O_2 Sensor Modeling and Simulation

Currently the Formula Car uses a Bosch O_2 Sensor to measure the air to fuel ratio at the exhaust of the engine. The previous team's design of the ECU does not have any O_2 sensor circuitry on the PCB. However, one of the customer's wants for the ECU this year is that the O_2 sensor is implemented on the ECU PCB. Upon further investigation it was found that the first year's team designed the O_2 sensor circuitry and the 2^{nd} year team removed it from the board and the code. The O_2 sensor circuitry was found, rebuilt using PSpice, and simulated in order to verify its functionality. The O_2 sensor circuitry is broken up into two separate circuits and simulated separately. The two different circuits are the circuit that measures the internal resistance of the O_2 sensor which is used by the microcontroller to adjust the heater in the O_2 sensor to maintain the optimal internal resistance of 80Ω. The second circuit is used to measure the cell voltage of the O_2 sensor, which is used to measure the air to fuel ratio. The optimal cell voltage level is 0.45V. The operation of both circuits is described in each section, including the simulation analysis.

O_2 Sensor Internal Resistance

The circuit schematic shown in figure 1 is the circuit used to measure the internal resistance of the O_2 sensor. This circuit operates by using the resistor, R3, as a reference value to compare to the internal resistance. Resistor R3 is used as a voltage divider and the voltages above and below the resistor are sampled by two different op-amps. These op-amps are used as buffers in the circuit and they feed into two op-amps that have gains that are different by a factor of two in order to compare the actual internal resistance to the desired internal resistance. The next stage of the circuit is used to rectify the AC signals and convert them to DC signals and the final stage of the circuit compares the two DC values and outputs a DC voltage centered at 2.5V with variations in levels above or below the 1.5V representing resistances above or below the desired 80 ohms. Several simulations were performed at the output of the circuit (U18), the outputs of U16 and U17, and the inputs of U11 and U10 at internal resistances equal to, above, and below 80 ohms.

O_2 Sensor Cell Voltage

The circuit schematic shown in figure 2 is the circuit used to measure the cell voltage of the O_2 sensor. The first stage of this circuit just acts as a buffer for the rest of the circuit. The second stage of the circuit is a low-pass filter stage that filters out any AC content in the signal, leaving only the cell voltage of the O_2 sensor. The third stage of this circuit is a differential amplifier which compares the cell voltage to the optimal cell voltage value of 0.45V. This stage leads to two op-amps, one serving as a proportional controller and the other serving as an integral controller. The fourth stage sums the outputs of the previous stage to for a PI controller. The final stage is used to measure the current flowing through the 62 ohm resistor and the op-amp takes this value and outputs a voltage centered at 2.5V and voltages above or below 2.5V represent cell voltages less than or greater than the desired 0.45V. Several simulations were performed at the output of the circuit (U11) and the output of U14 for variations in the input cell voltage.

Time

0s

5ms

10ms

15ms

20ms

25ms

30ms

35ms

40ms

45ms

50ms

O2 Sensor Internal Resistance Circuit Simulations

Time

0s

1ms

2ms

3ms

4ms

5ms

6ms

7ms

8ms

9ms

10ms

Time

0s

1ms

2ms

3ms

4ms

5ms

6ms

7ms

8ms

9ms

10ms

Time

0s

10ms

20ms

30ms

40ms

50ms

60ms

70ms

80ms

90ms

100ms

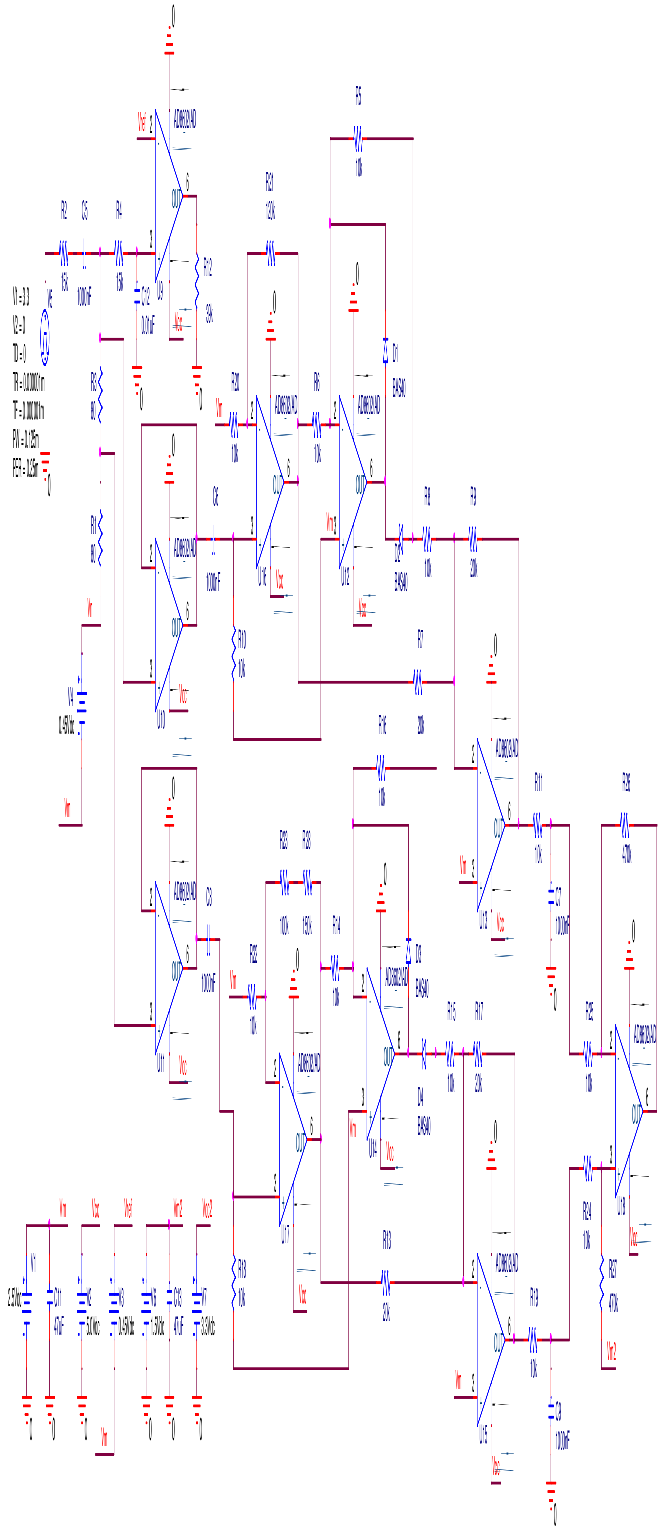

Figure 1 O2 Sensor Internal Resistance Circuit Schematic

Simulation Analysis

Figures 2-4 represent the output voltage simulation results of the O2 sensor internal resistance circuit. The simulation testing was done by varying the resistor R1 on the schematic which represents the internal resistance of the O2 sensor. The resistor values tested were 80 ohms, 110 ohms, and 50 ohms respectively. From these three simulations it shows that for the desired internal resistance of 80 ohms the output voltage is approximately 1.495V, which is the reference voltage. For resistances greater than or less than 80 ohms the output voltage of the circuit increases or decreases by the amount of error between the internal resistance and the ideal 80 ohms. This is shown in the simulations shown in figures 3 and 4.

Figure 2 Simulation of Output Voltage (U18) for Internal Resistance of 80 ohms

Figure 3 Simulation of Output Voltage (U18) for Internal Resistance of 110 ohms

Figure 4 Simulation of Output Voltage (U18) for Internal Resistance of 50 ohms

Figures 5-7 represent the output voltage simulation for the U16 and U17 op-amps used in the O2 sensor internal resistance circuit. At this stage in the circuit the voltage waveforms should equal each other if the internal resistance of the O2 sensor is equal to the desired 80 ohms. If the internal resistance is less than the desired 80 ohms then the voltage signal from U16 should be greater than the output voltage from U17. Also, if the internal resistance is greater than the desired 80 ohms then the voltage signal from U17 should be greater than the output voltage from U16. These characteristics are shown below in the simulation results.   These two op-amps are just used to act as buffers.

Figure 5 Simulation of U16 and U17 Output Voltages for Internal Resistance of 50 ohms

Figure 6 Simulation of U16 and U17 Output Voltages for Internal Resistance of 80 ohms

Figure 7 Simulation of U16 and U17 Output Voltages for Internal Resistance of 110 ohms

Figures 8-10 represent the simulation results for the input voltage to the U10 and U11 op-amps. At this point in the circuit the internal resistance is being referenced to the 80 ohm resistor. The input to the U10 op-amp should be twice the amplitude of the U11 op-amp. If the internal resistance is less than 80 ohms then the amplitude of the U10 op-amp will be less than twice the amplitude of the U11 op-amp. If the internal resistance is greater than the 80 ohms then the amplitude of the U10 op-amp will be greater than twice the amplitude of the U11 op-amp. The simulation results shown below represent the desired operation. These op-amps purpose is mainly just to sample the internal resistance voltage and buffer the rest of the circuit to maintain its impedance.

Figure 8 Simulation of U10 and U11 Output Voltages for Internal Resistance of 110 ohms

Figure 9 Simulation of U10 and U11 Output Voltages for Internal Resistance of 80 ohms

Figure 10 Simulation of U10 and U11 Output Voltages for Internal Resistance of 50 ohms

O_2 Sensor Cell Voltage Circuit Simulations

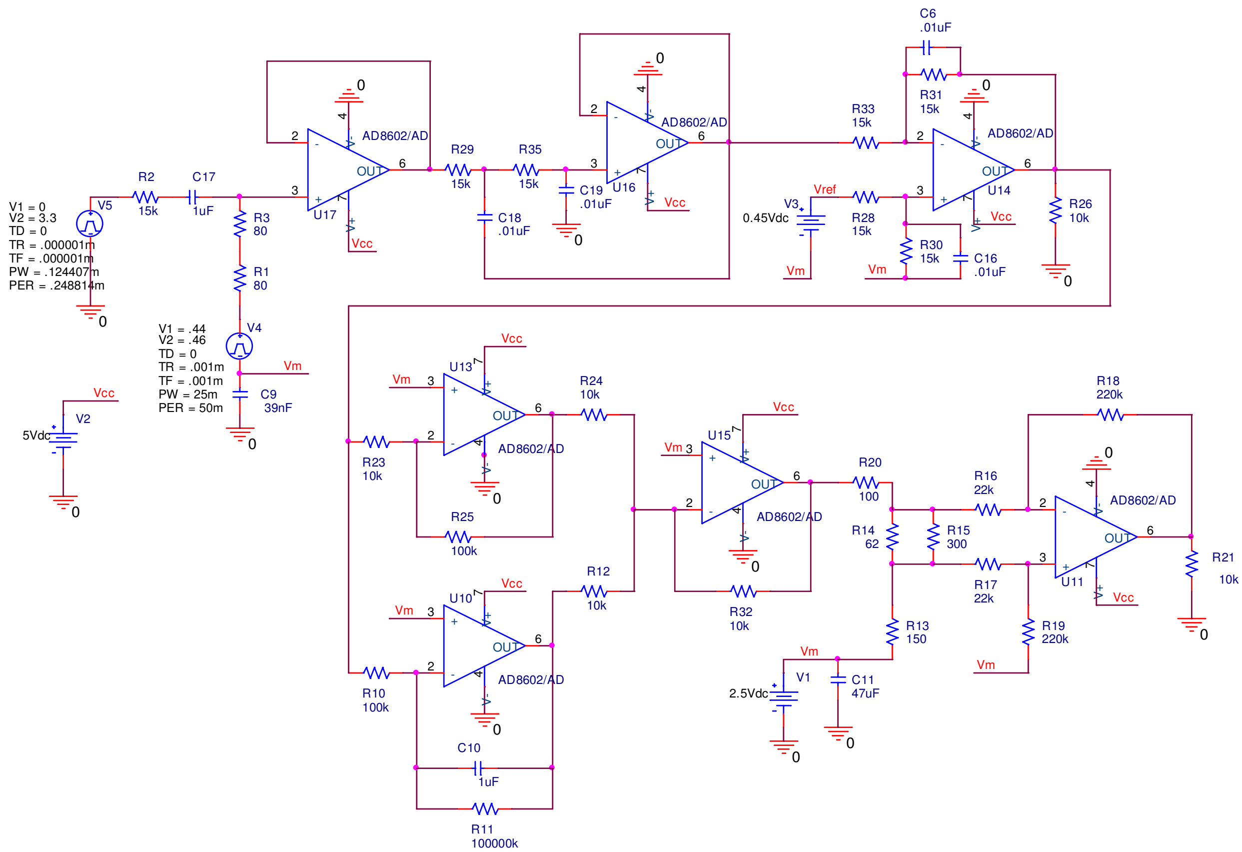

Figure 11 O2 Sensor Cell Voltage Circuit Schematic

Figures 12 and 13 represent the simulation results for the O2 sensor cell voltage circuit. This testing was done by applying a voltage pulse to the input of the circuit that represents the cell voltage of the O2 sensor. The circuit was simulated at the output of U 14 which is a low-pass filter. The ideal cell voltage is 0.45V and the pulse varies from 0.44V to 0.45V. The results of the simulation are shown in figure 12 and show that the waveform is centered about the 2.5V reference and voltages above the 2.5V represent cell voltages above the desired value and voltages below the 2.5V represent cell voltages below the desired value. Figure 13 represents the simulation of the output of the circuit at U11. This shows the output for the PI controller and the voltage waveform shows the amount that the cell voltage needs to be adjusted in order to obtain the desired 0.45V.

Figure 12 Simulation of U14 Output Voltage for an Input Cell Voltage of 0.44 to 0.46V

Figure 13 Simulation of U11 Output Voltage for an Input Cell Voltage of 0.44 to 0.46V