MOSFET Controlled B-Field

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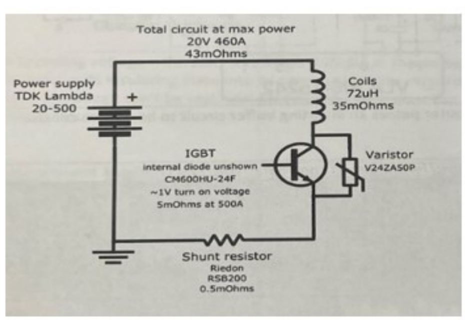
Introduction

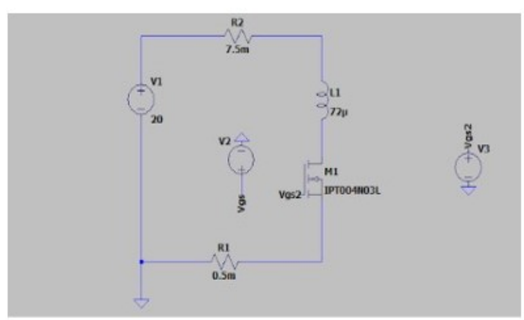
Many atomic physics research requires controlled large magnetic fields in certain parts of the experiment such as a Stern-Gerlach. In this document, we investigate the application of a circuit that could run a 500 A current through a coil that could create the desired strong magnetic field for the experiment. Field Effect Transistors (FET) are known to be adequate analog control transistors that provide a reasonable region of operation. Previously there was an Insulated-gate bipolar transistor (IGBT) controlled circuit in use. However it has an unknown driver circuit, which could cause issues down the road. Moreover, the IGBT wears rather quickly, and so we would like to develop a simpler yet more robust circuit that could be controlled. In this report I will provide an analysis of the individual components of the circuit as well as an overview or demonstration of the entire circuit.

Methodology

First, I would like to provide an overview of the circuit. In figure 1 I plot the previous IGBT circuit along with the new circuit. We see that this is a straightforward circuit that should theoretically run 500 Amperes. Both Transistors are built for this purpose.



Previous IGBT Circuit



New MOSFET Circuit

Figure 1: Transistor Circuits

The FET we are using has component number MOSFET: IXTN600N04T2. This can take up to 600 Amperes of current with a power capacity of 940 Watts. We see here that we possess the right components that could handle this very large current. A small introduction to MOSFETs:

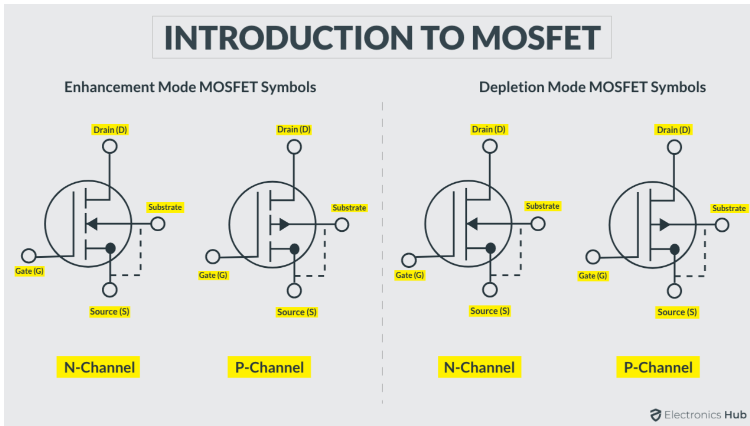


Figure 2: Types of MOSFETs

In figure 2, we see the four different kinds of MOSFETs. Enhancement means that running a voltage through the gate turns it on (short circuit), while Depletion means that running a voltage through the gate turns it off (open circuit).
For the purposes of the circuit we will use an n-type enhancement MOSFET that will be analogous to a normal NPN BJT transistor as seen in figure 3.

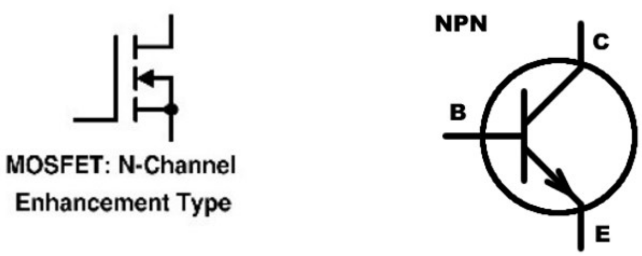


Figure 3: MOSFET analogy

In the following section I will go over the individual components of the circuit.

1 Individual Components

1.1 MOSFET: Turn on Voltage

For any transistor one of this first properties one must measure is the turn on voltage across the gate. We first place a load resistor behind the coil so as to limit the current and protect the components. We place a 10 Ω 25 W resistor so that it can handle large power values. Then we formed a DC sweep of the voltage across the gate and measured the voltage and current across the load resistor.

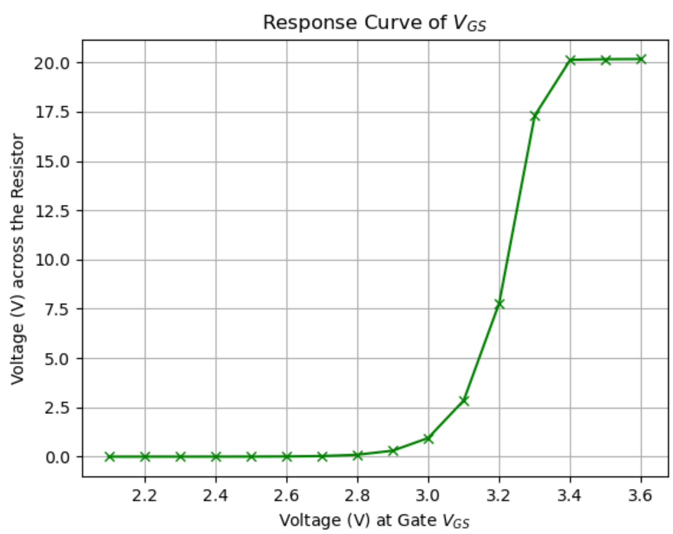


Figure 4: Load resistor voltage vs Gate voltage V_{GS}

In figures 4,5,6 we see the response of the transistor to different voltages across its gate. The turn on voltage is almost 3.0 V, which is quite high compared to the usual 0.6 V for the npn transistor. We also note that in the turn-on regime the response is perfectly exponential. The range of potentials that have this exponential behaviour is [2.2V,3.3V]. This provides us with a wide range of voltages that could be utilized in order to control the load voltage/current.

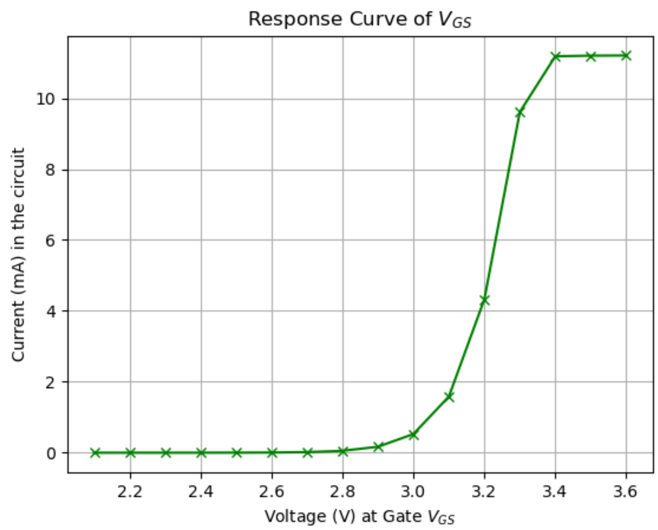


Figure 5: Load resistor current vs Gate voltage V_{GS}

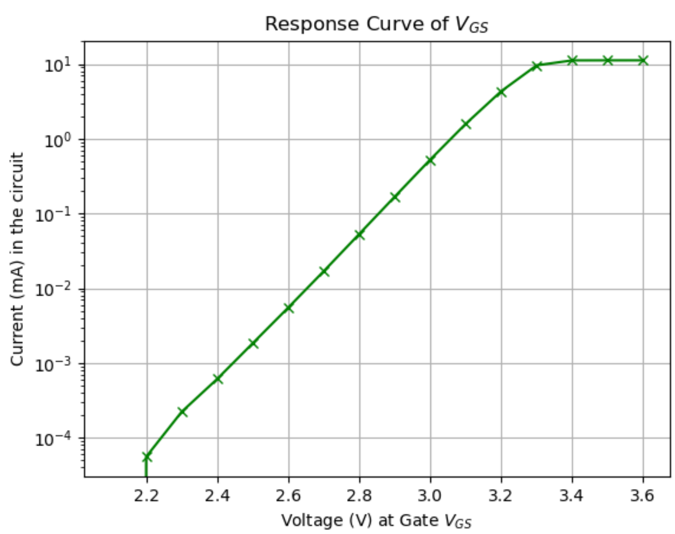


Figure 6: Load resistor Voltage vs Gate voltage V_{GS} on log scale

1.2 MOSFET: Resistance

Transistor Resistance is another crucial attribute that should be known before we can move forward with the project. For this experiment, we have swept the gate voltage and measured the voltage across the drain and the source V_{DS} along with the current reading. From there we obtained the Resistance. I plotted the Resistance vs the gate voltage, as seen in figure 7

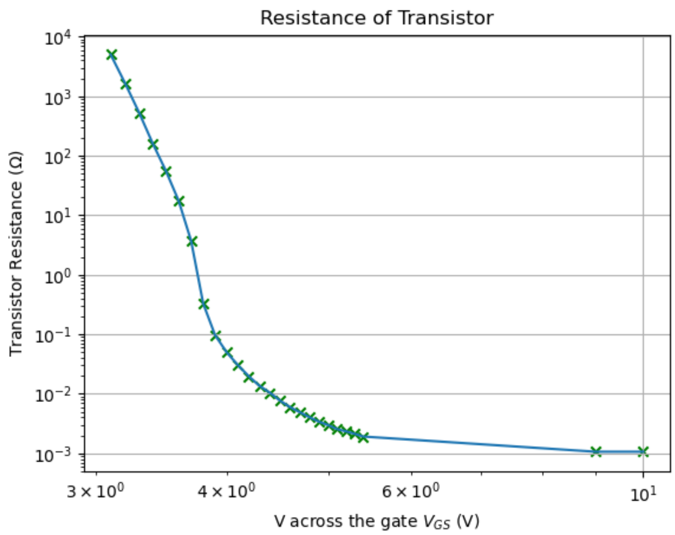


Figure 7: Transistor Resistance vs Gate voltage V_{GS} on log scale

This behavior is expected, as the transistor has 'infinite' or very high resistance in the beginning and then quickly goes down to the order of milliohms when its fully turned on. The turn on-resistance is at the order of $1.2\,\mathrm{m}\Omega$, which is similar to what the data sheet has stated ($1.3\,\mathrm{m}\Omega$).

1.3 Inductor

The coil we have used is composed of copper wires wrapped around 20 time (20 turns). So the magnetic field in the coil is:

$$B(r) = \frac{N\mu_o IR}{2r^2} \tag{1}$$

$R_{wire} = 40\,\mathrm{mm}$
$I = 0.47\,\mathrm{A}$
At the center of the wire:

$$B(r) = \frac{N\mu_o IR}{2r^2} = \frac{20 \cdot \mu_o \cdot 0.47}{2(40 \times 10^{-3})} = 1.47 \times 10^{-4} \text{ Tesla} \tag{2}$$

Theoretically we should have B(r) = 1.47 Gauss
Using a hall effect sensor we were able to get a reading of

$$B(r) = 1.25\,\text{Gauss} \qquad \text{(Experimental Measurement)} \tag{3}$$

We see that these two values are not too far apart. Of course the equation used above includes assumptions of ideal behaviour. In the real world, there is always magnetic field noise in the region as well as electronic noise when measuring the value. The idea here however, is to note that equation (1) is a valid approximation of the magnetic field through the coil.

For electronics purposes however we care more about the inductance of the coil rather than the magnetic field it produces. Using an LCR meter we were able to obtain a value for the inductance across the coil.
The value we obtained was

$$L = 57.9\,\mu\text{H} \qquad \text{(Experimental Measurement)} \tag{4}$$

This value of inductance is important to use when we study back EMF phenomena and any inductance that goes around in the circuit.

Moving on we measure the Resistance of the coils. We run a low voltage through the coils and measure the current that passes through.

Voltage (V)	Current (I)
0.2	0.69
0.3	0.93
0.4	1.45
0.6	1.85

Calculating the average of these resistance values brings us to about

$$R_{coil} = 300\,\text{m}\Omega \tag{5}$$

Which is higher than the resistance of the actual coil that is used in the atomic physics experiment. However, it is still significant to measure this value as we wanted to understand the overall resistance of the circuit.

2 Control and Tuning

Since we are done with the component analysis we can now turn our attention to the control part of the circuit. The goal is to control the current through the coil as

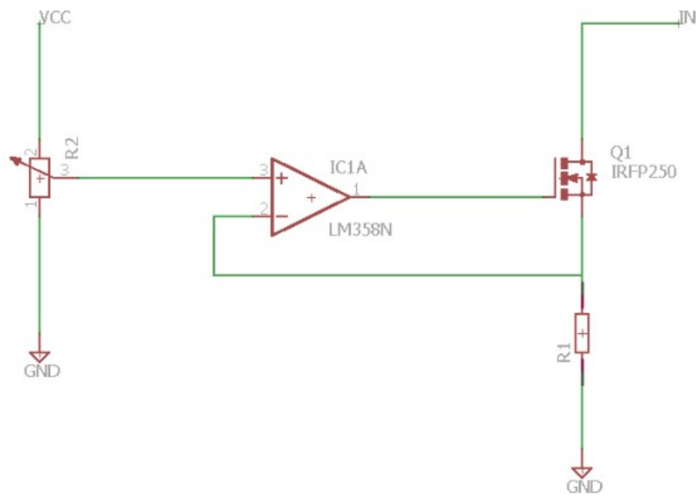


Figure 8: Control circuit using Op-amp

well as to change the current to any value we need. The inspiration behind this idea comes from this diagram posted in figure 8.
In figure 8 we see the control circuit. First we have the load current (500A) that passes from the drain to the source, which is controlled by the gate voltage. R_1 has a very small resistance value so that it can give information about the current without affecting it. The voltage we read off from that sense resistor is directly proportional to the current through Ohm's Law. This voltage value is fed to the inverting terminal of the op-amp.

Recall op-amp rules where it will always try to keep its inverting and non-inverting terminals as close to each other as possible. The op-amp will output whatever voltage necessary in order to keep the two voltage inputs the same.

The value of R_2 is a variable and depends on what we want the current through the circuit to be. The relationship between the voltage input into the non-inverting terminal vs the current that passes through the load, should be linear in the region of operation.

Results and Discussion

<u>Inductance and Response Times:</u>

Throughout our analysis we have tested the MOSFET to see its Response Times and the inductor's influence on the response time, if any. For this analysis we have run triangular voltage waves of different frequencies across the transistor gate and recorded the response. Please see figure 9.

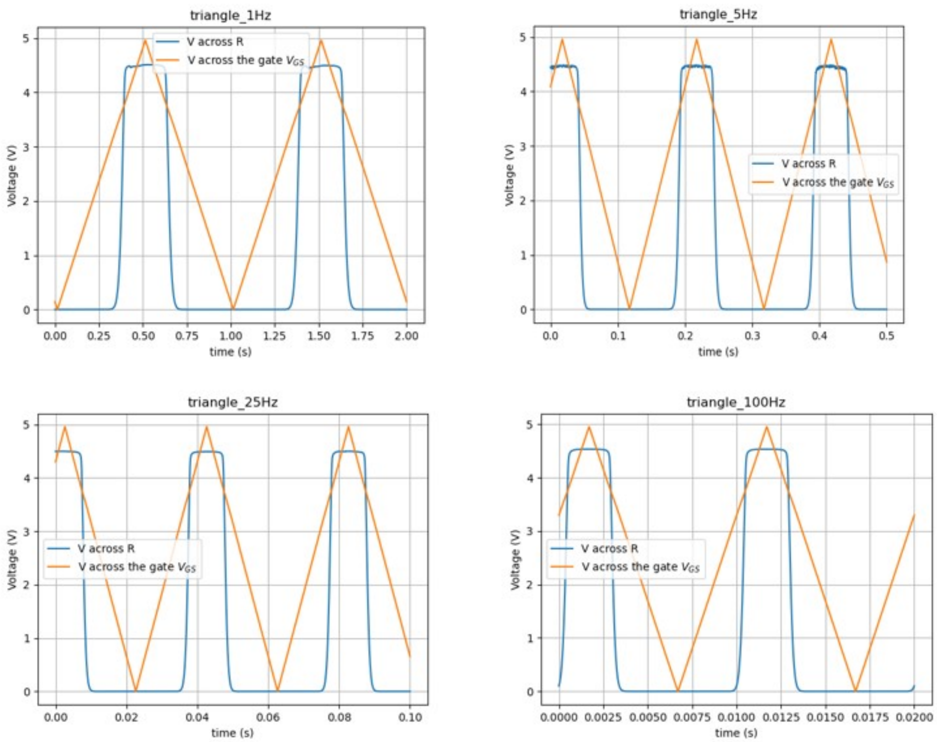


Figure 9: Response curves of the MOSFET

In here we have only included frequencies for up to 100 Hz. The response curve for each figure is within the expected limits. We do not see any spikes or unwanted oscillations. The current simply "turns" on or off depending on the gate voltage.

However in the real circuit we have a turn on time of about 1 ms. Which is none of the cases portrayed here. In order to perform this we must run a 500 Hz triangular frequency across the gate and measure the response time accordingly. Here is the result in figure 10.

When we investigate faster turn-on speeds we observe unwanted spikes and oscillations, such as the ones seen in figure 10. At the saturation point, we should see convergence with no oscillations. But our system does have oscillations (one). Why is there that oscillation?

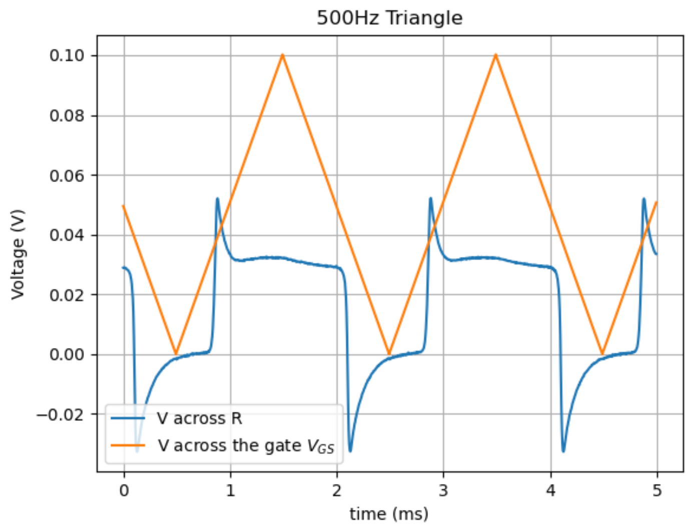


Figure 10: Response curves of the MOSFET at 500 Hz

I hypothesize that this is due to the inductor aggressively turning off.

$$V = L\frac{dI}{dt} \tag{6}$$

Using the normal inductance equation listed above, we see that, during the exponential regime, the inductor keeps on building more and more voltage across itself. That is because the current through it is increasing exponentially. Then, after that, the current suddenly stops increasing. The current levels out.

At this point ideally, $V = L\frac{dI}{dt} = 0$,

However, the inductor cannot realistically turn off that fast, that accurately, without over shooting. So we see here the effect of the inductor overshooting and rising up until it levels out. We see this behaviour in both the turn on and turn off regimes. This could raise some problems down the road. In here we are only reporting this phenomena in case we do face problems with the circuit. We shall return and solve this problem in the future.

Power Dissipation Across the MOSFET:

All transistors have power ratings which cannot be exceeded; otherwise it would break down. Our transistor can take about 940 Watts worth of power across them. When turned fully on or off there is usually no problem. However there is a certain region when the voltage through the drain and the current are both non zero. We were able to obtain a plot of the power across the resistor, and then we scaled it up to the desired values of current and voltage. We see in figure 11, that indeed we reach a power level of almost 1200 W which is higher than the power rating. This is only for a very specific region of the gate voltage, however, and can thus be eliminated. In either way, it is worthwhile to acknowledge this issues and try to avoid it as much as possible.

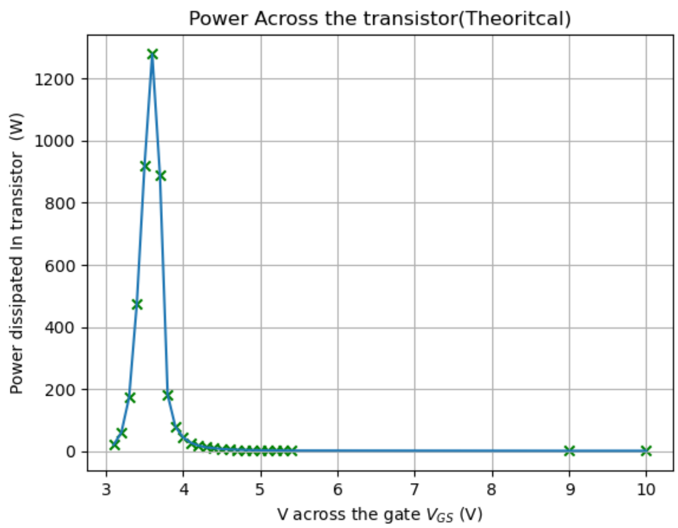


Figure 11: Power Across the MOSFET

Control Circuit:

We turn our attention back to the results of our control circuit. First we start by building the circuit into LTspice in order to simulate the result.

In figure 12, we see the results of the circuit depicted in figure 8. Indeed we see the blue line which is the current that passes through the load, is linear with respect to the input voltage to the op-amp. The green line is the output of the op-amp at different gate input voltages. We see that this behavior is not necessarily linear. That is because the response of the transistor is no longer linear. Theoretically our control works and produces the currents we want.

However when we build the actual circuit we face two main problems:

1. Oscillations at the Gate
2. Gain issues with the shunt resistor

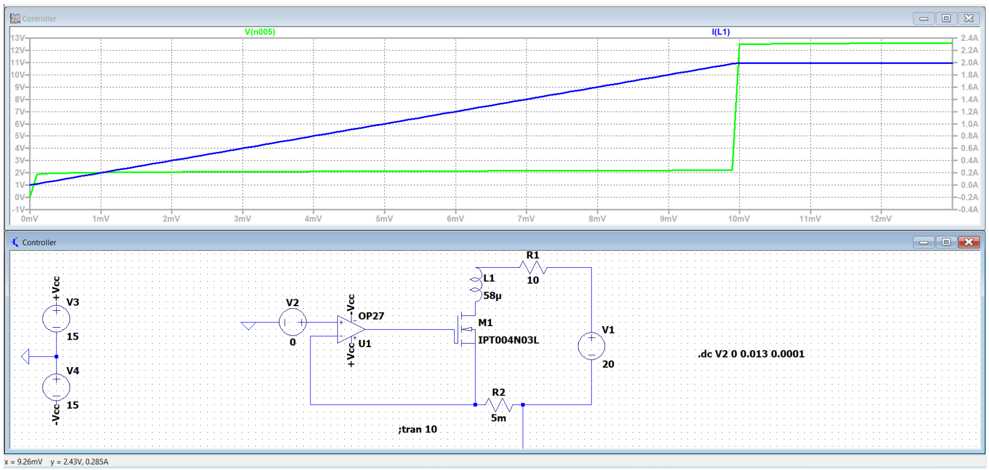


Figure 12: Control Circuit

2.0.1 Oscillations

A closer look at the voltages at the gate vs time, we see that there is plenty of oscillations that occur at a certain regime. Oscillations, especially aggressive ones with high amplitudes and frequency, will damage the MOSFET and so we would like to eliminate them.

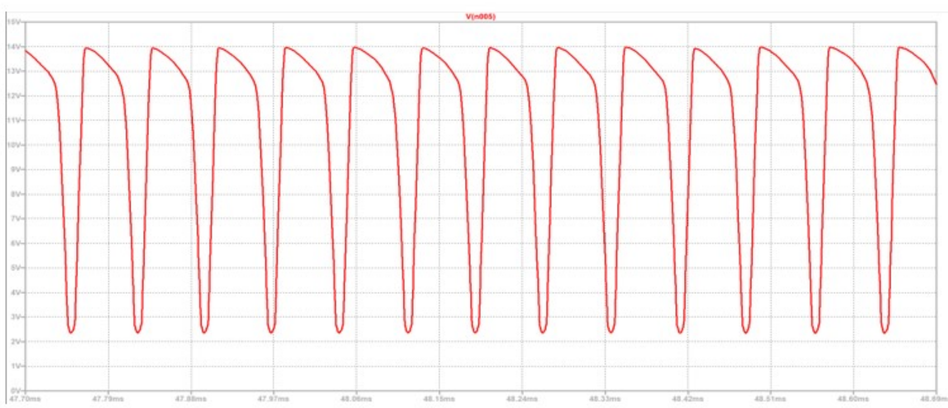


Figure 13: Oscillations at the gate

These oscillations are not healthy for the MOSFET, and to solve this issue, we must understand its origins. The MOSFET gate is essentially a capacitor, and some op-amps are notorious for not dealing properly with capacitive loads. They cause back and forth oscillations that are never healthy for the device. The capacitor across the gate is on the order of a few nanoFarads, which is not negligible. The OP27 and LM324 are not good op-amps to drive capacitive loads. Yet there are always solutions when dealing with unwanted oscillations.

After performing the simulation, we build the actual circuit and observe the oscillations seen in figure 14.

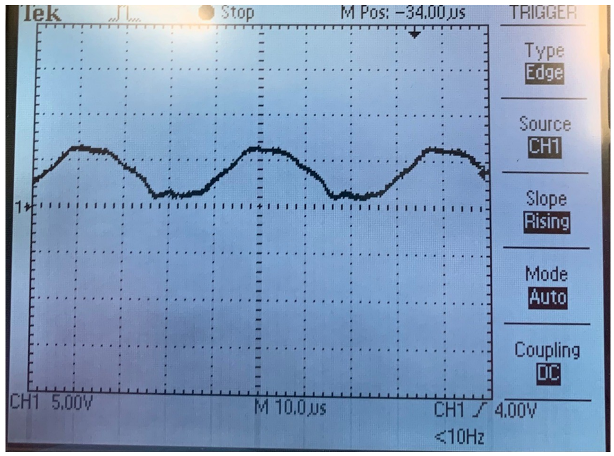


Figure 14: Oscillations at the gate (actual)

First in order to deal with these the oscillations we artificially get rid of them by adding a low pass filter. We create a passive low pass filter with a cut off frequency of 10 Hz, so as to not greatly decrease the response times. After doing so, we see that indeed our problems are fixed. The voltage no longer oscillates and it now gives out a DC level voltage that follows the trend seen in figure 12. Here is an experimental value of the sweep seen in figure 12.

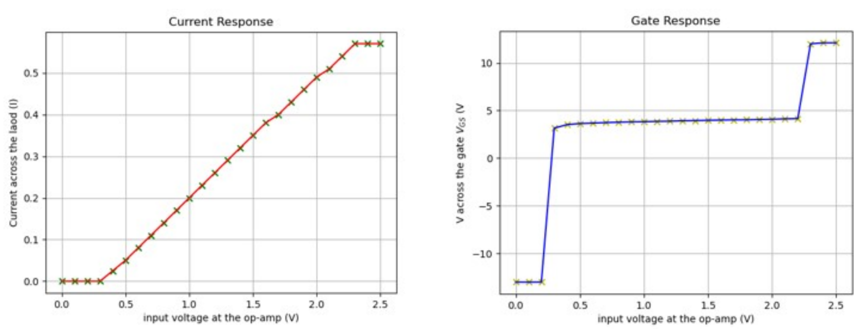


Figure 15: DC Sweep of the op-amp input voltage (actual)

Perhaps our ability obtain that linear relationship depicted in figure 15 on the left is a true indicator that our control is capable of providing us with the desired response.

Another solution to this oscillation problem is to just place a load resistor between the op-amp output and the MOSFET gate. This did help with the oscillations as depicted in figure 16.

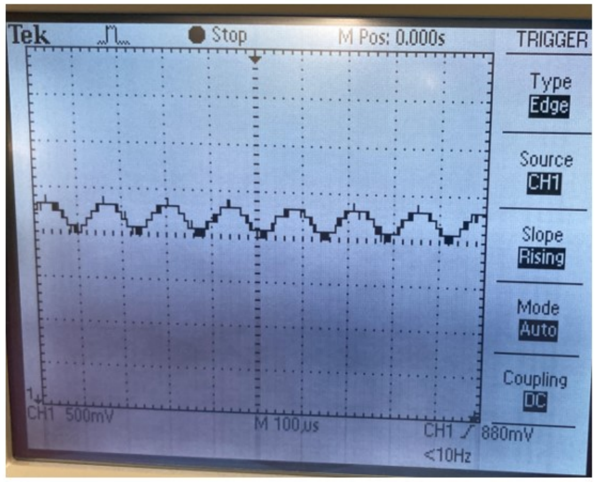


Figure 16: Load resistor effect on oscillations

We see that adding a load resistor of only 20 k Ω limits the oscillations to 400 mVpp, which is a great improvement from the raw oscillations. Even though this still has some oscillations, it has the advantage of not slowing down response times the way low pass filters do.

Finally, we could replace the op-amps we have with op-amps that are fit to deal with capacitive loads. Some op-amps have the capability to deal with 'Unlimited" capacitive loads. A great example of this is the Op-amp LM7322. This op-amp is specifically designed to drive MOSFETs. We were able to install the model on LT-spice and simulate it. Indeed there were no oscillations when this op-amp was used to drive the MOSFET. Unfortunately, we could not test it out in real time as there were none in the lab. Here is an LTspice simulation (Figure 17)

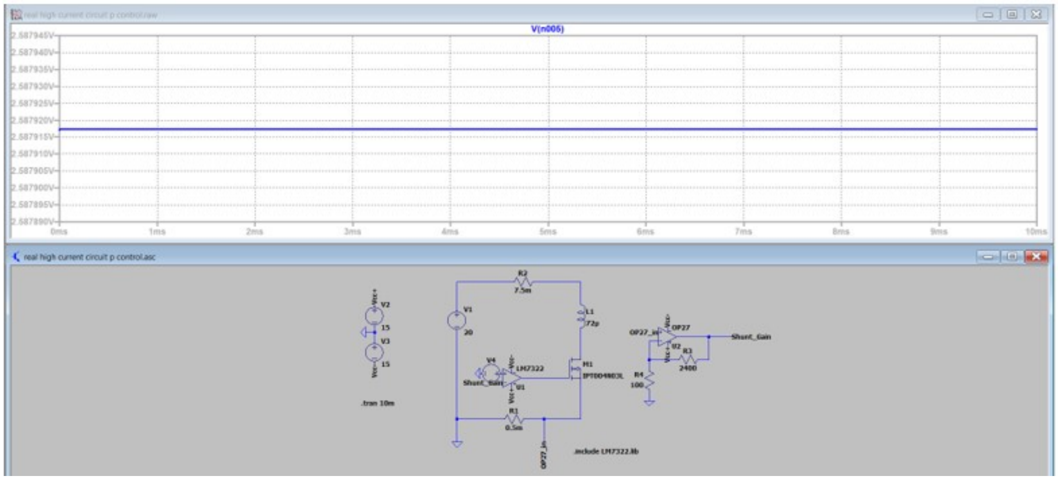


Figure 17: LM7322 op-amp greatly reduces oscillations

2.0.2 Gain Issues

The shunt resistor in use has a small value of only 5 mΩ. With our current circuit, we are supplying a max of 1 A in order to protect the circuit. So the max voltage is 5 mV, which is a very small number to accurately measure and amplify. This voltage is also very prone to noise and background interference. So we have decided to use an instrumentation amplifier, to measure the voltage across the resistor, as it deals better with low values. Then, we fed that into the control op-amp. But there were still a plethora of noise signal and messy gain values. First I tested out the instrumentation amplifier, and it works well when tested with the myDAQ. It has also worked well with higher sense resistors. We have placed a 1Ω resistor instead of 5mΩ in order to increase the voltage value, and indeed it produced the desired amplified voltage.

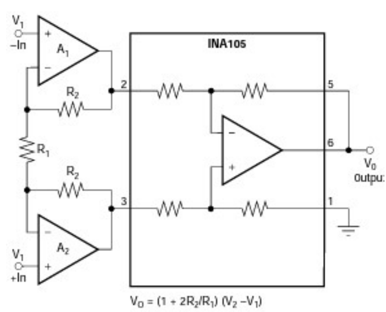


Figure 18: Instrumentation Amplifier used to measure the voltage across the sense resistor

So for very low currents, the shunt resistor reads very small voltages which are harder to deal with. In order to use the shunt resistor, high currents ($\geq$ 100 A) should be used.

Another solution to this problem is to implement a high gain hall effect sensor that could read off the magnetic field value form the wires. These could potentially be less prone to noise and issues regrading low current values.

Conclusion

So far in this project we have been able to create a circuit that can control the magnetic field at any value we desire. So we built a working high current MOSFET circuit that could be properly controlled and tuned using non-inverting op-amps. We have also provided an analysis of the different components used in this circuit.

In the future we would like to perform Varistor testing across the MOSFET, in order to further protect it from absorbing excess power. We would also like to have a more robust control that is less prone to noise and unwanted oscillations. Finally we might switch to a hall effect sensor instead of using a shunt resistor, as it is usually more robust and less influential to the circuit.