

# Design an Operational Amplifier for Neutro Chemical Sensor

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**Abstract** - This project needs to design an operational amplifier (op-amp) for neutro chemical sensor. The op-amp is amplifying the input current in nanoampere (-800nA to 800nA) and converts the signal into voltage. This low power amplifier designed with high gain and high sensitivity because output current from neutron chemical sensor very small. The designed consists combination of current amplifier, differential amplifier, voltage amplifier, class AB power amplifier and high sensitivity current-to-voltage converter. The low power amplifier output should capable to drive the voltage-to-frequency converter (VFC). This op-amp is a part of the main project the wireless voltammetry recording in unaesthetized behaving rats. Vivo voltammetry is a valuable technique for rapid measurement of dopamine in the brain of freely behaving rats. Using a conventional voltammetry system, however, behavioral freedom is restricted by cables connecting the head assembly to the measurement system. This system consisted of a potentiostat and transmitter system activation pulse to a carbon fiber recording electrode where the process would produce the signal and then the op-amp converts the signal into voltage before convert the signal into frequency by VFC. The Multisim8 software is used to design and simulate the op-amp circuit.

**Keywords:** Voltammetr, Neutron Chemical Sensor, Operational Amplifier.

## I. INTRODUCTION

The design used a low power operational amplifier as one of sub components in the voltammetry system. Low power means that the voltage and current supplies to the op-amp is very low to make it operate. The op-amp is apart of the voltammetry system. The op-amp is use to convert current into voltage where the current produced by neutron chemical sensor. The neutron chemical sensor build of three electrodes, recording electrode, reference electrode and auxiliary electrode where it function to measure concentration of the chemical in the brain.

The project used the dopamine as the reference chemical for analysis. Dopamine is one of the chemical in the human brain to detect Parkinson disease. The neutron chemical sensor is the measurement part of the voltammetry system. The project focuses on design the vivo voltammetry

system that uses to measure dopamine in the brain of the freely moving rats. In history, the system is not the new system. There are several teams have created the system but still bulky and need to be improve. In vivo voltammetry system is where considering the real conditions and environment.

In vivo voltammetry has become a powerful method of recording changes in extracellular transmitter concentration in unrestrained animals [4], allowing examination of amounts of extracellular transmitter similar to microdialysis, but with higher time resolution. With recent increase in time resolution and demonstration of stable recording over very long-term studies [5]. One of the remaining limitations with both conventional voltammetry and microdialysis is the presence of cables connecting the head assembly to the measuring system [1].

The entire devices as invented were in vitro where it use the instrument and outside the real environment. The in vitro system has the limitation and bulky measurement system restriction of cables connecting the head assembly of rat to the measuring systems. In this project, the main project aimed is developing a wireless voltammetry system that would be small and light enough to be fixed to a unaesthetized behaving rat, while maintaining high sensitivity to dopamine, sub-second time resolution, and very long-term capability of a conventional wired voltammetry system [1].

To overcome difficulties in the previous wireless system, this project generated voltage waveforms in a remote unit on the animal and used radio waves, rather than the infrared radiation, to mediate measured current from the remote unit to a home-base unit. To realize the overall system of wireless voltammetry system, apart of the system in the remote voltammetry system is an op-amp where it receives a signal from electrode measured dopamine. Then the signal would convert into voltage signal. This portion of main project objectives to design the operational amplifier that use for voltammetry sensor.

## II. OBJECTIVES

The objectives are to design the good op-amp with low input current and voltage for voltammetry system base on the specifications given to convert current to voltage and the output voltage can drive voltage-to-frequency circuit. The design specifications used low power op-amp with input current  $-800\text{nA}$  to  $800\text{nA}$  and used the  $3\text{V}$  low voltage DC supply.

## III. SCOPE OF WORK

This project required to design the new op-amp that can be used for neutron chemical sensor. Design process conducted using the design software Multisim8. Multisim8 is higher performing computers and modern software architecture with complete design library. The design process includes the combination of several application or differences types of amplifier. The task on this project is to design the op-amp as one of the components in the remote system consisted in the voltammetry system. The op-amp receives the signal from the neutron chemical sensor. The reference voltage from the potentiostat is  $100\text{mV}$  to  $250\text{mV}$  supply to electrode. The Figure 1 showed the wireless voltammetry system.

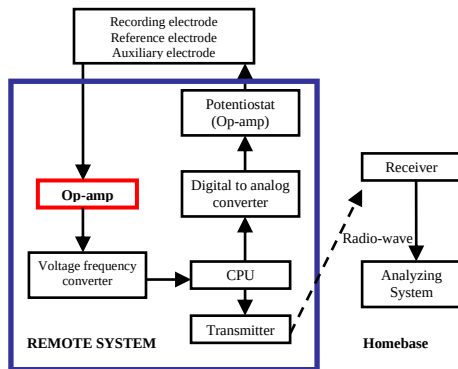


Figure 1: Diagram of the wireless voltammetry system [1].

The electrolysis process of the dopamine will produce the current as input to the op-amp. The function of op-amp in the voltammetry system is to amplify the very small current produced from electrolysis process in the brain and convert the current signal to voltage signal. The graph in Figure 2 showed the reaction of the input voltage supply to electrode and the output current for dopamine electrolysis process.

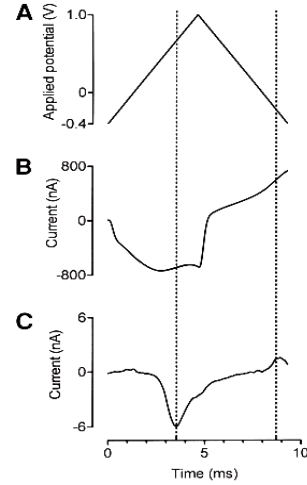


Figure 2: Voltammetry signal of Dopamine. Graft A is the applied potential voltage. Graft B and C are the output current from the electrolysis process [8].

From the graph consider the output current produce from the electrolysis process is very small. Observe the potential voltage applied to the electrode is  $100\text{mV}$  to  $250\text{mV}$  and the current output is approximately in the range  $1\text{nA}$  to  $800\text{nA}$ . For design purpose, taken the current input specification is from  $-800\text{nA}$  to  $800\text{nA}$  alternating current. Input current in sinusoidal wave with  $100\text{ Hz}$  frequency. The output voltage is as the supply to voltage-to-frequency converter. Design used the low voltage DC supply  $3\text{V}$ . Figure 3 showed the block diagram of the design stage. The inner operational amplifier device needs to design because the project future development will develop as fabricate op-amp.

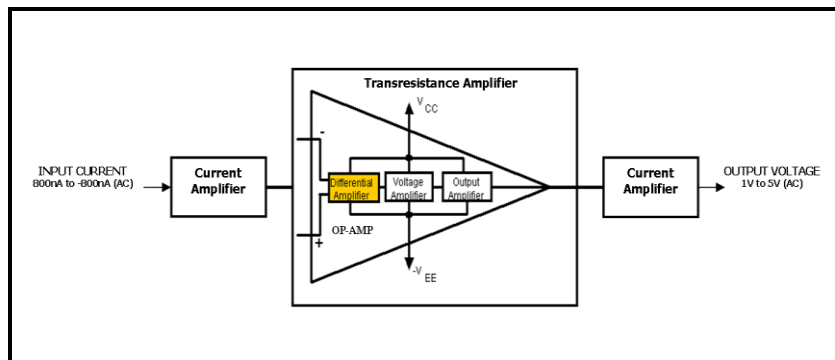
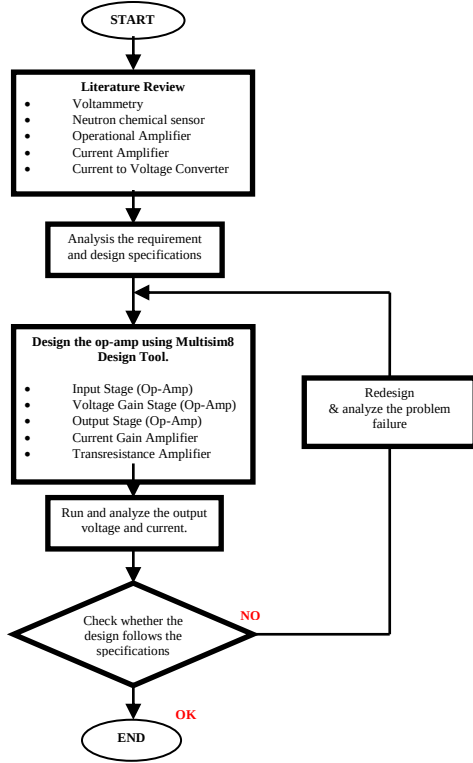


Figure 3: Operational Amplifier Block Diagram

#### IV. METHODOLOGY/DESIGN PROCESS

The design process represent by the diagram in Figure 4. Design process conducted in several block circuit before finally combines overall circuits become fully functions op-amp. The design started by design operational amplifier device consists of input stage, voltage gain stage and output stage.



**Figure 4:** Block diagram of design process flow from the start until finish overall design process complete operational amplifier

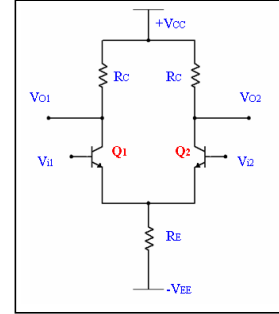
##### A. Operational Amplifier

The design starts with the design the op-amp device. The op-amp is a device with the differential amplifier at the input and the single-ended output which has larger differential voltage gain input stage. Then the next stage is the gain stage that functions as voltage gain to the op-amp. The output stage at the end of op-amp stage design to has ability to pass ac signals with large amplitudes and little distortion.

##### 1. Input Stage Differential Amplifier with current mirror

The first stage or 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 very small input

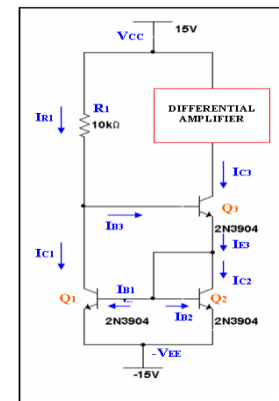
current enables to utilize the ideal op-amp equations for circuit analysis purposes. This stage also provides the DC gain of the amplifier. Design using long-tailed pair to perform a differential amplifier. Long-tailed pair has ability to reject common-mode signals like thermal noise makes it an extremely useful amplifier for the purpose of rejecting the noise. A typical differential amplifier circuit is shown in Figure 5.



**Figure 5:** Differential Amplifier

This project design using the single ended mode where only one input signal is applied at either input terminal while the other input is grounded.

The current mirror used to gave the constant current to differential amplifier replacing the function of RE. Current mirror has an output high resistance (impedance) and the current produced by the source is constant and its value can be adjusted to any desired value. A current mirror is a circuit designed to copy a current through one active device by controlling the current in another active device of a circuit, keeping the output current constant regardless of loading. This projects design used the Wilson current mirror. Wilson current mirror is a circuit configuration designed to provide a constant current source or sink. The circuit is shown in Figure 6.



**Figure 6:** Wilson current mirror circuit

## 2. Voltage Gain Stage

The next stage of the op-amp is the voltage gain stage. The gain stage is mainly responsible for gaining up the input signal and sending it to the output stage. Practical transistor amplifiers usually consist of a number of stages connected in cascade, several stages may be combined forming a multistage amplifier. Additional amplification can be required to provide a signal having some specified level. In this project design the multistage amplifier need to furnish high input impedance simultaneously with a large voltage gain, low output impedance and a large voltage gain. In this multistage design a commonly used common-emitter to common-emitter to common-collector amplifier. Figure 7 above showed a direct coupled multistage amplifier built with NPN and PNP transistors.

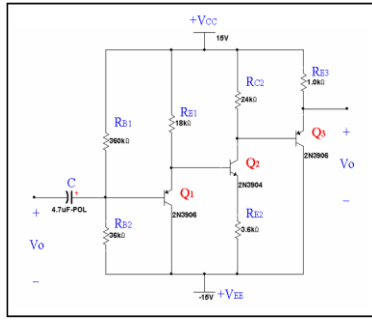


Figure 7: Multistage voltage amplifier circuit

## 3. Output Stage

The final stage of op-amp is output stage. This minimizes the loading of the output of the op-amp device by output stage. Op-amps must have very high input impedance, very high open loop gain, and very low output impedance. It is next to impossible to achieve all these three in one single stage. This is why op-amps generally have three different stages.

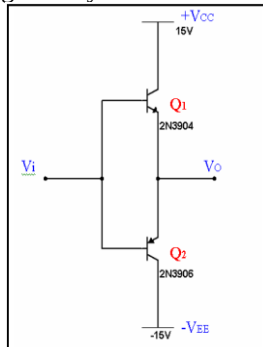


Figure 8: Push-pull output stage circuit.

Design output stage in this project using a push-pull output stage is a type of electronic circuit that can drive either a positive or a negative current into a load. The requirements of the output stage include a

current gain, low output impedance, and the ability to pass ac signals with large amplitudes and little distortion. Figure 8 showed the design schematic of a push-pull stage.

## 4. Current Amplifier

The current amplifier in this design used at the input and output of the op-amp. Circuits received the low current input from the neutron chemical sensor should firstly be amplify. Same purpose at the output stage current amplifier the current at the output so small cause of by drop in op-amp. The output current need to gain before can drive the next circuit (voltage-to-frequency converter circuit). At the input op-amp used the feedback pair, method using for current amplifier with high current gain. This circuit design placed at the front of overall operational amplifier design to amplify very small current. The feedback pair connection is a two-transistor circuit operates such the Darlington circuit. Figure 9 showed the feedback pair circuit.

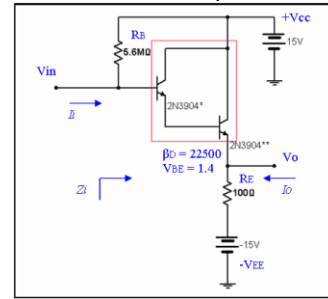


Figure 9: Feedback pair circuit

The output current amplifier used Darlington connection where the composite transistor acts as a single unit. The Darlington connection current gain is the product of the current gains of the individual transistors. Figure 10 showed the Darlington emitter follower circuit.

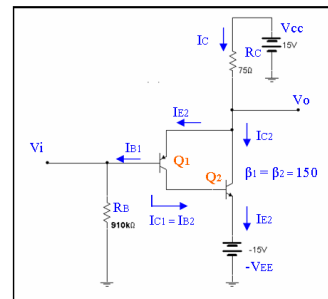


Figure 10: Darlington emitter follower circuit

## 5. Transresistance Amplifier

A current-to-voltage converter (I-V converter), also called transresistance amplifier. The amplifier circuit accepts an input current and yields an outputs voltage

of the type where  $K$  is the gain of the circuit in volts per ampere. A current-to-voltage converter is a circuit that performs current to voltage transformation. It is apparent that high-sensitivity applications may require unrealistically larger resistance. Unless proper fabrication measures are adopted, the resistance of the surrounding medium, being in parallel with  $R$ , will decrease the net feedback resistance and degrade the accuracy of the circuit. Figure 11 showed a widely used technique to avoid this drawback. The circuit utilizes a T-network to achieve high sensitivity without requiring unrealistically larger resistance.

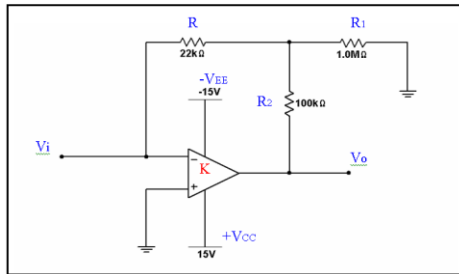


Figure 11: High sensitivity I-V converter

## 6. Complete Operational Amplifier Circuit

After design the each component in the op-amp then all the circuits design combined together become one complete op-amp. Several circuit improvement and analysis should do before choose the better op-amp circuit to drive voltage-to-frequency converter circuit.

Firstly the change the circuit parameter other from base design spec such as the voltage supply (1.5V and 5V) and also change the transistors because different type of transistor have different characteristics. The best circuit parameters choose as final op-amp design. Analysis of op-amp for analyzes circuit characteristic either follows the specifications requirement such as low power op-amp, circuit sensitivity and ability to drive voltage-to-frequency circuit.

## V. RESULTS AND DISCUSSION

The results showed the input and output of each stage and the complete operational amplifier. The simulations results captured from Multisim8 using Tektronix Oscilloscope. For simulations references, the yellow wave is the input signal and the blue wave is the output signal.

### 1. Differential Amplifier (Input Stage)

The differential amplifier stage produces the output at emitter of pair differential transistor. This is because the output here given more stable wave and better current gain but the voltage gain approximately 1.

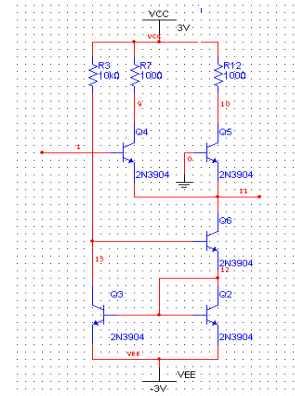


Figure 12: Differential amplifier design stage

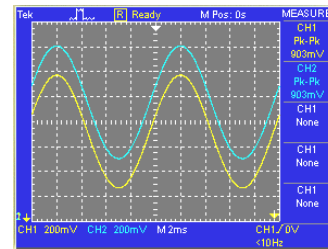


Figure 13: Feedback pair circuit simulation

The input wave and output wave of this stage approximately the same ( $A_v \approx 1$ ). The important of this circuit is it an extremely useful amplifier for the purpose of rejecting the noise and current gain.

### 2. Multistage Amplifier (Gain Stage)

Multistage circuit amplifies the signal using the capacitor as coupled to separate the bias current stage to stage of the multistage. The multistage amplifier used direct coupler.

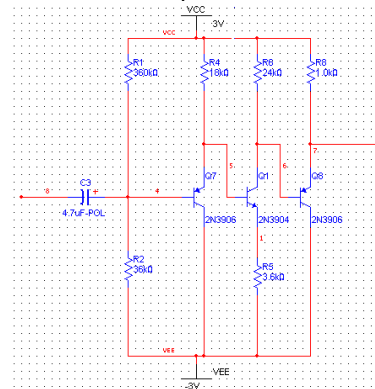


Figure 14: Multistage voltage amplifier design stage

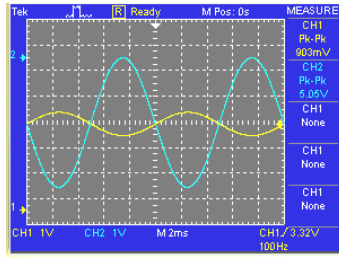


Figure 15: Multistage circuit simulation

The op-amp voltage gain stage simulation result can showed the output signal is amplify. From the data we can compute.

$$A_v = \frac{V_{pk@pk\ out}}{V_{pk@pk\ in}} = \frac{5.05V}{903mV} = 5.59$$

### 3. Push-Pull Class AB Amplifier (Output Stage)

Push pull output stage using Class AB power amplifier is the better output stage with low distortion and high efficiency. The result showed the wave is same with just only little drop on voltage peak-to-peak around 0.04V. Designs use the simple output stage circuit to give the good output wave without effect much to the signal from gain stage.

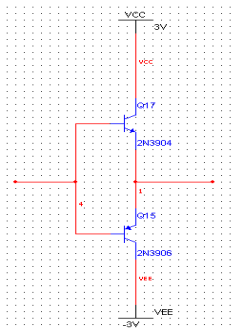


Figure 16: Push-pull output stage design

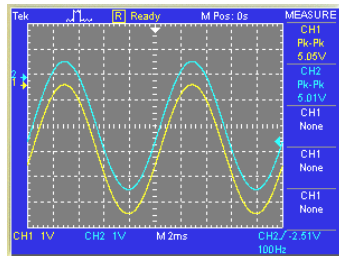


Figure 17: Output stage circuit simulation

### 4. Input and Output Op-Amp Current Amplifier

The current amplifier placed at the front (input side) and back (output side) of op-amp. At the input circuit, design used the theories of the feedback pair to gain the current. Simulations results as in Figure

18. The simulation result without much gain on voltage gave the same input output wave. From the analysis data measured using ammeter, the current gain.

$$A_i = \frac{I_{out}}{I_i} \approx \frac{I_{p@pin}}{I_i} = \frac{48.7\mu A}{602nA} = 80.897$$

Showed the circuit gain very large current.

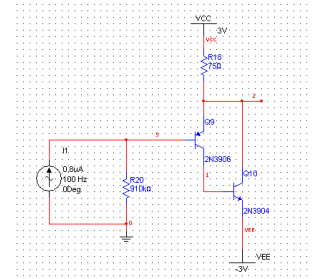


Figure 18: Feedback pair circuit design

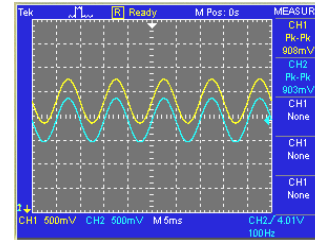


Figure 19: Feedback pair circuit simulation

Also same for the Darlington circuit, the results is not the same as in the theoretical calculations but its still get the huge current gain. The voltage gains so small same as calculations approximately 1.

$$A_i = \frac{I_{out}}{I_i} \approx \frac{I_{p@pin}}{I_i} = \frac{315\mu A}{635pA} = 496$$

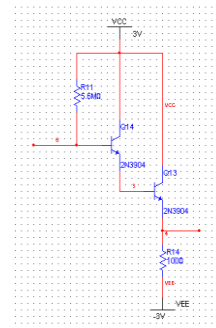


Figure 20: Darlington pair circuit design

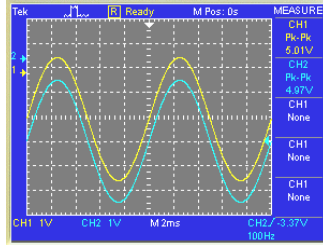


Figure 21: Darlington pair circuit simulation

## 5. Complete Operational Amplifier Circuit

Combination op-amp circuit improves by change the parameters. The several low power transistors been choose and the analysis as in Table 1.

|                                                                                                | Av (1.5V) | Av (3V) | Av (5V) |
|------------------------------------------------------------------------------------------------|-----------|---------|---------|
| - Low power general purpose transistor<br>PNP 2N3904 (2N3903)<br>NPN 2N3906 (2N3905)           | 0.66      | 3.25    | 4.68    |
| - Low power general purpose transistor<br>PNP BC178 (BC177, BC179)<br>NPN BC108 (BC107, BC109) | 0.72      | 4.45    | 5.2     |
| - Low power transistor amplifier<br>PNP BC212 (BC214)<br>NPN BC183 (BC182, BC184)              | 0.72      | 4.46    | 5.2     |
| - Small signal Transistor<br>PNP BC327 (BC328)<br>NPN BC337 (BC338)                            | 0.83      | 4.02    | 5.3     |

Table 1: Table of parameter change analysis for circuit improvements

From the table the best transistor can be use is low power transistor amplifier - [PNP BC212 (BC214) and NPN BC183 (BC182, BC184)]. Choose the low voltage 3V for this design to give low power amplifier as possible. But depend on the combinations circuit for future development either use 3V or 5V each more suitable.

Circuit has feedback for stable output signal. The transresistance feedback with the high sensitivity as showed in Figure 22. The circuit designs represent the op-amp design with standard op-amp symbol.

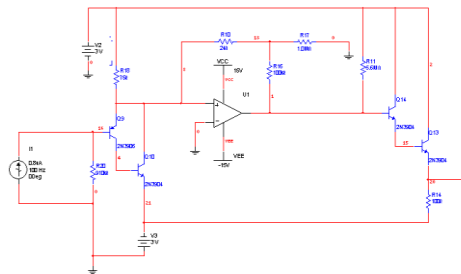


Figure 22: High sensitivity I-V converter circuit design.

Tranresistance amplifiers convert the current to voltage. The main purposes in the design are as feedback for op-amp and also as the circuit with high sensitivity factor. The circuit sensitivity can be measure from the simulation result.

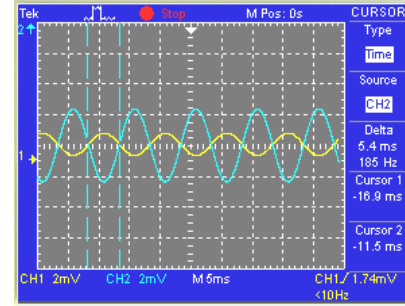


Figure 23: Output stage circuit simulation

Using cursor to measure the time taken between the input wave and output wave as in Figure 23. The delay between input output signal is 5.4ms. The sub second resolutions showed the sensitivity of the circuit.

From the transfer functions analysis, the results showed in Figure 24. The input impedance of the op-amp is 52.50Ω and the output impedance is 3.77Ω. The high input impedance and low output impedance are the main characteristic for high sensitivity op-amp. The one of the specifications of this project is the better sensitivity op-amp.

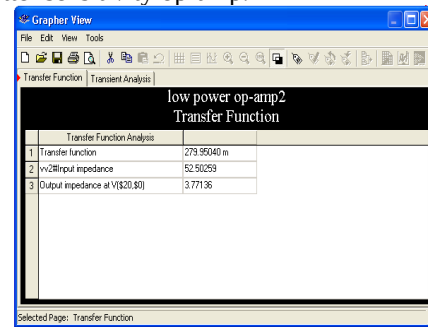


Figure 24: Output stage circuit simulation

Then the combination overall circuit to form low power amplifier and then analysis the input output wave and their capabilities to drive voltage to frequencies converter. The specifications use the low power op-amp as design requirement. The measured using wattmeter showed in Figure 25. The measured value for circuit low power is 0.5 Watt.

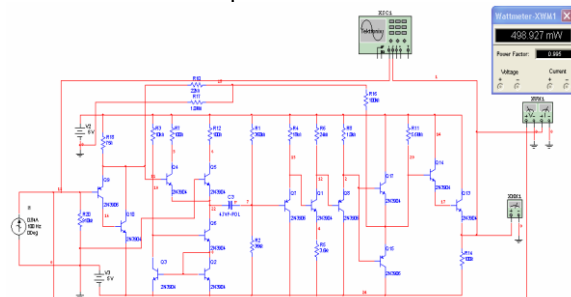


Figure 25: Low power operational amplifier design.



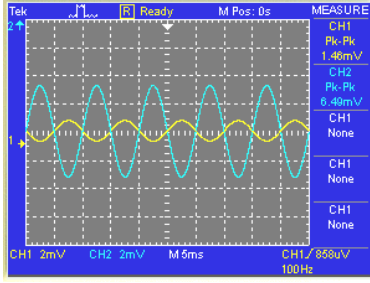


Figure 26: Low power op-amp simulation.

The wave showed the amplifying output wave (blue) with the voltage gain  $A_v \approx 4.44$ . To sure the circuit can drive voltage-to-frequencies converter. Then combine the both circuit together as showed in Figure 28.

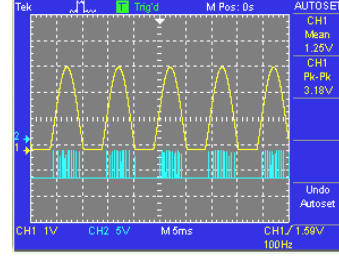


Figure 27: Simulation combination op-amp and voltage to frequency circuit.

The circuit capable to drive other circuit but it still problem and the wave not fully stable not may cause by the coupling between both circuits.

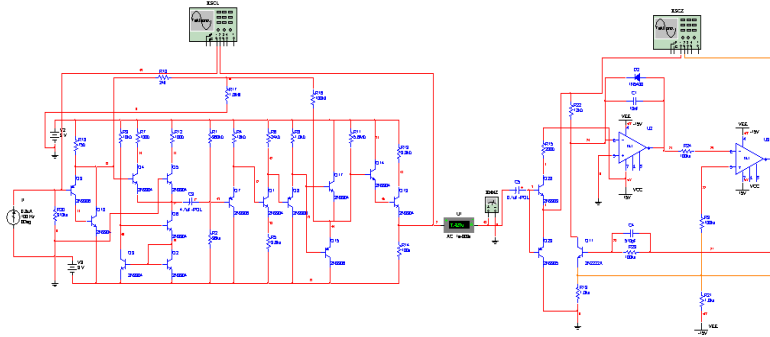


Figure 28: Combination op-amp circuit and voltage to frequency circuit.

## VI. CONCLUSIONS

In conclusion, the objectives of this project are achieved. The objectives are to design the good low power operational amplifier for voltammetry system. The design specifications of the low power op-amp are the input is very small approximately in nanoampere. For design purpose used the current input in range 800nA to -800nA. Then convert the current signal to voltage as op-amp output that can drive voltage-to-frequency circuit.

Overall the simulations results of the op-amp circuit with low input current and the low supply voltage can produces stable sinusoidal wave without distortions. The good signal output can drive the voltage-to-frequency converter circuit. The important for this low power op-amp design is the capable of to receive input current and produce better output voltage for voltage-to-frequency circuit. The task design operational amplifier gives lot of improvement on understanding in the electronic circuit devices and circuit theories. The project is the own design operational amplifier that can be improve for the future development.

## VII. FUTURE DEVELOPMENT

For the future development, all of design part should be combines together and can be interconnect each other base on the specifications. Then, the design need to fabricate into the small microchip that can plant in the brain. The future development involve the semiconductor fabrications tasks, from electronic circuits design convert to layout design and finally fabricate into chip.

## REFERENCES

- [1] Kagoshi, M., Nakazato, T., Yoshimi, K., Moizumi, S., Hattori, N., Kitazama, S., October 2007 "Wireless voltammetry recording in unenesthetised behaving rats", Science Direct.
- [2] Crespi, F., Dalessandro, D., Annavazza-Lodi, V., Heidbreder, C., Norgia, M., 2004. "In vivo voltammetry: from wire to wireless measurement", J. Neurosci. Method 140 (1-2), 153-161.
- [3] De Simon, M.G., De Luigi, A., Cools, A., 2006, "Miniaturized optoelectronic system for telemetry of in vivo voltammetry signals", J. Neurosci, Method 33 (2/3), 233-240.
- [4] Kissinger, P.T., Hart, J.B., Adams, R.N., 1973, "Voltammetry in brain tissue - a new



- neurophysiological measurement", *Brain Res.* 55 (1), 209-213.
- [5] Nakazato, T, Akiyama, A., 2002, "Behavior activity and stereotype in rats induced by L-DOPA metabolites: a possible role in the adverse effects of chronic L-DOPA treatment of Parkinson's disease", *Brain Res.* 930 (1-2), 134-142.
  - [6] Boylestad, R.S., Nashelsky, L., 2006, "Electronic Devices and Circuit Theory", New Jersey: Pearson Prentise Hall, Ninth Edition, p: 521, 567.
  - [7] Franco, S., 2002, "Design with Operational Amplifier and Analog Integrated Circuit", New York: McGraw-Hill, Third Edition, p:584-660.
  - [8] Paul, E.M. Philip, Donita, L. Robinson, Garret, D. Stuber, Reginna, M. Carelli, R. Mark Wighman, 2003, "Real-Time Measurement of Physic Change in Extracellular Dopamine Concentration in Freely Moving Rats by Fast-Scan Cyclic Voltammetry", Philip et al.
  - [9] G. Mulliken, M. Naware, A. Bandyopadhyay, G. Cauwenberghs, N. Thokar, "Distributed Neurochemical Sensing: In Vitro Experiment" , IEEE international Symposium on Circuits and Systems, ISCAS 2002.
  - [10] Jerald G. Greame, Grewe. Tobey, 1971, "Operational Amplifier: Design and Applications", New York, Mc Graw Hill.
  - [11] Jerald G. Greame, 1971, "Applications of Operational Amplifier: Third generation techniques", New York, Mc Graw Hill.
  - [12] Robert G. Irvine, 1994 "Operational Amplifier Cherecteristics and Applications", Englewood Cliff, Practice Hall, p: 20-46.
  - [13] David A. Bell, 1990, "Operational Amplifier, Applications, Troubleshooting and Design", p:1-17.
  - [14] George B. Rutkowski, 1992, "Operational Amplifier and Hybrid Circuits", New York, Mc Graw Hill, p: 9-18
  - [15] Wikipedia, "Operational Amplifier", [http://en.wikipedia.org/wiki/ Operational\\_amplifier](http://en.wikipedia.org/wiki/Operational_amplifier) : accessed on 9 September 2008, 9.45 pm.