DESIGN POTENTIOSTAT CIRCUIT FOR NEUROCHEMICAL SENSING

Ahmad Farhan Bin Yahaya
Bachelor of Electrical Engineering (Hons)
Faculty of Electrical Engineering
University Teknologi MARA
40450 Shah Alam, Selangor, Malaysia
Email: praqze_dash350@yahoo.co.uk

ABSTRACT

This paper presents electrochemical cell that will be applied to potentiostat circuit to show its characteristics. The potentiostat circuit consists of electronic devices and components, including op amp, to set up a control circuit for neurochemical sensing. The circuit is required to go under simulation tools such as PSice, Multisim or Simulink to design and simulate the circuit for analyzing its performance and parameters involved. The voltage source, V_{src}, of the circuit should be same with the voltage cell, V_{cell}, between reference electrode and working electrode. Output voltage is depending on current flow across electrochemical cell.

Keyword: electrochemical cell, potentiostat, neurochemical,

1.0 INTRODUCTION

Neurochemical such as nitric oxide, acetylcholine, serotonin, glutamate, dopamine or nerve growth factor is an organic molecule that participates with neural activities. The neurochemical can act as neurotransmitter that controls some part in our body. Acetylcholine assists motor function and is involved in memory. Serotonin plays a regulatory role in mood, sleep, and other areas. Glutamate usually causes adjacent cells to fire an action potential. Dopamine plays a part in movement, alertness, and sensations of pleasure.

Dopamine is a catecholamine neurotransmitter in the brain. Lack of dopaminergic neurons in the basal ganglia is implicated as a cause of Parkinson's disease [1] [2]. Neurochemical can be detected by integrated systems that would be useful in conducting research on animal models of disorders like epilepsy and stroke.

In neurochemical sensing, a voltage is applied to stimulate an oxidation-reduction (redox) reaction [2]. The electrodes electrochemically detect the neurotransmitter dopamine. Potentiostat is a common application that can measure the neurochemical. A potentiostat is an electronic instrument that controls the voltage difference between a working electrode (WE) and a reference electrode (RE). The potentiostat implements this control by injecting current into the cell through a counter or auxiliary electrode (AE).

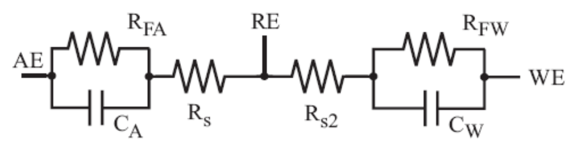

Figure 1: Electrical model of an electrochemical cell.

The working electrode (WE) is the electrode where the potential was controlled and where the current was measured. The working electrode serves as a surface on which the electrochemical reaction takes place. The working electrode can be bare metal or coated. The reference electrode is used in measuring the working electrode potential. A reference electrode (RE) should have a constant electrochemical potential as long as no current flows through it. The counter or auxiliary electrode (AE) is a conductor that completes the cell circuit. The current that flows into the solution via the working electrode leaves the solution via the counter electrode.

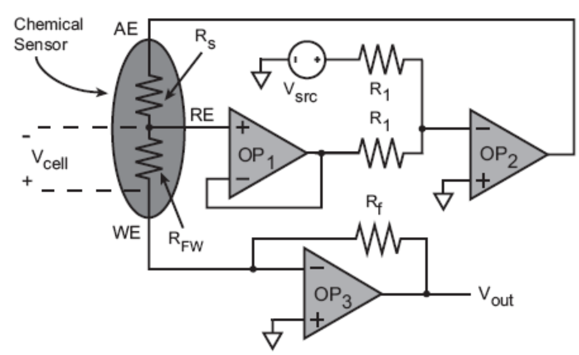

Figure 2: Standard single-ended potentiostat.

An electrochemical cell typically consists of three electrodes that are auxiliary (AE), reference (RE) and working electrodes (WE). Figure 1 represents an electrical circuit equivalent of an electrochemical cell [3] [4] [5] [6]. R_S and R_{S2} are the resistances of the solution. R_{FA} and R_{FW} represent faradaic resistances, and C_A and C_W are the double-layer capacitances associated with the AE and WE respectively. Since R_{S2} and R_{FA} are typically small, they can be neglected, and at DC, the model simplifies into two series resistors [3].

Figure 2 shows a typical potentiostat using the standard, single-ended (SE) topology [3] [4] [5] [6]. The potentiostat is used to ensure V_{cell} tracks V_{src} under varying current loading conditions. To determine the concentration of an analyte, V_{src} is applied to the sensor between the working and reference electrodes using equation (1).

$$V_{cell} \equiv V_{WE} - V_{RE} = V_{src} \tag{1}$$

When V_{cell} reaches an analyte's redox potential, a redox current, I_{redox}, that is proportional to the analyte's concentration is generated at the working electrode. R_{FW} is the faradaic resistance of the WE, and is given by equation (2).

$$R_{FW} \equiv V_{cell} / I_{redox} \tag{2}$$

The control circuitry comprises three operational amplifiers [7] [8]. OP_1 acts as a voltage buffer in order to translate between electrical and electrochemical potentials and allowing no current to flow through it.

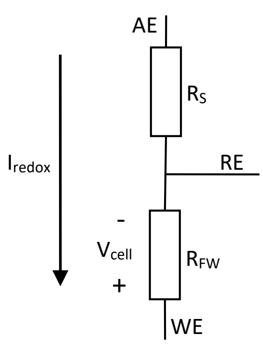

Figure 3: Simplify electrical model.

Since no current draw into RE, the current through R_S and R_{FW} are the same that is I_{redox}. Figure 3 shows the direction of I_{redox} through electrochemical cell. OP_2 sources/sinks the current specified by the control voltage to/from the counter electrode to enable the reduction/oxidation reaction. Figure 4 shows current-to-voltage converter for potentiostat circuit.

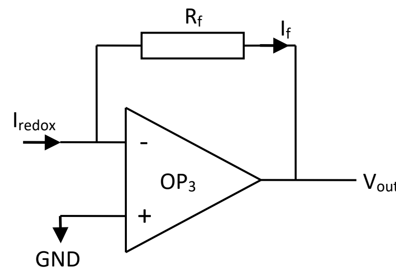

Figure 4: Current-to-voltage converter.

OP_3 and R_f force a virtual ground using equation (3) at the WE and provide current-to-voltage conversion such that,

$$V^+ = V^- = 0 \tag{3}$$

Applying Ohm's Law at R_f,

$$I_f = \frac{V^- - V_{out}}{R_f} \tag{4}$$

Substitute equation (3) into equation (4),

$$I_f = -\frac{V_{out}}{R_f} \tag{5}$$

Since no current draw into OP_3, I_{redox} is direct through R_f which mean,

$$I_{redox} = I_f \tag{6}$$

Substitute equation (6) into equation (5) and rearrange the equation,

$$V_{out} = -I_{redox} R_f \tag{7}$$

Equation (7) will be used to determine the output of the circuit. The value of R_f is determined by the range of currents to be measured [8]. The circuit ensures that the electrochemical cell voltage V_{cell} tracks the source control voltage V_{src}.

Op amps are fairly cheap and widely available from many different vendors. Op amps can perform many different operations [9]. It has very large open loop gain, differential input stage, and use feedback to establish and control the relationship between the output and input signals. The output of the op amp is controlled by negative feedback or positive feedback which generates gain and oscillation.

Figure 5 shows the block diagram in op amp that can be divided in 3 stages. The differential input stage of the amplifier must have very high input impedance. This will cause the op-amp to draw very negligible amounts of input current. The voltage gain stage is mainly responsible for gaining up the input signal and sending it to the output stage. The output stage delivers current to the op-amp's load and it may or may not have short circuit protection.

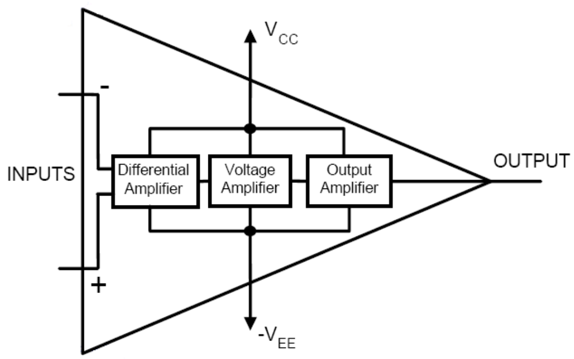

Figure 5: Op amp block diagram.

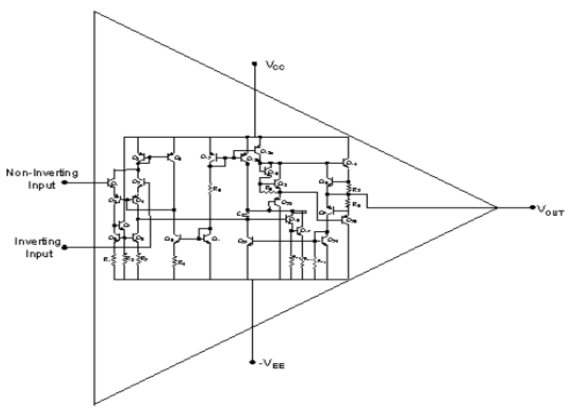

Figure 6: Op amp internal circuit.

Figure 6 shows the internal circuit of op amp. It can be separated into several sections. The biasing circuit of the amplifier provides the device with the current that it needs for driving all of the transistors in it. The high impedance load at the differential input stage converts the differential signal of the input transistors into a single ended signal. The single ended signal is then delivered to the voltage gain stage. Active load is when a transistor current source is used as a load resistance. It can achieve very high gains without the actual need for high resistors. By using an active load, we no longer need to have the high supply voltage. Transistors at the output amplifier can provide larger currents with minimal temperature effect on the device.

2.0 METHODOLOGY

The potentiostat circuit was simulated with simulation tool that is Multisim. Multisim has various devices and components to be chosen for circuit simulation. All op amps in this circuit are using IC LM741 from National Semiconductor.

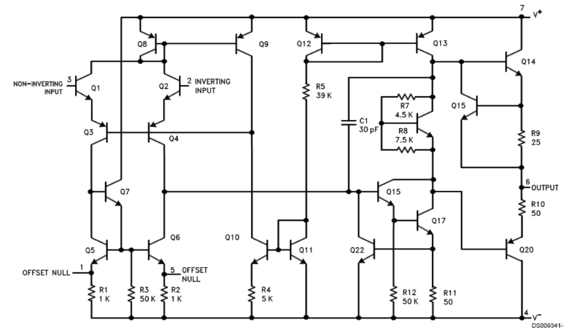

Figure 7: Schematic diagram of LM741.

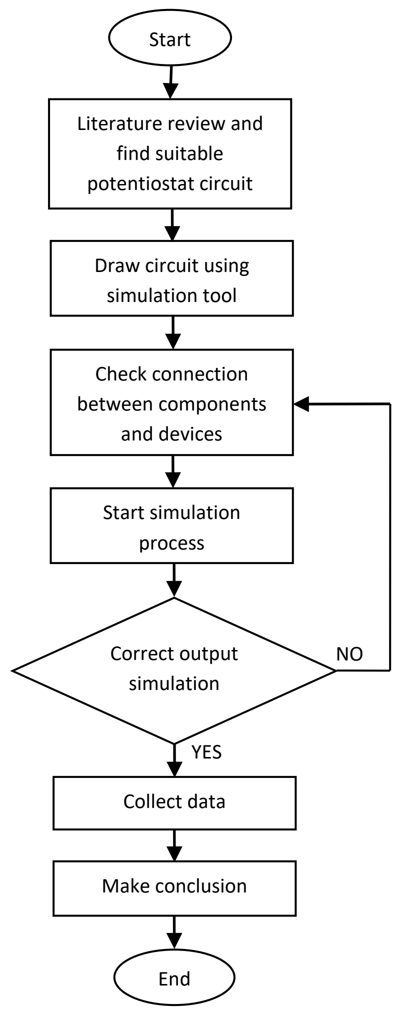

Figure 8: Flowchart of simulation circuit.

Figure 7 shows the schematic diagram of LM741. IC LM741 is very generally use in op amp application. The amplifiers offer many features which make their application nearly foolproof: overload protection on the input and output, no latch-up when the common mode range is exceeded, as well as freedom from oscillations [10].

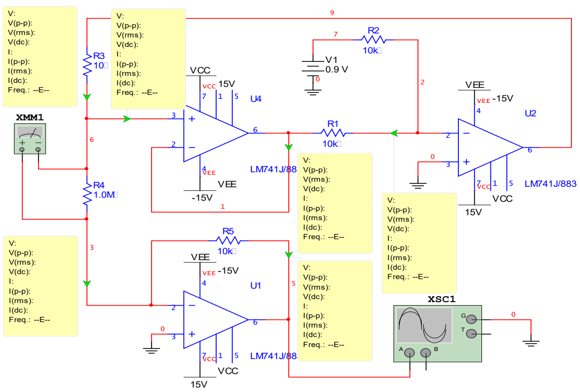

Figure 9: Potentiostat circuit in Multisim simulation.

Figure 8 shows the flowchart of the simulation on potentiostat circuit. Parameters like V_{src}, V_{cell}, I_{redox}, I_f and V_{out} are taken from the simulation to analyze the circuit. The devices and components are varies to different kind of value to check the validity of the circuit. V_{cell} must tracks V_{src} even the value of the other components are changing any kind of value. A voltmeter is connected between reference electrode and working electrode. Figure 9 shows complete potentiostat circuit in Multisim simulation.

Since this paper shows the simulation of the potentiostat circuit, the characteristic between I_{redox} and dopamine is taken from previous experiment to compare it so that this potentiostat circuit is within the range of the dopamine value.

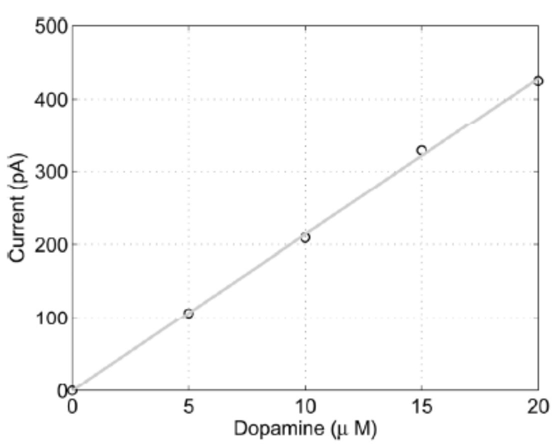

Figure 10: I_{redox} of the potentiostat circuit response to dopamine.

Following electrical testing and characterization of the potentiostat, the basic neurotransmitter measurements were performed. A standardized solution of dopamine was prepared [11] to test the potentiostat circuit in vitro. Figure 10 shows the relationship between I_{redox} and dopamine [12].

3.0 RESULT AND DISCUSSION

The result was taken from the simulation to analyze the output.

Table 1: Potentiostat circuit supplied by V_{src} with +0.9V

R_{FW} (Ω)	I_{actual} (nA)	I_{redox} (nA)	I_f (nA)	V_{out} (mV)	V_{actual} (mV)
10 k	- 90000	- 89900	- 90000	900.995	900.000
51 k	- 17647.06	- 17600	- 17700	178.040	176.471
100 k	- 9000	- 8990	- 9060	91.638	90.000
220 k	- 4090.91	- 4090	- 4160	42.586	40.909
430 k	- 2093.02	- 2090	- 2160	22.623	20.930
620 k	- 1451.61	- 1450	- 1520	16.214	14.516
680 k	- 1323.53	- 1320	- 1390	14.394	13.235
750 k	- 1200	- 1200	- 1270	13.700	12.000
820 k	- 1097.56	- 1100	- 1170	12.676	10.976
910 k	- 989.01	- 989	- 1060	11.591	9.890
1 M	- 900	- 900	- 970	10.702	9.000
1.1 M	- 818.18	- 818	- 888	9.884	8.182
1.2 M	- 750	- 750	- 820	9.203	7.500
1.3 M	- 692.31	- 693	- 763	8.627	6.923
1.5 M	- 600	- 600	- 670	7.704	6.000
1.6 M	- 562.50	- 563	- 633	7.330	5.625
1.8 M	- 500	- 501	- 571	6.705	5.000
2 M	- 450	- 451	- 521	6.205	4.500
3.9 M	- 230.77	- 231	- 301	4.015	2.308
6.2 M	- 145.16	- 146	- 216	3.159	1.452
8.2 M	- 109.76	- 111	- 181	2.806	1.098
10 M	- 90	- 90.8	- 161	2.608	0.900
15 M	- 60	- 60.9	- 131	2.309	0.600
20 M	- 45	- 45.9	- 116	2.159	0.450

It can be seen that the value of output measure in Multisim and calculation don't indicate large difference between them as shown in Table 1 and Table 2. The output value is very small amount where every value can make the different for the circuit outcome. The V_{src} is set to 900mV while R_1 and R_f were set to 10kΩ.

Table 2: Potentiostat circuit supplied by V_{src} with -0.9V

R_{FW} (Ω)	I_{actual} (nA)	I_{redox} (nA)	I_f (nA)	V_{out} (mV)	V_{actual} (mV)
10 k	90000	90100	90000	- 898.995	- 900.000
51 k	17647.06	17700	17600	- 174.915	- 176.471
100 k	9000	9010	8940	-88.378	- 90.000
220 k	4090.91	4090	4020	- 32.250	- 40.909
430 k	2093.02	2100	2030	- 19.255	- 20.930
620 k	1451.61	1450	1380	- 12.836	- 14.516
680 k	1323.53	1330	1260	- 11.554	- 13.235
750 k	1200	1200	1130	- 10.318	- 12.000
820 k	1097.56	1100	1030	- 9.293	- 10.976
910 k	989.01	991	921	- 8.207	- 9.890
1 M	900	902	832	- 7.316	- 9.000
1.1 M	818.18	820	750	- 6.497	- 8.182
1.2 M	750	751	681	- 5.815	- 7.500
1.3 M	692.31	694	624	- 5.237	- 6.923
1.5 M	600	601	531	- 4.314	- 6.000
1.6 M	562.50	564	494	- 3.938	- 5.625
1.8 M	500	501	431	- 3.313	- 5.000
2.0 M	450	451	381	- 2.812	- 4.500
3.9 M	230.77	232	162	- 0.618	- 2.308
6.2 M	145.16	146	76.20	0.238	- 1.452
8.2 M	109.76	111	40.70	0.593	- 1.098
10 M	90	91.0	21.00	0.790	- 0.900
15 M	60	60.4	- 9.05	1.091	- 0.600
20 M	45	45.9	- 24.10	1.241	- 0.450

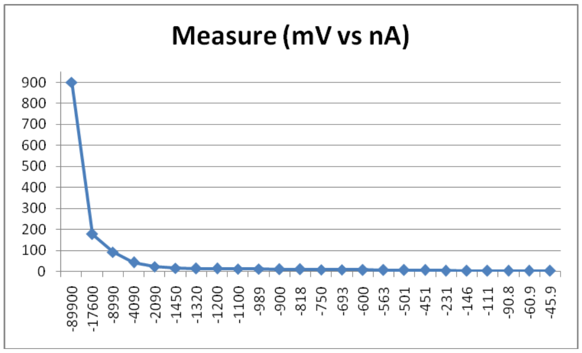

Figure 11: V_{out} (mV) versus I_{redox} (nA) for V_{src}+

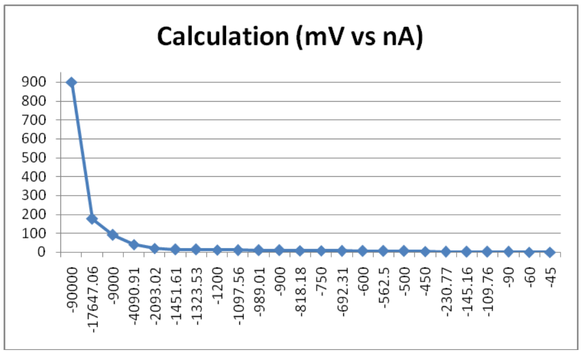

Figure 12: V_{actual} (mV) versus I_{redox} (nA) for V_{src}+

A dummy load cell with R_S and R_{FW} were set to 10Ω and 1MΩ respectively to characterize the circuit. Figure 11 & 12 show the difference between the measured value and calculation value. This circuit is supply with positive V_{src} of 0.9V. In this simulation, the value of R_{FW} only has change. R_{FW} is at the electrochemical cell between reference electrode and working electrode. I_{redox} is proportional to the neurochemical concentration. The changing of resistor R_{FW} will represent with the changing of neurochemical concentration. Figure 13 & 14 is almost the same operation like Figure 11 & 12. The only difference was the value of V_{src} of -0.9V. This is to show if there are any difference in supplying the circuit with $\pm V_{src}$.

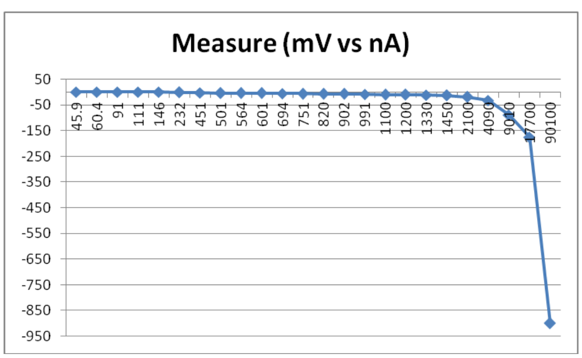

Figure 13: V_{out} (mV) versus I_{redox} (nA) for V_{src}-

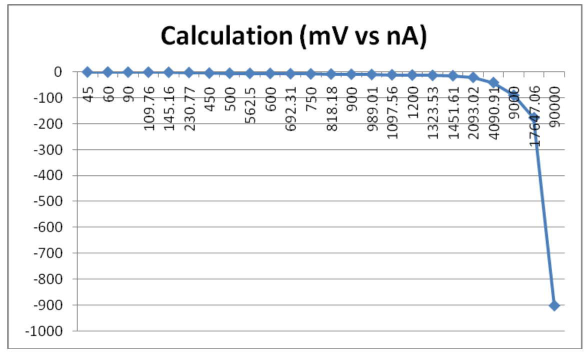

Figure 14: V_{actual} (mV) versus I_{redox} (nA) for V_{src}-

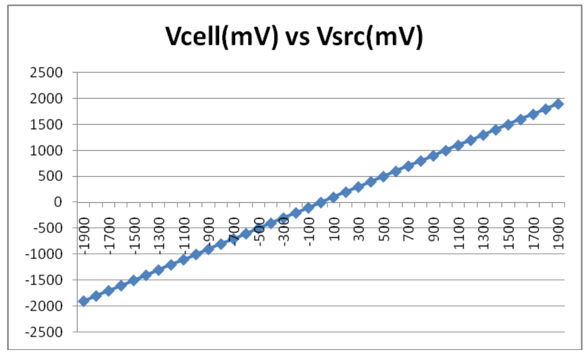

Figure 15: V_{cell} tracks $V_{src}\pm$

Table 3: V_{src} was varied from -1.9V to 1.9V and maintain R_{FW}

V_{src} (mV)	V_{cell} (mV)	I_{actual} (nA)	I_{redox} (nA)	I_f (nA)	V_{out} (mA)	V_{actual} (mV)
- 1900	- 1901	1900	1903	1833	- 17.326	- 19
- 1800	- 1801	1800	1802	1732	- 16.325	- 18
- 1700	- 1701	1700	1702	1632	- 15.324	- 17
- 1600	- 1601	1600	1602	1532	- 14.323	- 16
- 1500	- 1501	1500	1502	1432	- 13.322	- 15
- 1400	- 1401	1400	1402	1332	- 12.321	- 14
- 1300	- 1301	1300	1302	1232	- 11.320	- 13
- 1200	- 1201	1200	1202	1132	- 10.319	- 12
- 1100	- 1101	1100	1102	1032	- 9.318	- 11
- 1000	- 1001	1000	1002	932	- 8.317	- 10
- 900	- 900.695	900	902	832	- 7.316	- 9
- 800	- 800.696	800	801	731	- 6.315	- 8
- 700	- 700.696	700	701	631	- 5.314	- 7
- 600	- 600.697	600	601	531	- 4.313	- 6
- 500	- 500.697	500	501	431	-3.312	- 5
- 400	- 400.698	400	401	331	- 2.311	- 4
- 300	- 300.698	300	301	231	- 1.310	- 3
- 200	- 200.699	200	201	131	- 0.309	- 2
- 100	- 100.700	100	101	30.8	0.692	- 1
0	- 0.700	0	0.701	-69.3	1.693	0
100	99.299	- 100	- 99.4	- 169	2.694	1
200	199.299	- 200	- 199	- 269	3.695	2
300	299.298	- 300	- 300	- 370	4.696	3
400	399.298	- 400	- 400	- 470	5.697	4
500	499.297	- 500	- 500	- 570	6.698	5
600	599.297	- 600	- 600	- 670	7.699	6
700	699.296	- 700	- 700	- 770	8.700	7
800	799.296	- 800	- 800	-870	9.701	8
900	899.295	- 900	- 900	- 970	10.702	9
1000	999.295	- 1000	- 1000	- 1070	11.703	10
1100	1099	- 1100	- 1100	- 1170	12.704	11
1200	1199	- 1200	- 1200	- 1270	13.705	12
1300	1299	- 1300	- 1300	- 1370	14.706	13
1400	1399	- 1400	- 1400	- 1470	15.707	14
1500	1499	- 1500	- 1500	-1570	16.708	15
1600	1599	- 1600	- 1600	- 1670	17.709	16
1700	1699	- 1700	- 1700	- 1770	18.710	17
1800	1799	- 1800	- 1800	- 1870	19.711	18
1900	1899	- 1900	- 1900	- 1970	20.712	19

Figure 15 shows that evey change in V_{src} the V_{cell} will always tracks the value and make V_{cell} as close as the V_{src}. The range for this graph is from -1.9V to 1.9V. The value of R_{FW} is maintain at 1MΩ to see the affect of the output as shown in Table 3.

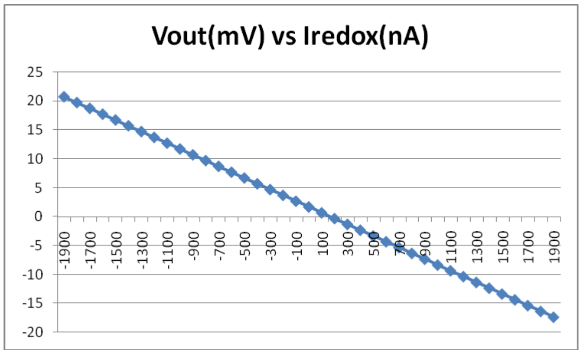

Figure 16: V_{out} depend on I_{redox}

Figure 16 shows that V_{out} is depend on the I_{redox} from working electrode and the value of R_f. The graph is negative slope because the current-to-voltage converter has negative feedback so the output value depends on current direction.

The current is move from V_{out} to working electrode. I_{redox} and I_f should be same value in the simulation but op amp has additional current at the input that is small amount. Since I_{redox} that produced in the circuit is small too so any additional current that small value can affect the final output. That why I_{redox} isn't same with I_f when measured in the simulation. The results show that I_{redox} is different from previous experiment on dopamine because the circuit used for previous experiment was more precise than this circuit.

4.0 CONCLUSION

The potentiostat circuit can be simulated with various simulations tools to analyze the characteristic of the circuit. The control amplifier, OP_2, is to make sure that V_{cell} will always tracks V_{src} either for positive and negative value. I_{redox} is proportional to the neurochemical concentration which generated at the working electrode. V_{out} value is depending on oxidation-reduction current and feedback value of current-to-voltage converter.

5.0 FUTURE DEVELOPMENT

The potentiostat can be design to be more sensitive at the electrochemical cell to make more reliable for neurochemical sensing. The current-to-voltage converter can't able to convert the current more precisely even that change is minimal.

6.0 ACKNOWLEDGEMENT

I would like to take this opportunity to express my gratitude and appreciation to my supervisor Pn Zurita Binti Zulkifli and Pn Norsabrina Binti Sihab for their valuable guidance and help in completing this paper.

7.0 REFERENCE

[1] T. Wichmann and M.R. DeLong, "*Pathophysiology of Parkinsonian motor abnormalities*," Adv. Neurol., vol. 60, pp. 53–61, 1993.

[2] K. Murari, M. Stanacevic, G. Cauwenberghs, N. V. Thakor, "Integrated Potentiostat for Neurotransmitter Sensing," IEEE Engineering in Medicine and Biology Magazine, pp. 23-29, 2005.

[3] S.M. Martin, F.H. Gebara, T.D. Strong, R.B. Brown, "*A low-voltage, chemical sensor interface for systems-on-chip: The fully-differential potentiostat*," Proceedings ISCAS, vol. 4, pp. 892-895, 2004.

[4] Bard, and L. Faulkner, *Electrochemical Methods*, New York: John Wiley & Sons, 1980.

[5] K. Kraver, M. Guthaus, T. Strong, P. Bird, G. Cha, W. Hold, and R. Brown, "*A mixed-signal sensor interface microinstrument*," Sensors and Actuators A, vol. 91, pp. 266-277, 2001.

[6] E. Lauwers, J. Suls, W. Gumbrecht, D. Maes, G. Gielen, and W. Sansen, "*A CMOS multiparameter biochemical microsensor with temperature control and signal interfacing*," IEEE J. Solid-State Circuits, vol. 36, pp. 2030-2038, Dec. 2001.

[7] R. Reay, S. Kounaves, and G. Kovacs, "*An integrated CMOS potentiostat for miniaturized electroanalytical instrumentation*," IEEE Intl. Solid-State Circuits Conf., 1994.

[8] S. B. Prakash, P. Abshire, M. Urdaneta, M. Christophersen, and E. Smela, "*A CMOS Potentiostat for Control of Integrated MEMS Actuators*," IEEE/NLM Life Science System & Applications Workshop, Bethesda, Maryland, pp. 5555-5558, 2006.

[9] Peggy Alavi, "*Op-Amp Basic*," Presentation Transcript, Amplifiers Group of National Semiconductor, 3 September 2003.

[10] National Semiconductor, General Description of LM741 Operational Amplifier, www.national.com, May 1998.

[11] G. Mulliken, M. Naware, A. Bandyopadhyay, G. Cauwenberghs, and N. Thakor, "*Distributed neurochemical sensing: in vitro experiments*," in Proc. IEEE Int. Symp. Circuits Syst. (ISCAS'2003), Bangkok, Thailand, May 2003.

[12] K. Murari, A. Rege, G. Cauwenberghs, M. Stanacevic and N. V. Thakor, "*VLSI Potentiostat Array With Oversampling Gain Modulation for Wide-Range Neurotransmitter Sensing*," IEEE Transactions on Biomedical Circuits and Systems, Vol. 1, No. 1, March 2007.