University of Colorado Boulder
ECEE Department

ECEN 2270 - Electronics Design Lab - Spring 2024
Location: Engineering Center, ECEE 281, T,TH, 3:30 - 5:20 PM
Instructor: Steven Dunbar
Lab Title: Lab 3: DC Motor Driver & Feedback Controller
Date of Experiment: April 4, 2024
Name: Connor Sorrell

<u>Introduction and Objectives</u>

Introduction:

In this lab we continue our exploration of electronic circuit design, with a deeper focus on implementation and understanding of a feedback control system. We delve into the design, simulation of H-Bridge circuits, motor drivers, virtual ground, compensator, and direction control circuits. We build and test these circuits both in SIMetrix and through hands-on experimentation, exploring the functionality and integration while conducting both open-loop and closed-loop tests to fully understand their operations. Through many adjustments to parameters, a speed feedback control loop will be made and perform as expected. Throughout the lab, high quality standards are adhered to, in order to ensure the Vs output of the loop operates effectively, and that results from simulation and the breadboard align closely. This lab enhances our understanding of each component's role within the broader system and propels us many steps closer to realizing our goal of constructing a functional robotic car.

Objectives:

Throughout the lab, there are some key objectives that are accomplished:

- The H-Bridge circuit is built and tested. Both its concepts and its physical implementation are fully understood.
- The motor driver circuit is built both on SIMetrix and constructed via soldering and is simulated, tested, understood and validated.
- The importance of the virtual ground circuit is well understood. It is built in SIMetrix and implemented on the breadboard.
- The compensator circuit is built, designed, tested, and understood on SIMetrix, in both an open-loop and closed-loop test. This includes the difference amplifier, integrator, and virtual ground-to-ground circuits.
- The compensator circuit is implemented onto the breadboard and is tested and validated with both an open-loop test and a closed-loop test.
- The direction control circuit is built in SIMetrix and its function with the H-Bridge circuit is well understood.
- The direction control is added to the closed-loop circuit implementation and is tested and validated.
- The entire feedback control loop is both simulated in SIMetrix and tested on the

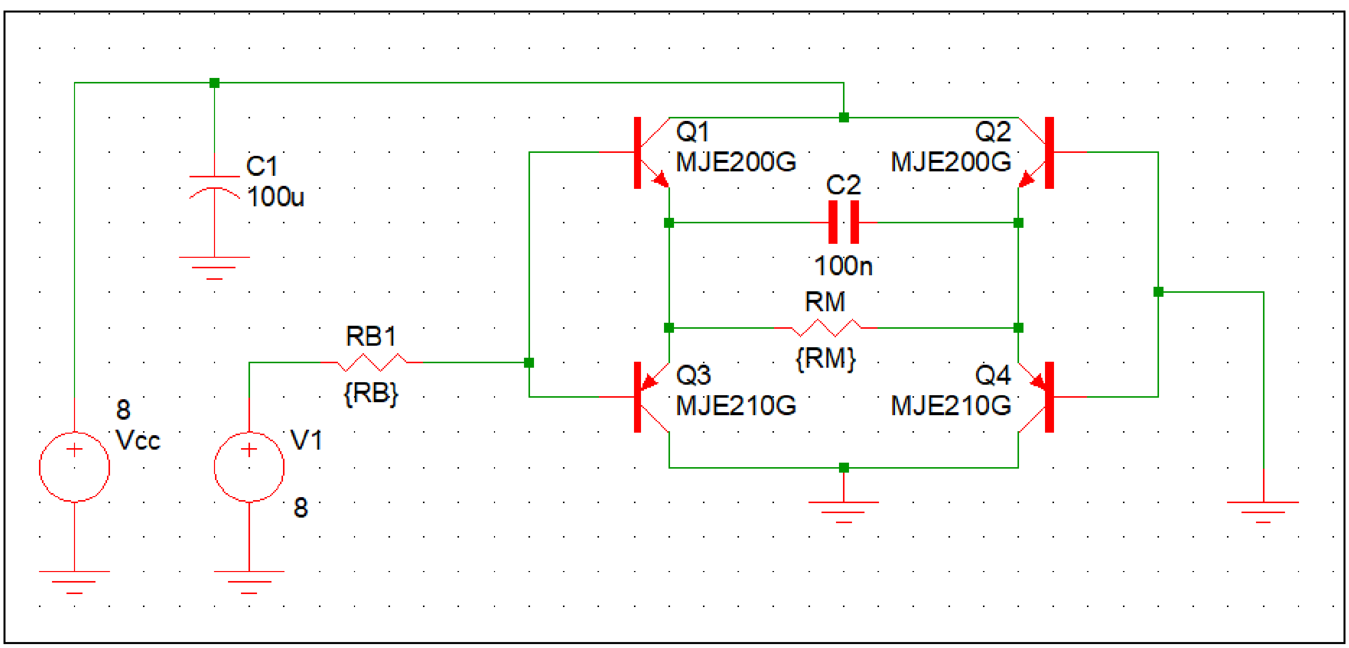
breadboard comprehensively, with trigger times, component values, time constants, damping factor, and more being adjusted to achieve expected results.

- The quality of all schematics and hardware circuit builds satisfy good experimental lab practice requirements.
- The Vs output of the feedback speed control loop in both the simulation and the breadboard implementation is operational and produces reasonable values in agreement with one another.

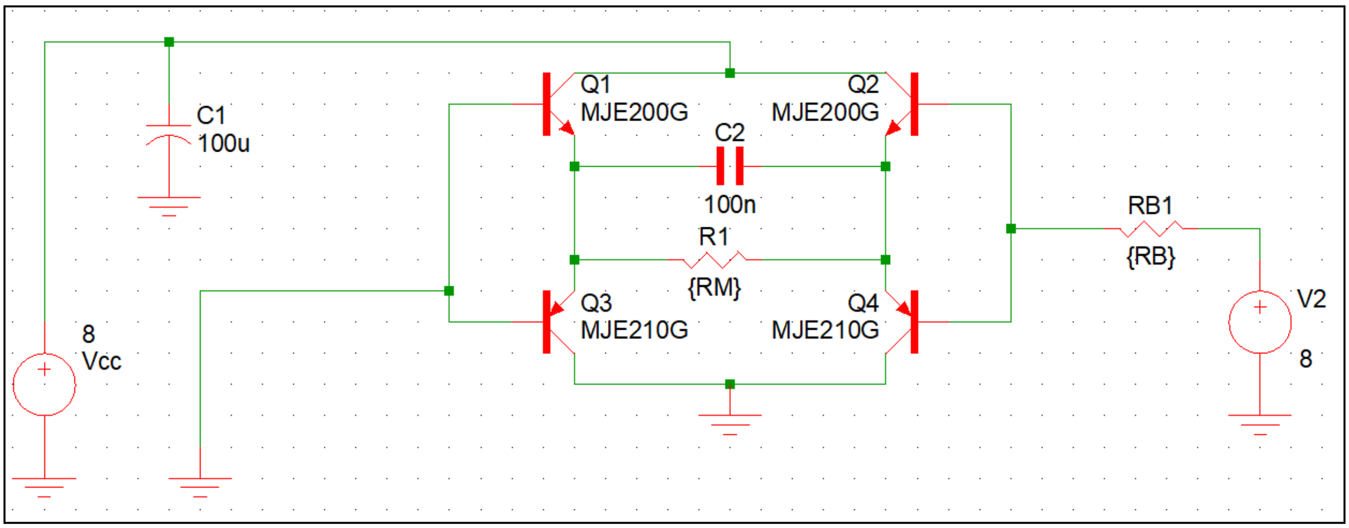
Experiment 3.A.2: Getting to Know the H-Bridge Circuit

To get familiar with the H-Bridge Circuit, we built the two circuits shown below in SIMetrix and then used a DCOP simulation for simulation device bias voltage, current, and power dissipations. We used Rm = 1.5 Ohms for two stalled motors in parallel and Rm = 10 Ohms for two motors spinning freely. We measured values for both the forward and backward directions.

Forward H-Bridge



Backward H-Bridge



R_M	V_{B1}	V_{B2}	**DC+**	**DC-**	I_{RM}	P_{Q1}	P_{Q2}	P_{Q3}	P_{Q4}
1.5Ω	3.53	0	2.77	0.764	1.34	6.93	126p	22.7p	1.02
10Ω	6.37	0	5.65	0.720	0.493	1.15	127p	78.7p	0.355
1.5Ω	0	3.53	0.764	2.77	1.34	126p	6.93	1.02	22.7p
10Ω	0	6.37	0.720	5.65	0.493	127p	1.15	0.335	78.7p

Experiment 3.A.3: Simulate the Motor Driver Circuit

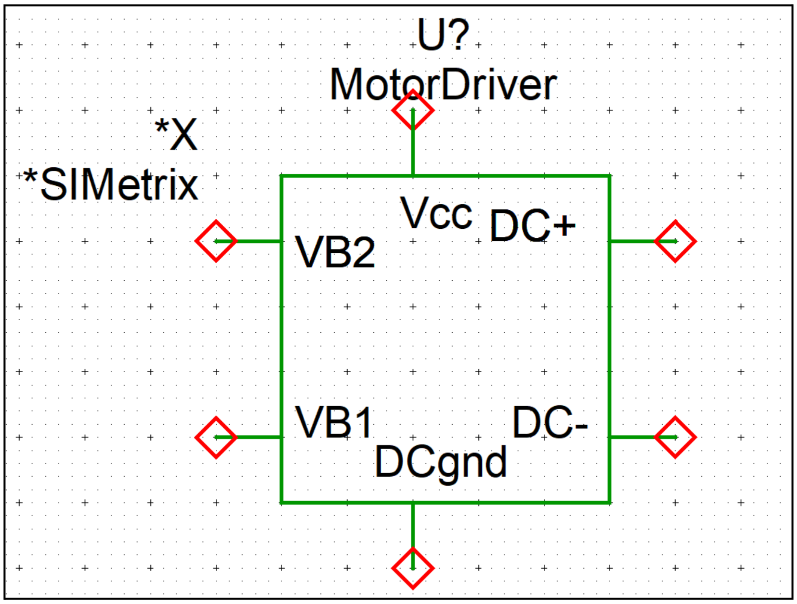


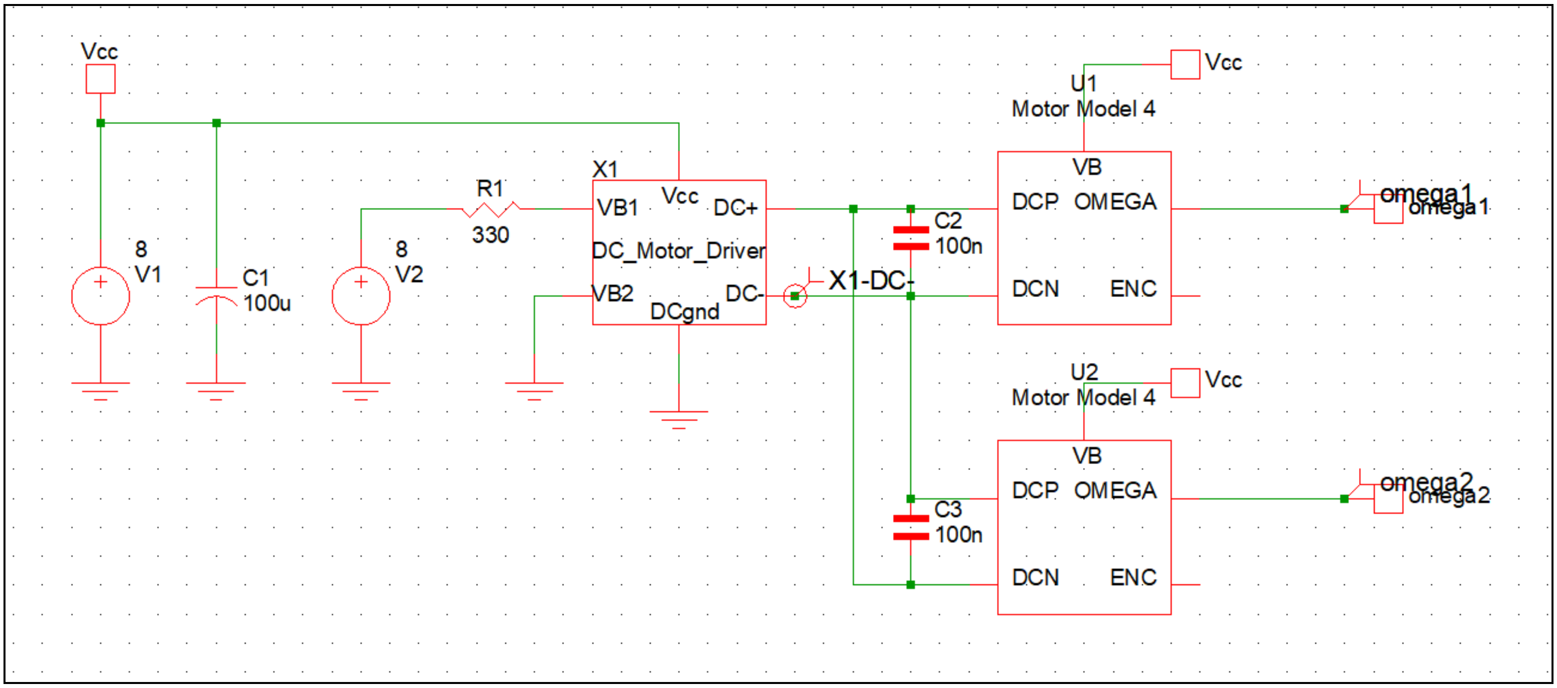
Figure: Motor Driver Subcircuit

Here we used Rb = 330 ohms and measured the total motor current, as well as omega1 and omega2 for both the following cases:

<u>You will notice that X2 runs forward and X3 runs backward. Why is it wired that way?</u>

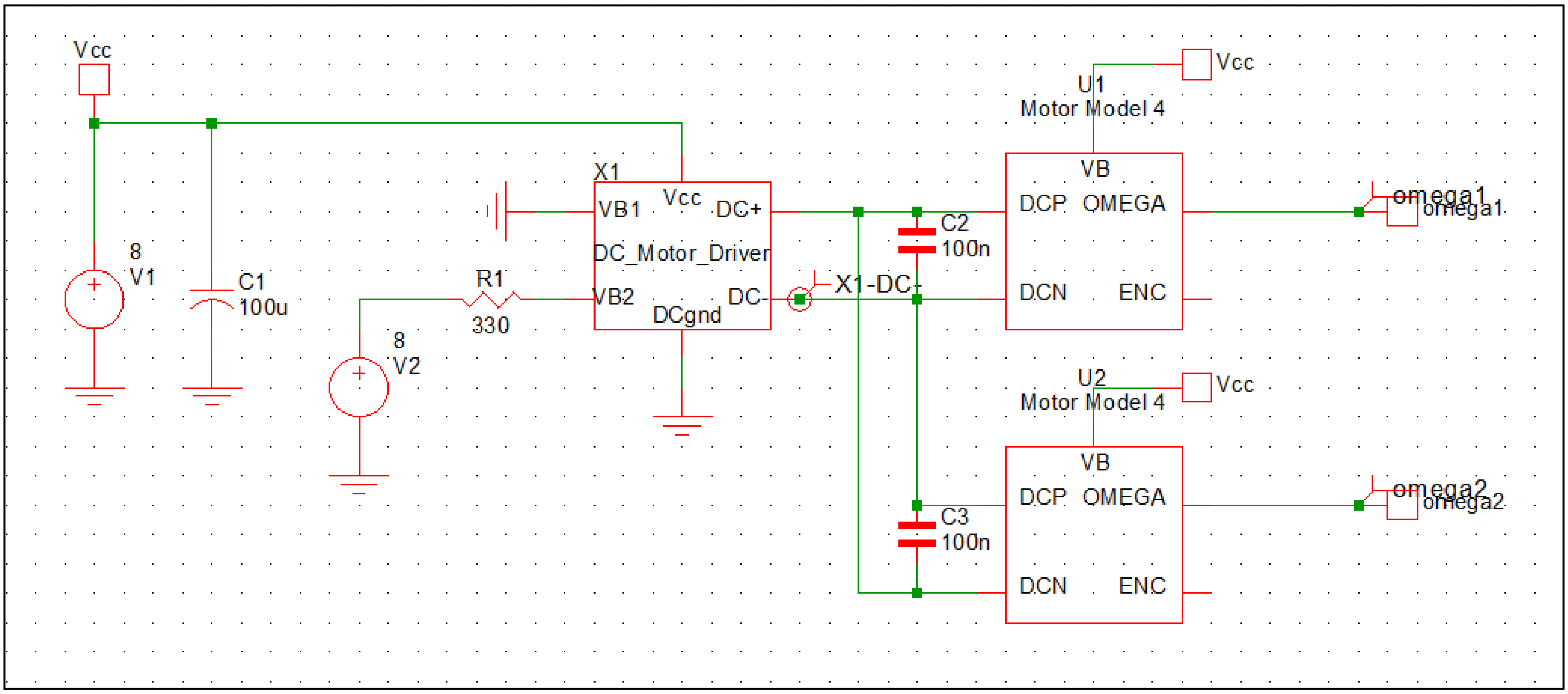
X2 and X3 are both DC motor models connected to the output of the motor driver. The direction in which the motor runs (forward or backward) is determined by the polarity of the voltage applied to its terminals. In DC motors, reversing the polarity of the supplied voltage will simply reverse the direction of the motor. In our case, in our robot chassis, our two motors are installed in such a way that one is mirrored compared to the other. So, when they have the same input polarity, the physical orientation of the motors means that “forward” for one motor is “backward” for the other. This opposite rotation of the wheels’ motors translates to a forward rotation of each wheel on the chassis.

Forward Motor Driver Circuit



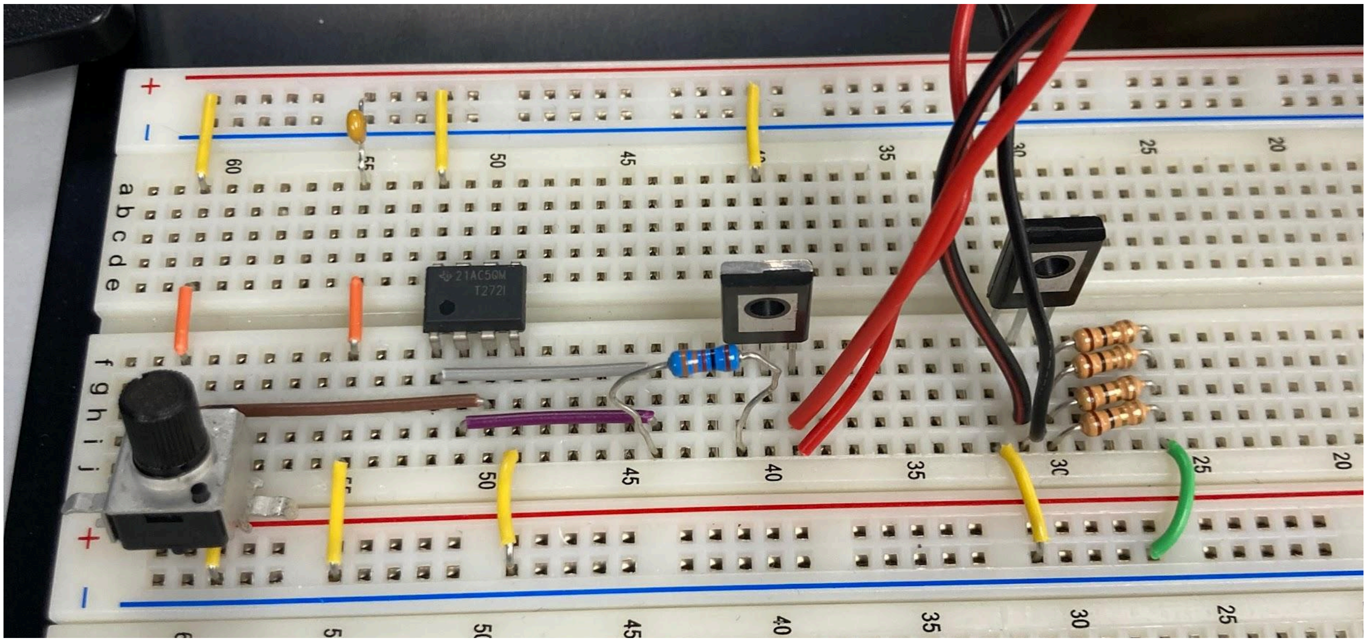
	Total Motor Current	Omega1	Omega2
Freely Running Motors	0.545 A	0	-13.46
One Stalled	1.17 A	0	7.07
Both Motors Stalled	1.4 A	0	0

Backward Motor Driver Circuit



	Total Motor Current	Omega1	Omega2
Freely Running Motors	-0.300 A	-15.83	15.83
One Stalled	-1.15 A	0	7.27
Both Motors Stalled	-1.40	0	0

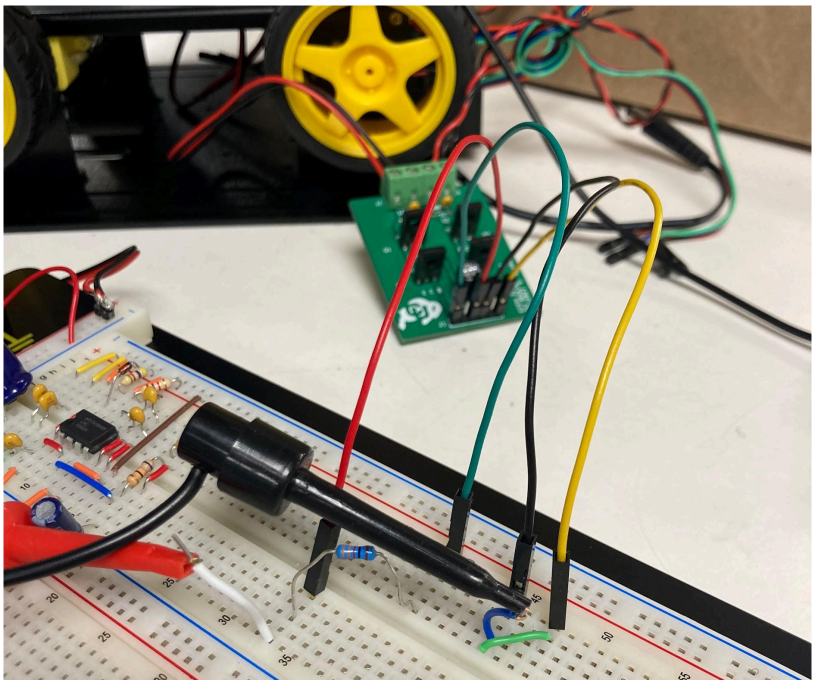
Experiment 3.A.4: Testing Motor Driver Circuit on Breadboard



	Total Motor Current [A]	DC+ [V]	DC- [V]
Freely Running Motors	Connor: 0.53	Connor: 5.9	Connor: 0.785
One Stalled	Connor: 0.996	Connor: 3.26	Connor: 0.880
Both Motors Stalled	Connor: 0.998	Connor: 2.22	Connor: 0.873

Experiment 3.A.5: Construct the Motor Driver Circuit

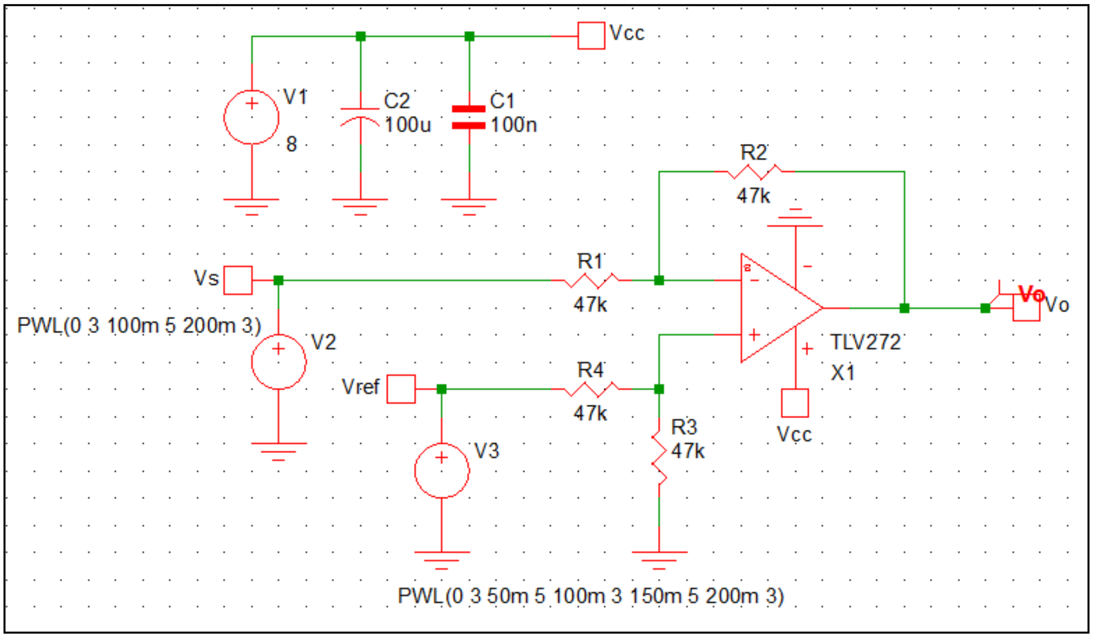
Experiment 3.A.6: Test the Motor Driver Circuit



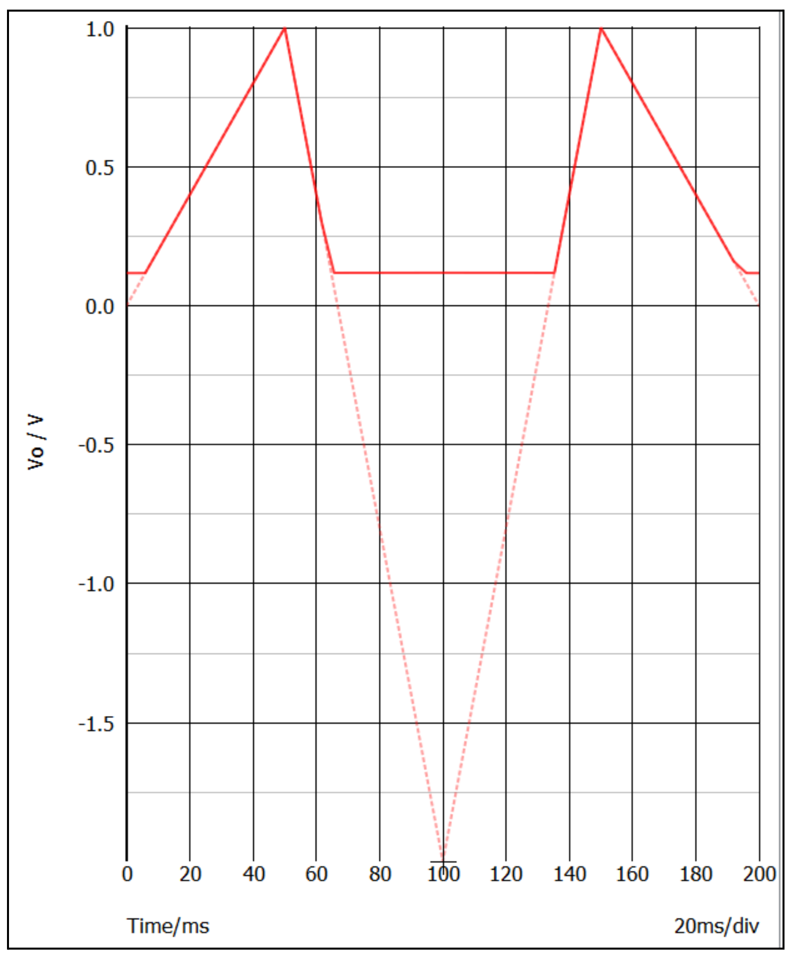
R_M	V_{B1}	V_{B2}	**DC+**	**DC-**
1.5Ω	2.95	0	2.00	0.85
10Ω	6.72	0	5.93	0.78
1.5Ω	0	2.94	0.86	2.18
10Ω	0	6.62	0.78	6.01

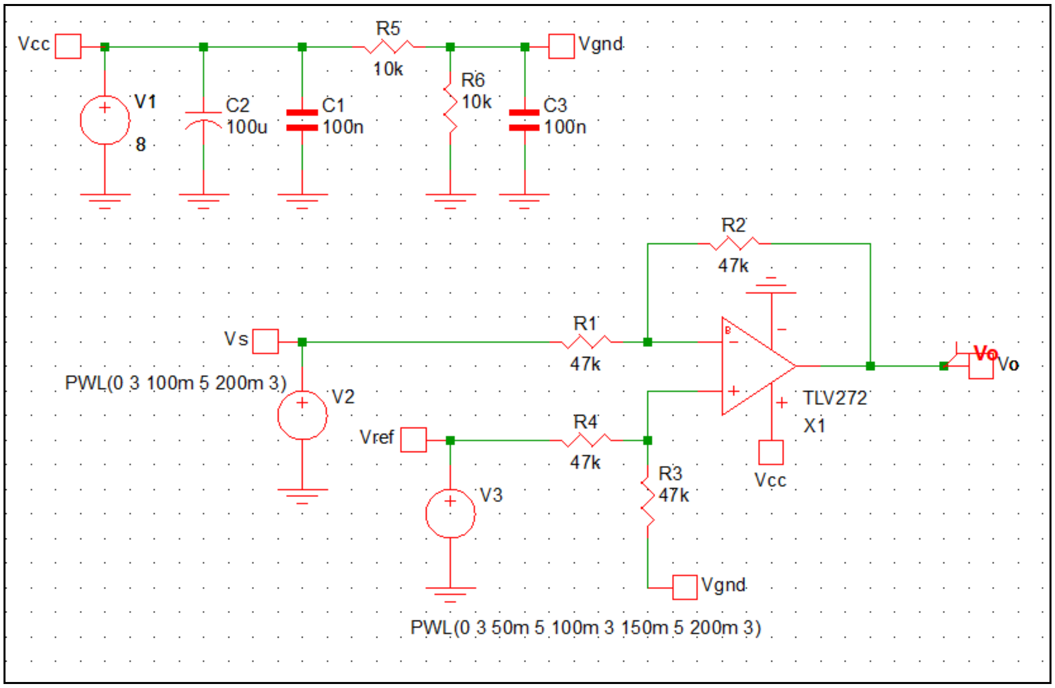
Both forward and reverse motor direction works as expected, and both wheels turn in the same direction as intended.

3.B.2 Making the Case for Virtual Ground



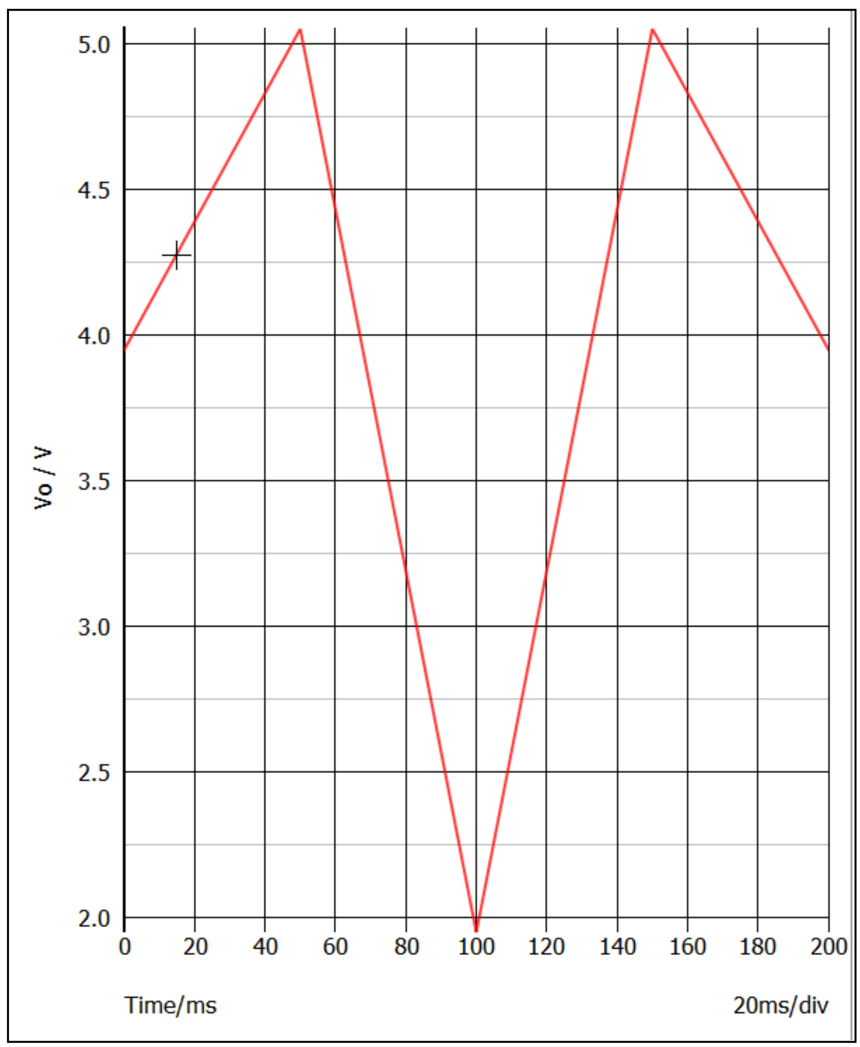
Above is the schematic for the difference amplifier circuit tested to make a case for the virtual ground. To the right is the Vo of this schematic with an 8V and 0V supply to the Opamp. The dotted line shows the Vo of the 8V and -8V supply to the same circuit for reference. As seen from the transient for the case of 0V to the -Vcc of the opamp, the negative voltages clip to a constant voltage of 119mV. This is not a favorable operating condition, as we do not want the amplifier to clip due to limited power supply to the opamp.



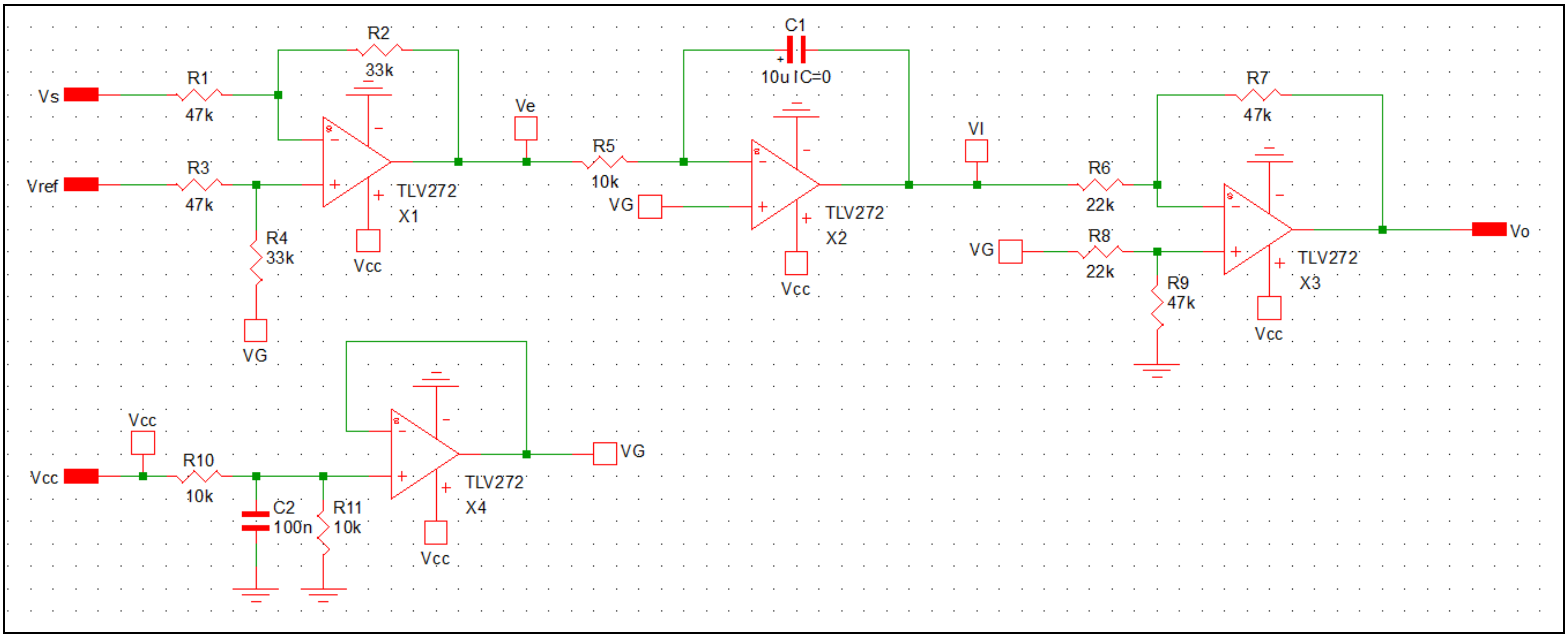


Above is the schematic for the same circuit, but with a virtual ground introduced. The transient of the output, Vo, is on the right. As can be seen, this circuit does not clip, and has a full range of its amplitude. This is due to the total magnitude of the voltage being higher as a result of the virtual ground under the R3 resistor. Since the lowest voltage of the output is still positive, the opamp does not clip the signal.

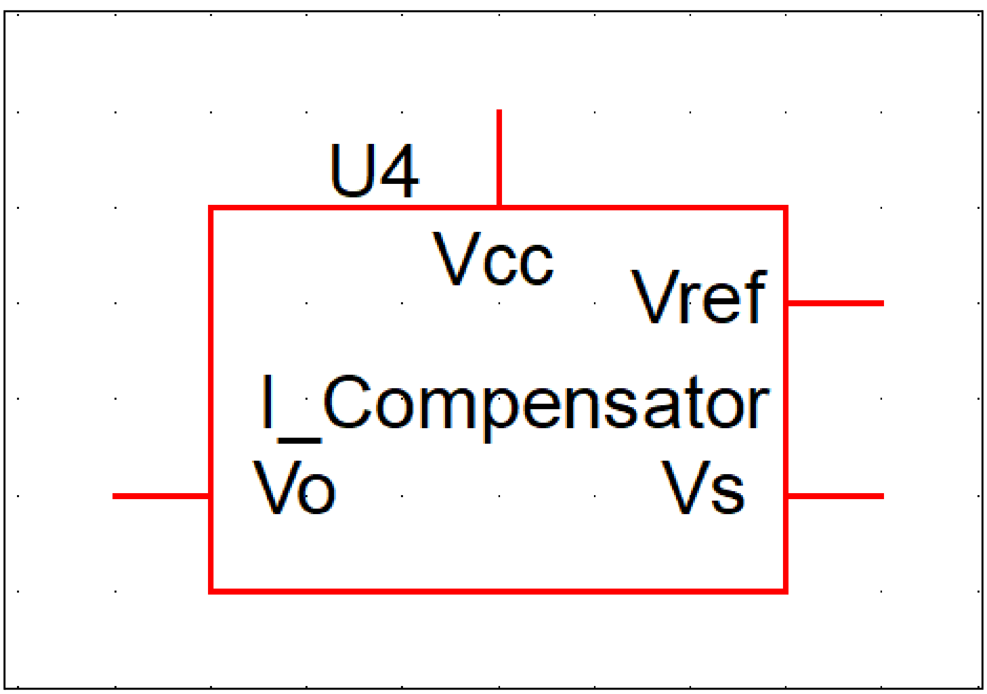
This concept will be important for circuits with a single voltage supply because it allows us to connect the Vcc- of the opamp to ground. Since we can raise the voltage of the signal to be fully positive using virtual grounds, we can prevent the clipping of the signal at negative voltages.



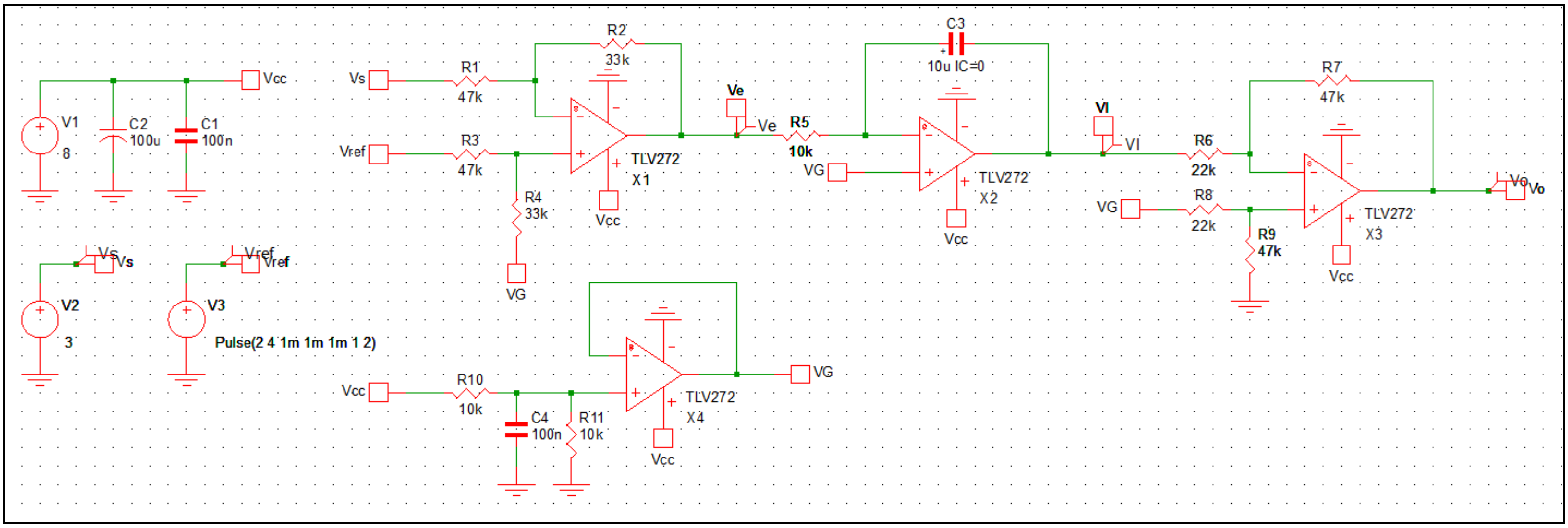
3.B.3 I-Compensator Circuit in SIMetrix



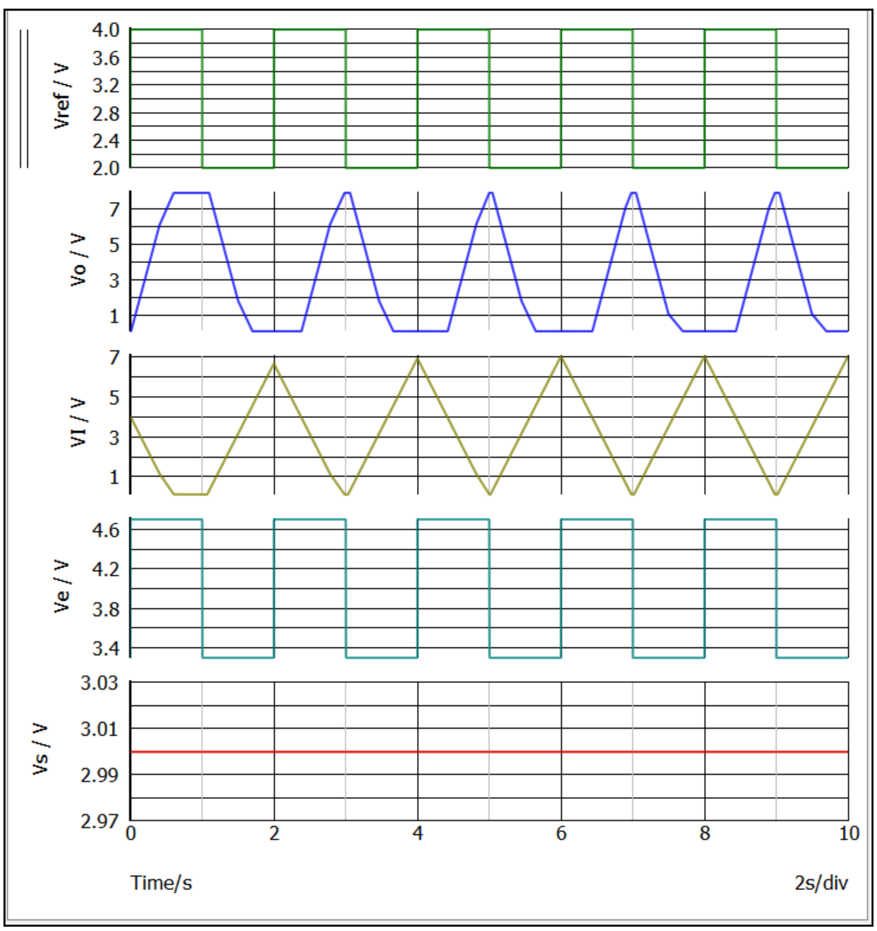
Above is the schematic for the open-loop I-Compensator circuit.
Directly below is the sub-circuit symbol.



3.B.4 I-Compensator Circuit Test (Open-Loop) in Simetrix



Above is the schematic for the open-loop operation of the I-Compensator circuit. Directly below are the transient voltages of the output of each opamp, as well as the Vs and Vref voltages.



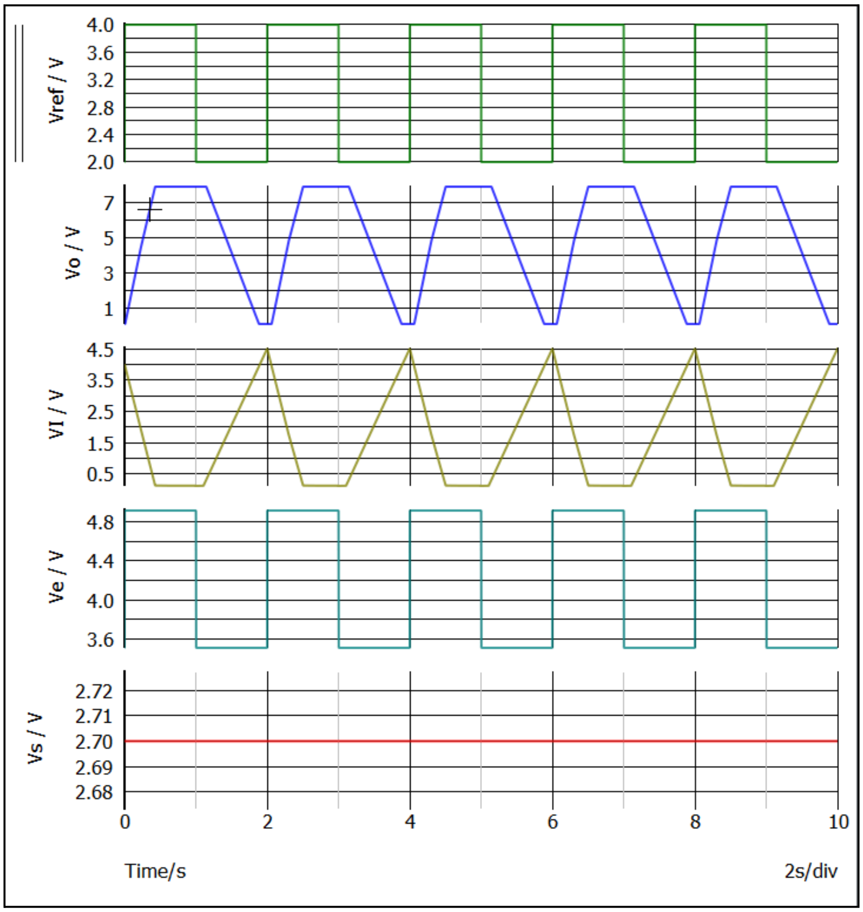
Explain the functions and values of the Ve (error), VI (integrator), and Vo (output) waveforms.

Ve (error): This is the error signal, representing the difference between the desired value and our measured value. The waveform shows that the error is a square wave with an amplitude of about 1.5V, suggesting that our circuit is constantly overshooting and then undershooting our changing PWM desired voltage value.

VI (integrator): This waveform represents the integrator components output, which decreases the error over time. This circuit aims to eliminate the error by integrating the error term. The larger the error, the larger the integrator response will be. The triangle wave represented by VI shows that the integrated error increases linearly when the error is positive, and then decreases linearly when our error is negative. The waveform suggests that the integrator proportionally reacts to the accumulated error and adjusts the output to minimize the error. Overall, this waveform is helping to eliminate the error by correcting it over time.

Vo (output): This is the output of the controller. It nearly represents a sinusoidal shape showing that it is periodically adjusting to itself, as it tries to correct the process by accounting for both the magnitude and duration of the error.

Change Vs to a smaller value, e.g., 2.7V (leave Vref unchanged) and explain how and why Ve, VI, and Vo change.



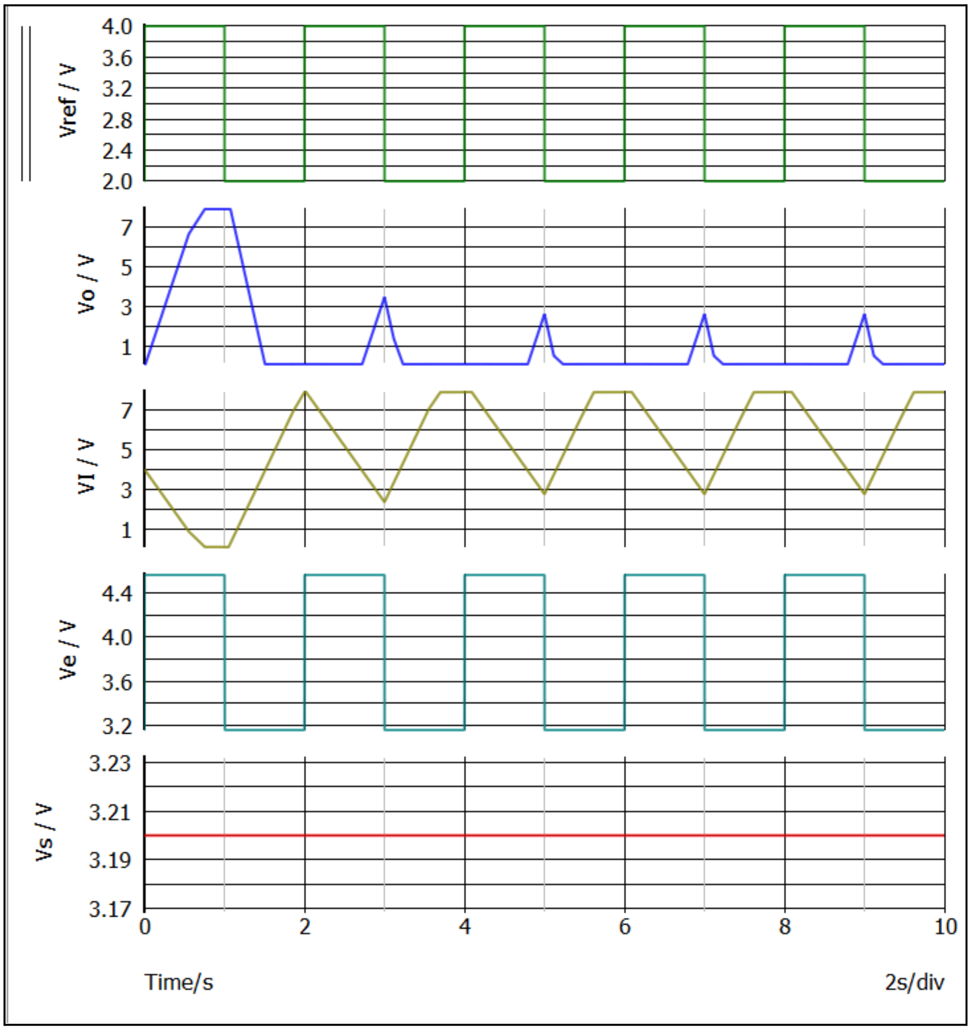
The amplitude of Ve increases because the difference between Vref and Vs becomes even larger. Ve would still be a square wave, but the amplitude would be larger to reflect the increased error.

The amplitude of VI decreases because, with an increased error, the integrator will accumulate the error faster. This means it will have a steeper slope during rise and fall because the error (area under the curve) increased. Because of this, the integrator contributes a stronger action to correct the overall signal, resulting in a slightly smaller amplitude.

Vo's positive duty cycle increases because, with more error, the controller will act faster to bring the signal to the desired value. To do this, Vo stays at its higher level for a longer period of time in each cycle, therefore increasing its positive duty cycle.

Negative duty cycle decreases because the controller is spending more time on the high side to correct the increased error. The controller now needs to apply less "negative" action since the problem is that our error value is mainly too low, not too high.

Change Vs to a larger value, e.g., 3.2V (leave Vref unchanged) and explain how and why Ve, VI, and Vo change.

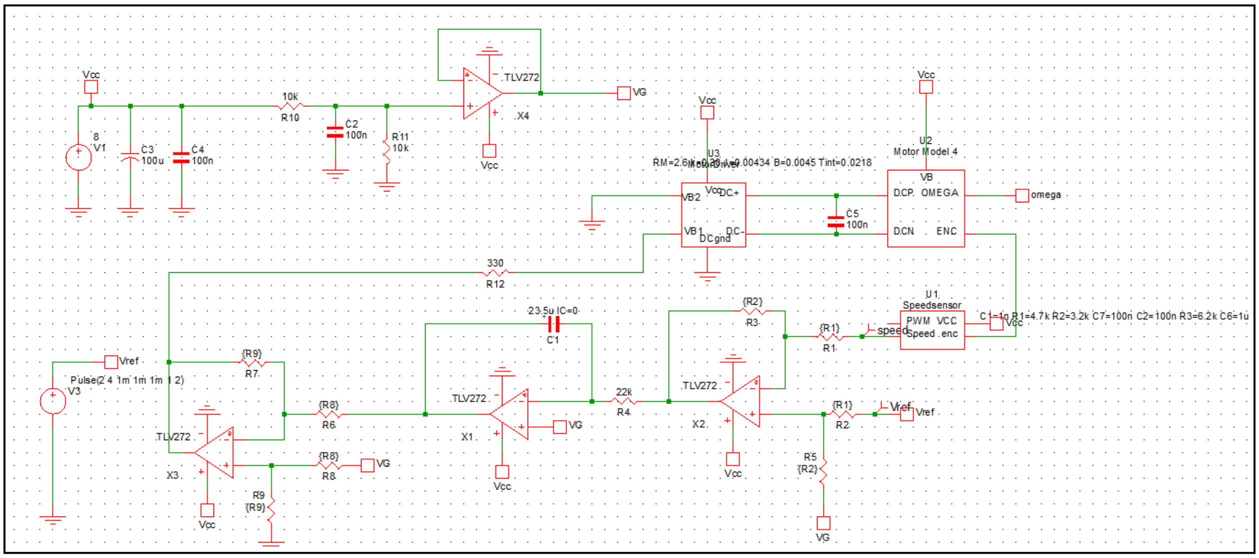


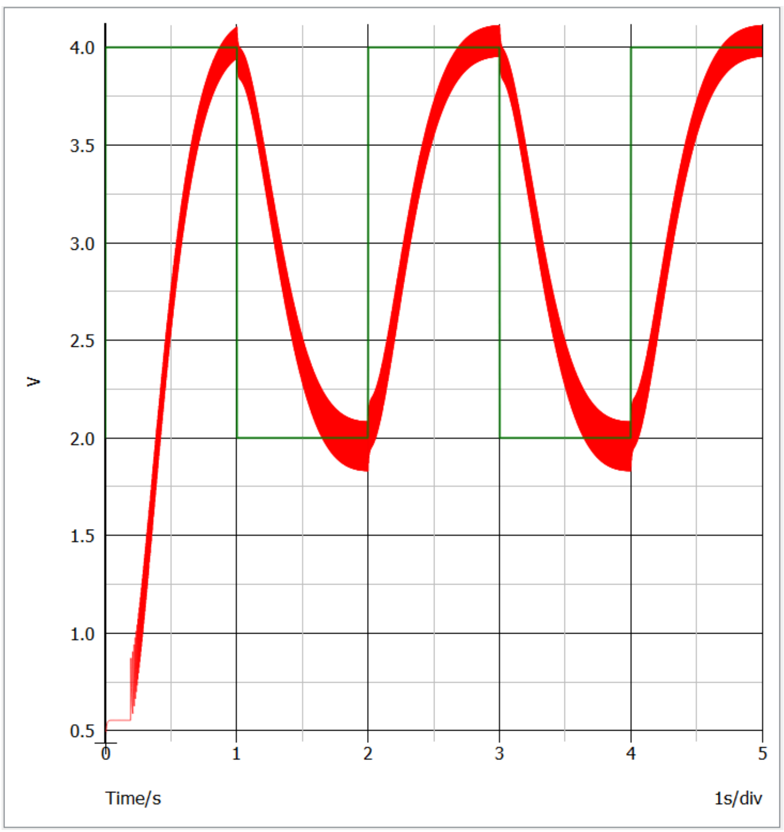
The amplitude of Ve decreases because the difference between Vref and Vs becomes smaller. Ve would still be a square wave, but the amplitude would be larger to reflect the increased error.

The amplitude of VI decreases because with an decreased error, the integrator will not have to accumulate the error significantly. This means it will have a less steep slope during rise and fall because the error (area under the curve) decreased. Because of this, the integrator contributes a weaker action in order to correct the overall signal, resulting in a slightly larger amplitude.

Vo's positive duty cycle decreases significantly because with less error, the controller will act slower to bring the signal to the desired value. To do this, Vo stays at its lower level for a longer period of time in each cycle, therefore decreasing its positive duty cycle. Vo's amplitude also decreases due to the error decreasing.

3.B.5 Closed Loop with I-Compensator in Simetrix





In the simulation, the reference speed is represented by the PWM (green) wave. The green line represents Vs, the output speed, as it responds to the control system. Initially, there is a rise in the red curve, as the system starts and tries to reach the desired speed. Then, over time, the speed adjusts itself in an attempt to follow the PWM signal. The oscillations in the red line show that the system is trying to keep up with and match the reference, but the overshoot and undershoot indicate that our system is not perfectly tuned. However, this simulation is extremely useful in determining the control parameters (RI, CI), and is very useful for understanding the effect of our damping factor. In our case, our damping is very close to ideal, but still not perfect.

-Determine RI and CI for $\zeta \approx 1$ using your motor and speed sensor circuit parameters

$$G_{dc} = \frac{1}{K_{sense}} \qquad \omega_o = \sqrt{G_o \omega_m K_I K_{sense}} \qquad \zeta = \frac{\omega_m}{2\sqrt{G_o \omega_m K_I K_{sense}}}$$

$$\omega_m = \frac{k^2+BR}{JR} \qquad R = R_M + \frac{R_S}{100} \qquad R = 2.55 + \frac{330}{100} = 5.85$$

$$\omega_m = \frac{(.33)^2+(.0018)(5.85)}{(.0024)(5.85)} = 8.506$$

$$G_o = \frac{k}{k^2+BR} = \frac{.33}{(.33)^2+(.0018)(5.85)} = 2.763$$

$$G_m = \frac{k}{(k^2+BR)+JRs} = \frac{k}{\sqrt{(k^2+BR)^2+(JR)^2}} = \frac{.33}{\sqrt{(.33^2+(.0018)(5.85))^2+[(.0024)(5.85)]^2}} = 2.744$$

$$K_I = \frac{1}{R_I C_I}$$

$$K_{sense} = 0.33$$

$$1 = \frac{\omega_m}{2\sqrt{G_o \omega_m K_I K_{sense}}} \qquad \frac{1}{4}\omega_m^2 = G_o \omega_m K_I K_{sense}$$

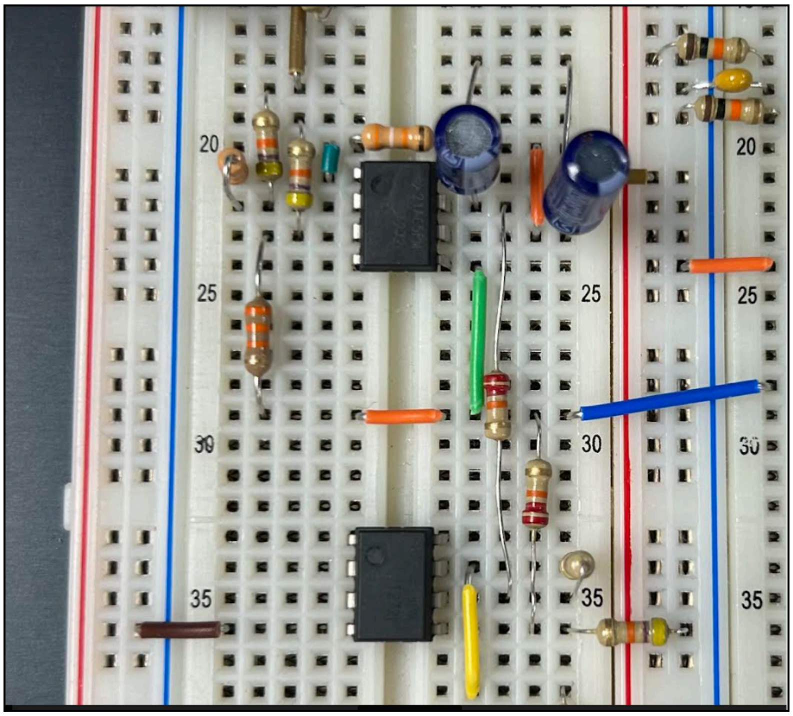
$$K_I = \frac{\omega_m^2}{4 G_o \omega_m K_{sense}} = \frac{\omega_m}{4 G_o K_{sense}} = \frac{8.506}{4(2.763)(.33)} = 2.332$$

$$K_I = 2.332$$

$$R_I C_I = 0.429 \qquad 100\mu F \ \& \ 4290\ \Omega$$

$$10\mu F \ \& \ 43k\Omega$$

3.B.6 Build Compensator Circuit



Picture shows the I-Compensator implementation on the breadboard

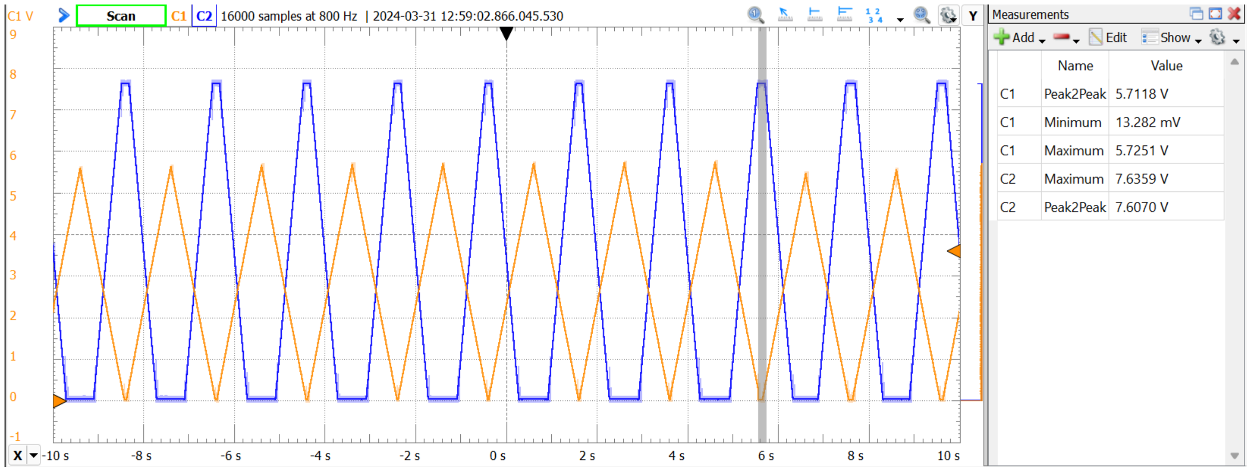
The physical system built above used a resistance, RI, of 39 kiloohms. The capacitance, CI, was 11 microfarads, created by putting two 22 microfarads in series.

3.B.7 Compensator Implementation Test (Open-Loop)

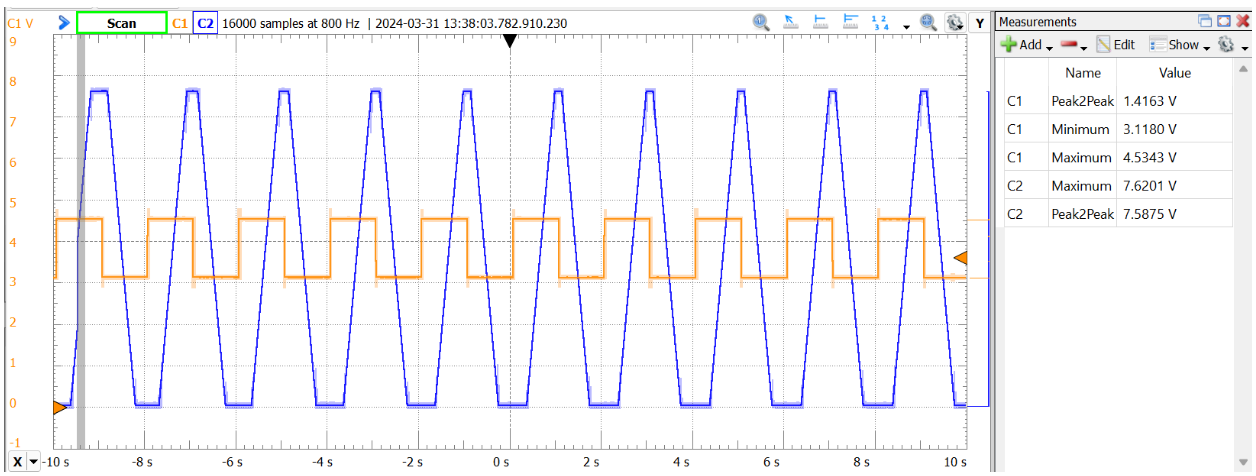
The test procedure involved supplying Vref with a square wave and Vs as a constant voltage.

<u>Vs = 3 V:</u>

VI (orange) and Vo (Blue)

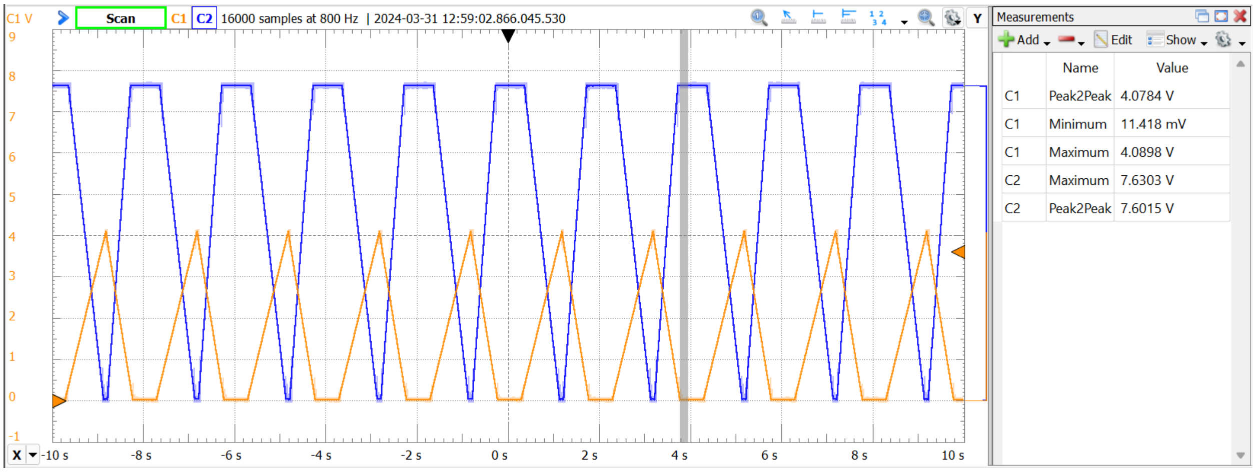


Ve (orange) and Vo (blue)

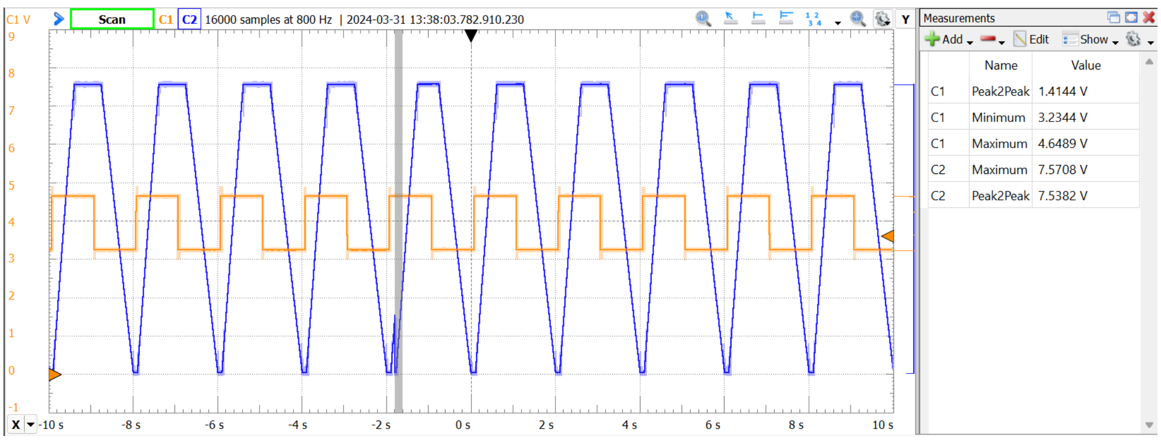


Vs = 2.8 V:

VI (orange) and Vo (Blue)



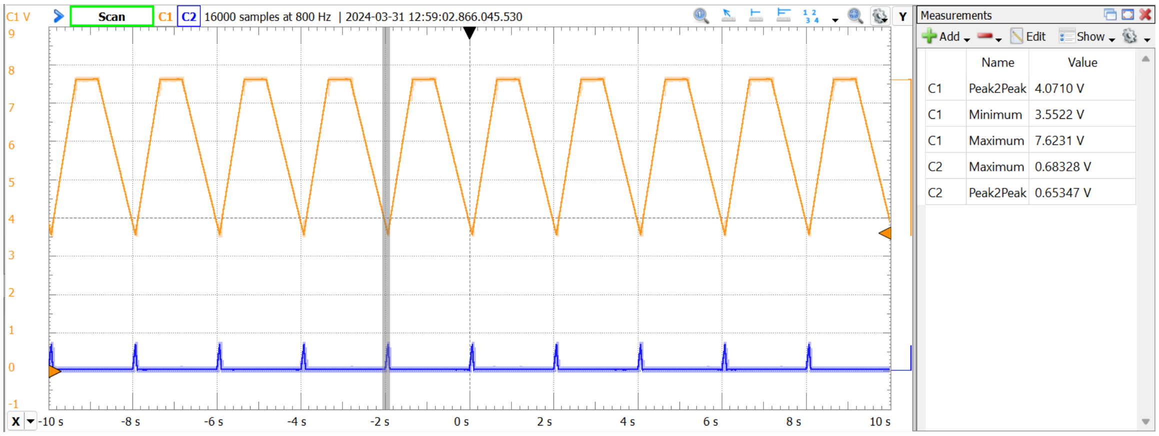
Ve (orange) and Vo (blue)



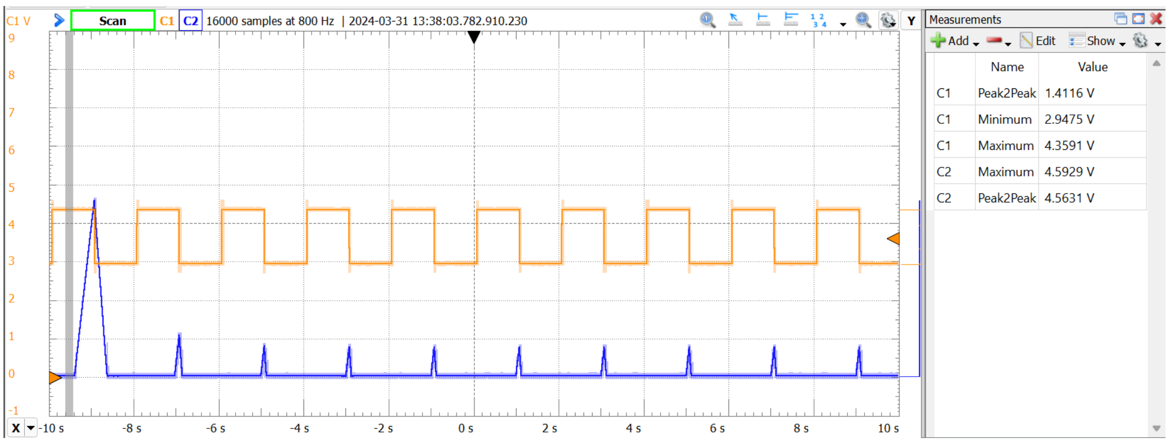
Just like in simulation, The amplitude of Ve increases, the amplitude of VI decreases, and Vo's positive duty cycle increases.

Vs = 3.2 V:

VI (orange) and Vo (Blue)

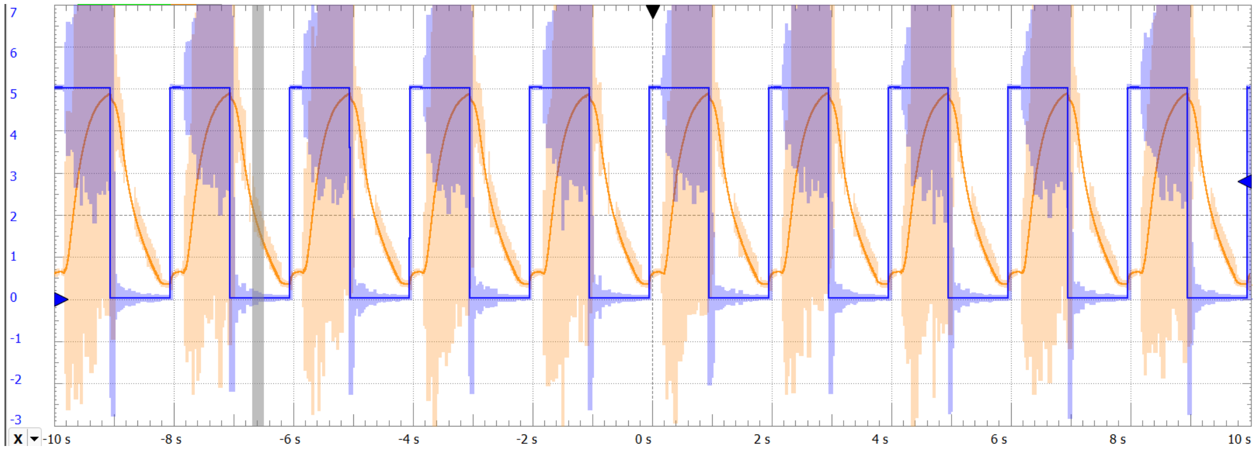


Ve (orange) and Vo (blue)



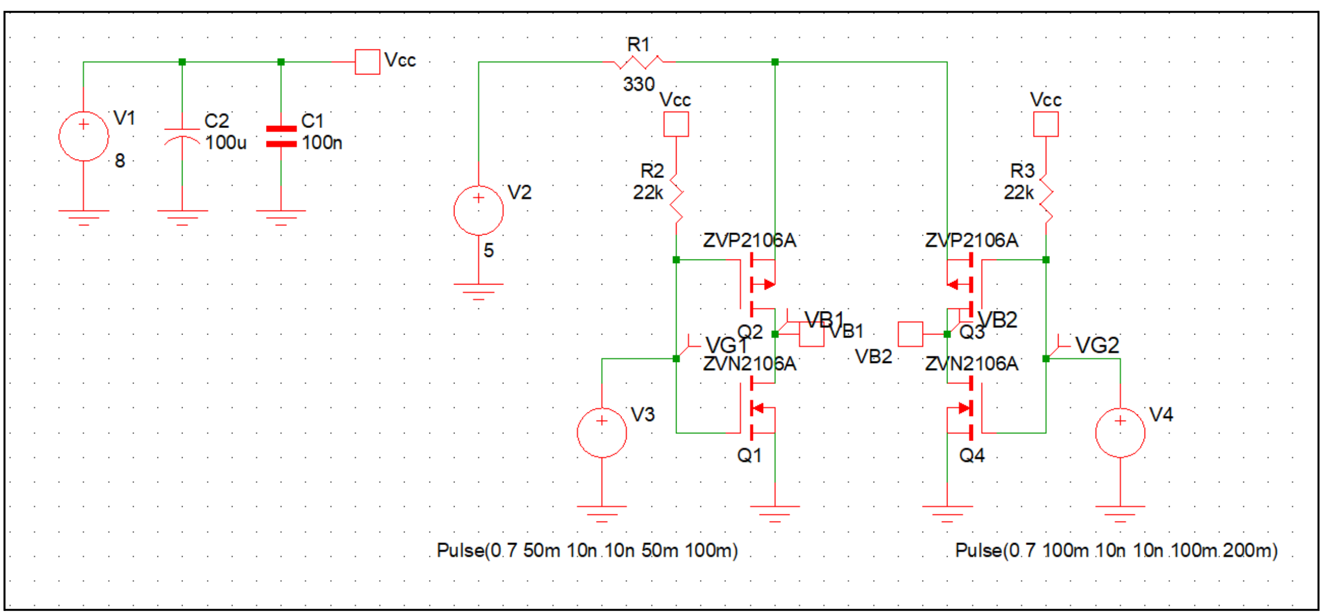
Just like in the simulation, the amplitude of Ve decreases, the amplitude of VI decreases, and Vo's positive duty cycle and Peak2Peak voltage decreases.

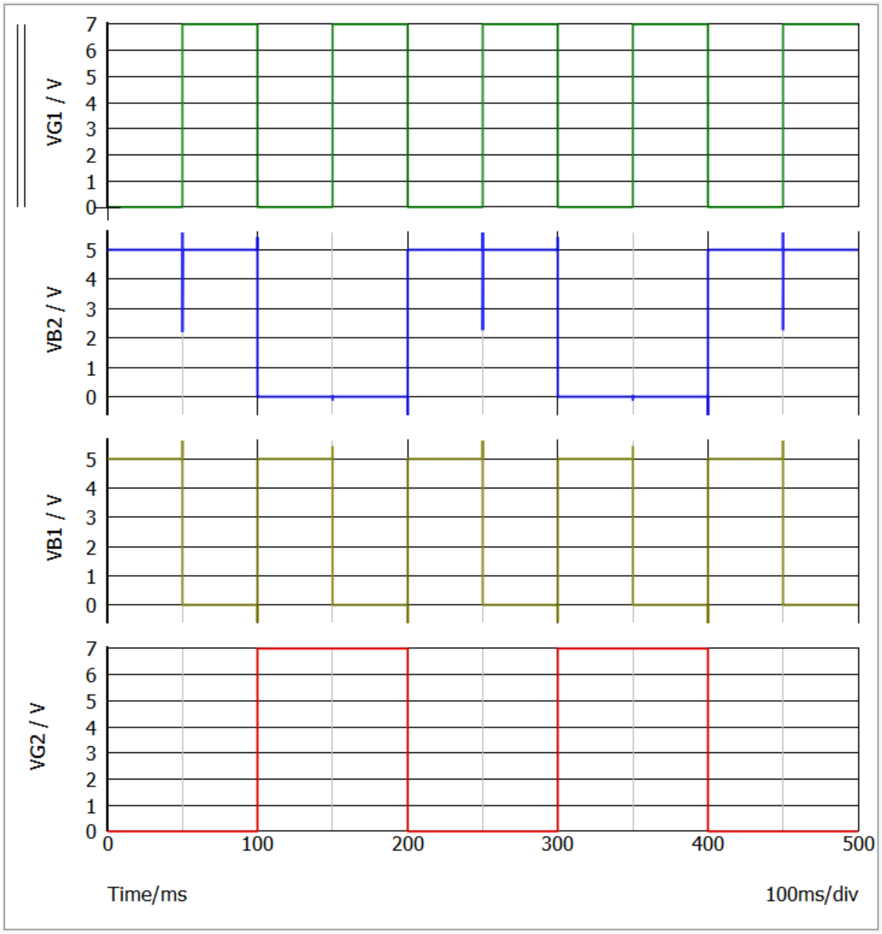
3.B.8 Test Closed-Loop with Compensator Implementation



V_s [V]	1.52	2.53	3.57	4.61	6.40
V_{ref} [V]	1.48	2.52	3.57	4.62	7.92

3.B.9 Direction Control in SIMetrix





<u>Which of the Mosfet transistors is on and which is off for the forward/backward directions?</u>

When the forward direction is activated the two Mosfet transistors on the right side of the circuit diagram are ON and the two on the left are off. On the contrary for the backward direction to be active the Mosfets on the Left are On, while the Mosfets on the right side of the circuit diagram are off.

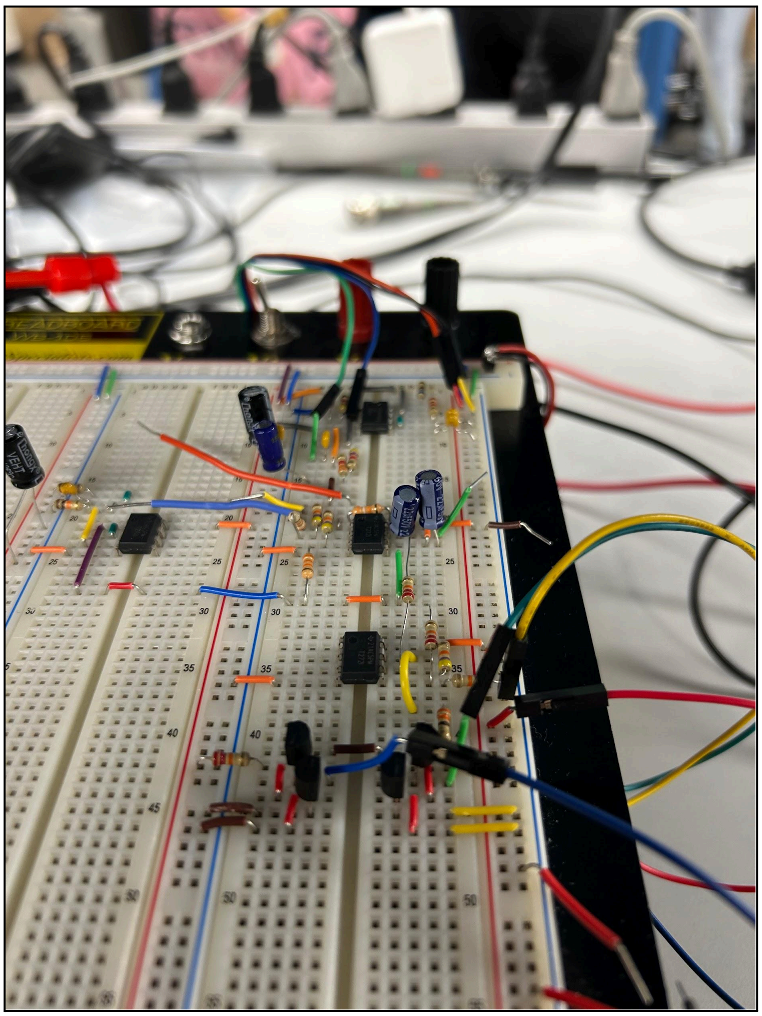
<u>Make a table that shows the relationship between VG1 (0 or 7V), VG2(0 or 7V) independent of VG1), and VB1, VB2 for V1 =5V</u>

VG1 [V]	**VG2 [V]**	VB1 [V]	VB2 [V]
0	0	5	5
	7	5	0
7	0	0	5
	7	0	0

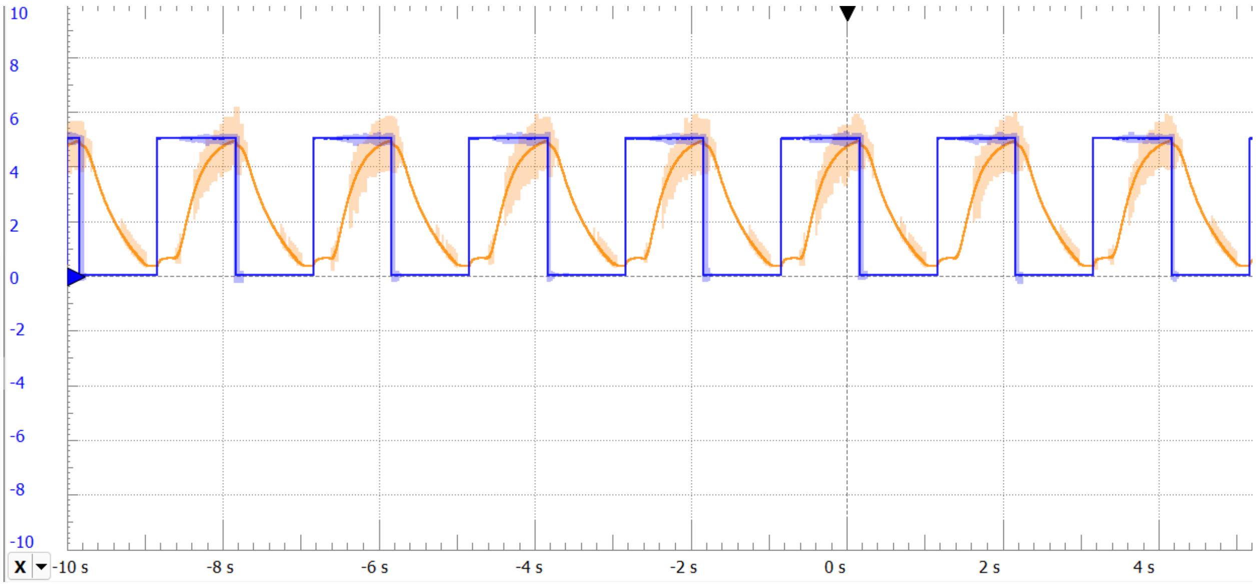
-Explain how we can test this circuit by itself when we implement it on the breadboard.

We plan to test this circuit on the breadboard by creating the circuit as seen below on the board. We will use two waveform generators to create the pulse train, and then use the power supply to supply the DC voltages. The oscilloscope will be used to probe the different voltage nodes to verify the functional operation of this direction controller. Additionally, the motors on one side of the board can be hooked up to the VB1 and VB2. This will cause the motors to spin, and we will verify they spin in the same, correct direction.

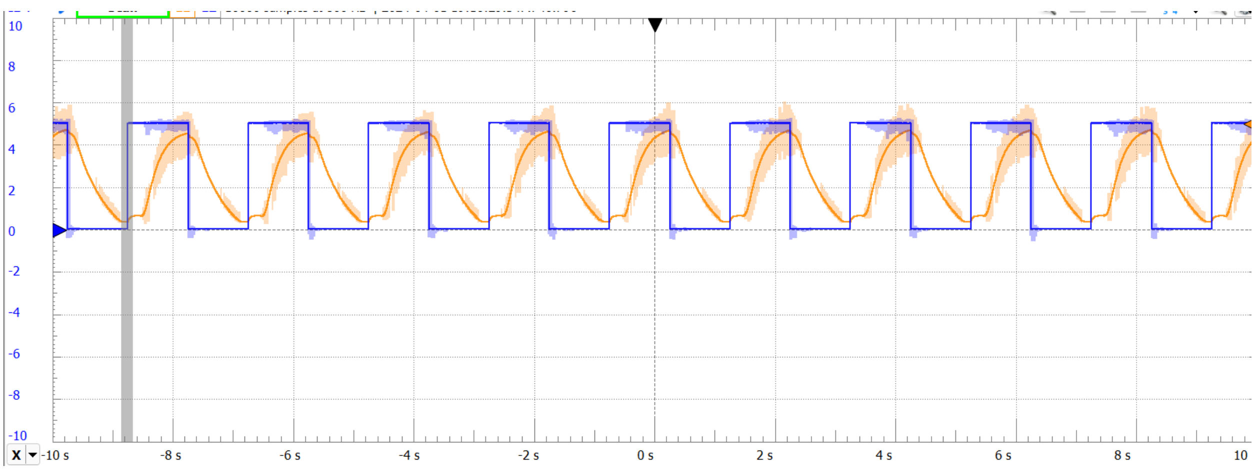
3.B.10 Add Direction Control to Closed-loop Circuit Implementation



Forward:

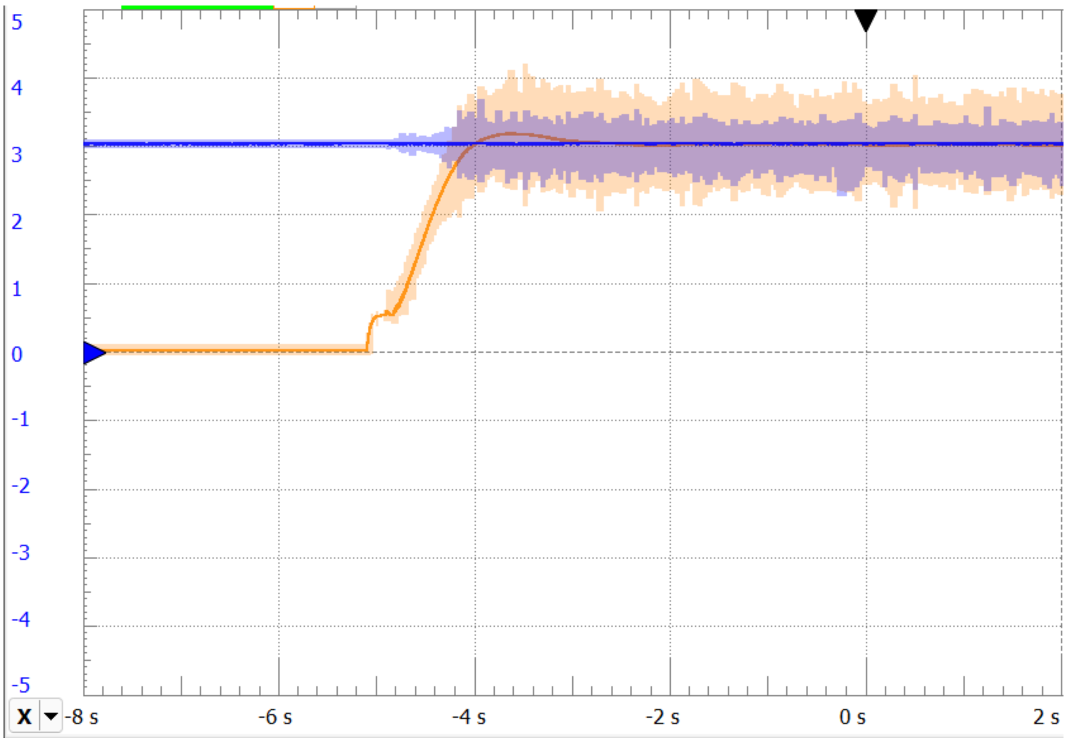


Backward:

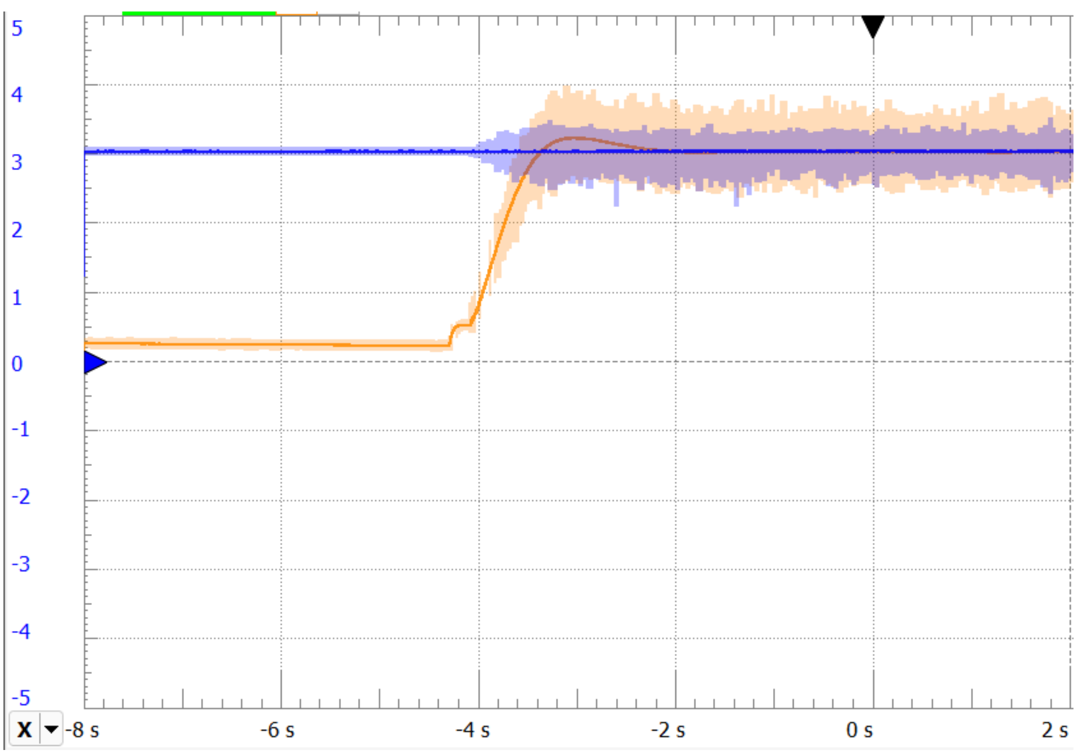


3.B.11 Test Overall Speed Control Loop Implementation

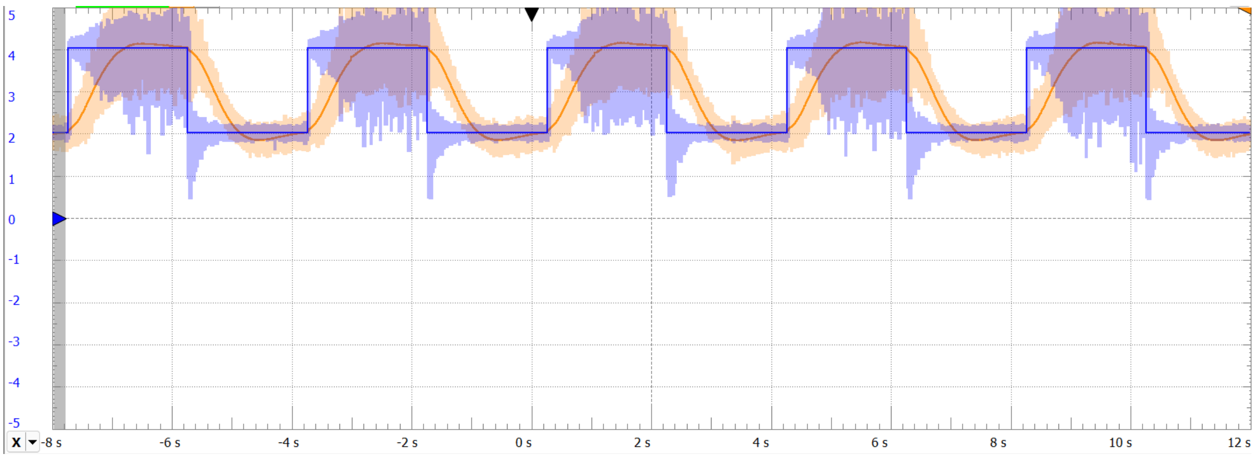
Static forward:



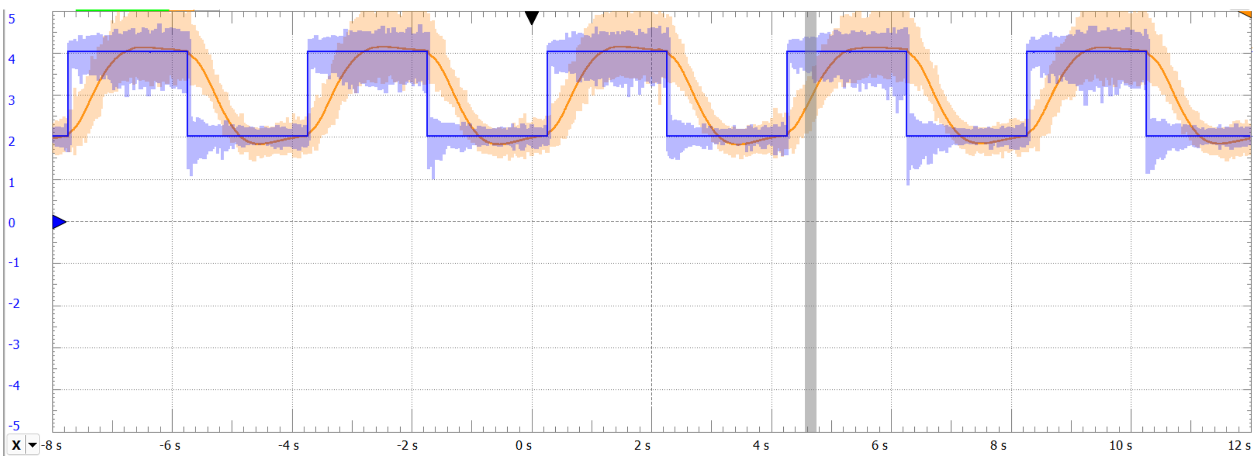
Static backward:



Dynamic forward:



Dynamic backward:



Based on our results, the overshoot is minimal and is corrected quickly meaning that our damping factor is slightly below 1 ($\zeta \approx .9$). We chose our values of RI and CI based on a damping factor equal to one, so our simulation with these values is accurate.

Conclusion

After a comprehensive exploration of electronic circuit design with a focus on feedback control systems, this lab has significantly advanced our understanding in many different types of circuit implementation. Through meticulous building, simulation, and testing of H-Bridge circuits, we successfully made effective motor driver and direction control circuits, strengthening our knowledge with transistors and how they interact. Through the building of the virtual ground, difference amplifier, and integrator circuits, we have also gained a deep insight into the complex interplay between circuit components, specifically op amps and their negative feedback. The application of both SIMetrix simulations and hands-on breadboard experimentation allowed us to validate our theoretical concepts with our true practical outcomes, which repeatedly helped us troubleshoot and understand certain aspects of the lab. It also greatly helped us ensure the reliability and functionality of our designs, and taught us the importance of simulating first, then building. In addition, the successful operation of the speed feedback control loop, which we achieved through careful adjustments, highlights the importance of being precise and paying attention to small details in electronic design. Countless problems were run into during the duration of this lab, but each was a learning experience that taught us the correct way to do things moving forward. The practical experience gained through this lab prepares us for more complex challenges moving ahead. Being a pivotal step in the construction of our car, this lab cemented many fundamental concepts and gave all of us even more confidence and skills that will be necessary for the future.

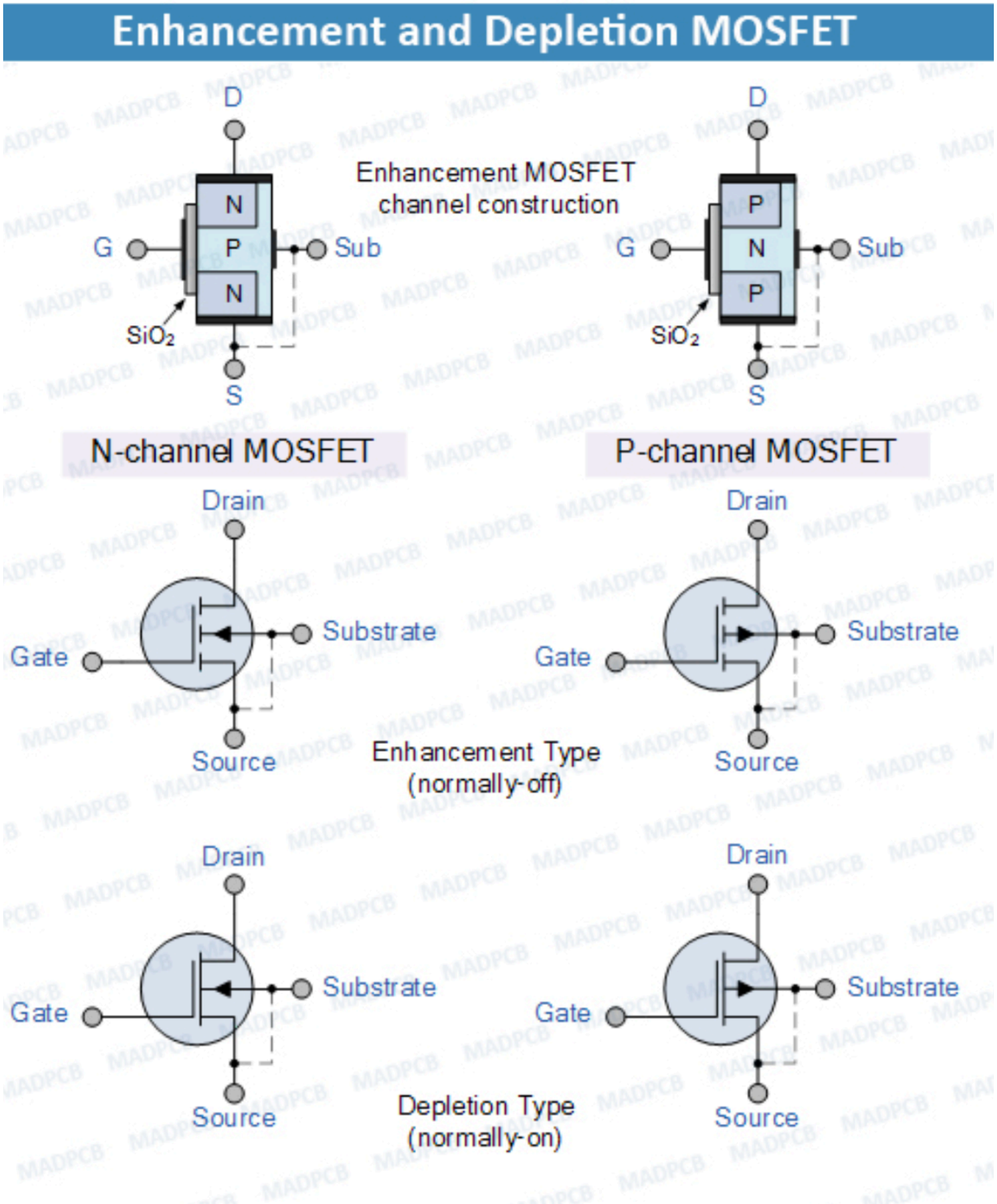
Lab Exploration Topics

Lab Exploration For Prelab A (MOSFET): Metal-Oxide-Semiconductor Field-Effect Transistors also known as MOSFETs come in a variety of types, each designed for specific applications and operating conditions.

Different Types of Mosfets:

- Depletion MOSFETs (D-MOSFETS) are designed to be naturally ON devices without any external voltage applied and conduct current. Once voltage is applied to the gate it reduces the conductivity, effectively turning off the device.
- Enhancement-mode MOSFETs (E-MOSFETs) are normally OFF devices. In that, they require a specific threshold voltage to be applied to the gate to start conducting current. They are the most common types of MOSFETs used in digital circuits.
- N Channel MOSFETs have a channel composed of N-type semiconductor material. They conduct when a positive voltage is applied to the gate relative to the source
- P-Channel MOSFETs have a channel composed of P-type semiconductor material. They conduct when a negative voltage is applied to the gate relative to the source
- Complementary MOSFETs (CMOS) are a special configuration where both N-channel and P-channel MOSFETs are used together. CMOS is commonly used in digital circuits due to its low power consumption and high noise immunity capabilities.
- Power MOSFETs are optimized for high-power applications such as motor control, power supplies, and potentially power amplifiers. They are specifically designed to handle high currents and voltages efficiently.

Schematic Symbols and Properties:



Enhancement and Depletion MOSFET

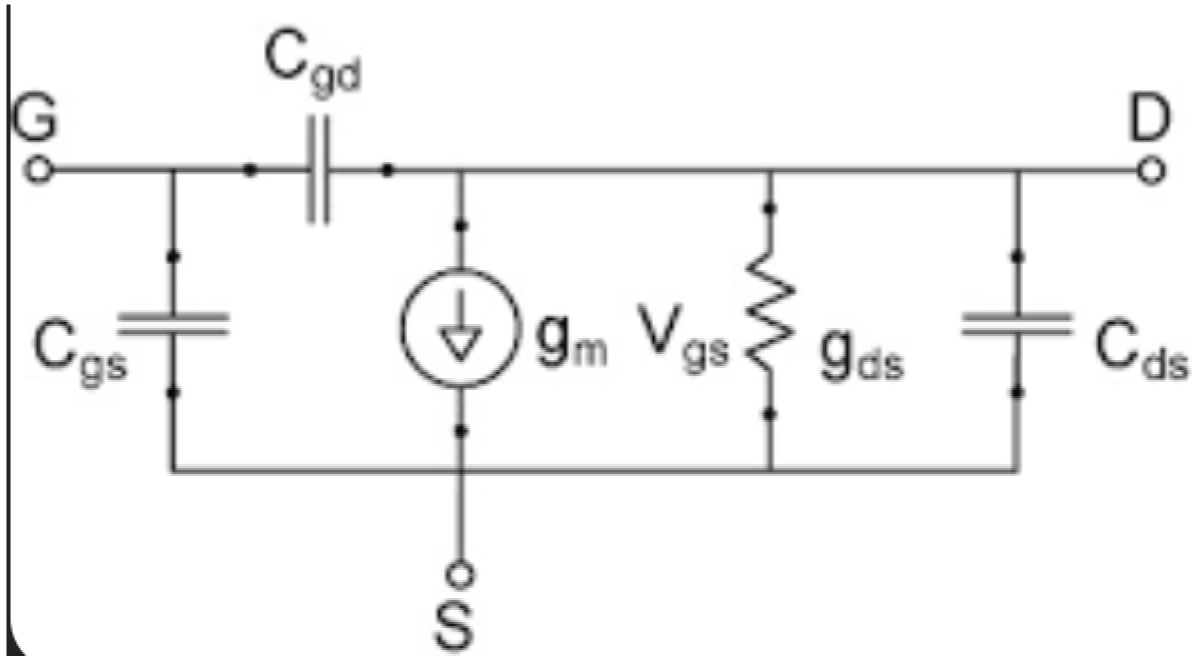
N-Channel Properties:

- Conducts when a positive voltage is applied to the gate relative to the source
- Lower resistance compared to P-channel MOSFETs

- Higher electron mobility compared to holes ultimately causing faster switching speeds

Positive Channel Properties:
- Conducts when a negative voltage is applied to the gate relative to the source
- Lower electron mobility compared to N-channel MOSFETs, resulting in effectively slower switching speeds
- Higher on-resistance compared to N-Channel MOSFETs

What they are Made From:
-Metal-oxide-semiconductor field-effect Transistors(MOSFETs) are made of several different layers of varying materials, each serving a specific purpose in their contribution to the overall operation.
-Substrate: This MOSFET is typically fabricated on a semiconductor substrate, commonly made of silicon. Other materials that could be used include Gallium arsenide (GaAs) or Silicon carbide (SiC).
-Source and Drain Regions: These are regions within the semiconductor substrate where electrical contacts are made. The source is where charge carriers enter the channel and the drain is where they exit. In an N-channel MOSFET, the source and region are covered with impurities to increase the concentration of the free electrons known as N-type doping. while in a P-channel MOSFET. They are doped with impurities to increase the concentration of "holes" also known as P-type doping.
-Channel region: MOSFET has this channel as a narrow bridge region between the source and the drain terminals where the current flows when the MOSFET is switched on. The conductivity can further be controlled by an electric field generated by the gate terminal
-Gate terminal: This terminal is separated from the channel by a thin insulating layer that prevents current flow between the gate and the channel. The gate is usually made of a conductive material, such as doped polysilicon or metal like aluminum or tungsten.
-Gate Oxide: This is an insulating layer between the gate terminal and the channel. It is typically made of Silicon Dioxide (SiO2) or a high-dielectric material in advanced MOSFETs.
-Channel Stop Implant: In modern MOSFETs, especially those fabricated using deep submicron technologies, a channel stop implant is often used to prevent the formation of unwanted channels that may arise on the surface.
-Contacts and Metallization: Metal contacts are placed in the source, drain, and gate terminals to provide electrical connections to the MOSFET. These contacts are typically made from aluminum, copper, or gold. Furthermore, metallization layers are used to interconnect various MOSFETs.



Operation Principles:

-Enhancement-Mode MOSFET: when no voltage is being applied to the gate. There is no conducting channel between the source and the drain terminals. When a positive voltage is applied (above a particular threshold)to the gate relative to the source in an N-channel MOSFET (also could be a negative voltage in a P-channel MOSFET), it creates an electric field in the channel region under the gate. This induces the electric field to attract and repel charge carriers forming a conducting channel between the source and drain terminals. This causes the MOSFET to be on, allowing current to flow between the source and drain terminals. The conductivity of the channel increases as the gate-source voltage increases beyond the threshold voltage.

-Depletion-Mode MOSFET: unlike enhancement-mode MOSFETs, depletion-mode MOSFETs have a conducting channel when no voltage is applied to the gate. When a negative voltage is applied to the gate relative to the source in an N-channel depletion mode MOSFET, it depletes the channel, reducing its conductivity. Applying a voltage with an absolute value less than the threshold voltage effectively turns on the MOSFET by reducing the depletion region, allowing current to flow between the source and drain terminals. Increasing the gate-source voltage beyond the threshold voltage further depletes the channel, reducing the conductivity and eventually turning off the MOSFET.

MOSFETs Vs BJTs:

-Structure: MOSFETs have a gate terminal separated from the channel by an insulating oxide layer, offering high input impedance and low power consumption. BJTs consist of three

semiconductor layers forming two junctions, providing high current gain but lower input impedance compared to MOSFETs.
-Operating Principle: MOSFETs operate by modulating the conductivity of the channel through an electric field controlled by the gate voltage. On the other hand, BJTs operate by modulating the conductivity of the transistor through the injection and diffusion of minority carriers controlled by the base current.
-Applications: MOSFETs are commonly used in digital circuits, power electronics, and integrated circuits. However, BJTs are commonly used in analog circuits, amplifiers, and high-power applications. Demonstrating that each component is simply unique and has several important functions for different applications.

Lab Exploration For Prelab B (Feedback Control Systems):

Common Feedback Control Systems:
-Thermostats inside of heating, ventilation, and air conditioning (HVAC) are an example of a feedback control system. It measures the room temperature adjusting the heating or cooling system to maintain the desired temperature setpoint.
-Autopilot systems also use feedback control to stabilize aircraft altitude allowing it to maintain on a route of a specified flight path. By continuously adjusting control surfaces, such as ailerons, elevators, and rudders; based on sensor feedback.
-Water level Control in Tanks utilizes control systems that regulate the level of water in tanks or reservoirs by controlling inlet and outlet valves. First sensors measure the water level, and feedback control adjusts valve openings to maintain the desired level

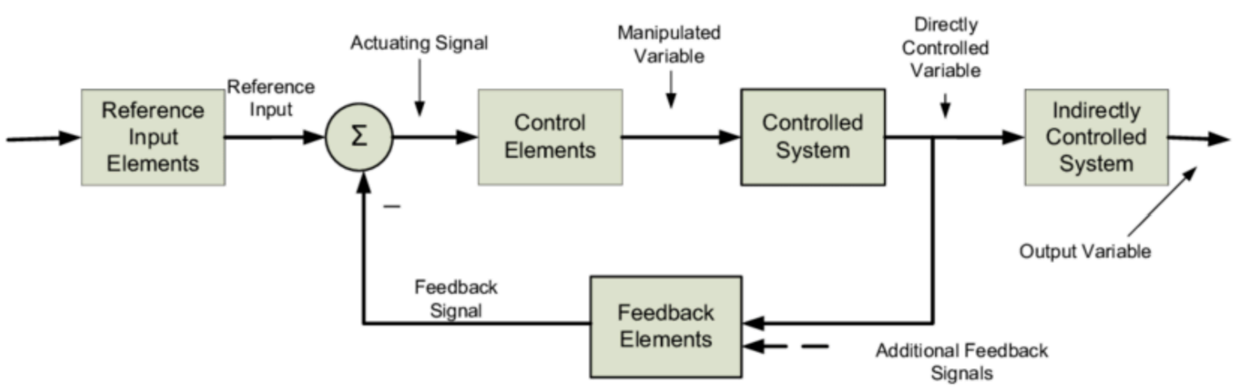
Negative Feedback systems:
The function of a negative feedback system is to maintain stability and homeostasis within a system by counteracting deviations from a setpoint or desired state. when a change occurs in the system, negative feedback mechanisms act to reverse or dampen the change, bringing the system back to its original state.

Positive Feedback Systems:
These systems differ from negative feedback systems as they family or reinforce changes in a system, driving it further away from a setpoint or equilibrium state. When a change is detected in the system positive feedback mechanisms amplify the change, leading to an increase in deviation from the original state.

Proportional Control: The proportional Control component produces an output that is proportional to the current error signal, which is the difference between the desired setpoint and the actual process variable. The proportional control alone will tend to cause oscillation around the setpoint if used independently.

Integral Control: This component integrates the error signal over time, which helps in eliminating steady-state errors in the system. The integral action is able to continuously adjust to the controller output based on the accumulated error over time. This helps eliminate any bias between the setpoint and the actual process variable.

Derivative Control: This component predicts the future behavior of the signal based on its rate of change. It produces an output proportional to the rate of change of the error signal. The derivative action contributes to the damping of the system response and improves the stability by reducing overshoot and oscillations.



The advantages of feedback control systems are that they improve accuracy and precision, because they continuously adjust the output in order to match desired values in real-time. This means that if the output at all deviates from its desired set point, the system can identify and correct the changes without any manual intervention. When built correctly, they are very reliable, stable and adaptable, and allow a system to compensate for any changes or disturbances. They correct operational processes and improve the optimization of performance overall.

The disadvantages of control systems are that they are complex and could require many components to design, oftentimes sensors and controllers. They also might introduce delays due to the time it takes to measure the error, process it, apply feedback, and repeat the cycle. This delay within the system could affect the response as well as its stability. Additionally, control systems are difficult to troubleshoot, because all parts work together simultaneously, it is hard to pinpoint an issue. Additionally, in the presence of an error, feedback loops can sometimes amplify the error, leading to an incorrect damping or overall instability.