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Voltage Balancing Model for Series Stacked Microbial Fuel Cell

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Abstract: Microbial Fuel Cell (MFC) is an emerging technology that can support future global energy demand if it is ideally harvested. Even though many studies, suggestions, structures, and designs have been proposed, the commercialization of MFC remains unachieved due to persistent challenges such as low power output and high operational costs. Connecting two or more cells in series can multiply the total output power of the MFC. However, voltage reversal often occurs in weaker cells when the voltage drops below 0 V, leading to power loss and potential damage to the entire stack, especially under fuel starvation or imbalance in cell performance. It has been suggested that a continuous supply of anodic substrate can prevent fuel starvation and improper conditions. However, the method to find the weak cells and the amount of anodic substrate to add has not yet been discussed. In this study, for the first time, a Matrix Laboratory (MATLAB) model is proposed to identify the weak cell in a series-stacked MFC and determine the appropriate amount of substrate to add to the anodic chamber of that cell using an Artificial Neural Network (ANN). The model finds the weak cells and then modifies their Open Circuit Voltage (OCV) by adding or reducing the Total Dissolved Solids (TDS) of the Anodic chamber until all the cells reach their optimal condition. This approach helps balance the voltages between cells and prevents voltage reversal. The model works fine with OCV ranging from -1.1 V to 1.1 V, TDS 1193 ppm to 3370 ppm, Temperature 296 K to 302 K, and pH 4.66 to 8.23. The model was tested and validated using 144 sets of actual data, yielding a Root Mean Square Error (RMSE) of 8.05229 and a coefficient of determination (R^2) of 0.98257.

Keywords: microbial fuel cell, voltage balancing, voltage reversal

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1. INTRODUCTION

Microbial Fuel Cell (MFC) is a future emerging technology that can generate electricity while removing pollutants [1]. However, low-power energy generation is the primary issue in generating electricity from the MFC. Stacking up several cells in series or parallel is suggested as one of the best solutions to multiply the voltage or current generated from the MFC to improve the output power [1-3]. Unfortunately, the Voltage Reversal (VR) becomes another critical issue when the cells are stacked in series or parallel [4-6]. When two or more MFC are stacked in series, one of the cells faces reversed polarity and shows the sum of the voltage, lower than expected [7-9]. High internal resistance, substrate concentration, pH, temperature, and biofilm thickness are some of the primary causes of the voltage reversal in MFC [10].

In a single-cell MFC, the oxidation reaction in the anodic chamber produces equal numbers of electrons and protons, with the electrons moving toward the cathode via the external circuit and the protons migrating to the cathodic chamber through the Proton Exchange Membrane [11].

The electrons and protons are reduced in the cathodic chamber to produce water. The problem occurs when the number of electrons and protons is not equal in the cathodic chamber due to improper mass transfer from the anodic to the cathodic chamber or unexpected electron and proton generation in the anodic chamber. When the number of electrons and protons in the cathodic chamber is not equal, then an excess of electrons or protons can occur in the cathodic chamber. If this situation is not detected and restored at the initial stage, the potential difference between the anode and cathode can cause the voltage reversal. In the single-cell MFC, the electrons and protons are produced in the same cell. However, the electrons and protons come from different cells when the cells are connected in series. Different cell conditions can produce different amounts of electrons and protons, which can cause an excess of electrons or protons in the cathodic chamber, leading to voltage reversal [11].

Voltage reversal in series-stacked MFC can be controlled by maintaining the substrate condition for each cell at a standard level. The substrate concentration or Total Dissolved Solutes (TDS), pH, and temperature are the three main input parameters that determine the open circuit voltage of an MFC [11].

1.1 Related Works

Initially, the experiment to stack the MFC in series was conducted by S.-E.Oh, and B.E.Logan in 2007 [12]. According to them, when more than one cell is connected in series, fuel starvation and improper conditions could occur in the system. Therefore, they suggest maintaining a continuous supply of anodic substrate can help prevent fuel starvation and unfavorable conditions, potentially addressing the voltage reversal issue in stacked MFC [12]. However, further studies are required to determine the optimal amount of fuel to be added to the anodic substrate for effective voltage reversal control.

Although numerous recent studies have shown that biological modification, anode enhancement, and system scale-up can boost the power output of MFC, the issue of voltage reversal remains unsolved [13-16]. Chao Zhao et al. use capacitive-hydrogel bioanodes to manage the voltage reversal in the stacked MFC [17]. In another study, Jeetendra Prasad et al. suggested various power management systems to control the voltage reversal of the MFC. [9].

The application of machine learning in MFC research remains limited, with only a few recent studies employing it to analyse and optimise specific parameters within MFC systems [18-21]. However, this is the first time an ANN model has been used to predict the OCV of the MFC cells based on selected input parameters.

1.2 Contributions

Adding constant fuel to the cells without a proper control algorithm will not solve the problem. To the author's knowledge, the amount of substrate that should be added to the anodic chamber and an algorithm to control the improper conditions of the MFC cells have not yet been explained in previous studies. Thus, this study proposes a simulation model using a machine learning algorithm for an MFC stacked in series to balance the voltages between the cells before the Voltage Reversal is expected. This is the first model to calculate the actual amount of wastewater or distilled water to be added to the weak cell in a Series Stacked MFC using MATLAB.

2. METHODOLOGY

This section outlines the development of the Voltage Balancing (VB) Model to manage the Voltage Reversal in stacked MFC. Before developing a model for the stacked MFC, a model for a single cell MFC is designed to predict the OCV based on the given input parameters using an Artificial Neural Network (ANN) obtained from the previous experiment, as discussed by Murugesu et al. [22].

Then, a three-cell series stacked MFC model is developed. Both developments use the waterfall model, suitable for linear and sequential approaches. For this research work, only five steps from this model are considered, and it seems no maintenance is required at this stage. The model is shown in Figure 1.

2.1 Developing a VB Model for a Single-Cell MFC

The main aim of the VB model for single-cell MFC is to determine the amount of wastewater or distilled water to supply to MFC to increase or decrease the TDS value to achieve the required OCV. The model contains four user inputs: the substrate's TDS, temperature, pH Value, and required OCV. The model will predict the amount of wastewater or distilled water added to the MFC to achieve the required OCV.

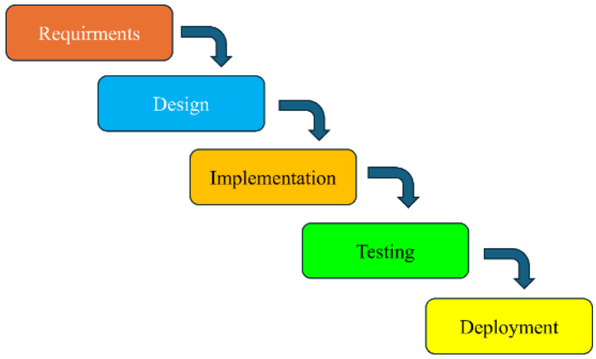


Figure 1. Modified Waterfall Model for Software Development

The maximum and minimum values for each input range are determined based on the experimental result [22]. The lowest pH value is 4.66, and the highest is 6.61. Therefore, for the VB model, the author set the lowest pH value at 4.50 and the highest at 7.00. The temperature readings from the experiment range from 298.8 to 302.0. Thus, the author established a range of 298 to 302 for the VB model. The experimental TDS readings range from 1193 to 3370. Consequently, the author set the VB model from 1000 to 4000. Distilled water typically has less than 10.0 ppm. Therefore, in this VB model, the range for distilled water is defined as 5 to 100 ppm. The TDS of wastewater varies significantly based on the materials and chemicals present. Hence, the author decides to set a minimum value of 500 ppm, slightly lower than the experimental value, and a maximum of 5,000 ppm, slightly higher than the experimental reading for the wastewater.

The volume of the MFC is based on the size of the anodic chamber used in the real setup. So, the author set 1 to 10 L as the range for this volume. Table 1 shows the range for each input set by the author for the user's input.

Table 1. The Range for Each Input

	Minimum	Maximum
TDS – Substrate (ppm)	1,000	4,000
Substrate Temperature (K)	298.0	302.0
Substrate pH	4.50	7.00
Distilled water TDS (ppm)	5	100
Wastewater TDS (ppm)	500	5,000
OCV (mV)	500	1,200
Substrate Volume (L)	1	10

When the user inputs the requested OCV (V_r) value, the system stores it and predicts the MFC's OCV (V_p) based on the input parameters. Then, the difference between V_r and V_p is calculated and stored as V_d:

$$V_d = V_p - V_r \qquad (1)$$

If the $V_d > 7$ mV shows that the predicted OCV is more than the requested OCV, then the predicted OCV must be decreased to achieve the requested OCV. To do that, the TDS of the MFC substrates is reduced by 30 ppm in each step until the V_d becomes smaller than 7 mV.

The step size for TDS is determined based on the accepted range for TDS using the step size precision method with 100 steps. The number of steps can be increased or decreased, depending on the precision required by the user. For this model, the author decides that 100 steps are sufficient for the accepted TDS range.

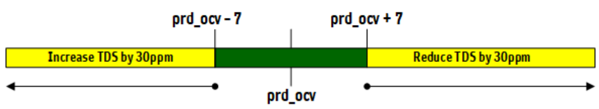
$$TDS_{step} = \frac{TDS_{max} - TDS_{min}}{100} \qquad (2)$$

$$TDS_{step} = \frac{4000 - 1000}{100} = 30\ ppm \qquad (3)$$

The same method is used to determine the limit for the OCV. The limitation is shown graphically in Figure 2.

$$V_L = \frac{1200 - 500}{100} = 7\ mV \qquad (4)$$

Determination of C_f based on the C_1 and C_2 value



Increase TDS by +/- 30ppm when the OCV is out of the range

Figure 2. Limitations and Decisions Used in Coding

Once the V_d is achieved below 7 mV, the system will calculate the difference between the initial TDS (C_1) and the required TDS (C_2). When $C_2 > C_1$, wastewater will be loaded into the MFC to increase the TDS. For this purpose, the system will assign the TDS of the wastewater as C_f. If the required TDS (C_2) exceeds the initial TDS, the system will assign distilled water as C_f to load distilled water.

$$V_2 = \frac{C_1 - C_f}{C_f - C_2} \times V_1 \qquad (5)$$

V_1: The initial Volume of the substrate (L)
V_2: Volume to Add from wastewater tank / distilled water tank (L)
C_1: Initial TDS of the Substrate (ppm)
C_f: Required TDS of the substrate (ppm)
C_2: The TDS of wastewater / distilled water (ppm)
* C_f = wastewater if $C_2 > C_1$
* C_f = Distilled water if $C_1 > C_2$

Two pumps are connected to the MFC to supply wastewater or distilled water. In actual design, a 12 V DC brushless pump is expected to provide the liquid to the MFC. The volume flow rate for this pump is 240 L/h. So, the VB model used this rate for the liquid supply duration of the MFC. Then, the system will decide the liquid to load.

The time the pump is ON, *t* in seconds, is determined by the amount of liquid (either wastewater / distilled water) to add to change the substrate's TDS. Once the Volume to add V_2 is determined, the time the pump is ON is determined by Equation 6 with the following considerations:

- Assuming the pump's flow rate is 240 L/h
- The pump can supply 240 L of liquid in 3,600 seconds
- This means, in 1 sec, the pump can supply 1/15 L of liquid
- Thus, to supply V_2 Liters of Liquid, the pump needs (t in seconds),

$$t = 15 * V_2 \qquad (6)$$

MATLAB App Designer is used to design the VB model. Before the coding takes place, a background picture to visualise the actual concept is created using Adobe Illustrator software. The background picture contains an MFC with electrodes, a wastewater tank, and a distilled water tank connected to the MFC chamber through a PVC pipe with a control pump. An indicator lamp is placed in both incoming liquids in the MFC chamber. The simulation interface screen is shown in Figure 3.

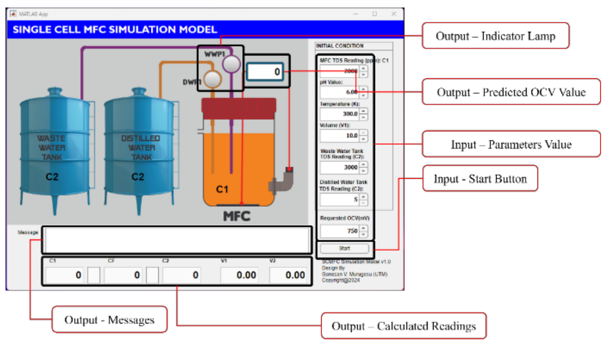


Figure 3. Simulation Interface Screen

The system design is divided into high-level design (HLD) and low-level design (LLD). The high-level design explains the overall architecture of the whole system, as shown in Figure 4.

The software for the VB model is developed using MATLAB coding. The interface is designed using MATLAB App Designer software. The ANN Model, which is used to predict the OCV, uses MATLAB Simulink software. The final software is converted into a MATLAB App using the "share" function from the MATLAB App Designer, as shown in Figure 5. Once the deployment process is complete, the app can be seen in the 'APPS' section in MATLAB windows, as shown in Figure 6.

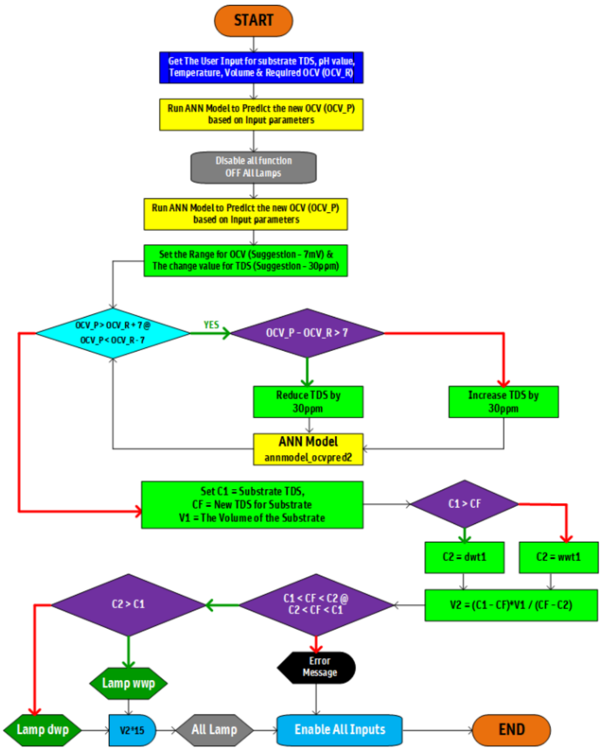


Figure 4. HLD Flow Chart for SCMFC Simulation Model

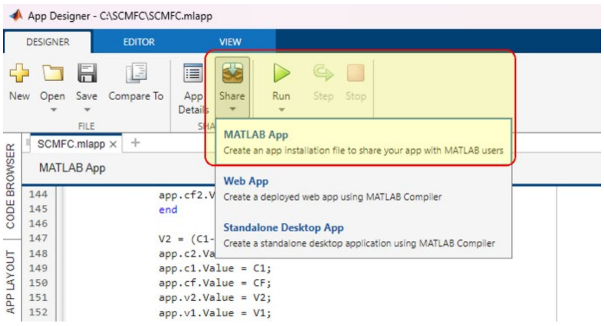


Figure 5. Convert the Simulation into a MATLAB App program

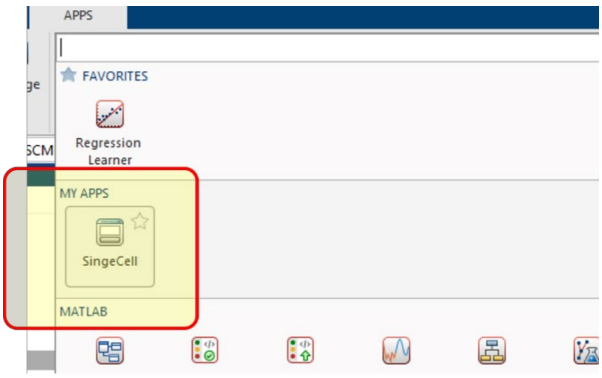


Figure 6. The Single Cell App is now running in the MATLAB window

2.2 Developing VB Model for Three-Cell Series Stacked MFC (TCSSMFC)

The main goal of developing the Three-Cell Series Stacked MFC is to manage the Voltage Reversal (VR) in the VB model. A single cell usually will not produce the VR because the electron and proton are from the same source.

However, the electrons and protons in TCSSMFC come from a different substrate source, which can produce excess electrons in the cathodic chamber, leading to VR. So, to avoid the VR happening in TCSSMFC, a control system is required to prevent the excess of electrons in the cathodic chamber by adjusting the TDS of the anodic substrate. By changing the TDS, the voltages among the cells can be balanced, and VR can be managed.

TCSSMFC consists of three Individual air cathode MFCs connected in series. However, the Anode of MFC-1 is connected to the cathode of MFC-3, the anode of MFC-3 is connected to the cathode of MFC-2, and the anode of MFC-2 is connected to the anode of MFC-1. Each MFC has a pump to supply wastewater and another to provide distilled water.

The VB model will predict the OCV for each MFC based on the user's input parameters and compare the values. When the user changes the input parameters for any MFC, the ANN model predicts the new OCV for each MFC. Then the comparison will be made between the MFC to determine the following action based on the following conditions:

Condition 1:
If any OCV value is less than the critical values (V_C), the system will warn the user to check all the MFCs and change the MFC with an OCV lower than the Critical OCV.

Condition 2:
If the range of the OCV (the difference between the highest and lowest OCV) is more than twice the OCV limit (V_L), then the system detects a gap between the OCV. So, the system will find the appropriate TDS to change the OCV for the selected MFC.

Condition 3:
The system is considered good if the OCV values do not fulfil conditions 1 or 2.

For this work, the author set the $V_C = 692$ mV, based on a 95% acceptance level using a normal distribution. The mean and standard deviation of the OCV distribution is 869.65 and 90.51, respectively. So, 5% rejection area at left and right tail gives 2.5% is rejected at the left tail. Using the following calculation, the Critical value for the OCV is determined as 692 mV.

$$P(Z < a) = 0.025$$

$$\frac{V_c - \mu}{\sigma} = -1.96$$

$$\frac{V_c - 869.65}{90.51} = -1.96$$

$$V_c = 692.25 \approx 692$$

There are three cells involved in this simulation model. Each cell contributes four input parameters: the TDS, pH value, temperature, and volume. Other than these, wastewater's TDS and Distilled Water's TDS are also required in the simulation. Additionally, the OCV limit is also included in this simulation model to let the user determine the limit of the OCV.

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MATLAB App Designer and Simulink are used to develop this simulation model. The model is designed for a three-cell MFC connected in series. The simulation interface screen is shown in Figure 7.

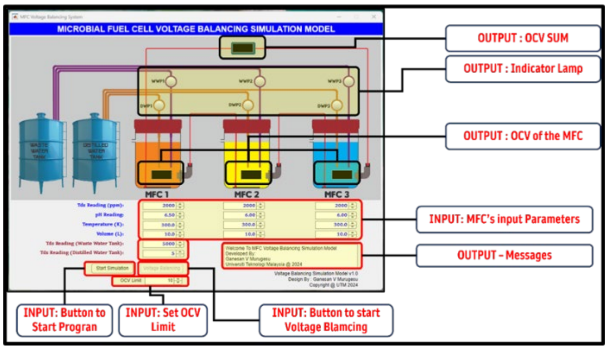


Figure 7. TCSSMFC Simulation Model Interface Screen

The program will start when the user presses the start button. Once the start button is pressed, it will predict the OCV for each MFC based on the given parameter values. If the difference between the highest OCV and the lowest OCV, V_r is more than twice the V_L, the system will suggest that the user start the 'Voltage Balancing' function. Users can change the parameter's value at any time. When users change the input parameter values (TDS, temperature, and pH), the system automatically runs the ANN model and predicts the new V_r. When the user presses the 'Voltage Balancing' button, the system will find the TDS of the weak or extreme cell and load distilled water or wastewater to achieve OCV within the requested limit. Separate modules are used to develop this simulation software as follows:

(a) Disable all inputs
This function is used to disable all the input components.

(b) Enable all inputs
This function is used to disable all the input components.

(c) Declaring all Variables
This function is used to declare all the variables used in this program. All the variables are stored in the workspace.

(d) Update all displays
This function updates all the input and output values each time the program executes the ANN model and other calculations. The values are taken from the workspace and displayed in the appropriate components.

(e) Finding the possibility of VR
The function "VoltageReversal" can determine whether the voltage reversal is possible. The main aim of the simulation is to detect the possibility of the VR and do voltage balancing before it happens. So, when any cell shows OCV below 500 mV, or the gap between the two cells is higher than the V_L (7 mV is used for testing), the system will request the user to start the voltage balancing function. However, the voltage balancing function can be set as automatic with a minor change in the coding in future modifications. Figure 8 shows the flowchart for the "VoltageReversal" function.

(f) Finding the TDS
The function "FindingTds" determines the TDS values for each MFC by changing it to 30 ppm in every iteration. First, the program finds the difference between the highest OCV and the OCV of the selected MFC. If the difference between them is more than 7 mV, the program will increase the TDS of the current MFC by 30 ppm. This process continues until the OCV of the selected MFC reaches at least 7 mV below the highest OCV. Then, the program will find the TDS of the wastewater. If the wastewater's TDS is higher than the required TDS for the selected MFC, the wastewater pump is activated to increase the TDS; otherwise, the distilled water pump is activated to reduce the TDS of the other two MFCs. All three MFCs will follow the exact process. "FindingTds" is the primary function and is followed by three sub-functions, which are "FindingTds1", "FindingTds2", and "FindingTds3". The flowchart for TDS function 1 is shown in Figure 8.

(g) Loading wastewater or distilled water
Six modules are used to load wastewater or distilled water into the MFC. Whenever the wastewater's TDS is higher than the current TDS and required TDS of the MFC, the wastewater is loaded into the respective MFC. If the wastewater is higher than the current TDS and lower than the required TDS, then the TDS of the other two MFCs is reduced to the nearest average value. Otherwise, the system will show a warning message to change the wastewater. The six modules used to load wastewater or distilled water are. The general flowchart to load wastewater or distilled water is shown in Figure 9.

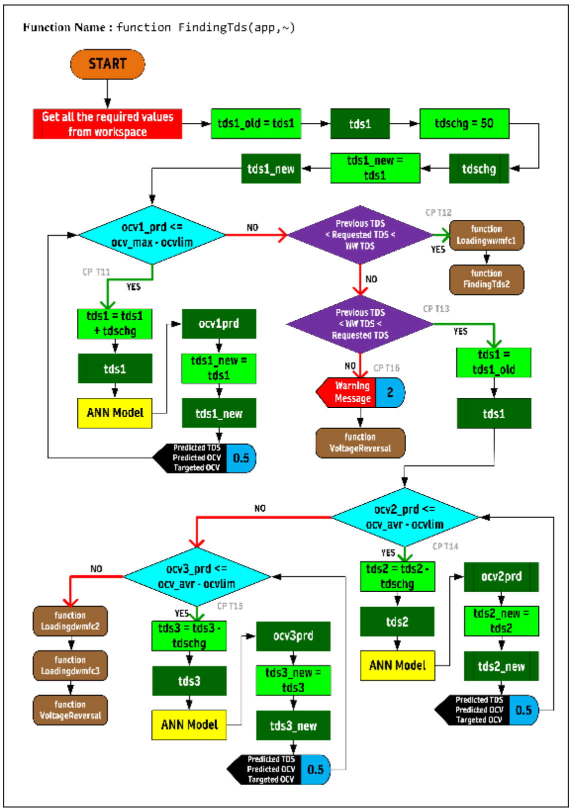


Figure 8. Flow chart for "Voltage Reversal" function

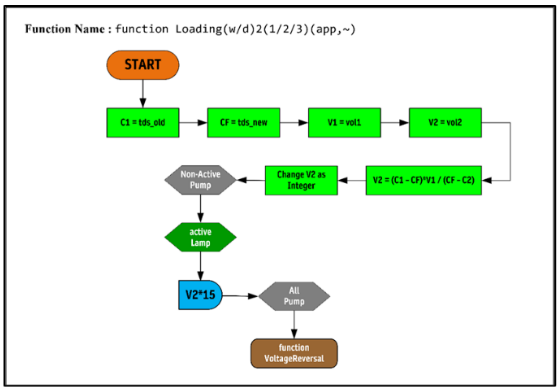


Figure 9. Flowchart for Loading Wastewater or Distilled Water Function

The simulation software was developed using MATLAB coding. The interface is designed using MATLAB App Designer software. The ANN Model, which is used to predict the OCV, uses MATLAB Simulink software. The final software is converted into a MATLAB App using the "share" function from the MATLAB App Designer, as shown in Figure 5.

3. RESULT AND DISCUSSION

The fourth stage of the Waterfall Model for Software Development is software testing. This section explains the results obtained from the testing process of the developed VB model.

3.1 Single-Cell MFC VB Model Test Result

The author simulated the VB model with different input values to test the functionality of the model. First, the author tests the model functionality to load wastewater. Then a test is done to load distilled water, and finally to generate the errors.

3.1.1 Test for Loading Wastewater

For the system to load wastewater, the requested OCV should be more than +7 mV compared to the predicted OCV. In this condition, the substrate's TDS should be increased to increase the substrate's OCV (predicted OCV). Then the system will find the difference between the initial TDS (C_1) and the required TDS (C_2) to calculate the wastewater volume (V_2) to add to the MFC. So, the author requested OCV at V_R = 850 mV for the following input parameters:

Test 1: C_1 = 1500, P = 6.00, T = 300, V_P = 743.5
Test 2: C_1 = 2000, P = 6.00, T = 302, V_P = 795.6
Test 3: C_1 = 1500, P = 6.50, T = 302, V_P = 787.2

The other parameters are set as follows:
MFC Volume, V_1 = 10 L
Distilled water TDS, = 5 ppm
Wastewater TDS = 3000 ppm

The simulation result is shown in Table 2, and the model output for test 1 is shown in Figure 10.

Table 2. Test Results for Loading Wastewater

Parameter	Test 1	Test 2	Test 3
Initial TDS (C_1)	1500	2000	1500
pH (P)	6.00	6.00	6.50
Temperature (T)	300	302	302
Predicted OCV (V_P)	743.5	795.6	787.2
Final OCV (V_f)	850.2	849.1	849.0
Wastewater TDS (C_2)	3000	3000	3000
Required TDS (C_f)	1800	2240	2430
Initial Volume (V_1)	10	10	10
Volume To Add (V_2)	2.50	3.16	16.2
Loading Time (t)	37.5	47.4	243.0

From the above result, $C_1 < C_f < C_2$, for all three tests. So, the system works fine without an error. The Final OCV is also close to the requested OCV.

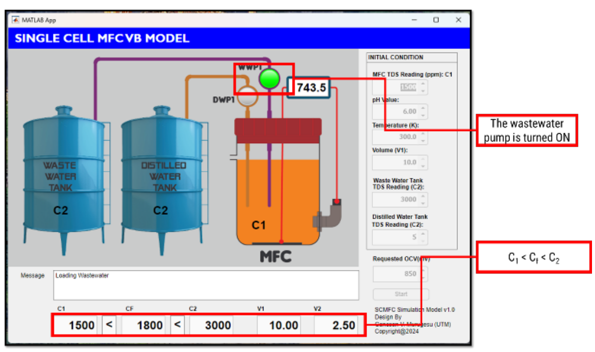


Figure 10. The model output for test 1

3.1.2 Test for Loading distilled water

For the system to load distilled water, the requested OCV should be less than -7 mV compared to the predicted OCV.

In this condition, the substrate's TDS should be decreased to reduce the substrate's OCV (predicted OCV). Then the system will find the difference between the initial TDS (C_1) and the required TDS (C_2) to calculate the distilled water volume (V_2) to add to the MFC. So, the author requested OCV at V_R = 750 mV for the following input parameters:

Test 4: $C_1 = 2000$, $P = 6.50$, $T = 300$, $V_P = 761.5$
Test 5: $C_1 = 2500$, $P = 6.50$, $T = 300$, $V_P = 825.5$
Test 6: $C_1 = 2500$, $P = 6.50$, $T = 302$, $V_P = 867.2$

The other parameters are set as follows:
MFC Volume, V_1 = 10 L
Distilled water TDS, = 5 ppm
Wastewater TDS = 3000 ppm

The simulation result is shown in Table 3, and the model output for test 2 is shown in Figure 11.

Table 3. Test Result for Loading Distilled Water

Parameter	Test 4	Test 5	Test 6
Initial TDS (C_1)	2000	2500	2500
pH (P)	6.50	6.50	6.50
Temperature (T)	300	300	302
Predicted OCV (V_P)	761.5	825.5	867.2
Final OCV (V_f)	752.9	750.3	756.5
Distilled Water TDS (C_2)	5	5	5
Required TDS (C_f)	1970	1960	2140
Initial Volume (V_1)	10	10	10
Volume To Add (V_2)	0.15	2.76	1.69
Loading Time (t)	2.25	41.4	25.35

From the above result, $C_2 < C_f < C_1$, for all three tests. So, the system works fine without an error. The Final OCV is close to the requested OCV for all three tests.

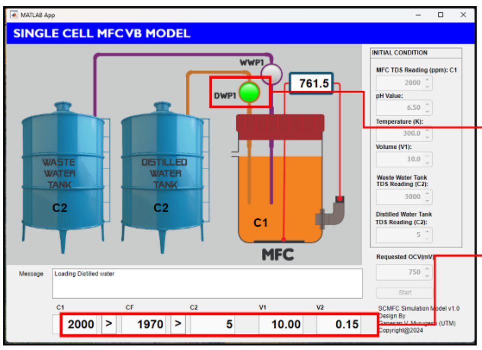


Figure 11. The model output for Test 4

3.1.3 Test for System Error

The author uses the same input parameters as in Tests 1 and 5 for Tests 7 and 8, respectively, to detect system errors. Table 4 shows the parameters used for Test 7 and Test 8. However, the TDS value for distilled water and wastewater is modified to be out of range as follows:

Test 7: $C_1 = 1500$, $P = 6.00$, $T = 300$, $V_P = 743.5$
$V_R = 850$, $C_{2(ww)} = 1700$

Test 8: $C_1 = 2500$, $P = 6.50$, $T = 300$, $V_P = 825.5$
$V_R = 750$, $C_{2(dw)} = 2000$

Table 5. Test Result for System Error

Parameter	Test 7	Test 8
Initial TDS (C_1)	1500	2500
pH (P)	6.00	6.50
Temperature (T)	300	300
Predicted OCV (V_P)	743.5	825.5
Substrate TDS (C_2)	1700	2000
Required TDS (C_f)	1800	1960
Initial Volume (V_1)	10	10

Test 7 shows that the required TDS is 1800, more than the initial and wastewater TDS ($C_1 < C_2 < C_f$). So, the program displays an Error Message as shown in Figure 12.

Test 8 shows that the required TDS 1960 is less than the initial and distilled water TDS ($C_f < C_1 < C_2$). So, the program displays an Error Message as shown in Figure 13.

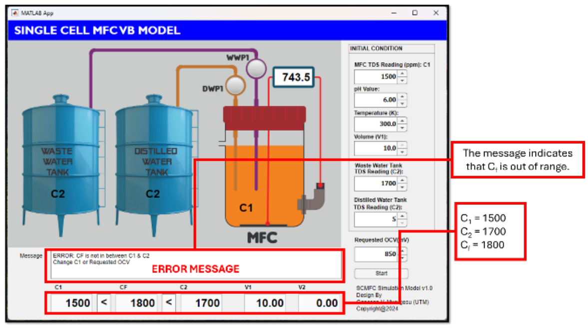


Figure 12. Test 7 Result: $C_1 < C_2 < C_f$

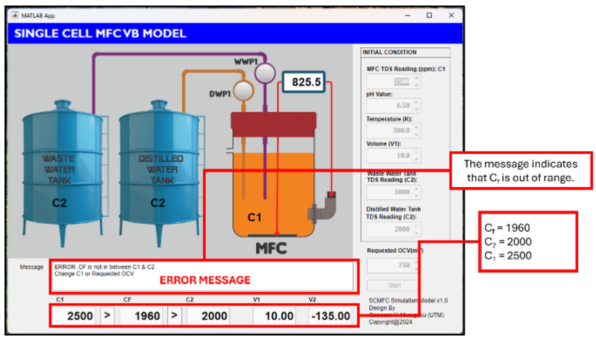


Figure 13. Test 8 Result: $C_f < C_1 < C_2$

3.2 Three-Cell MFC VB Model Result

The test for the three-cell MFC VB model is conducted to validate that the developed software fulfils all the requirements. There are 30 checkpoints set to perform the test for this model, as shown in Table 4.

3.2.1 Test Result for initial condition without starting the Voltage Balancing Function

Once the simulation starts, the program will wait for the "Voltage Balancing" button to execute the next level. Until the "Voltage Balancing" button is NOT pressed, the program predicts the OCV and notifies the user of the current status. Three conditions can happen as follows:

Table 4. 30 Checkpoints for Software Testing

Checkpoint	Purpose of the Test	
CP VR1	$(V_{P1}, V_{P2} \& V_{P3}) < V_C$	The voltage balancing button is pressed
CP CR2	$V_R \geq 2*V_L$	
CP VR3	System in Good Condition	
CP VR4	$(V_{P1}, V_{P2} \& V_{P3}) < V_C$	The voltage balancing button is NOT pressed
CP VR5	$V_R \geq 2*V_L$	
CP VR6	System in Good Condition	
CP T11	Predicting TDS for MFC1	
CP T12	Current TDS1 ≤ Required TDS1 ≤ Wastewater TDS	
CP T13	Current TDS1 ≤ Wastewater TDS ≤ Required TDS1	
CP T14	TDS prediction for MFC2 is running	
CP T15	TDS prediction for MFC3 is running	
CP T16	Wastewater TDS ≤ Current TDS1 & Required TDS1	
CP T21	TDS prediction for MFC2 is running	
CP T22	Current TDS2 ≤ Required TDS2 ≤ Wastewater TDS	
CP T23	Current TDS2 ≤ Wastewater TDS ≤ Required TDS2	
CP T24	TDS prediction for MFC1 is running	
CP T25	TDS prediction for MFC3 is running	
CP T26	Wastewater TDS ≤ Current TDS3 & Required TDS3	
CP T31	TDS prediction for MFC3 is running	
CP T32	Current TDS3 ≤ Required TDS3 ≤ Wastewater TDS	
CP T33	Current TDS3 ≤ Wastewater TDS ≤ Required TDS3	
CP T34	TDS prediction for MFC1 is running	
CP T35	TDS prediction for MFC2 is running	
CP T36	Wastewater TDS ≤ Current TDS3 & Required TDS13	
CP WW1	Loading Wastewater for MFC1	
CP WW2	Loading Wastewater for MFC2	
CP WW3	Loading Wastewater for MFC3	
CP DW1	Loading distilled water for MFC1	
CP DW2	Loading distilled water for MFC2	
CP DW3	Loading distilled water for MFC3	

Condition 1:
Any predicted OCV (V_{P1} / V_{P2} / V_{P3}) less than the Critical OCV, V_c

$V_{P1} \leq V_C$ or $V_{P2} \leq V_C$ or $V_{P3} \leq V_C$

For Condition 1, the author fixed the parameters for the MFC Volume as V1 = 10 L TDS of the wastewater at 5000 ppm and TDS of the distilled water at 5 ppm. The other three parameters (TDS, pH & Temperature) are changed as shown in Table 5 to monitor the output result.

Table 5. Output Result for Different Input Parameters before the Voltage Balancing Function is started

	MFC1	MFC2	MFC3	Result
C	1500	1750	1000	All the predicted OCVs are less than the Critical OCV: **SYSTEM ERROR**
P	6.25	6.25	7.00	
T	300	300	300	
V_P	671.5	679.4	653.5	
	$V_P < V_C$	$V_P < V_C$	$V_P < V_C$	
C	2000	1750	1000	Predicted OCVs for MFC2 and MFC3 are less than the Critical OCV: **SYSTEM ERROR**
P	6.25	6.25	7.00	
T	3000	300	300	
V_P	834.3	679.4	653.5	
	$V_P > V_C$	$V_P < V_C$	$V_P < V_C$	
C	2000	2000	1000	Predicted OCV for MFC3 is less than the Critical OCV: **SYSTEM ERROR**
P	6.25	6.25	7.00	
T	3000	3000	300	
V_P	834.3	834.3	653.5	
	$V_P > V_C$	$V_P > V_C$	$V_P < V_C$	
C	2000	2000	2200	Predicted OCVs for all the MFCs are more than the Critical OCV: **START VOLTAGE BALANCING**
P	6.25	6.25	6.25	
T	3000	3000	300	
V_P	834.3	834.3	853.5	
	$V_P > V_C$	$V_P > V_C$	$V_P > V_C$	

When the system Error occurs, the program will enter checkpoint 'CP VR4' to send a warning message to the users to check the MFCs substrate immediately, as shown in Figure 14(a).

Condition 2:
All predicted OCVs (V_{P1} / V_2 / V_{P3}) are more than the Critical OCV and the OCV range, V_R is more than twice the OCV limit (V_L). For Condition 2, the author fixed the parameters for the MFC Volume as V1 = 10 L TDS of the wastewater at 5000 ppm and TDS of the distilled water at 5 ppm. The other three parameters (TDS, pH & Temperature) are changed as shown in Table 6 to monitor the output result.

Table 6. Output Result for OCV Range more than twice the OCV Limit

	MFC1	MFC2	MFC3	Result
C	2000	2000	2500	**SYSTEM REQUIRED VOLTAGE BALANCING**
P	6.25	6.25	6.25	
T	300	300	300	
V_P	834.3	834.3	850.0	
	$V_P > V_C$	$V_P > V_C$	$V_P > V_C$	

The above result shows,

$V_{max} = 850.0$
$V_{min} = 834.3$
OCV Range, $V_R = 850.0 - 834.3$
$= 15.7 > 14\ (2*V_L)$

The system will enter 'CP VR5' to notify the user to start the voltage balancing as shown in Figure 14 (b).

Condition 3:
All predicted OCVs (V_{P1} , $V_{P2,}$ and V_{P3}) are more than the Critical OCV and the OCV range, V_R is less than twice the OCV limit (V_L). For Condition 3, the author fixed the parameters for the MFC Volume as V1 = 10 L TDS of the wastewater at 5000 ppm and TDS of the distilled water at 5 ppm. The other three parameters (TDS, pH & Temperature) are changed as shown in Table 7 to monitor the output result.

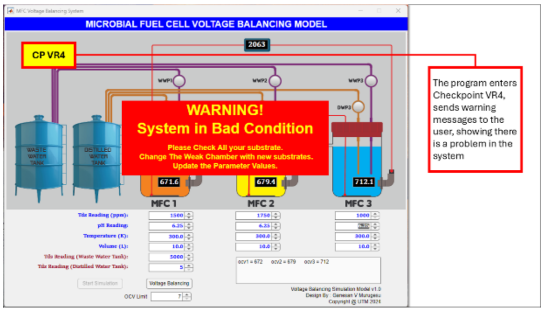
Table 7. Output Result for OCV Range less than twice the OCV Limit

	MFC1	MFC2	MFC3	Result
C	2000	2000	1990	**SYSTEM IN GOOD CONDITION**
P	6.25	6.25	6.24	
T	300	300	300	
V_P	834.3	834.3	839	
	$V_P > V_C$	$V_P > V_C$	$V_P > V_C$	

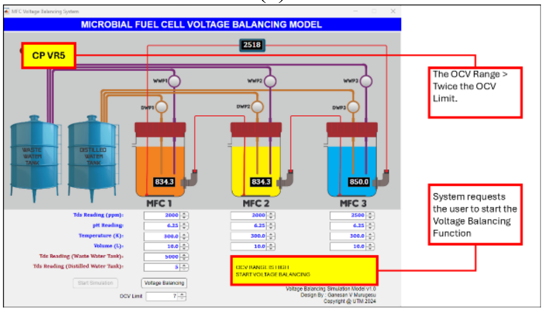
The above result shows,

$V_{max} = 838.6$
$V_{min} = 834.3$
OCV Range, $V_R = 838.6 - 834.3$
$= 4.3 < 14\ (2*V_L)$

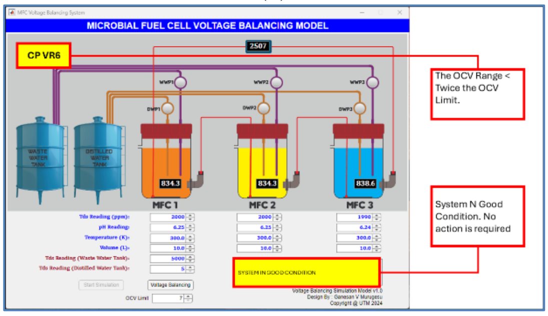
The program will enter 'CP VR6' to notify the user that the system is in good condition, as shown in Figure 14 (c).



(a)



(b)



(c)

Figure 14. Test Result When the Voltage Reversal Button is NOT pressed (a) CP VR4 (b) CP VR5 (c) CP VR6

3.2.2 Test Result when the Voltage Balancing Button is pressed

When the voltage balancing button is pressed, the program will find whether to do the voltage balancing based on the three conditions as discussed in section 3.2.1. For condition 1 ($V_{P1} \leq V_C$ or $V_{P2} \leq V_C$ or $V_{P3} \leq V_C$) and condition 3 ($V_{P1} > V_C$ and $V_{P2} > V_C$ and $V_{P3} > V_C$ and $V_R < 2^*V_L$), the same output as discussed above will be displayed. However, when condition 2 occurred, the program entered checkpoint "CP VR2" for voltage balancing as shown in Figure 15. At this point, the program will predict the TDS for all three MFCs and decide whether to add wastewater or distilled water to the MFCs based on different conditions.

3.2.3 Test Result for Loading Wastewater

Once the voltage reversal process starts, the program will calculate the required TDS for each MFC. When any MFC's TDS is higher than the other MFC (more than twice the OCV Limit) and the wastewater TDS is higher than the predicted TDS, the program will add wastewater to the corresponding MFC. The parameters, as shown in Table 8, are used for the following test. The output result is shown in Figure 16.

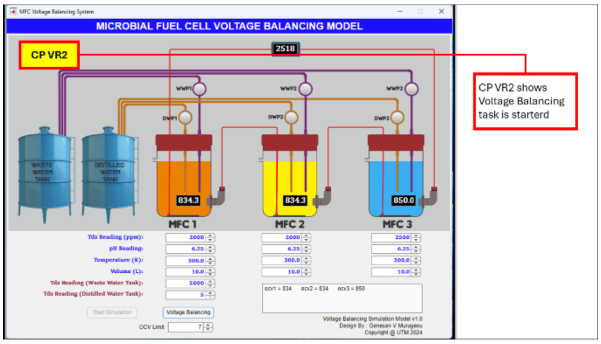


Figure 15. The test result for Condition 2 when the user starts the "Voltage Balance"

Table 8. Input parameters to load wastewater

	MFC1	MFC2	MFC3	Process
C_1	2000	2200	2500	**VOLTAGE BALANCING**
P	6.50	6.50	6.50	
T	300	300	300	
C_2	Wastewater TDS = 5000			
C_f	2480	2470	2500	
V_P	823.0	821.4	825.5	

The program will enter Checkpoints as follows:

VR2: $V_R > 2^*V_L$ ➔ Voltage Balancing required
OCV Range, V_R = 825.5 – 761.5 = 64 mV
So, 64 mV > 14 mV (2 x 7)
At this point, the system determines that the OCV Range is higher than twice the OCV Limit. So, the voltage balancing process is required.

T11: Predict the required TDS for MFC1 (C_{f1})
First, the system will predict the required TDS for MFC1.
The Predicted TDS, C_{f2} = 2480 ppm.
The Wastewater TDS, C_2 = 5000, and Initial TDS C_1 = 2000.

T12: $C_1 < C_f < C_2$ (For MFC 1).
The program enters Checkpoint T12.
At this stage, the program will calculate the amount of wastewater to add to the MFC1.

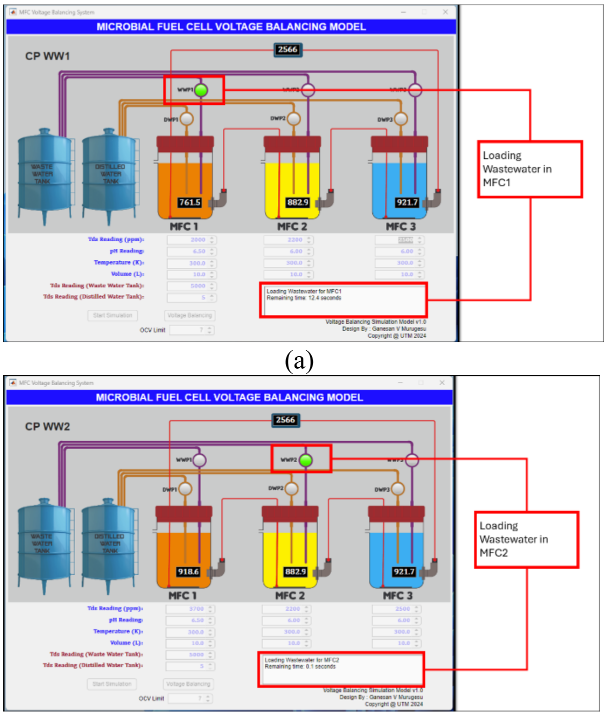
WW1: Loading Wastewater for MFC1
The WWP1 Lamp is green, showing the pump is turned ON to load wastewater to the MFC. The TDS of MFC1 changed, and the new OCV is displayed. V_P = 823.0 mV

T21: Next, the program predicts the required TDS for MFC2 (C_{f2}).
The Predicted TDS, C_{f2} = 2470 ppm.
The Wastewater TDS, C_2 = 5000, and Initial TDS C_1 = 2200.

T22: $C_1 < C_f < C_2$ (For MFC 2)
The program enters Checkpoint T22 and calculates the amount of wastewater to add to the MFC2.

WW2: Loading wastewater for MFC2. The WWP2 Lamp is green, showing the pump is turned ON to load wastewater to the MFC. The TDS of MFC2 changed, and the new OCV is displayed. V_P = 821.4 mV

T31: Predict the required TDS for MFC2 (C_{f2})
VR3: System in Good Condition



(a)

(b)

Figure 16. The result shows that the wastewater pump for (a) MFC1 and (b) MFC2 is turned ON

3.2.4 Test Result for Loading Distilled Water

Distilled water is loaded into the MFC to reduce the TDS of any MFC when the wastewater TDS is lower than the required TDS. As shown in Table 9, the parameters are set for the following test, where the TDS of wastewater is set lower than the predicted TDS. For this simulation, the TDS of the wastewater is set as 2100 ppm. The output is shown in Figure 17.

Table 9. Input parameters to load distilled water

	MFC1	MFC2	MFC3	Process
C_1	2000	2200	2500	DO VOLTAGE BALANCING
P	6.50	6.50	6.50	
T	300	300	300	
C2	Wastewater TDS = 2100			
C_f	2000	2050	2050	
V_P	761.5	766.6	766.6	

The program will enter Checkpoints as follows:

VR2: $V_R > 2{*}V_L$ ➔ Voltage Balancing required
OCV Range, $V_R = 825.5 - 761.5 = 64$ mV
So, 64 mV > 14 mV (2 x 7)
At this point, the system determines that the OCV Range is higher than twice the OCV Limit. So, the voltage balancing process is required.

T11: Predict the required TDS for MFC1 (C_{f1})
First, the system will predict the required TDS for MFC1.
The Predicted TDS, C_{f2} = 2480 ppm.
The Wastewater TDS, C_2 = 2100, and Initial TDS C_1 = 2000. So, when the Wastewater TDS is less than the predicted TDS, the system will skip to the following process to reduce the TDS of the other two MFCs.

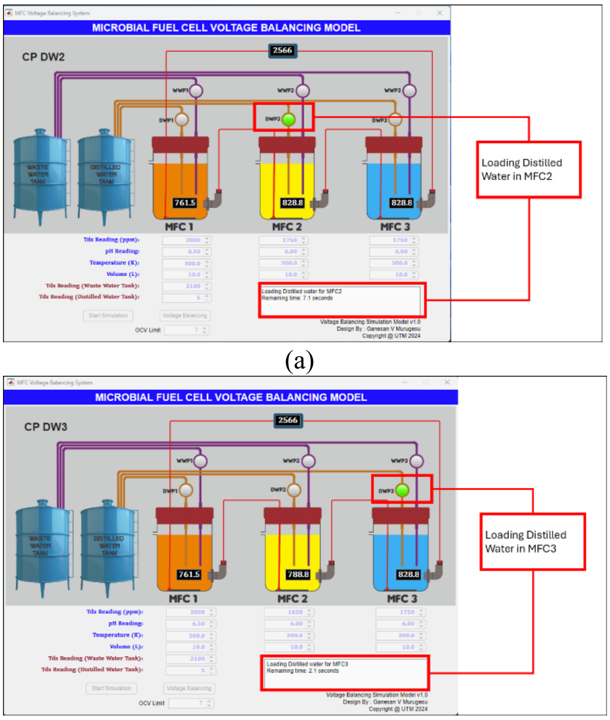
T14: The TDS of MFC2 is 2200. So, the system reduces the TDS of MFC2 to be close to MFC1's OCV. The final predicted TDS for MFC2 is 2050, which gives OCV 766.6 mV.

T15: Then the system will find and reduce the TDS of MFC3, so the OCV is closed to MFC1's OCV. This result shows that the predicted TDS for MFC3 is also 2050, which gives OCV 766.6 mV for MFC3.

DW2: Then the system enters checkpoint DW2, where distilled water is loaded into MFC2. The DWP2 lamp is turned on (green color) shows the distilled water pump is running.

DW3: Then the system loads distilled water into the MFC3. The DWP3 lamp is turned on (green color) shows the distilled water pump is running.

VR3: System in Good Condition



(a)

(b)

Figure 17. The result shows that the distilled water pump for (a) MFC2 and (b) MFC3 is turned ON

3.2.5 Test Result when Wastewater TDS is the lowest

The wastewater's TDS cannot be lower than the initial and predicted TDS of the MFCs' TDS. If this occurs, there should be some errors in the overall design sensors or the incoming wastewater. As shown in Table 10, the parameters are set for the following test, where the TDS of wastewater is set lower than the initial TDS.

Table 10. Input parameters to test System Error

	MFC1	MFC2	MFC3	Process
C_1	2000	2200	2500	WARNING! Wastewater TDS Too Low
P	6.50	6.50	6.50	
T	300	300	300	
C2	Wastewater TDS = 1800			

C_f	2000	2050	2050	
V_P	761.5	766.6	766.6	

At this point, the system will enter the checkpoint:

VR2: $V_R > 2*V_L$ ➔ Voltage Balancing required
OCV Range, $V_R = 825.5 – 761.5 = 64$ mV
So, 64 mV > 14 mV (2 x 7)
At this point, the system determines that the OCV Range is higher than twice the OCV Limit. So, the voltage balancing process is required.

T11: Predict the required TDS for MFC1 (C_{f1})
First, the system will predict the required TDS for MFC1.
The Predicted TDS, $C_{f1} = 2480$ ppm.
The Wastewater TDS, $C_2 = 1800$
Initial TDS $C_1 = 2000$.
So, $C_2 < C_1 < C_{f1}$
When the Wastewater TDS is less than the initial and predicted TDS, the system will skip Checkpoint T16

T16: Wastewater TDS < Current TDS1 & Required TDS1. The system will display a WARNING Message, as shown in Figure 18.

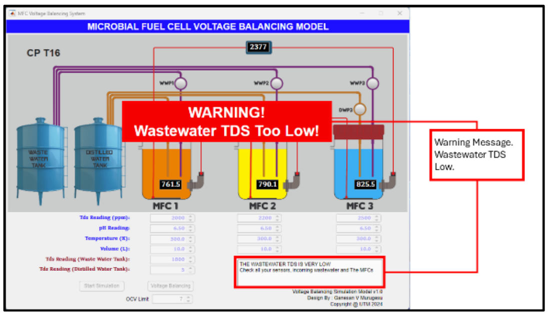


Figure 18. Test Result for checkpoint T16

3.3 Validating the Simulation Data

To validate that the simulation output is compatible with the experimental data, 144 sets of data, equal to ½ day, are simulated manually [22]. The result obtained from the simulation software was compared with the experimental output. From the calculation, the RMSE = 8.052294 and $R^2 = 0.98257$ show that the actual OCV and predicted OCV from the simulation model show a good result.

4. CONCLUSION

The Voltage Balancing model is designed to balance the voltages between the MFC cells by adjusting the TDS values. In the first stage, a single-cell MFC Voltage Balancing Model is developed to predict the OCV based on three input parameters, as discussed earlier. Then, the three-cell Voltage Balancing Model has been developed. This model will identify the possibility of voltage reversal in the system and suggest that the user start the voltage balancing task. Once the voltage balancing task is activated, the system will find the cell with the lowest MFC and adjust the TDS by adding wastewater. However, if the TDS of wastewater is lower than the required TDS, the system will reduce the TDS of the other two MFCs. The process continues until the OCV differences between the cells are below twice the OCV limit.

This study is focused on developing the VB model to balance the voltages between the MFC cells when they are connected in series to increase the output voltages and power. The voltage reversal issue becomes the primary issue in a series-connected MFC. Previous studies suggested that continuous wastewater supply can avoid voltage reversal. However, previous studies have not discussed the amount of wastewater to add. Thus, this study has been conducted to determine the required amount of wastewater or distilled water in the anodic chamber to balance the OCV by controlling their TDS. Then, a MATLAB model is developed to balance the voltages between the MFCs by adjusting the substrate TDS. The model was tested and validated using 144 sets of actual data, yielding a Root Mean Square Error (RMSE) of 8.05229 and a coefficient of determination (R^2) of 0.98257.

Even though the study is only developing the VB model, the idea behind this study can help more researchers conduct more research to find a comprehensive model that can generate higher voltages and power. This model can be developed further and integrated with hardware to get a robust solution for the Voltage Reversal issues in MFC designs.

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