water Sci. Technol.* 57 (2008) 965–971.
- [24] F. Harnisch, R. Warmbier, R. Schneider, U. Schröder, Modeling the ion transfer and polarization of ion exchange membranes in bioelectrochemical systems, *Bioelectrochemistry* 75 (2009) 136–141.
- [25] C. Picioreanu, M.C.M. van Loosdrecht, T.P. Curtis, K. Scott, Model based evaluation of the effect of pH and electrode geometry on microbial fuel cell performance, *Bioelectrochemistry* 78 (2010) 8–24.
- [26] B.V. Merkey, D.L. Chopp, The performance of a microbial fuel cell depends strongly on anode geometry: a multidimensional modeling study, *Bull. Math. Biol.* 74 (2012) 834–857.
- [27] F. Fang, G. Zang, M. Sun, H. Yu, Optimizing multi-variables of microbial fuel cell for electricity generation with an integrated modeling and experimental approach, *Appl. Energy* 110 (2013) 98–103.
- [28] R. Sedaqatvand, M. Nasr Esfahany, T. Behzad, M. Mohseni, M.M. Mardanpour, Parameter estimation and characterization of a single-chamber microbial fuel cell for dairy wastewater treatment, *Bioresour. Technol.* 146 (2013) 247–253.
- [29] N. Jayasinghe, A. Franks, K.P. Nevin, R. Mahadevan, Metabolic modelling of spatial heterogeneity of biofilms in microbial fuel cells reveals substrate limitations in electrical current generation, *Biotechnol. J.* 9 (10) (2014) 1350–1361.
- [30] B. Sirinutsomboon, Modeling of a membraneless single-chamber microbial fuel cell with molasses as an energy source, *Int. J. Energy Environ. Eng.* 5 (93) (2014) 1–9.
- [31] M. Esfandiyari, M.A. Fanaei, R. Gheshlaghi, Mathematical modeling of two-chamber batch microbial fuel cell with pure culture of *Shewanella*, *Chem. Eng. Res. Des.* 117 (2017) 34–42.
- [32] L. Woodward, M. Perrier, B. Srinivasan, B. Tartakovsky, Maximizing power production in a stack of microbial fuel cells using multiunit optimization method, *Biotechnol. Prog.* 25 (2009) 676–682.
- [33] S. Attarsharghi, L. Woodward, O. Akhrif, An improved maximum power extraction scheme for microbial fuel cells, *IECON 2012, 38th Annu. Conf. IEEE Ind. Electron. Soc.* (2012) 910–915.
- [34] H.C. Boghani, J.R. Kim, R.M. Dinsdale, A.J. Guwy, G.C. Premier, Control of power sourced from a microbial fuel cell reduces its start-up time, increases bioelectrochemical activity, *Bioresour. Technol.* 140 (2013) 277–285.
- [35] A. Kebir, L. Woodward, O. Akhrif, Extremum-seeking control with anticipative action of microbial fuel cell's power, 23rd Mediterr. Conf. Control Autom. June 16–19 (2015), pp. 933–939.
- [36] A. Kebir, O. Akhrif, L. Woodward, Extremum-seeking control of a microbial fuel cell power using adaptive excitation, *IECON 2016 - 42nd Annu. Conf. IEEE Ind. Electron. Soc.* 3 (2016), pp. 4127–4132.
- [37] A. An, J. Wang, H. Zhang, G. Yang, Dynamics analysis of a microbial fuel cell system and pid control of its power and current based on the critical proportion degree method, *Environ Engg Manage J.* 14 (8) (2015) 1821–1828.
- [38] M. Yan, L. Fan, , Constant voltage output in two-chamber, microbial fuel cell under fuzzy PID control, *Int. J. Electrochem. Sci.* 8 (2013) 3321–3332.
- [39] H.C. Boghani, I. Michie, R.M. Dinsdale, A.J. Guwy, G.C. Premier, Control of microbial fuel cell voltage using a gain scheduling control strategy, *J. Power Sources* 322 (2016) 106–115.
- [40] D. Recio-Garrido, M. Perrier, B. Tartakovsky, Modeling, optimization and control of bioelectrochemical systems, *Chem. Eng. J.* 289 (2016) 180–190.
- [41] R. Patel, D. Deb, Parametrized control-oriented mathematical model and adaptive backstepping control of a single chamber single population microbial fuel cell, *J. Power Sources* 396 (2018) 599–605.
- [42] A. Yewale, R. Methekar, S. Agrawal, Dynamic analysis and multiple model of control of continuous microbial fuel cell (CMFC), *Chem. Engg. Res. Des.* 148 (2019) 403–416.
- [43] R.N. Methekar, V. Prasad, R.D. Gudi, Dynamic analysis and linear control strategies for proton exchange membrane fuel cell using a distributed parameter model, *J. of Power Sources* 165 (1) (2007) 152–170.
- [44] A.L. Fradkov, I.V. Miroshnikov, V.O. Nikiforov, Nonlinear and Adaptive Control of Complex Systems, Springer Science Business Media, Netherlands, Dordrecht, 1999.
- [45] G. Grimholt, S. Skogestad, Optimal PID control of double integrating processes, 11th IFAC Symposium on Dynamics and Control of Process Systems, including Bio-systems; NTNU, Trondheim, Norway, June 6–8, 2016.
- [46] S. Patwardhan, S. Manuja, S. Narsimhan, S. Shah, From data to diagnosis and control using generalized orthonormal basis filters. Part II: model predictive and fault tolerant control, *J. Process Control* 16 (2006) 157–175.
- [47] R. Methekar, Advanced Control of PEMFC Using Data Driven Models, Ph.D. thesis, IIT Bombay, India, 2010.