Circuit Design for Bacterial Detection System

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ABSTRACT

Infection of bacteria nowadays has become a serious matter, especially in medical health care. Some species of bacteria could bring disease and threaten death. Much research is concerned with the detection and prevention of harmful bacteria. Recently, electrochemistry is important for analyses in applications including clinical diagnostics, environmental, food monitoring, quality control, and wearable devices for personal health. The electrochemistry technique is one of the ways to detect the existence of bacteria. Designs of a circuit that act like a potentiostat were proposed in this study. Simulation on the analog circuit was examined to get the best circuit construction. In detecting a bacterium, different electrochemical techniques such as cyclic voltammetry (CV) were used. This project focuses on designing an analog circuit of a potentiostat. The measurement of the current at the working electrode is the desired result that will characterize the performance of the circuit as well as the sample detected.

Keywords: Electronics circuit, Microcontroller, Amplifier circuit, Analogue-to-digital converter, Bacterial detection

1 Introduction

A bacterial detection system can be done through the electrochemical technique. Electrochemical sensors or biosensors normally are designed using the configuration of a potentiostat circuit. A potentiostat is an equipment used for the analysis of the electrochemical reaction, oxidation, and reduction. It is designed to control the potential applied on the working electrode, relative to a reference electrode in a multiple electrode electrochemical cell. Potentiostat measures the current flowing between the working electrode and the counter electrode. The heart of designing a potentiostat is the operational amplifier which has dual inputs of a very high impedance. One of the inputs inverts the polarity of the signal voltage which is inverting input while another one is non-inverting which keeps the same polarity as the input signal [1].

A potentiostat is an electronic instrument used for measuring the electrical current and controlling the differential voltage that is needed in performing the electroanalysis. The commercially available potentiostat is an instrument that is suitable only for laboratory use. It could not be ignored that a commercial benchtop potential is equipment that could provide the best performance in terms of accuracy, stability, and sensitivity. However, the large size, high power consumption, and high cost of over a few thousand dollars of this equipment give the main challenges for point-of-use and in a resource-limited setting. These limitations make the researchers nowadays have to come up with the idea of making small, less power consumption and affordable device that act closely the same as the actual potentiostat. The small size of the device not only minimizes the usage of components and material constructed but it could also reduce the waste when that equipment is no longer able to be used. Moreover, the small size of the potentiostat could also provide a quick analysis that may overcome the duration of the analysis. The performance of an electrochemical detector is depending on the needs of the application. Accurate detection of the specific type of bacteria is important in electrochemical analysis. In this research, electrochemical sensing is used to detect the existence of bacteria and specify their types. In general, the most critical performance factors for

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a tiny electrochemical device are its sensitivity. Sensitivity is a factor depending on the detected small incrementation value of the specific bacteria concentration. A sensor with higher sensitivity allows lease targeted concentration to be used.

The objectives of this project are to design a circuit for a bacterial detection system that acts like a potentiostat moreover, to measure the performance of the electrochemical process (anodic and cathodic peak current) on the circuit design proposed, and finally, to investigate the electrical performance such as power consumption of potentiostat circuit which will be designed in a compact and small size.

2 Research Background

The electrochemical sensor has attracted researchers' attention recently. This is because its quantitative determination substrate such as pathogen, protein, or hormone could lead to a scientific revolution. The fundamental of an electrochemical sensor is its ability to recognize the specific elements with high accuracy as well as able to detect the targeted sample with high selectivity. Wang et al. [2] have mentioned in their study that the reaction of biochemical on the electrode surface can modify the chemical and physical values such as pH, ions, voltage drop, resistance, or even current. The changes lead to the measurement value of the sensor where an electrical signal is induced. In the research, it was observed that changes in the concentration of the analyte can change the reading value of the sensor [2].

In the field of analytical chemistry, the majority of authors were satisfied with the relationship between the sensor display analytical response that is proportional to the concentration of analytes. Ideally, the reference electrode is highly non-polarizable since it keeps its potential of the solution by an overall equilibrium equation with fast kinetics. This means in practice reference electrode is able to sink or source the current without showing its potential. Butler-Volmer Equation 1 is used to get the current where perturbation of potentials occurs. At the same time, the working electrode has a higher polarization degree making the surface with a variable potential able to probe certain electrode reactions with high sensitivity [3].

$$I = I_O[\exp\left(\alpha \frac{nF}{RT}(E - E_O)\right) - \exp\left(-\frac{nF}{RT}(1-\alpha)(E - E_O)\right)] \qquad (1)$$

I : Current response of one electrode reaction based on the anodic and cathodic contributions (A).

E: Externally applied potential E_O: Equilibrium potential of the electrode reaction

α: Charge transfer coefficient n: Number of electrons transferred per mole

F: Faraday (96 485 A s mol^{-1}) R: Ideal gas constant (8.31 J K^{-1} mol^{-1}

T: Absolute temperature (K) I_O : Exchange current (A)

Amperometry means experiment that the response is the current. In an electrochemical biosensor, the amperometric technique is used to monitor the current response at a controlled potential step where this potential is applied between the reference electrode and the working electrode. The result of responses in the chemical analytes and electrode surfaces is obtained from the different excitation methods on the reference or working electrode. The target molecule in a sample matrix is determined by the biological recognition reactions caused by electroactive agents at the electrode surface into a current signal. The targeted molecule can be nucleic acids, antibodies, or enzymes. Various amperometric techniques are applied in biosensors as differential pulse voltammetry (DPV), cyclic voltammetry (CV), chronoamperometry, and square wave voltammetry (SWV). Amongst these methods, cyclic voltammetry is the most reliable electrochemical method in investigating the redox process of molecular species and electron transfer-initiated reactions [4].

Amongst the amperometric techniques, Cyclic Voltammetry (CV) is one of the electrochemical techniques that are most useful since it is the basic electrochemical test for the material. Choudhary et al. [5] reported that the current produced from CV measurement is recorded by sweeping the potential from positive to negative and vice versa within the desired limit. The results obtained is function in analyzing the electrochemical behavior of the electroactive sample. The scan rate can be designed to produce the slope of the ramp signal which is expressed in terms of volts per unit time. It can be varied to get the different performances of the electrochemistry. Based on the scan rate, one can expect some changes in the oxidation and reduction peak currents along with peak potentials. The incremental scan rate that is able to increase the peak current or faradaic current shows a good rate capability along with better pseudocapacitive behavior of the electrode material. A higher scan rate allows a higher number of oxidation and reduction reactions since there is an increase in the number of electroactive species at the surface of the working electrode. However, for a slower scan rate, there is a possibility of missing the peak current [5].

3 Materials and Methods

3.1 Project Framework

3.1.1 Block Diagram

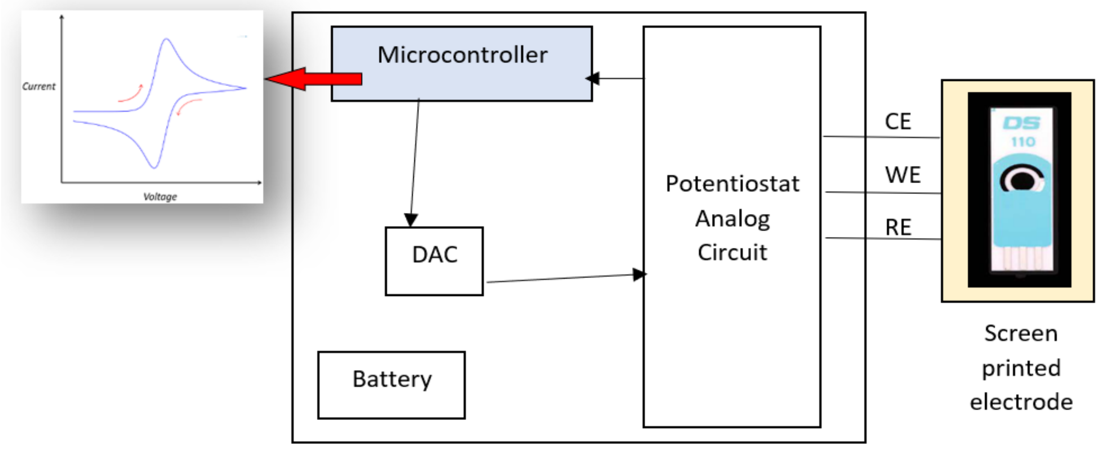

Figure 1: *Block Diagram of the project*

The Block diagram in Figure 1 shows a schematic of the overall circuitry analog and digital circuitry. The microcontroller gives the command on the potential range, step voltage, scan rate, and the number of performed cycles. Digital-to-analog converter (DAC) converts the command and produces a triangular shape voltage waveform before sending it to the potentiostat analog circuit. At this stage, some designs can use pulse width modulation (PWM) to replace DAC to provide a triangle waveform. The measurement observed on the current at the working electrode is the desired result that will characterize the performance of the circuit as well as the sample detected.

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3.1.2 Project Framework

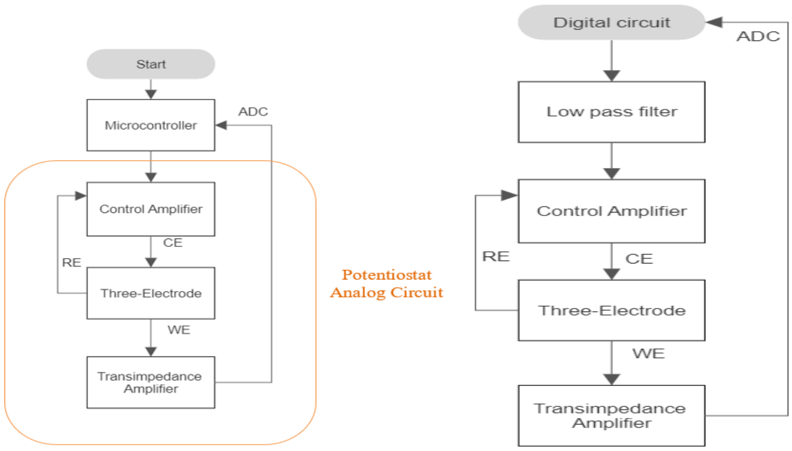

Figure 2: *Operational flow for a bacterial detector system*

The operational flow of the bacterial detection system is illustrated in Figure 2. Starting from placing the sample on the electrode before powering it on the microcontroller. The PWM signal is produced from the microcontroller sending it to the filtering stage. The filter reduces noise on the signal and past it to the control amplifier. The control amplifier then works in adjusting the potential value at the counter electrode and feeding it back to the reference electrode. The control amplifier is there to ensure that the voltage at the reference electrode is the same as the input signal of the control amplifier. When the electrochemical process reacts on the electrode, the resulting signal from the oxidation and reduction reaction is then transmitted out from the working electrode. The current signal from the working electrode is converted to a voltage by the trans-impedance amplifier. After that, the analog voltage signal is converted back to a digital signal by an Analog-to-Digital converter (ADC) embedded inside the microcontroller.

3.2 Implementation on Breadboard

Due to limiting of getting a raw sample of bacteria, 3 mM Potassium Ferricyanide $K_3[Fe(CN)_6]$ in 0.1 M KCL is used as a sample. Figure 3 shows the testing circuit on the breadboard connected to Metrohm DropSens 110 carbon electrode and oscilloscope for probe data collection.

3.2.1 Experimental Setup Procedure

Following are experimental setup procedures for onboard potentiostat circuit implementation. The medical glove is strictly used for safety purposes. The electrode mentioned is for single use only. Reusing this electrode could give different measurements (basically will obtain a higher peak current due to electrode surface changes).

1. Construct the circuit on the breadboard using available components.

2. Electrode and sample preparation

   a. Prepare electrode with desired modification technique (blank/ Graphene Oxide (GO)/ GO-aptamer).

   b. Drop on the sample with the desired volume on the surface of the electrode. Ensure that there is no vibration or wind surrounding which may affect the read of the potentiostat.

3. Power on the circuit and use an oscilloscope to observe the output data.

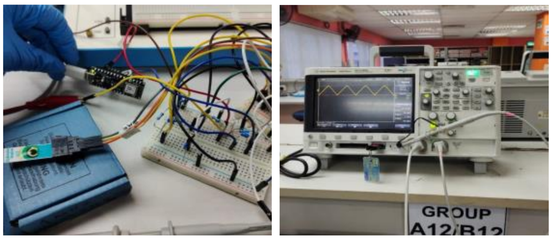

Figure 3: *Testing on Breadboard and measuring output using an oscilloscope*

3.2.2 Material Specification

Table 1: *Main components for potentiostat*

Component	**Model**	**Cost (RM) per unit**
Arduino Board	Nano33 BLE	99.62
Operational amplifier	TLV2774 /LM324A	19.93/1.00
Screen-printed Carbon electrode	DropSens SPCEs (refs. 110, C110)	20.09

Table 1 shows the main component and its price for breadboard implementation testing.

3.3 Analog Circuit Simulation

3.3.1 Design Approach

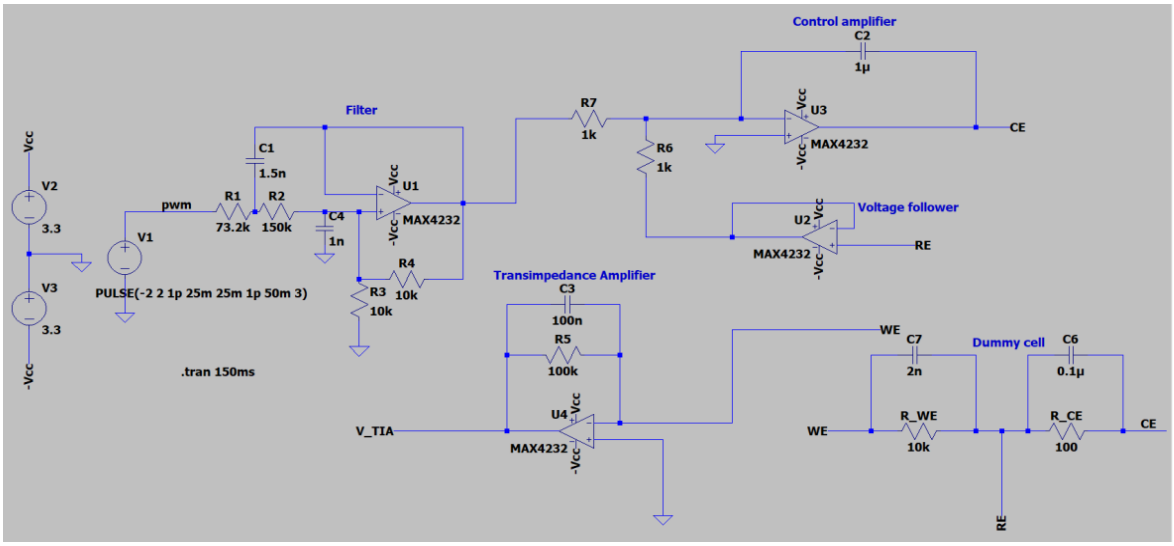

Figure 4: *Design Approach*

For the design approach, 2nd order Butterworth low pass filter is used where the cut-off frequency is 1 kHz. A gain configuration was also added to the filter for amplification of the measured signal in case the desired peaks has not much different. This gain also could prevent the need for an additional stage of filter which gives benefit in minimizing the power consumption. At the control amplifier stage, a capacitor C2 is applied on negative feedback to avoid self-oscillation of the op-amp [6].

4 Results and Discussion

4.1 Potentiostat Analog Circuit Simulation Result

Table 2: *Output peak current with different values of feedback resistor at TIA for design approach*

Feedback resistance value at TIA (Ω)	Output peak current (μA)
1k	± 8
5k	± 8
10k	± 8
20k	± 7.6
50k	± 6.4
80k	± 5.2
100k	± 4.4

Table 3: *Varying Scan Rate. Set feedback resistor at 10kΩ*

Preset voltage [V]	Time changes $\Delta t = t_1 - t_0$ [ms]	Scan rate [V/s]	Current range [μA]
4	25	160	± 8
2	25	80	± 4
0.2	25	8	± 0.6

Observing the results obtained from the circuit design approach, a 100 kΩ feedback resistor at transimpedance amplifier with a supplied voltage range of ±2 V provides the anodic and cathodic peak current range of about ±4.4 μA which is much lower. This is due to a gain configuration at the filtering stage. The magnitude of peak current is steady at feedback resistance under 20 kΩ as shown in Table 2. ±8 μA is said to be the maximum peak current that could produce in this circuit. Looking into the change in scan rate in Table 3, the changes can be made by varying the Preset voltage while maintaining the same time step. From the simulation result, a higher scan rate produces a higher magnitude of peak current at anodic and cathodic scans.

4.2 Comparison of Different Circuit Design

The commercial potentiostat offers an operational window of current and voltage range at ±10 V and ±2 A respectively.

Table 4: *Potentiostat performance comparison*

Electrical Performance	Commercial potentiostat	UWED paper	Paqari Stat	This work
Current range	± 2A	± 180 µA	± 255 µA	± 8 µA
Voltage range	± 10V	± 1.5V	± 1.5V	± 2V
Power consumption	300W	20mW	NA	53.1mW

5 Conclusion and Future Work

This research project involves designing an analog circuit for a bacterial detection system using LTspice simulator software. The best design performance is used for implementation on a breadboard and further development. The simulation result shows that a larger feedback resistance value at the transimpedance amplifier makes the reading of current at the working electrode becomes lower. Furthermore, the scan rate has an impact on the anodic and cathodic peak current according to the Randles-Sevcik equation where the increase in scan rate would increase the peak current at the working electrode. From the simulation result analysis, fewer electrical components consume less power.

In this research, experimental on actual potentiostat was also conducted to study its performance and understand clearer on its working principle. From this experiment, it is proved that a higher scan rate gives a higher peak current. The experiment also observed the performance of the different modified electrodes. The peak current produced is depending on the material conductivity of the surface electrode.

Besides that, a test on the designed analog circuit was also conducted. The circuit was constructed on Arduino Nano33 BLE. However, the result obtained from the testing is not aligned with the simulation result. In the future, further development for hardware-based needs to be done including developing the microcontroller command. To provide the device with the latest technology, it is recommended to add a wireless feature to this circuit.

6 Declarations

6.1 Acknowledgments

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6.2 Competing Interests

There is no conflict of interest.

6.3 Publisher's Note

AIJR remains neutral with regard to jurisdiction claims in published maps and institutional affiliations.

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