P09222 Engineering Analysis

MOSFET Replacement/Failure Analysis Status:

Background:

Testing was completed last year by P08221 on the ECU, including results showing that the FDS6612A does produce the desired outputs during operation, but will fail on occasion for unknown reasons. The Formula Car battery produces +12.0Vdc across the injector circuit. A high voltage (+5.0Vdc) sent to the gate of the MOSFET turns it on making the device act like an open circuit, allowing current to flow across the injector through the MOSFET to ground. A low voltage sent to the device will turn the MOFET off, disconnecting the injector from ground and restricting current flow. P08221 believed that failure of the FDS6612A could have been caused by improper testing procedures, but still recommended looking into a potential replacement part. Two minor flaws were determined with the MOSFET which are more likely to cause the failures observed during operation than improper operating procedures. First, the power dissipated across the MOSFET device can cause the part to overheat. Without a heat sink, the device could fail during operation. A normal sized heat sink has been added to the PCB under each transistor to prevent this from occurring. Second, the injector contains a very large inductance, resulting in a massive emf voltage if not handled properly. To solve this problem, a 1N4004 diode has been placed across the injector to dissipate emf voltage and the MOSFET transistor has been upgraded to the more robust FDS8884.

Simulation Data:

Injector Parameters: (Constant resistance of 12.5 ohms)

Frequency	L (Parallel)	L (Series)	Z (ohms)
1KHz	28.7 mH	14.57 mH	128.3; 45.63°
10KHz	8.1 mH	4.217 mH	367.6; 46.2°
100KHz	2.74 mH	1.654 mH	128.3; 1.337°

Table 1: RLC Meter Measurements of Injector Impedance

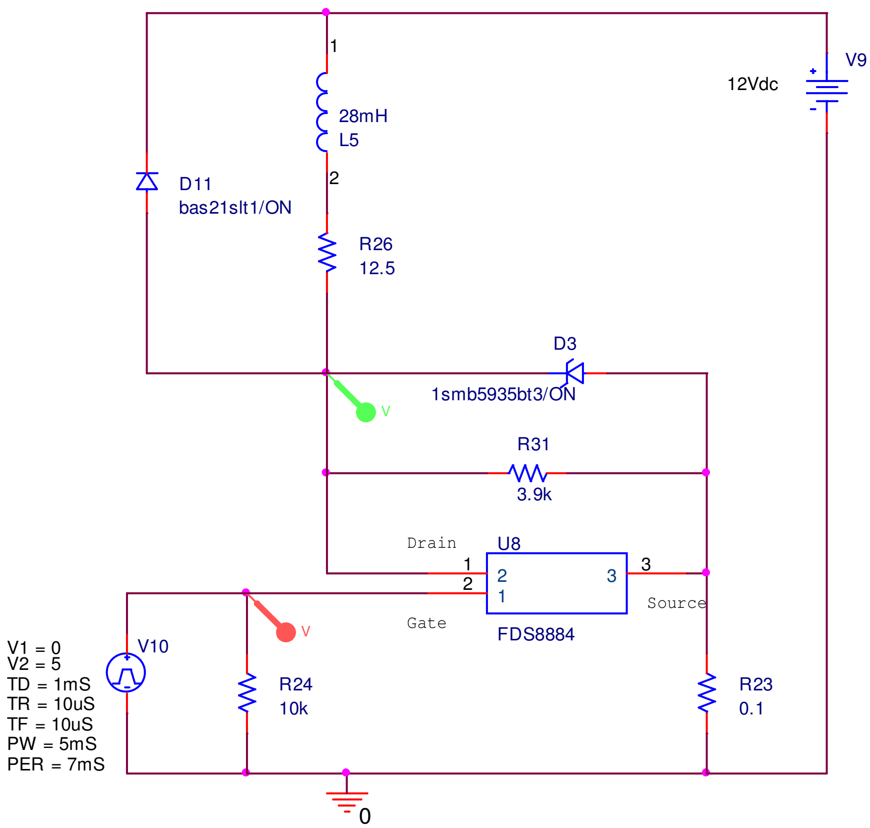


Figure 1: Injector Simulation Design with Implementation of Injector Feedback Diode

Figure 2: Injector Simulation Output Voltages with Implementation of Injector Feedback Diode

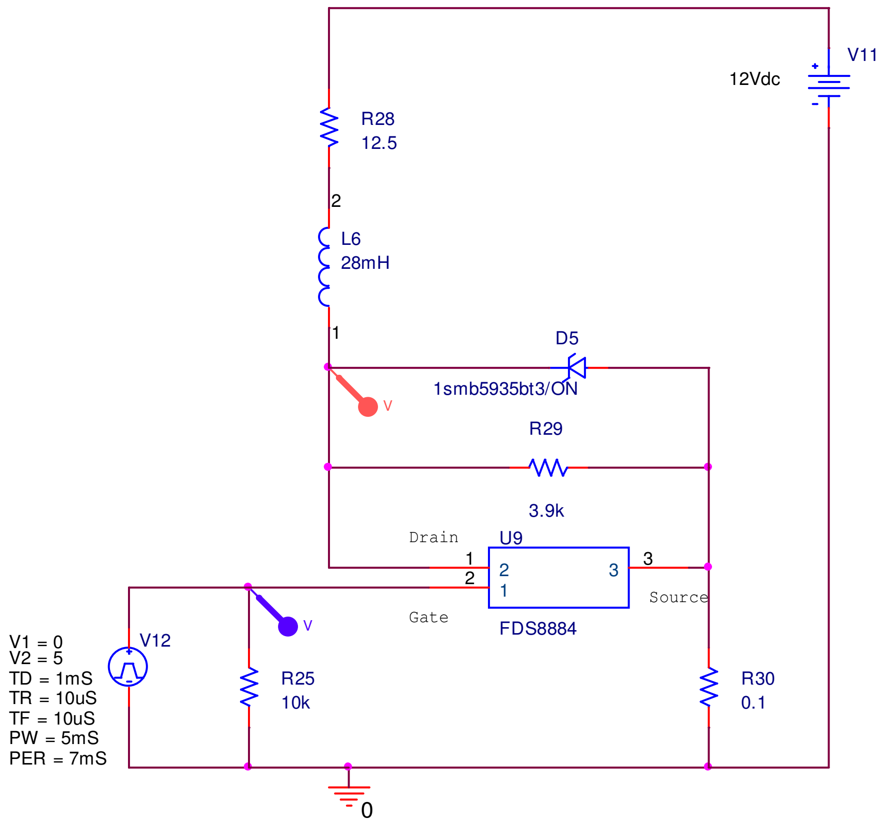


Figure 3: Injector Simulation Design without Implementation of Injector Feedback Diode

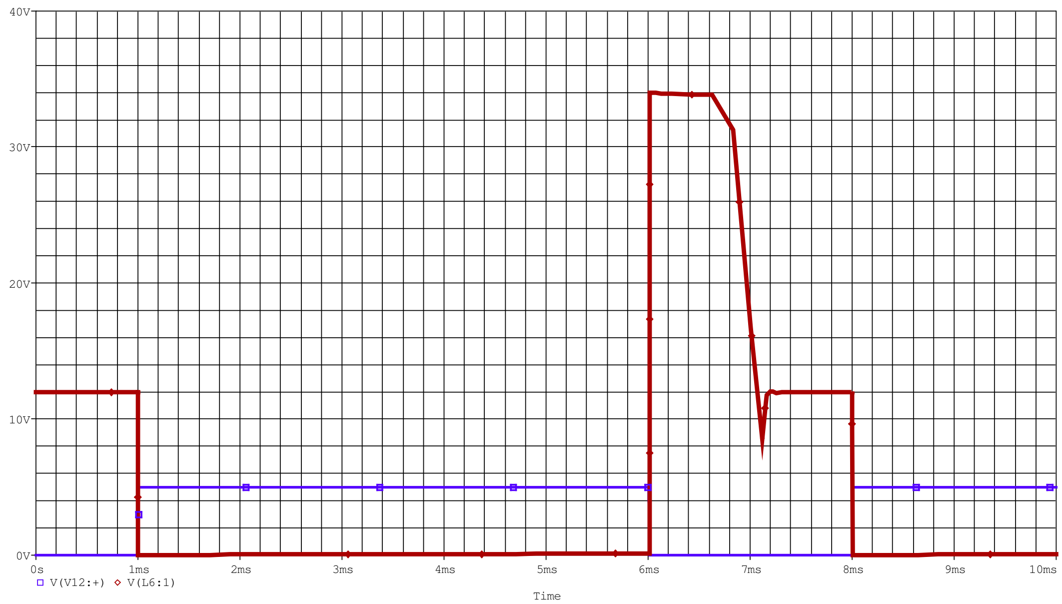


Figure 4: Injector Simulation Output Voltages without Implementation of Injector Feedback Diode

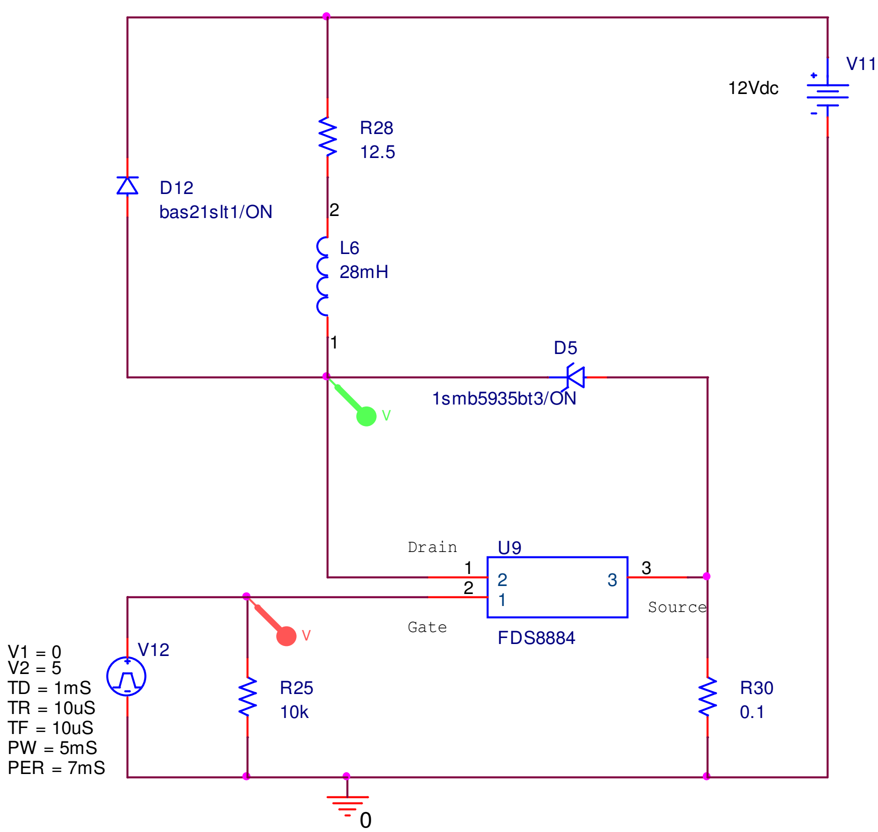


Figure 5: Injector Simulation Design with Implementation of Injector Feedback Diode but without Source-Drain Feedback Resistor

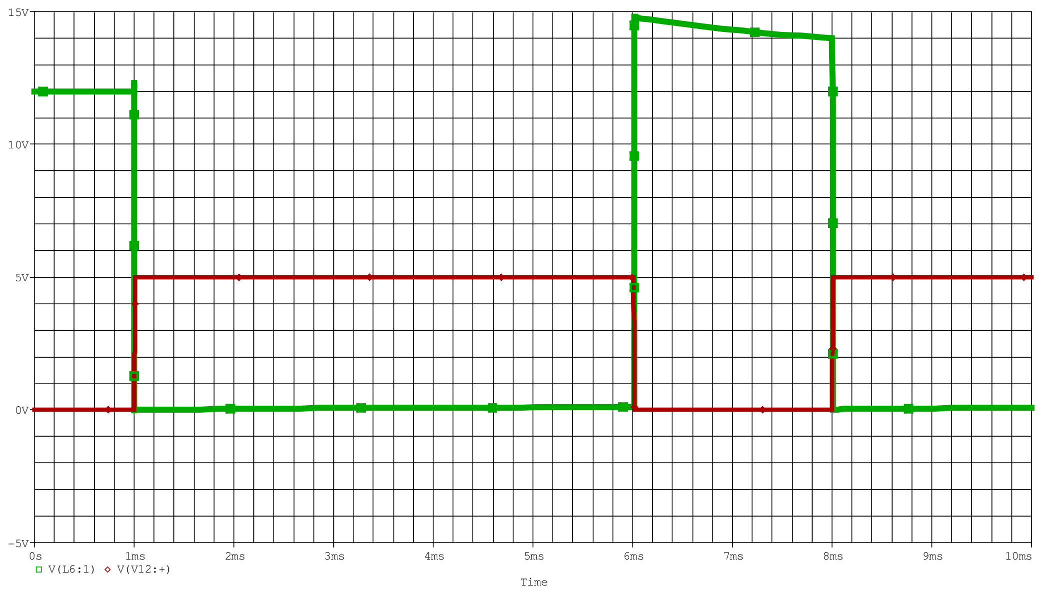


Figure 6: Injector Simulation Output Voltages with Implementation of Injector Feedback Diode but without Source-Drain Feedback Resistor

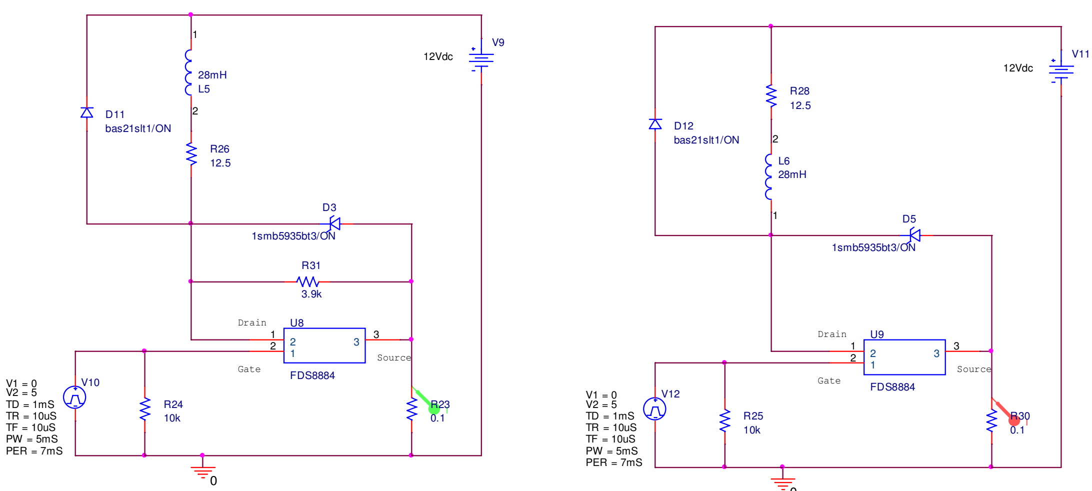


Figure 7: Comparison of Injector Simulation Designs Using Injector Feedback Diode to Observe Effect of Source-Drain Feedback Resistor

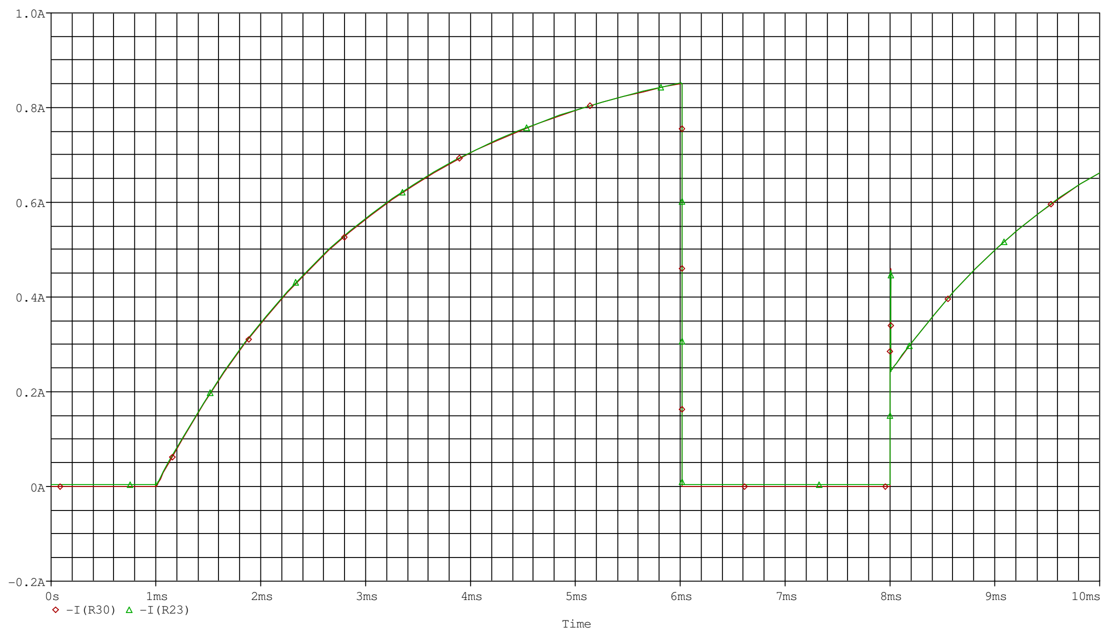


Figure 8: Comparison of Injector Simulation Output Currents with Use of Injector Feedback Diode to Observe Effect of Source-Drain Feedback Resistor

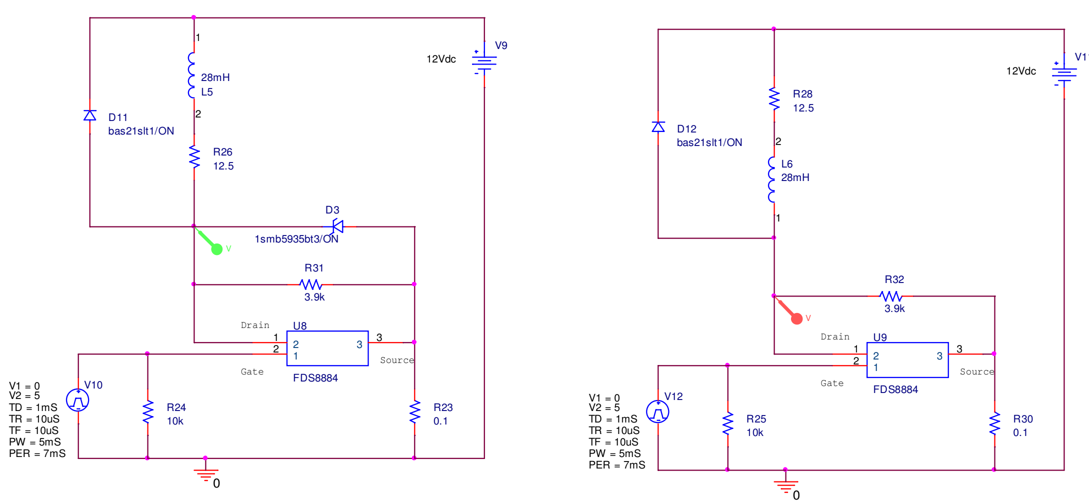


Figure 9: Comparison of Injector Simulation Designs Using Injector Feedback Diode to Observe Effect of Source-Drain Feedback Zener Diode

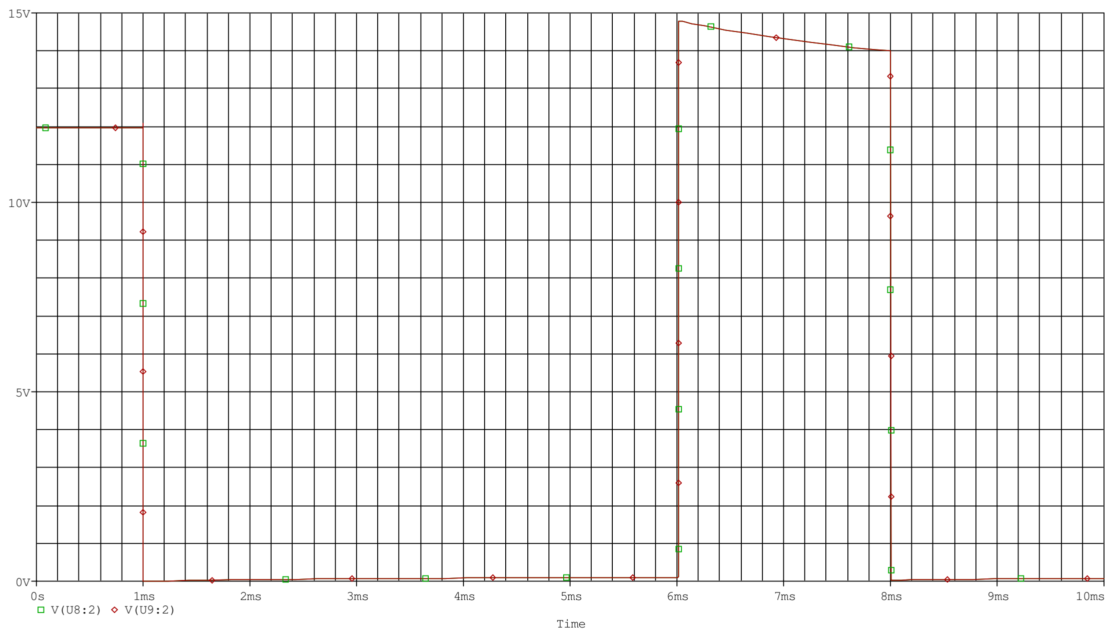


Figure 10: Comparison of Injector Simulation Output Voltages with Use of Injector Feedback Diode to Observe Effect of Source-Drain Feedback Zener Diode

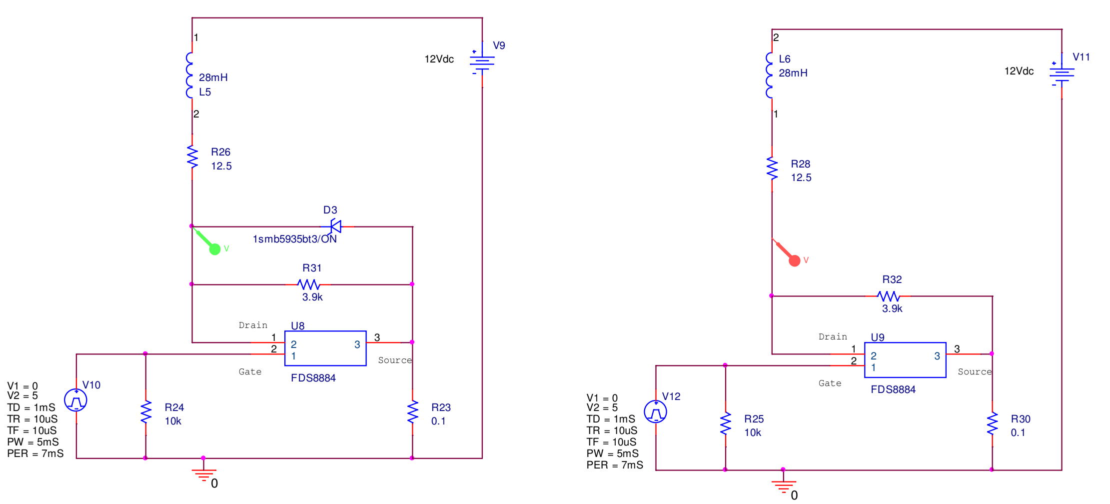


Figure 11: Comparison of Injector Simulation Designs without Injector Feedback Diode to Observe Effect of Source-Drain Feedback Zener Diode

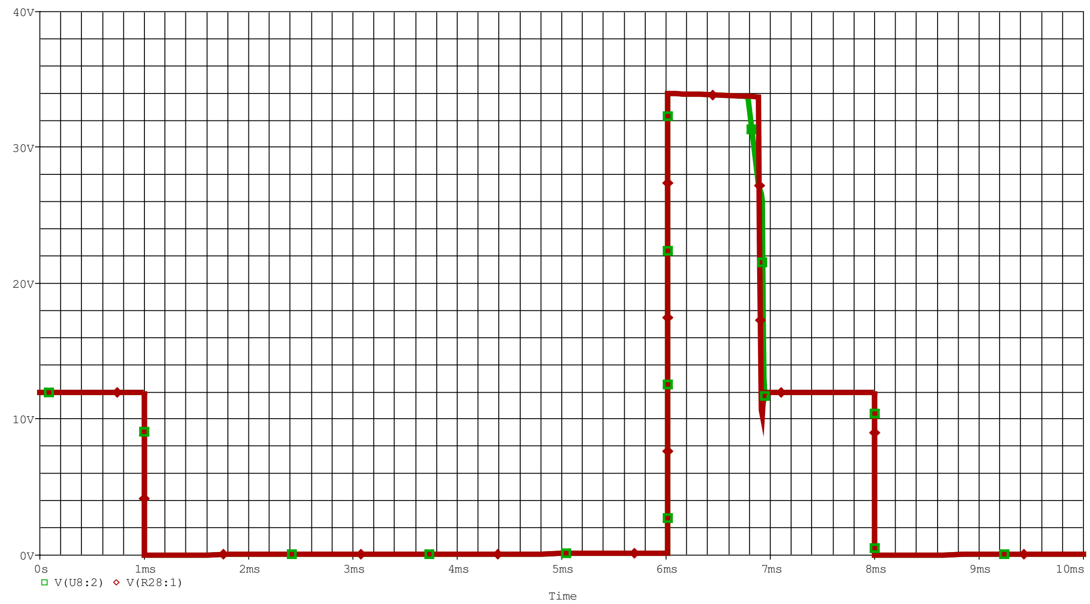


Figure 12: Comparison of Injector Simulation Output Voltages without Use of Injector Feedback Diode to Observe Effect of Source-Drain Feedback Zener Diode

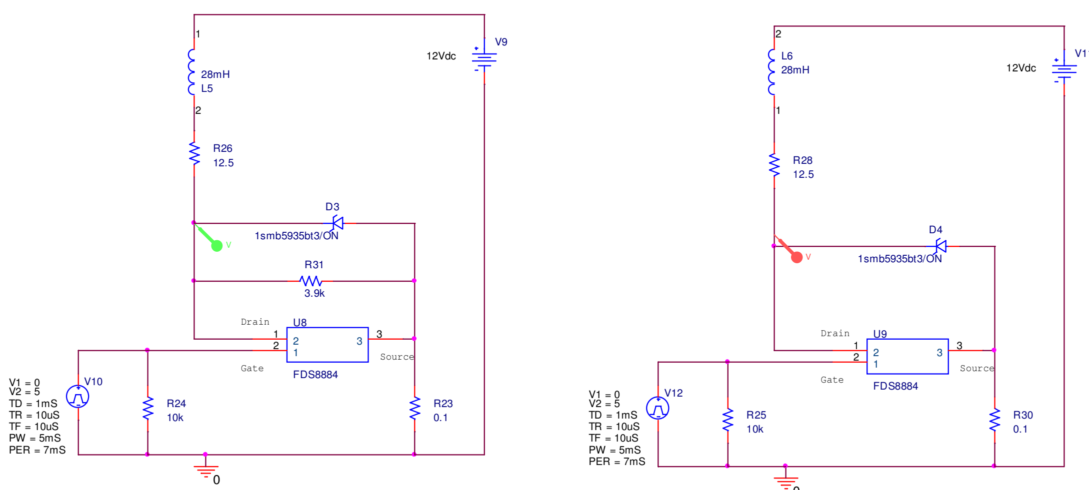


Figure 13: Comparison of Injector Simulation Designs without Injector Feedback Diode to Observe Effect of Source-Drain Feedback Resistor

Time
0s
5ms
10ms
15ms
20ms
25ms
30ms
35ms
40ms
45ms
50ms
V(U18:OUT)
0.4V
0.6V
0.8V
1.0V
1.2V
1.4V
1.6V

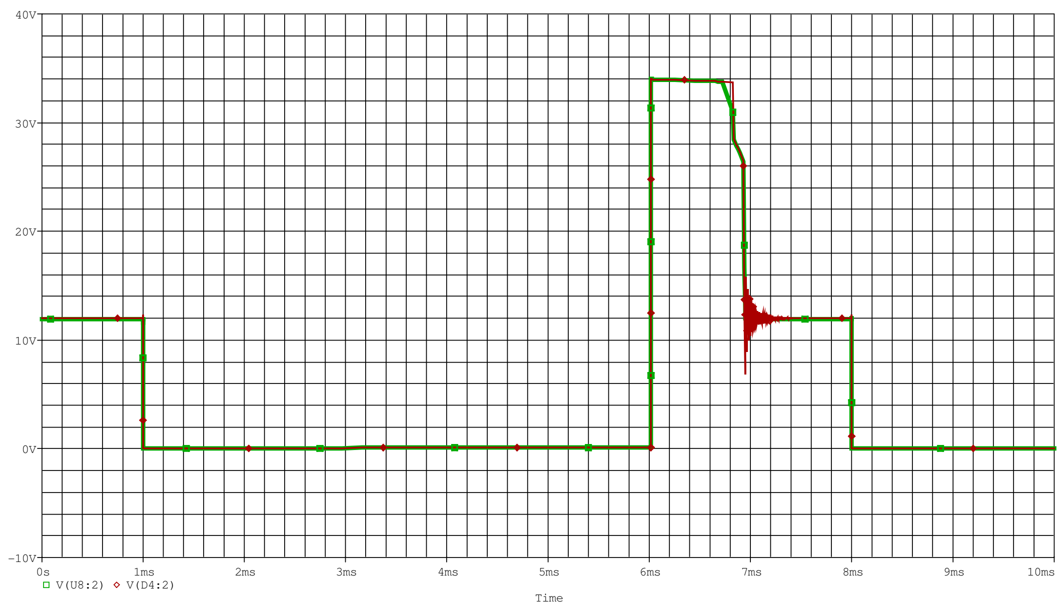


Figure 14: Comparison of Injector Simulation Voltages without Injector Feedback Diode to Observe Effect of Source-Drain Feedback Resistor

Time
0s
1ms
2ms
3ms
4ms
5ms
6ms
7ms
8ms
9ms
10ms
V(U10:+)
V(R3:1)
2.92V
2.93V
2.94V
2.95V
2.96V

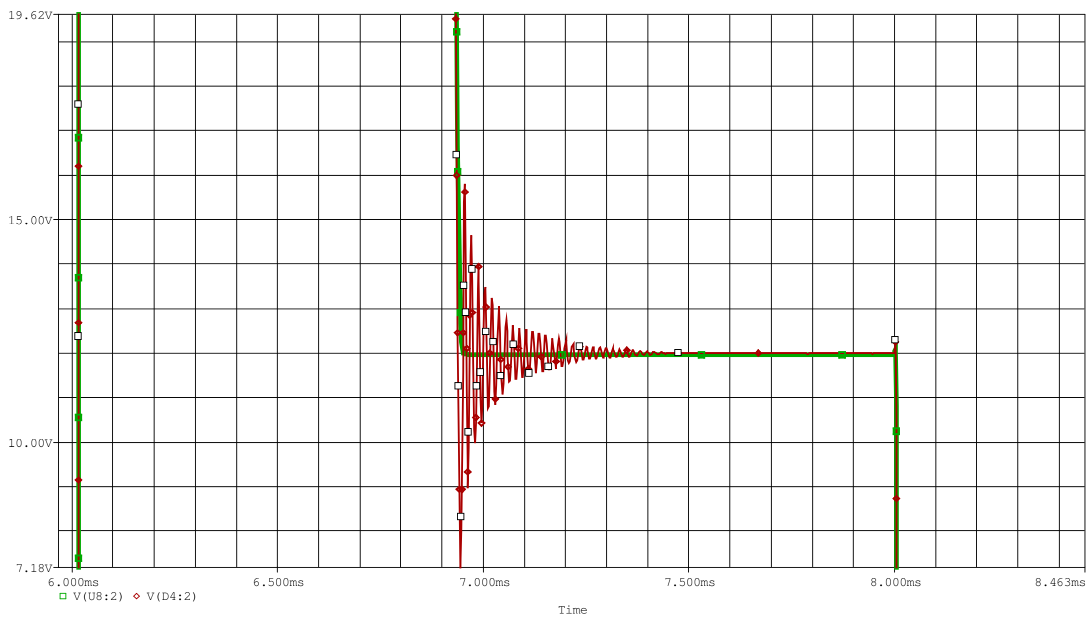


Figure 15: Comparison of Injector Simulation Voltages without Injector Feedback Diode to Observe Effect of Source-Drain Feedback Resistor (Detailed View)

Hardware Data:

Time
0s
10ms
20ms
30ms
40ms
50ms
60ms
70ms
80ms
90ms
100ms
V(U11:OUT)
180uV
182uV
184uV
186uV
188uV
190uV
192uV

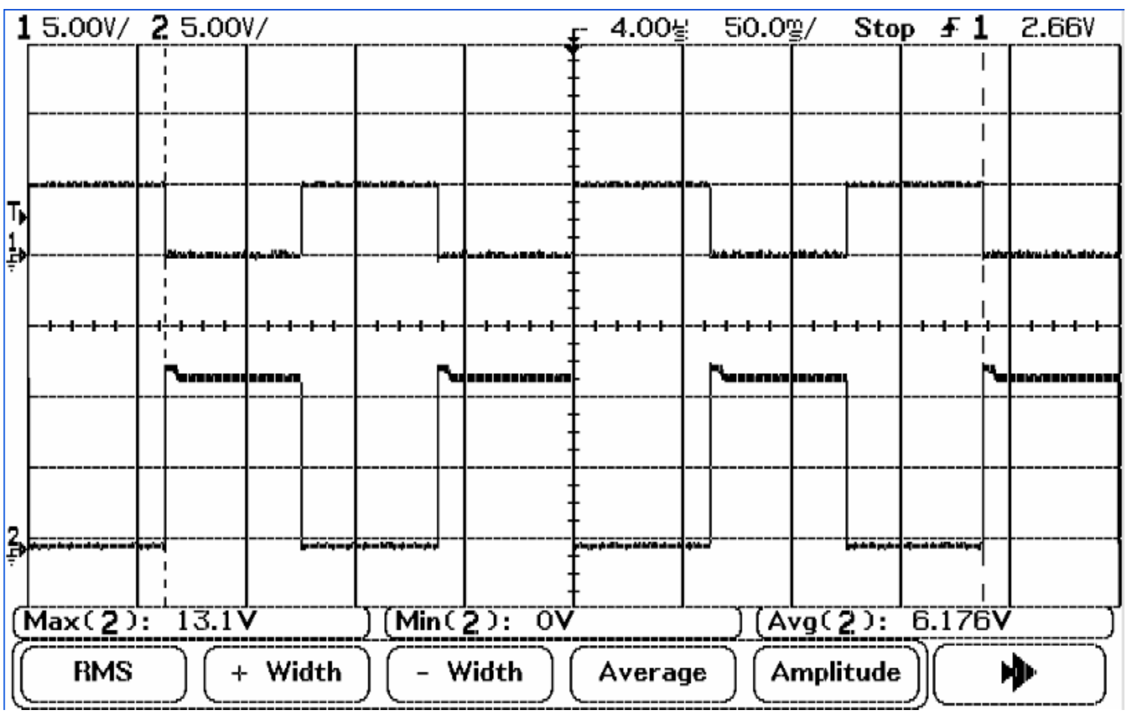


Figure 16: Injector Hardware Output/Input Voltages with Implementation of Injector Feedback Diode (Measured Voltages are Output)

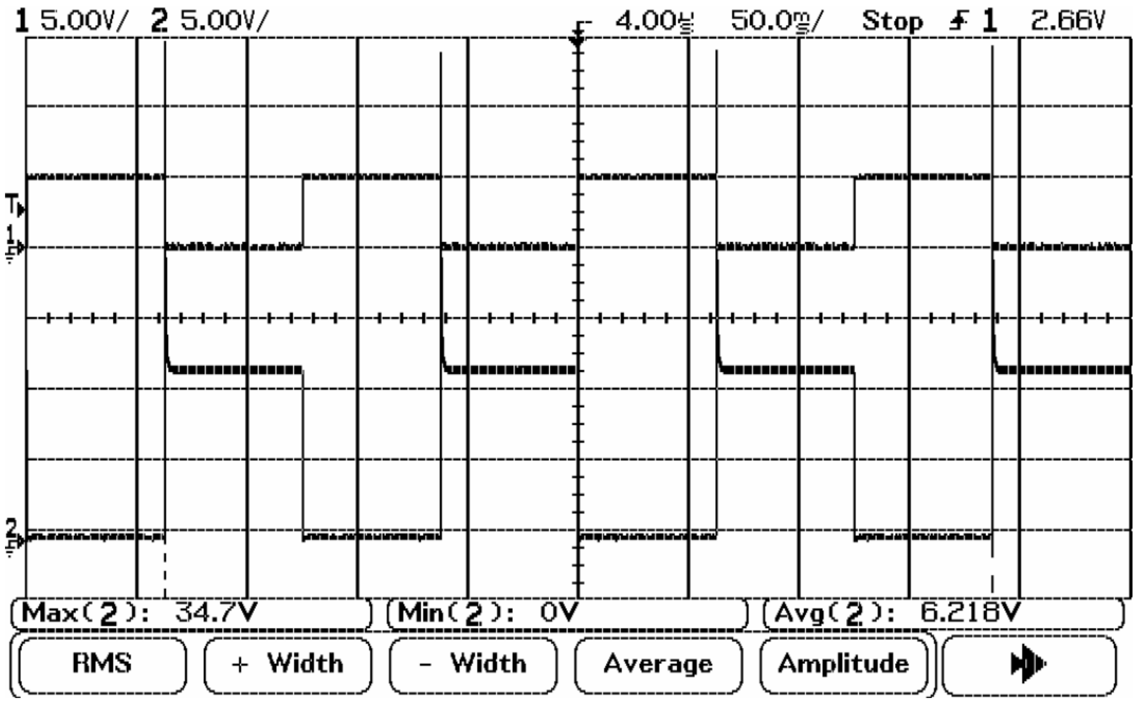
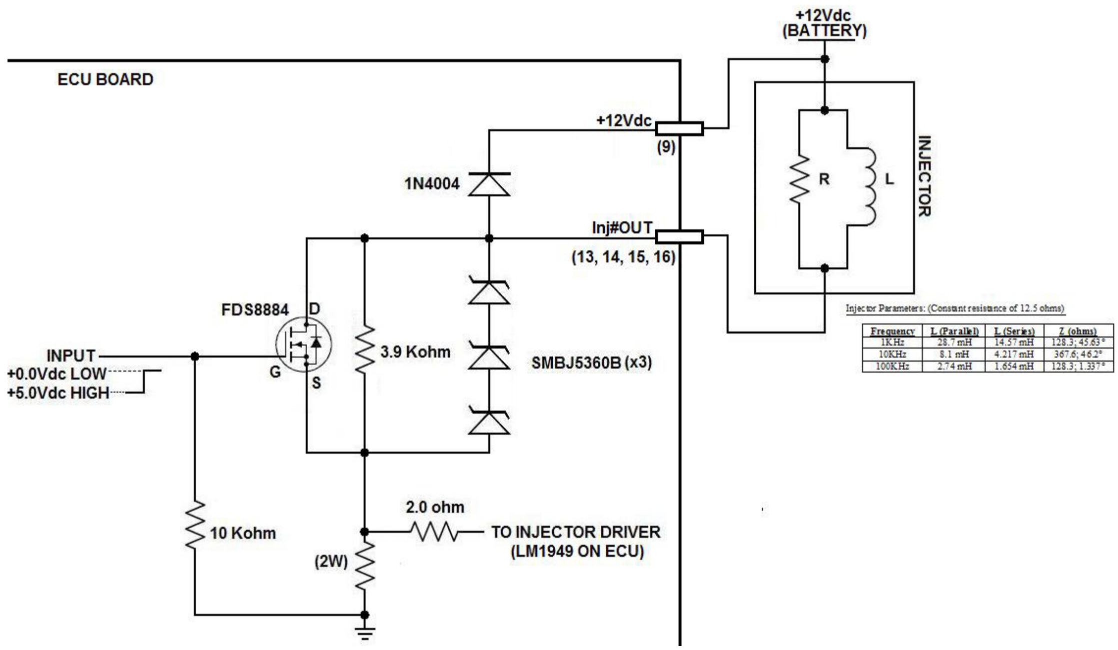


Figure 17: Injector Hardware Output/Input Voltages without Implementation of Injector Feedback Diode (Measured Voltages are Output)

Data Analysis:

Based on the Hardware and Software results, the addition of a feedback diode across the injector will allow for more reliable operation for the injector. While the FDS8884 transistor can handle higher currents than the previous FDS6612A, the +40Vdc emf voltage observed in simulation and the +34.7Vdc emf voltage pulse observed during hardware would destroy either device. The addition of the injector feedback diode may make the source-drain feedback zener diodes/resistors obsolete. The zener diodes eliminate some of the emf voltage, but not as well as the injector feedback diode. The feedback resistor cleans up some of the oscillation observed during operation, but again not as well as the injector feedback diode. However, these parts may have some additional purpose with the injector driver circuit, not included in hardware or software. Due to the relatively low cost of the parts and their potential for use in tandem with other devices on the board, the source-drain feedback system will remain unchanged.



Frequency	L (Parallel)	L (Series)	Z (ohms)
1KHz	28.7 mH	14.57 mH	128.3; 45.63°
10KHz	8.1 mH	4.217 mH	367.6; 46.2°
100KHz	2.74 mH	1.654 mH	128.3; 1.337°

Figure 18: Final Design of the Injector Control Circuit (MOSFET Device Section Only)

Op-Amp/Relay Failure:

Background:

The AD8397 op-amp used to control the fan, fuel pump, relay 1, and relay 2 (additional relay systems to be added during a future design), while assumed to be operational, was replaced multiple times by P08221 during their testing due to repeated burn-outs on the device. P08221 could not determine the exact cause of the failure and had no suggestions/recommendations for continuation as the original design had been created by the original ECU design team. Analysis of the relay control scheme indicated that not only would the AD8397 fail during operation, the design scheme would be near impossible to implement properly. The microcontroller sends +3.3Vdc to the AD8397 op-amp to turn off the relay. This voltage is increased and sent to the output of the relay. The +12Vdc input to the relay would theoretically be countered by a large enough voltage at the relay's output node (connected to the AD8397's output), reducing current flow and turning off the relay. The microcontroller would then shut down the +3.3Vdc input to turn the relay back on. Various flaws in this scheme were detected during analysis and simulation testing. A new design implementing PMOS transistors has been tested and is in the process of being finalized.

Simulation Data:

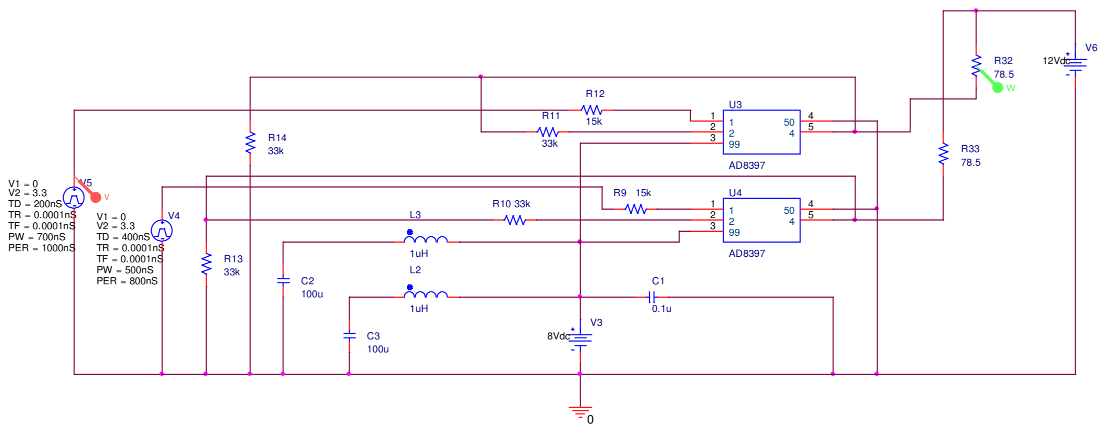


Figure 19: Simulation Circuit for Original ECU Relay Control Scheme

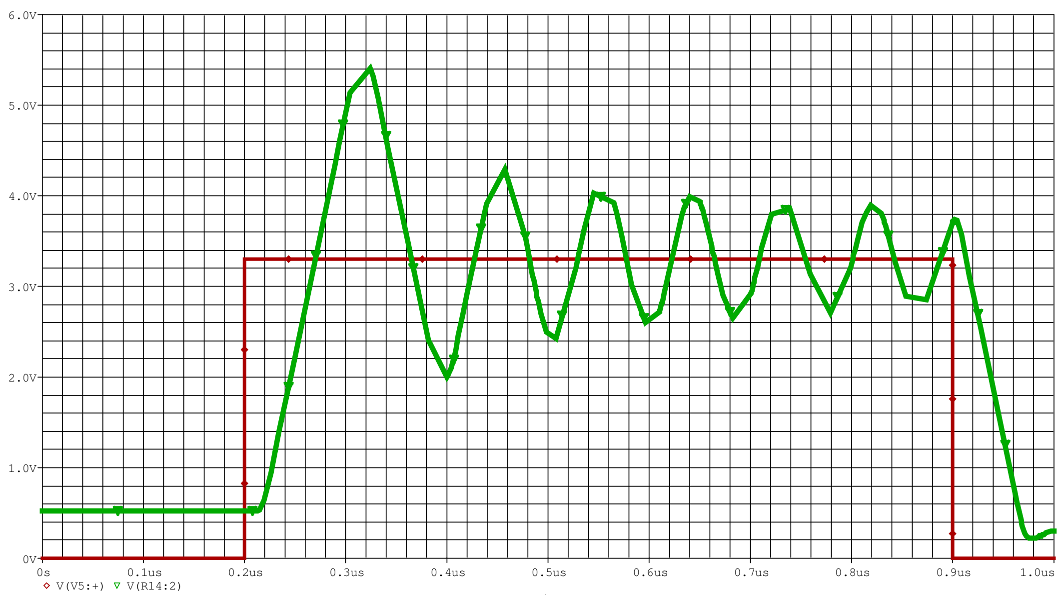


Figure 20: Simulation Voltage Outputs for Original ECU Relay Control Scheme

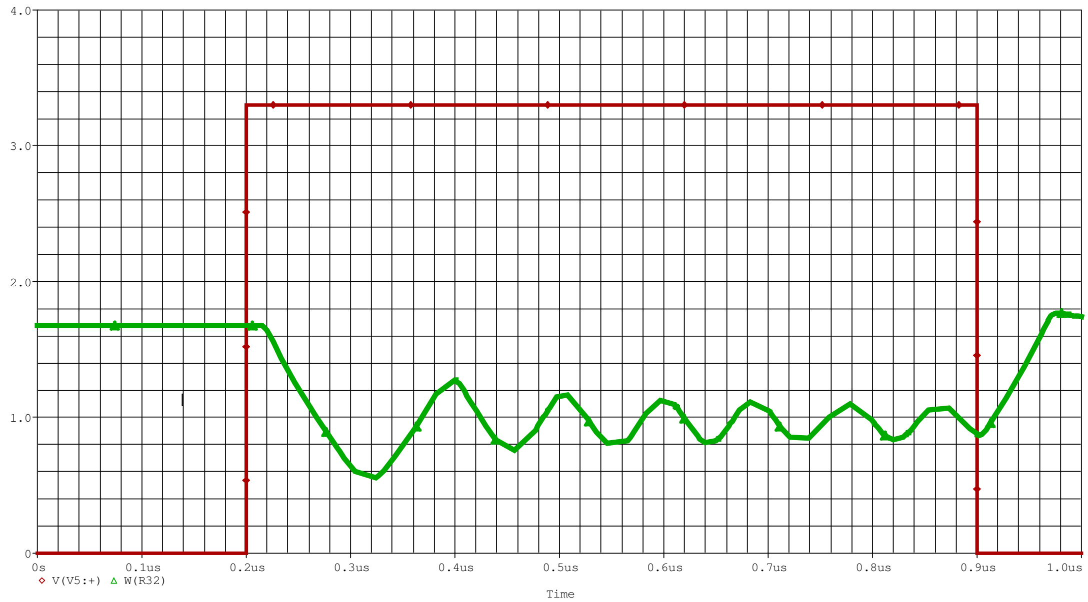


Figure 21: Simulation Power Dissipation for Original ECU Relay Control Scheme

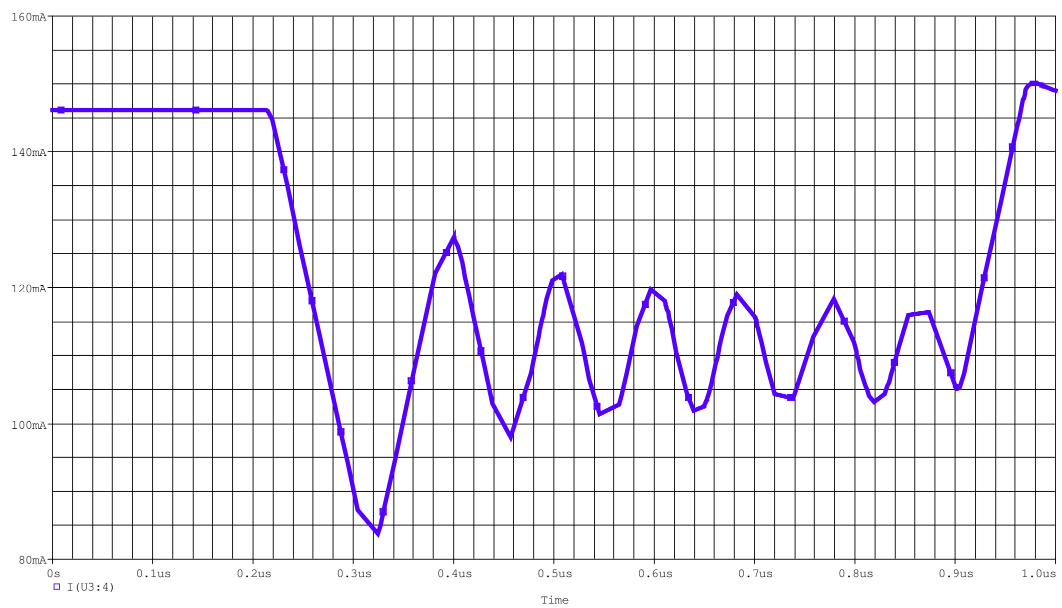


Figure 22: Simulation Output Current for Original ECU Relay Control Scheme

Hardware Testing Data:

Measured Resistance of Fan/Fuel Pump Relay: **78.5ohms**

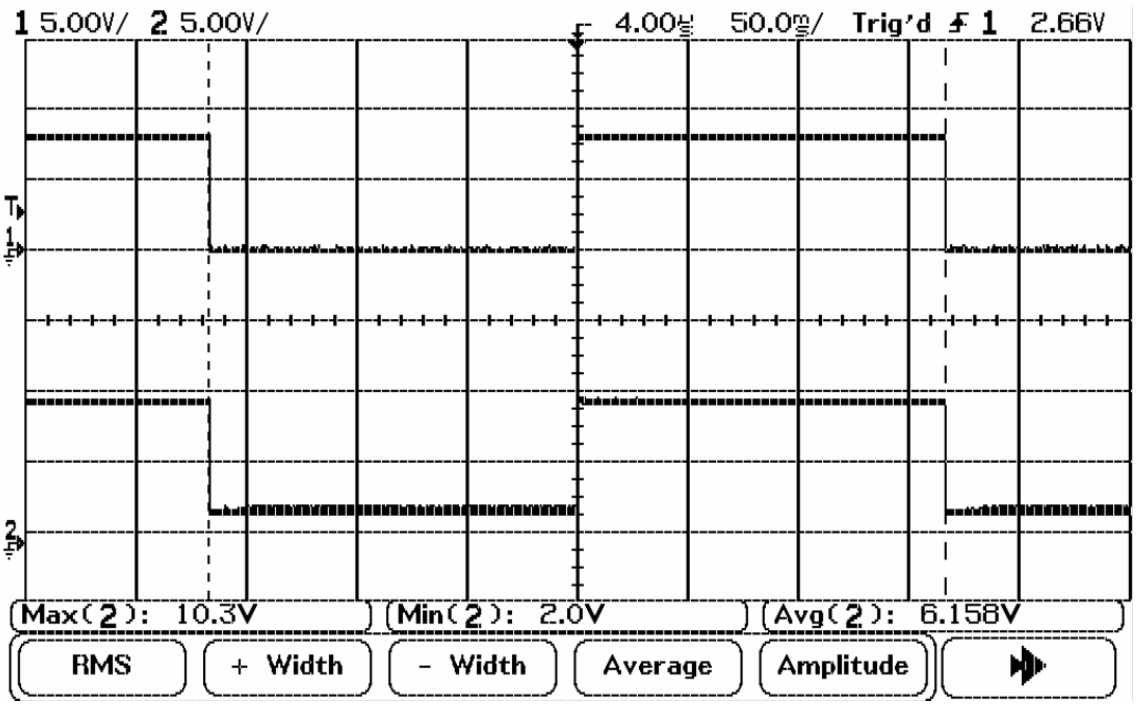


Figure 22: Hardware Output Voltages Measured During Testing of New PMOS Design (8.0Vp-p Input)

Data Analysis:

Basic theoretical and simulation analysis of the AD8397 op-amp design scheme indicated numerous flaws:

The AD8397 can only handle a maximum of 250mA total output current (125mA/Amp). The 78.5 ohm resistance of the relay is not enough to reduce the output current that low during operation and this value will only decrease during operation (the relay is represented by a constant resistance in parallel with a wire coil – resistance for the coil will decrease as more power is applied). According to simulation, each amplifier will take more than their maximum value during normal operation.

The voltage gain/output is flawed. During operation, the amplifier will have (according to simulation) near unity gain, producing far less than +12.0Vdc and preventing the relay from turning off. Even if the resistance loop is changed to allow for higher gain, the +8.0Vdc supply will prevent the critical +12.0Vdc output value from being reached.

Each amplifier is already dissipating almost 2.0W of power during operation, resulting in approximately 4.0W net power dissipation. Even if a heat sink is added to the amplifier, it cannot handle any more than 2.75W during operation. The present ECU PCB does not use a heat sink and can only deal with a net loss of 1.0W at room temperature, resulting in near instantaneous failure.

With these problems apparent and the success of the Injector Control scheme, a new design using PMOS FDS6673 devices to control the relay was implemented in hardware testing. The voltage from the microcontroller was fed into the gate of the FDS6673 instead of the AD8397 op-amp. The use of a PMOS transistor allows for the same operational code to be used as before with the same results: a "high" output turns off the relay while a "low" output turns on the relay. Hardware testing revealed that the maximum output voltage of the microcontroller (+3.3Vdc) is insufficient to activate the PMOS; at least +7.5Vdc is necessary for nominal operation. Returning the AD8397 amplifiers to the board will allow for magnification of the microcontroller signal and allow for ideal operation in conjunction with the FDS6673 PMOS transistors. A Pspice simulation of the circuit shown below in Figure 23 is in process to determine the ideal resistor values for operation.

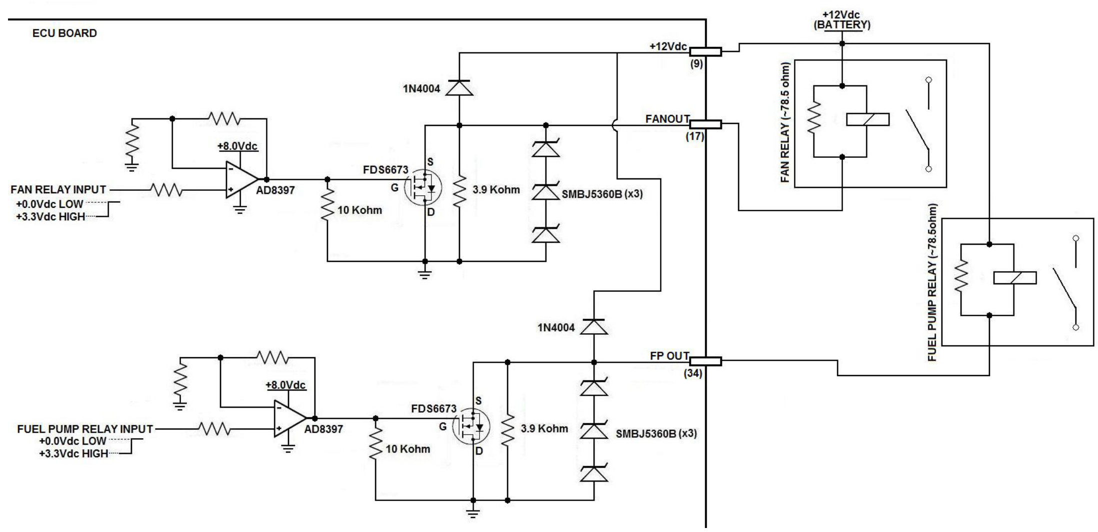


Figure 23: Circuit Schematic for New Relay Control Scheme

Replacement Voltage Regulator Status:

Background:

P08221 was unable to get the existing ECU voltage regulator start-up sequence to operate properly during testing. Failure was likely caused by timing issues, as the 1.9V supply required a single voltage regulator (12V to 1.9V) and the 3.3V supply required two different voltage regulators (12V to 5V to 3.3V). For proper startup of the microcontroller, the 3.3Vdc must reach the device first, followed by the 1.9Vdc within a limited time frame. Detailed testing has shown that the TPS70302 voltage regulator will not only be sufficient to power the microcontroller start-up sequence, but also the additional logic circuits located on the board.

Hardware Testing Data:

Device	Max Supply Current	Number of Devices on ECU
AD8604	1.3mA/Amplifier	3 devices/12 amplifiers

LM1949	54mA	4
SN74AHCT125	50mA	2
TMS470	20mA	1
Net Supply Current Required: **215.6mA**		

Table 2: +3.3Vdc Powered Logic Devices and Their Required Supply Currents

Device	**Resistance**	**Voltage**	**Current**	**Power**
Power Supply	-	5.038 Vdc	0.31 A	1.5618 W
3.3Vdc Load	9.96 Ω	3.281 Vdc	329.4 mA	1.0765 W
1.9Vdc Load	48.26 kΩ	1.907 Vdc	0.0403 mA	0.07535 mW
1.9Vdc Divider A	9.936 kΩ	0.684 Vdc	0.0688 mA	Negligible
1.9Vdc Divider B	17.80 kΩ	1.214 Vdc	0.0682 mA	Negligible
3.3Vdc Divider A	32.39 kΩ	1.213 Vdc	0.0374 mA	Negligible
3.3Vdc Divider B	55.05 kΩ	2.069 Vdc	0.0376 mA	Negligible
TPS70302	-	-	-	**0.485W**

Table 3: Test Results for Voltage Regulator Design (Large 1.9Vdc Load)

Device	**Resistance**	**Voltage**	**Current**	**Power**
Power Supply	-	5.0277 Vdc	0.41 A	2.0614 W
3.3Vdc Load	9.96 Ω	3.239 Vdc	325.2 mA	1.0533 W

1.9Vdc Load	17.497 Ω	1.882 Vdc	104.1 mA	0.2024 mW
TPS70302	-	-	-	**0.8057W**

Table 4: Test Results for Voltage Regulator Design (Small 1.9Vdc Load)

Data Analysis:

Analysis of the results from hardware testing shows only minor difficulties with the new voltage regulator design. The most difficult problem to overcome will be the high power dissipation through the device, although a heat sink pad under the regulator is being added to the PCB. Even when drawing near 100mA over the ECU's maximum expected current, the regulator performed as expected. Since the regulator is designed to handle up to 1.0A of current per voltage output, there should be no difficulties in using this design on the ECU. The SEQ pin controls the activation sequence of the two voltage outputs, starting up the +3.3Vdc, then the +1.9Vdc after the +3.3Vdc has reached 80% of its intended voltage output. Should this sequence need to be reversed for any reason, the SEQ pin can be connected to a positive voltage. Additional designs for the regulator involving constant voltage levels (the TPS70351 will output a constant 3.3Vdc and 1.8Vdc without the resistor biasing scheme) and a voltage reset switch are being taken into consideration.

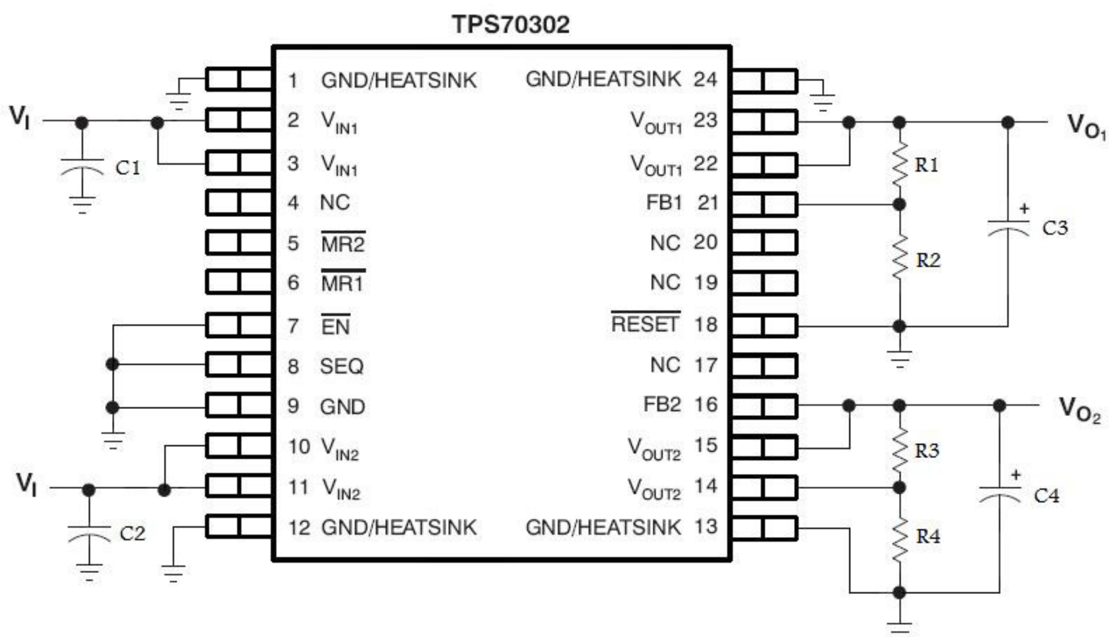


Figure 24: Circuit Schematic for New Voltage Regulator Scheme

Resistor	Resistance		Capacitor	Capacitance
R1	51.1 kΩ		C1	0.22 uF
R2	30.1 kΩ		C2	0.22 uF

R3	10 kΩ		C3	22.0 uF
R4	18 kΩ		C4	47.0 uF

Table 5: Resistor and Capacitor Values for Figure 24

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 2nd 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.

O2 Sensor Internal Resistance Circuit Simulations

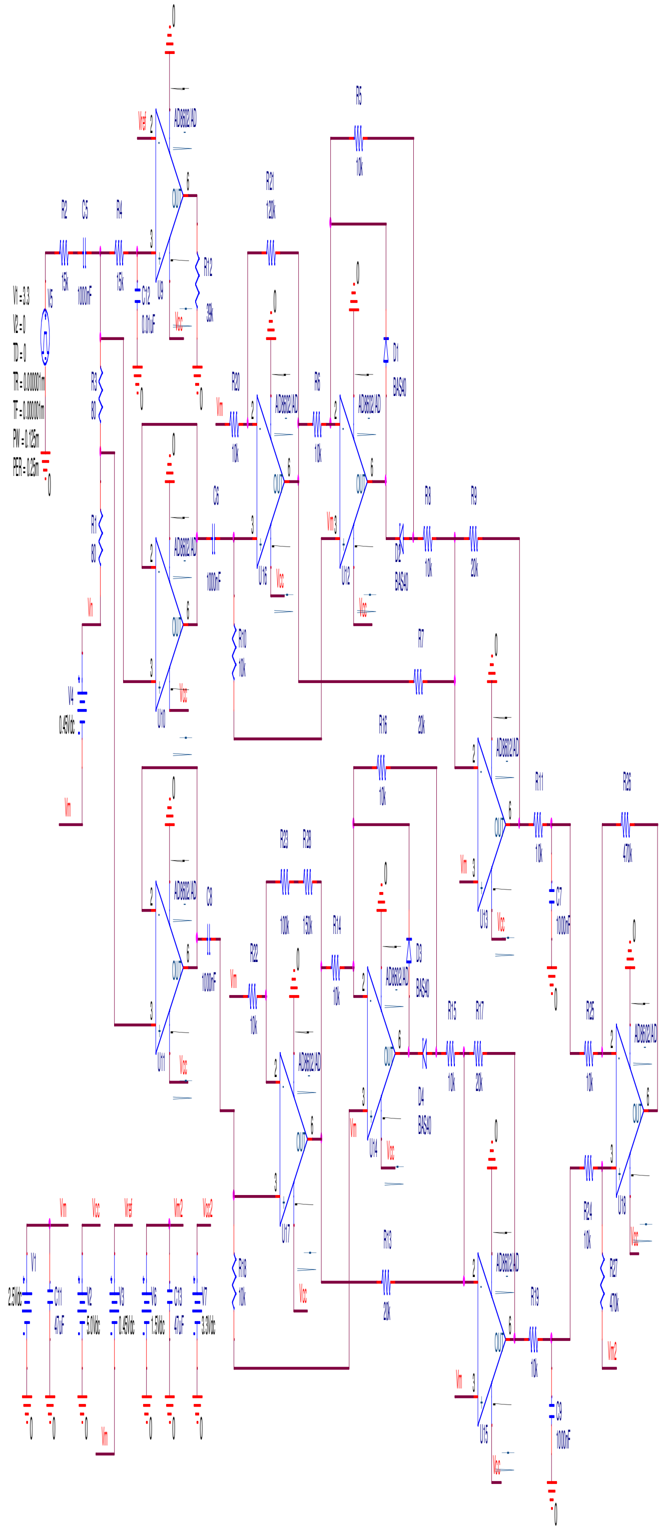


Figure 1 O2 Sensor Internal Resistance Circuit Schematic

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

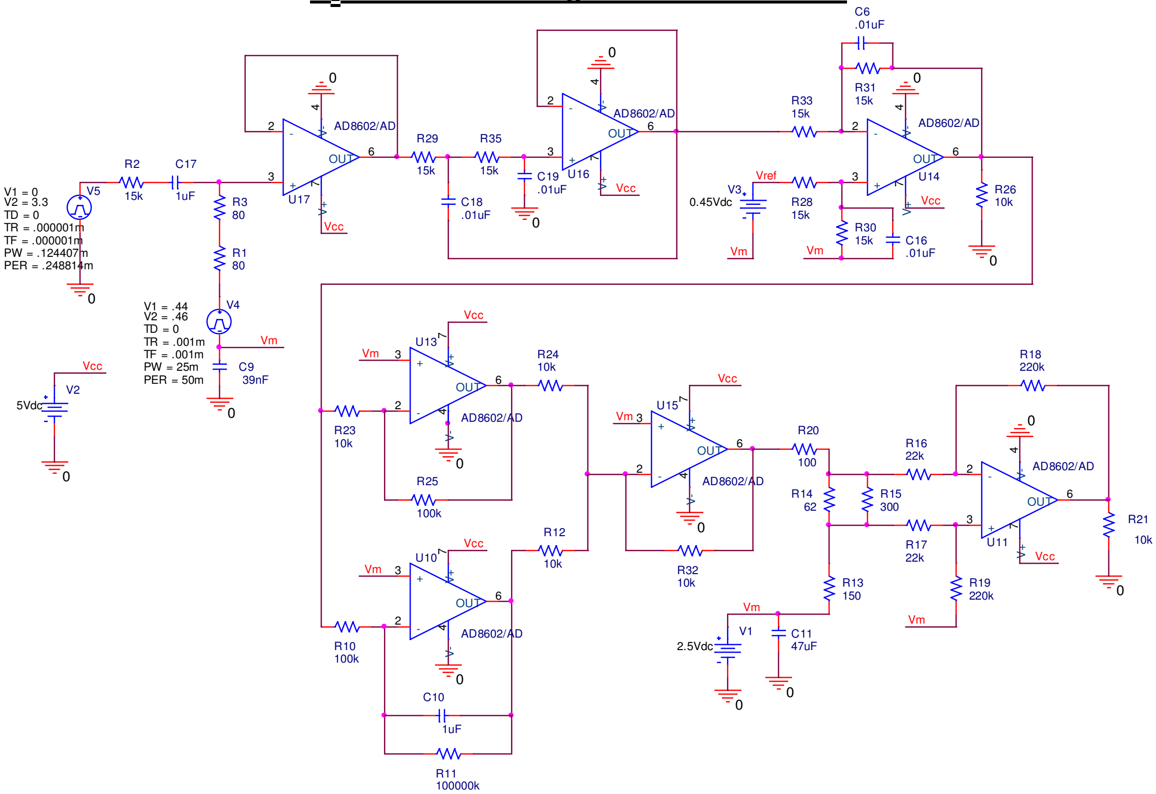


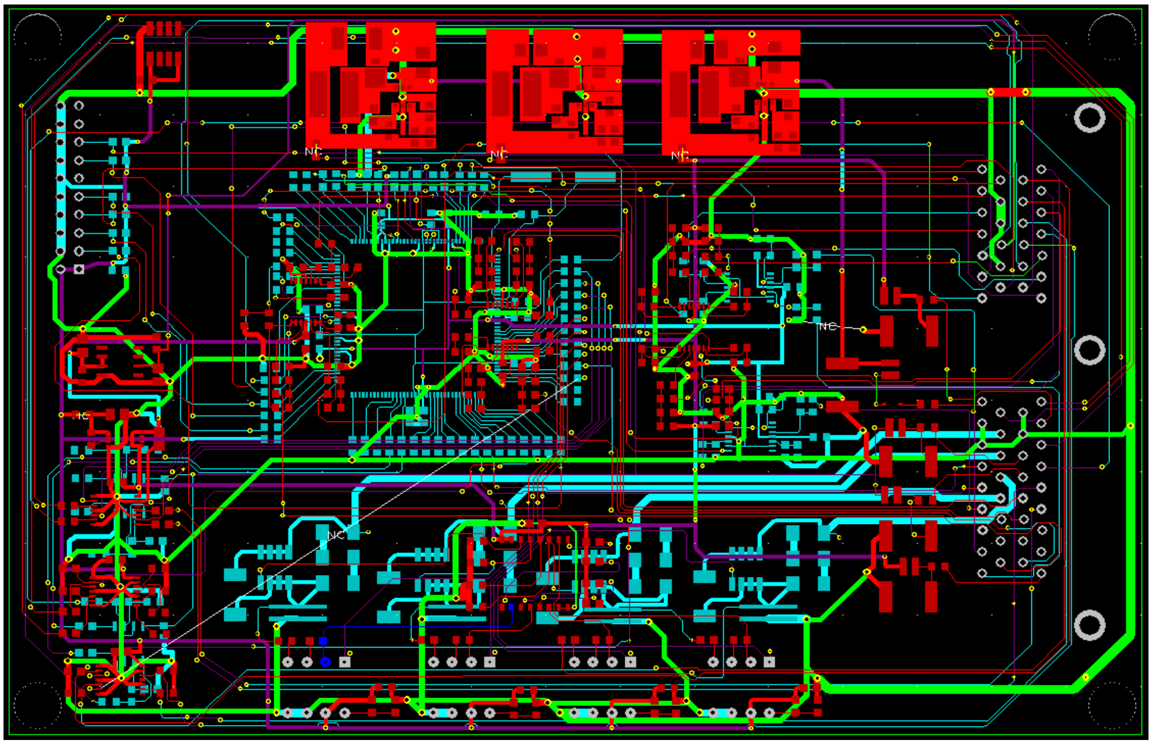
Figure 11 O2 Sensor Cell Voltage Circuit Schematic

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.

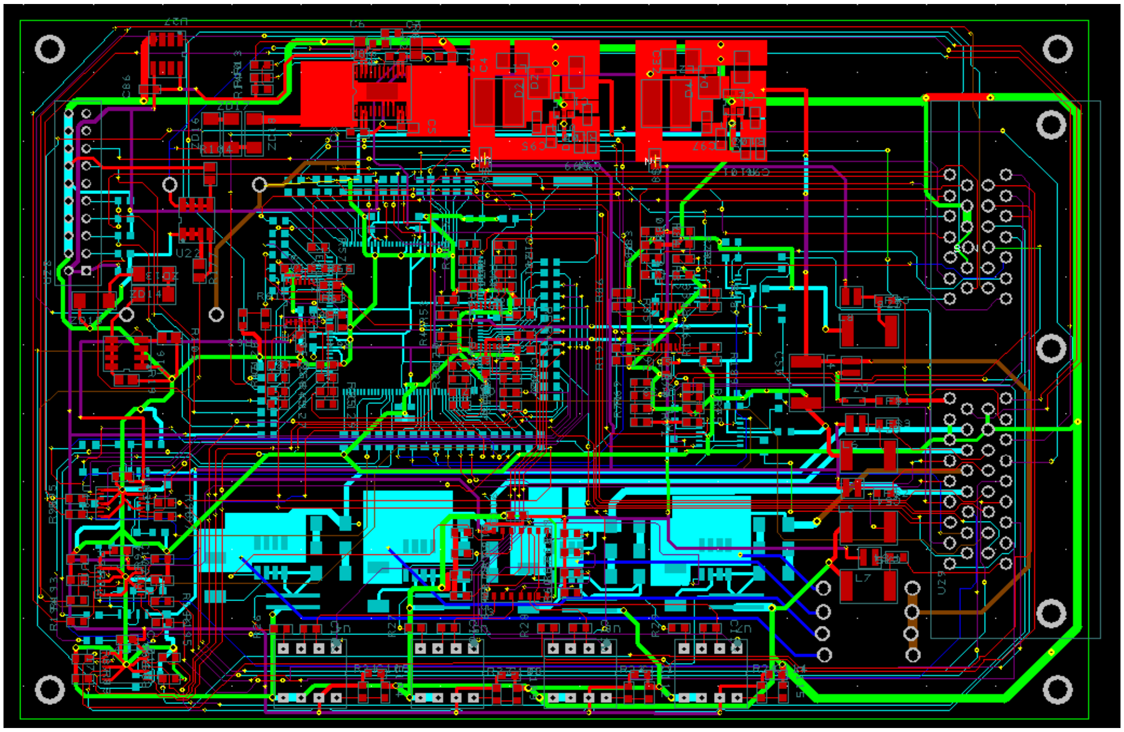
Figure 12 Simulation of U14 Output Voltage for an Input Cell Voltage of 0.44 to 0.46V

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

PCB Board - P08221



Latest Revisions - P09222



Programming Logic

The big issue with the software is the code size. With small modifications, including removing the code related to the temperature, as well as decreasing the size of the ignition timing table, the software is able to be compiled without hitting the 16kB code limit; the final code size is 14736 bytes, with 11536 bytes data memory, and 280 bytes of constants. The tables are currently being initialized in functions; to reduce the code size, the table initialization can be moved to the global declaration of the variables; this would have a sizable impact on the code memory size, but the data memory would increase by the same amount. Depending on the IAR Embedded Workbench IDE restrictions on Flash downloads, this might still pose a problem; unfortunately, due to technical issues with the dev board setup this has not been tested.

Another potential method to reduce code size, which would not have the impact on data memory, would be to replace the tables with functions to calculate the outputs. However, this would likely lead to a decrease in accuracy and precision; as the specification on accuracy and precision is to be within ½° at worst case, and ideally within ¼°, this method will only be implemented if the accuracy and precision are deemed acceptable and there is a need.