UNIVERSITY OF COLORADO - BOULDER

ECEN 2270
ELECTRONICS LAB | SPRING 2024

ECEN 2270 Electronics Lab: Lab 2

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College of Engineering & Applied Science
UNIVERSITY OF COLORADO BOULDER

I. Experiment A

A. Exploration Topics

What are BJTs made from?

Very pure silicon, and some from germanium, but certain other semiconductor materials are sometimes used.
Reference

What different types of BJTs are there?

PNP & NPN

What are the inner workings of a BJT?

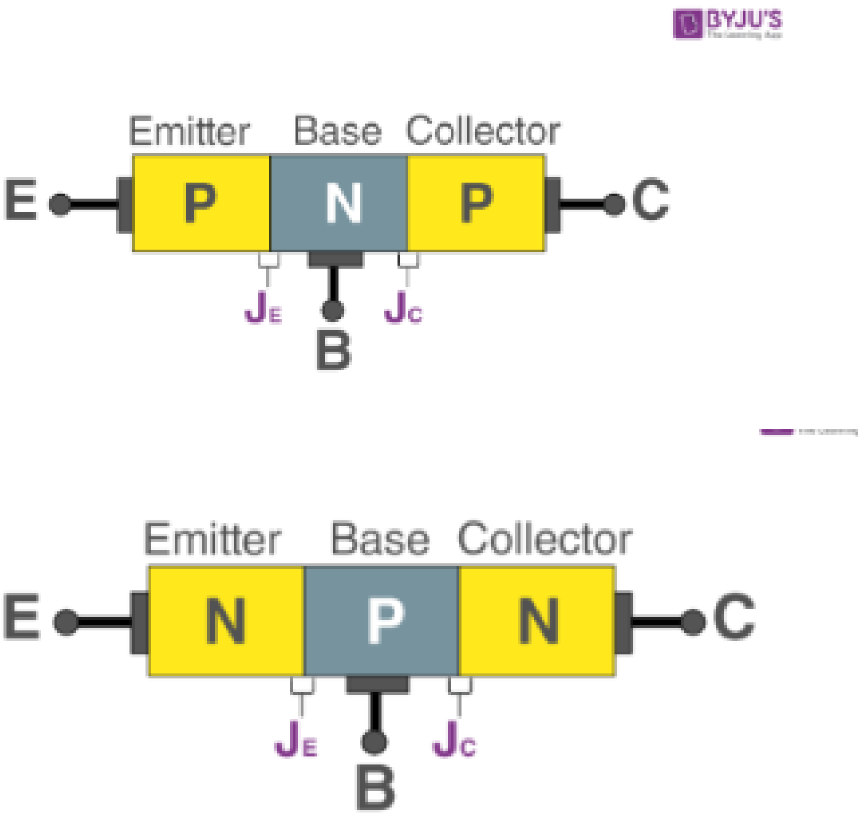


Fig. 1 PNP and NPN Transistor

When a voltage is applied across the base-emitter junction (V_{BE}) in the forward bias direction, it allows the majority carriers (electrons in NPN or holes in PNP) to flow from the emitter to the base. This creates a thin layer within the base region where majority carriers recombine with minority carriers. This layer is known as the depletion region.
Reference

What are the key electrical parameters of BJTs (in particular power transistors)?

- Type number
- Current Gain (β)
- Collector-Emitter Voltage (V_{CEO})
- Emitter-Base Voltage (V_{EBO})
- Collector-Base Voltage (V_{CBO})
- Collector current (I_C)

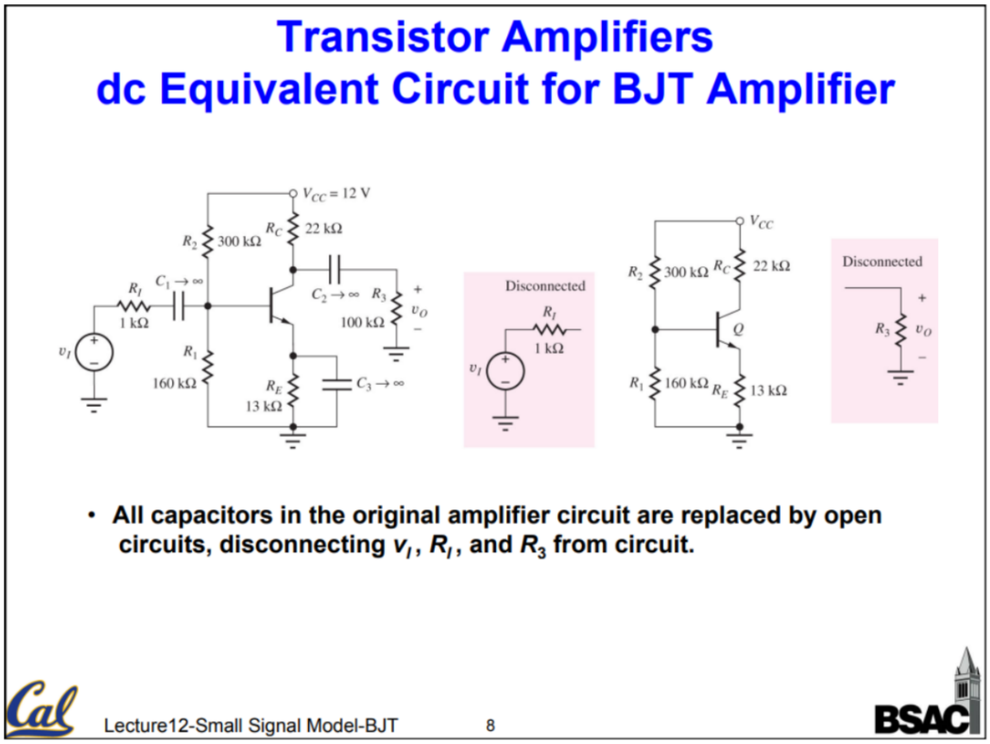
- Total Power Dissipation (P_{tot})

Reference

What are the different modes of operation of BJTs?

- Active Mode: the transistor operates as an amplifier. The base-emitter junction is forward-biased, allowing a small base current to control a much larger collector current.
- Saturation Mode: occurs when the base-emitter junction is forward-biased, and the collector-emitter junction is also forward-biased.
- Cutoff Mode: occurs when both the base-emitter junction and the collector-emitter junction are reverse-biased.

What are simple equivalent circuits used to design BJT circuits?

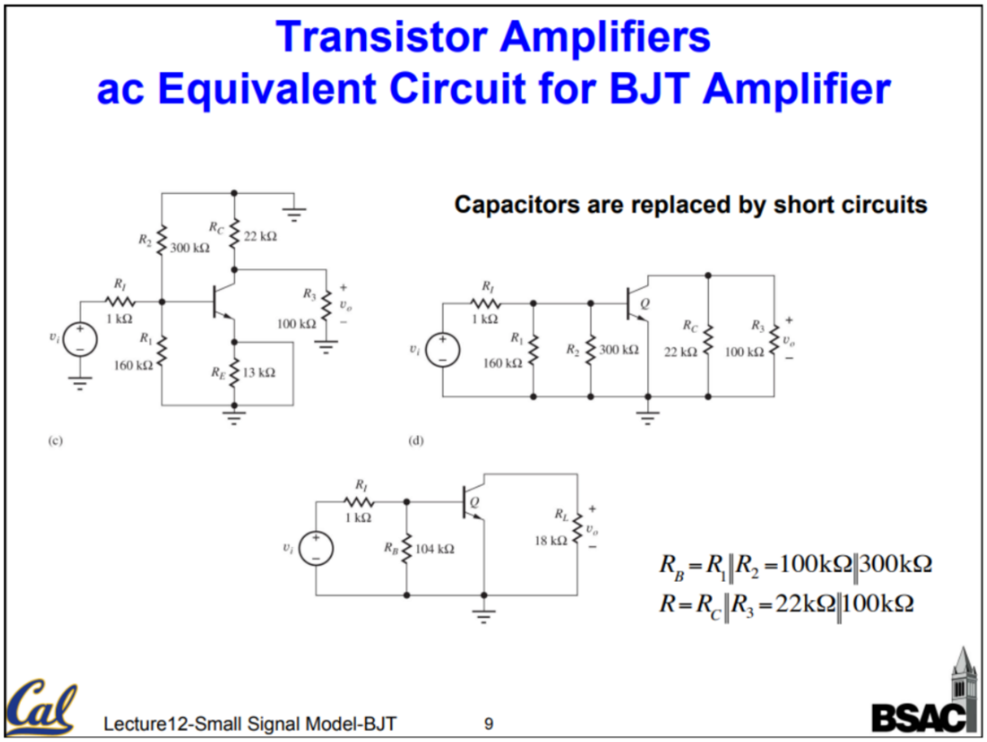


Transistor Amplifiers
dc Equivalent Circuit for BJT Amplifier

- **All capacitors in the original amplifier circuit are replaced by open circuits, disconnecting v_I, R_I, and R_3 from circuit.**

Lecture12-Small Signal Model-BJT 8

Fig. 2 Equivalent Transistor Circuit



Transistor Amplifiers
ac Equivalent Circuit for BJT Amplifier

Capacitors are replaced by short circuits

$$R_B = R_1 \| R_2 = 100\text{k}\Omega \| 300\text{k}\Omega$$
$$R = R_C \| R_3 = 22\text{k}\Omega \| 100\text{k}\Omega$$

Lecture12-Small Signal Model-BJT 9

Fig. 3 Equivalent Transistor Circuit

Reference

How does the common collector circuit work and what does it amplify?

"A common collector amplifier is a type of electronic circuit used to amplify a weak input signal. It is also known as an emitter follower, as the output voltage follows the input voltage with a slight voltage drop.

A common collector amplifier consists of a transistor with its emitter connected to ground, its collector connected to the power supply, and its base connected to the input signal. The output signal is taken from the collector, and the emitter acts as a buffer between the input and output signals. The transistor acts as a voltage follower, providing high input impedance and low output impedance."

Reference

How does the common emitter circuit work and what does it amplify?

The common emitter circuit utilizes a BJT to amplify input signals. The base-emitter junction is forward-biased, allowing a small input signal to control the much larger collector current. As the input signal modulates the base current, the transistor amplifies this variation, producing an amplified output signal across the collector load resistor. Due to the phase reversal characteristic of the amplifier, the output signal is inverted compared to the input. Proper biasing establishes the transistor's operating point for linear amplification. With its wide frequency response and high voltage gain, the common emitter circuit serves as a versatile amplifier used in various electronic applications, including audio and radio frequency amplification.

B. 2.A.2

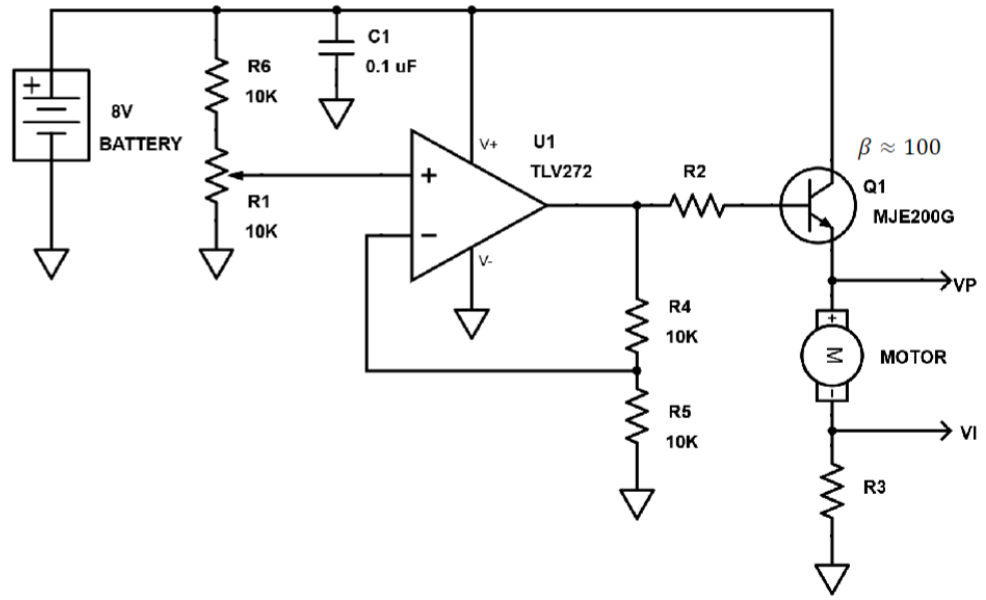


Fig. 4 Variable Voltage Circuit Schematic

This circuit is a variable voltage supply circuit. It takes a input voltage supply and uses a potentiometer to divide the voltage down to a variable value that is inputted into an Op-Amp. This Op-Amp (assuming an ideal Op-Amp) doubles the input voltage of the positive terminal. Since the potentiometer varies (ideally) from 0Ω to 10kΩ, then the Op-Amp input voltage varies from 0V to 4V and the output varies from 0V to 8V. The capacitor C_1 smooths the input voltage in the event it is subject to a non-perfect DC wave.

The transistor takes the voltage at the output of the Op-Amp and the maximum 8V input voltage and limits the current to 2A. This is done by picking a specific value of R_2. This 0A to 2A current is pushed through the motor based on the voltage at the output of the Op-Amp. Lastly, R_3 is chosen so that we may identify the current going through the motor via Ohms Law. This value is chosen to be low such that as little voltage drops across it as possible while also not exceeding the power limitations. The motor is expected to not have a voltage drop of more than 8V (assuming R_3 has no voltage drop) and a maximum current of 2A (limited via the transistor Q_1 and R_2).

The values of R_2 and R_3 are derived in **Appendix A**.

C. 2.A.3

The circuit from section 2.A.2 was implemented on the breadboard and used to vary the voltage applied to the motor in order to test and determine the motor parameters as documented in the following sections.

D. 2.A.4

V_{dc} [V]	V_i [V]
0.28	0.039
1.35	0.33
3.78	0.57

Table 1 Motor Voltages (see Figure 4)

R_m can be calculated using the equation:

$$R_m = \frac{V_{dc}}{I_{dc}} = \frac{V_{dc} R_3}{V_i}$$

Where $R_3 = 0.375\ \Omega$ and V_i is the voltage at the Emitter or voltage drop across R_3. Lastly, we plot the current through the motor (I_{dc}) against the Voltage across the motor (V_{dc}) and find the slope (which has units of V/A = Ω) to get R_m. Doing so results in a motor resistance of $R_m = 2.433\ \Omega$.

E. 2.A.5

V_{dc} [V]	V_i [A]	f_{enc} [Hz]
1.44	0.059	266
2.05	0.06	623
3.26	0.072	1020
4.37	0.098	1300
5.04	0.106	1600
5.45	0.11	1850
6.33	0.114	2050

Table 2 Motor Voltages (see Figure 4)

To determine k, B and T_{int}, we must first find k.

k can be determined via the equation:

$$k = \frac{V_{emf}}{\omega} = \frac{960(V_{dc} - I_{dc} R_m)}{2\pi f_{enc}}$$

Once we have a specified value of k, we may notice that plotting it against ω yields a relatively flat line, since this is the case, we can approximate k as the average or mean of all k values. Thus, $k = 0.5195\ \frac{Nm}{A}$.

If we plot ω against Torque ($T = kI_{dc}$), the slope of a line determined by a first order polynomial fit shall be B, and its y-intercept T_{int}. Thus $B = 0.0005$ Nms and $T_{int} = 0.0141$ Nm.

F. 2.A.6

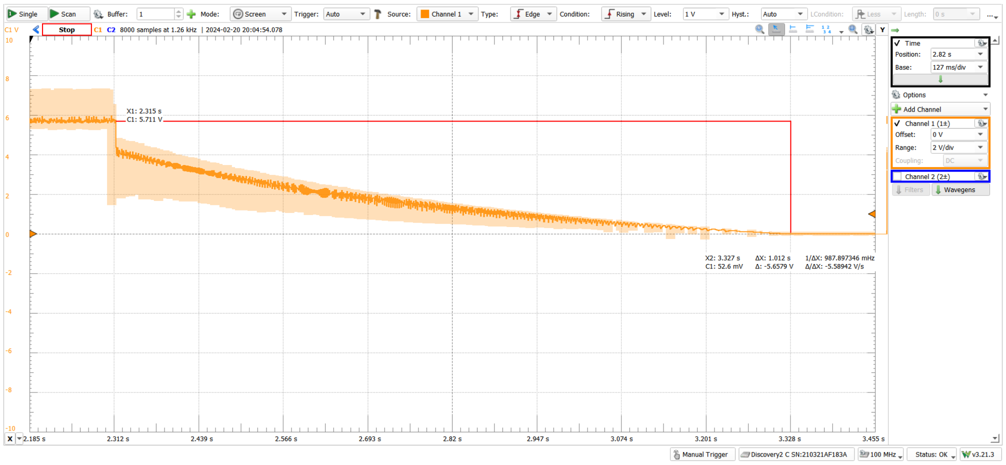

Buffer: 1
Mode: Screen
Trigger: Auto
Source: Channel 1
Type: Edge
Condition: Rising
Level: 1 V
Hyst.: Auto
LCondition: Less
Length: 0 s
8000 samples at 1.26 kHz | 2024-02-20 20:04:54.078
X1: 2.315 s
C1: 5.711 V
X2: 3.327 s
C1: 52.6 mV
ΔX: 1.012 s
Δ: -5.6579 V
1/ΔX: 987.897346 mHz
Δ/ΔX: -5.58942 V/s
Time
Position: 2.82 s
Base: 127 ms/div
Channel 1 (1±)
Offset: 0 V
Range: 2 V/div
Coupling: DC
Channel 2 (2±)
Discovery2 C SN:210321AF183A
100 MHz
Status: OK
v3.21.3

Fig. 5 Motor Spin-down Voltage (V_{dc})

When the motor supply is turned on, V_{dc} should ideally be a constant DC value. However, significant noise may be observed in the V_{dc} waveform on the scope. Why is there noise in V_{dc}? How could the noise be reduced? Hint: Consider including a large DC decoupling capacitor across V_{dc}, e.g., an electrolytic 100 µF capacitor (watch out for the polarity of the capacitor leads!)

J can be calculated using the equation:

$$J = \frac{-B\tau}{\ln\left(\frac{T_{int}}{B\omega_{max}+T_{int}}\right)}$$

Where τ is the settling time of the motor, taken from **Figure 5** in seconds, and ω_{max} is the maximum angular wheel speed before the power is removed:

$$\omega_{max} = \frac{2\pi f_{max}}{960}$$

Thus, $\tau = 1.012$ s, $\omega_{max} = 13.42\ \frac{rad}{s}$ and $J = 0.0013$ kgm^2.

G. 2.A.7

Let us first verify R_m:

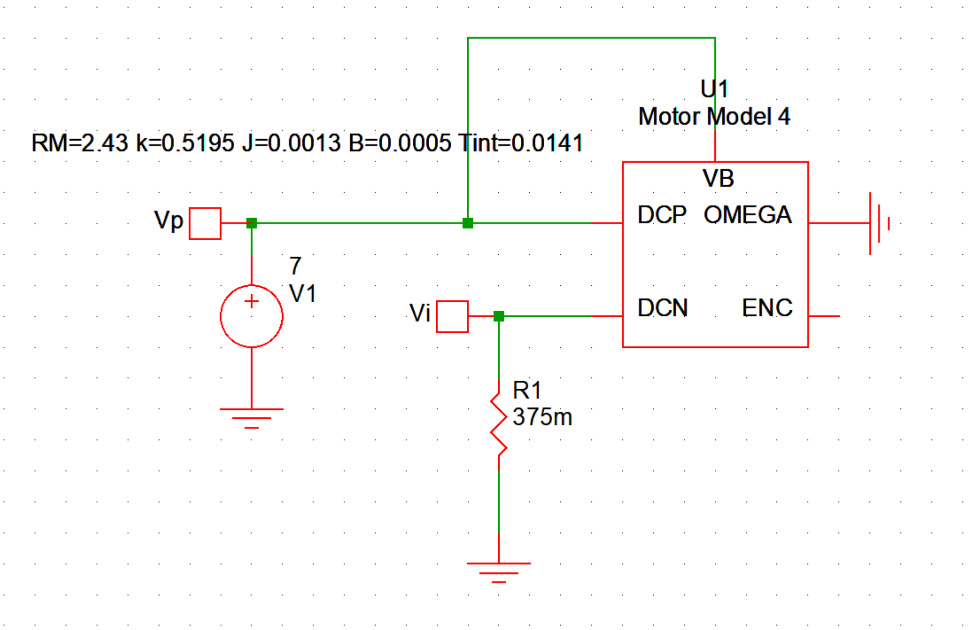


Fig. 6 Motor Resistance Verification Circuit

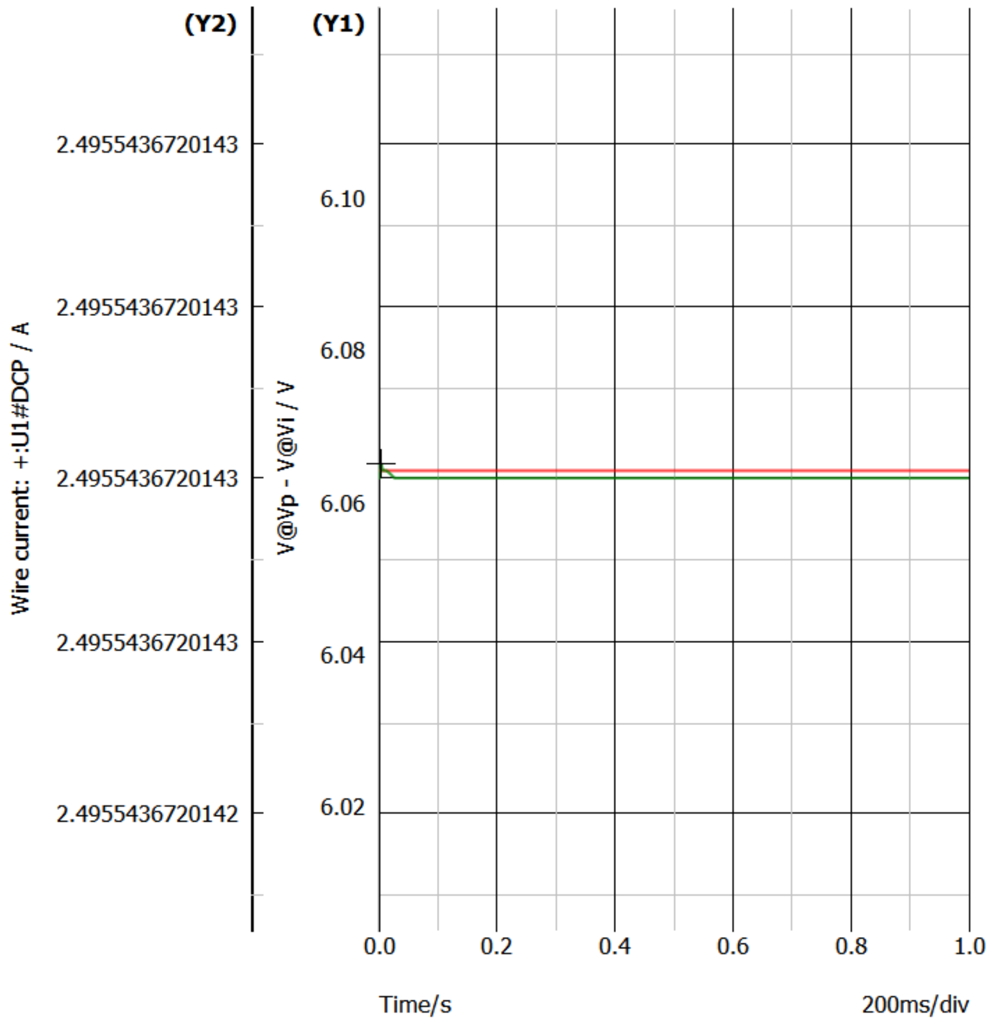


Fig. 7 Motor current and Voltage

As seen in **Figure 7**, the motor has a Voltage difference of 6.06V. When subject (without the current limiting transistor as seen in **Figure 4** to 2.5A and a (estimated) R_m of 2.43Ω, the Motor voltage difference should be 6.075 V, which is about the same value. This confirms R_m.

While k, B and T_{int} cannot be directly tested, we can validate J, which uses the values of B and T_{int}. This can be tested by confirming the spindown time of our simulated motor to be similar to our actual motor.

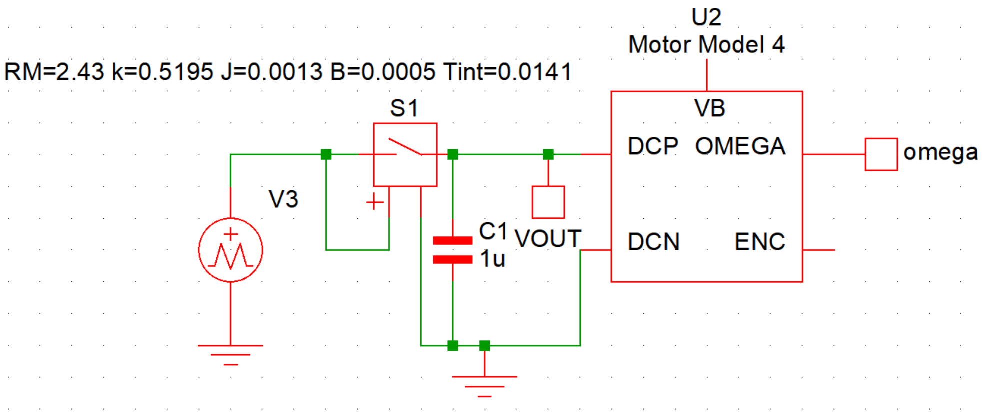


Fig. 8 Motor *J* Verification Circuit

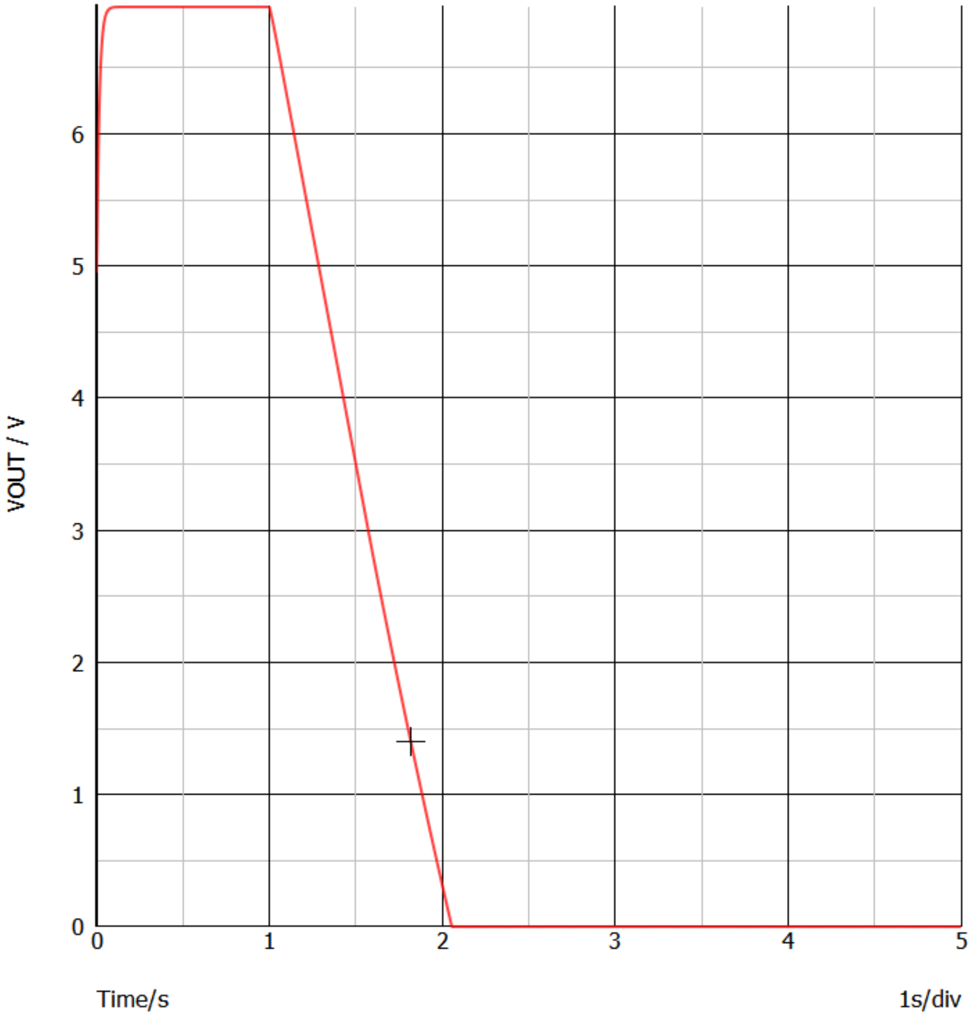


Fig. 9 Motor Back EMF Voltage

As seen in **Figure 9**, the spindown time of our motor is 1.05 s, similar to our estimated τ from **Figure 5**. This confirms our J value.

II. Experiment B

A. Exploration Topics

How should R_1 be chosen in relation to R_T and how should R_1 chosen in relation to R_{in}? If the requirements for the two cases are conflicting, what compromise should be chosen? How do the values of R_T and R_{in} affect τ_1?

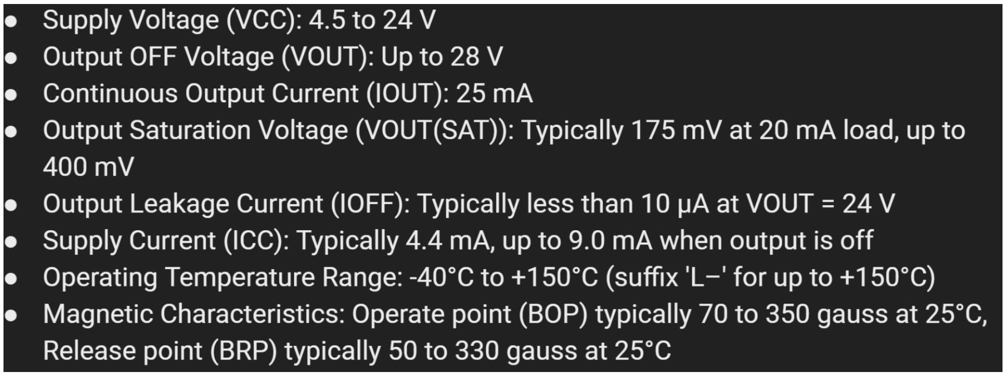
We know that $R_T \ll R_{in}$ and that τ_1 needs to equal R_1C_1. When choosing R_1 with the idea of τ_1 in mind, it is clear that $R_1 > R_T$ so that R_1 is the major control of the current through the entire circuit. $R_T \ll R_{in}$ shows that $R_1 < R_{in}$, which makes sense because we want current to travel through C_1 rather than R_{in}. If requirements for R_T and R_{in} exist, compromises to our ideal R_1 choosing strategy must change. For example if R_T is large, R_1 would need to decrease from ideal to keep the current consistent as seen by C_1. If R_{in} is small, R_1 would need to increase from ideal to balance the charging and discharging process of C_1. R_T and R_{in} modify the equivalent resistance seen by C_1, R_T out of line increases the time constant, R_{in} out of line decreases the time constant.

How should C_1 be chosen in relation to C_{in}? How does C_{in} affect τ_1?

C_1 and C_{in} are in parallel and their cumulative capacitance has to be taken into consideration to make sure the time constant is unaffected. If $C_1 \gg C_{in}$, then C_{in} will have a minimal effect on the time constant, whereas if $C_1 \ll C_{in}$, then the time constant will increase due to the increased total capacitance assuming C_1 remains the same across both cases. C_1 affects τ_1 by its ability to increase the time constant thus slowing the response to changes in voltage across the circuit.

In the context of the trigger circuit for Experiment 2.B, what is the source and what are its parameters? What is the load, and what are its parameters? Hint: Look at the data sheets of the A3144 Hall Effect Sensor and the LMC555 Timer.

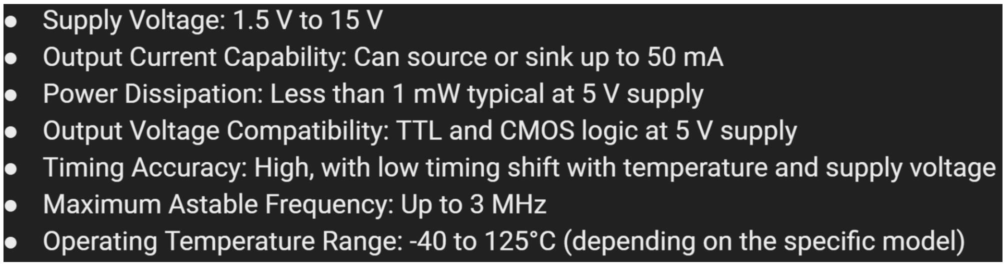
The source is motor outputting signals through the encoder due to the hall effect sensor.



- Supply Voltage (VCC): 4.5 to 24 V
- Output OFF Voltage (VOUT): Up to 28 V
- Continuous Output Current (IOUT): 25 mA
- Output Saturation Voltage (VOUT(SAT)): Typically 175 mV at 20 mA load, up to 400 mV
- Output Leakage Current (IOFF): Typically less than 10 µA at VOUT = 24 V
- Supply Current (ICC): Typically 4.4 mA, up to 9.0 mA when output is off
- Operating Temperature Range: -40°C to +150°C (suffix 'L–' for up to +150°C)
- Magnetic Characteristics: Operate point (BOP) typically 70 to 350 gauss at 25°C, Release point (BRP) typically 50 to 330 gauss at 25°C

Fig. 10 **Source**

The load is the LMC555 timer.



- Supply Voltage: 1.5 V to 15 V
- Output Current Capability: Can source or sink up to 50 mA
- Power Dissipation: Less than 1 mW typical at 5 V supply
- Output Voltage Compatibility: TTL and CMOS logic at 5 V supply
- Timing Accuracy: High, with low timing shift with temperature and supply voltage
- Maximum Astable Frequency: Up to 3 MHz
- Operating Temperature Range: -40 to 125°C (depending on the specific model)

Fig. 11 **Load**

In the case where C_1 is being charged and discharged through R_1 (as is the case for the 555 'one-shot' timer circuit), how does R_1 affect the maximum current drawn by the circuit? What if C_1 is a 'leaky' capacitor, e.g., with a parallel resistance of 1MΩ? How do these considerations constrain the choice of R_1?

A smaller R_1 will allow more current to flow, while a larger R_1 will limit the current. The presence of the leak means that even when C_1 should not be charging or discharging, a small amount of current will still flow out of C_1. This leak results in a decreased time constant. This constrains the choice of R_1 because if R_1 is too high the leak would dominate the charging and discharging process. If R_1 is too low, the LMC555 timer properties as stated in problem 3 may be exceeded and cause breakage within the circuit.

B. 2.B.2

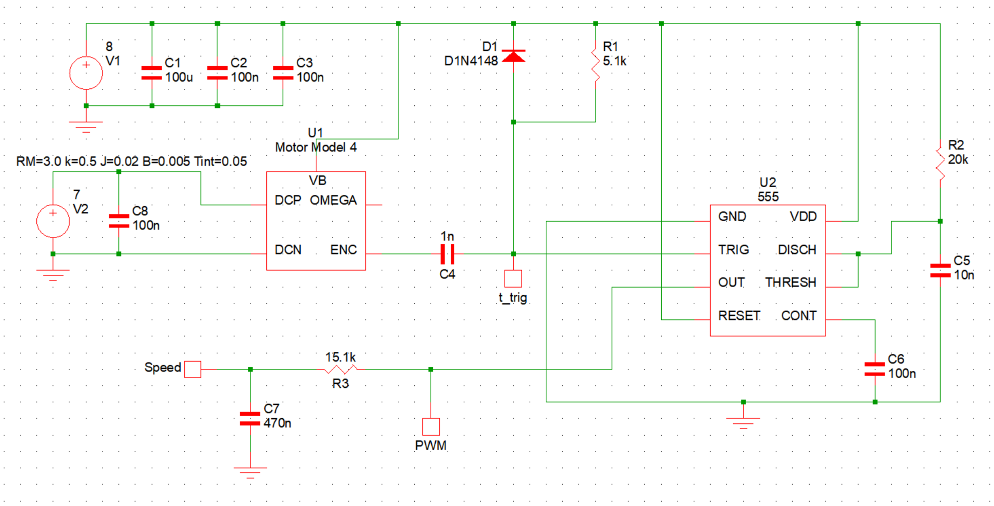


Fig. 12 Speed Sensor Circuit Schematic

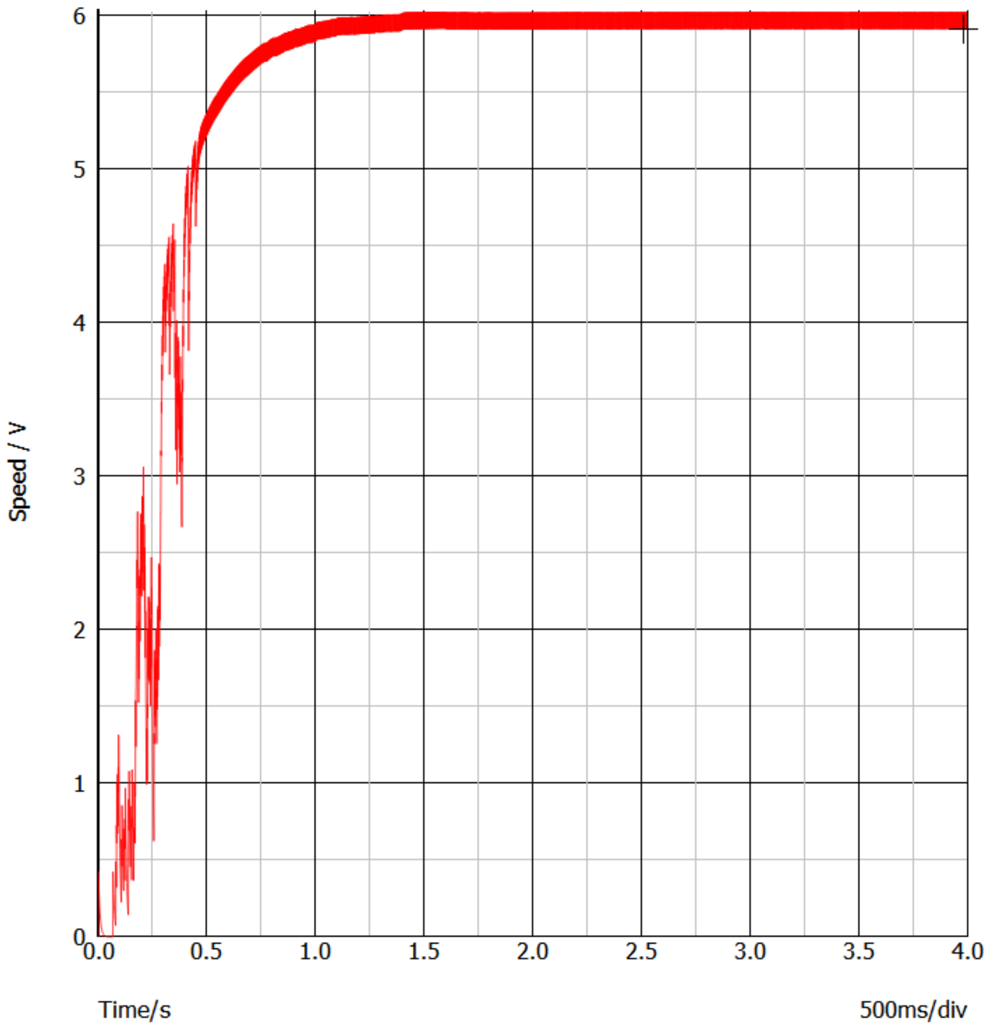


Fig. 13 Speed Sensor Output Voltage

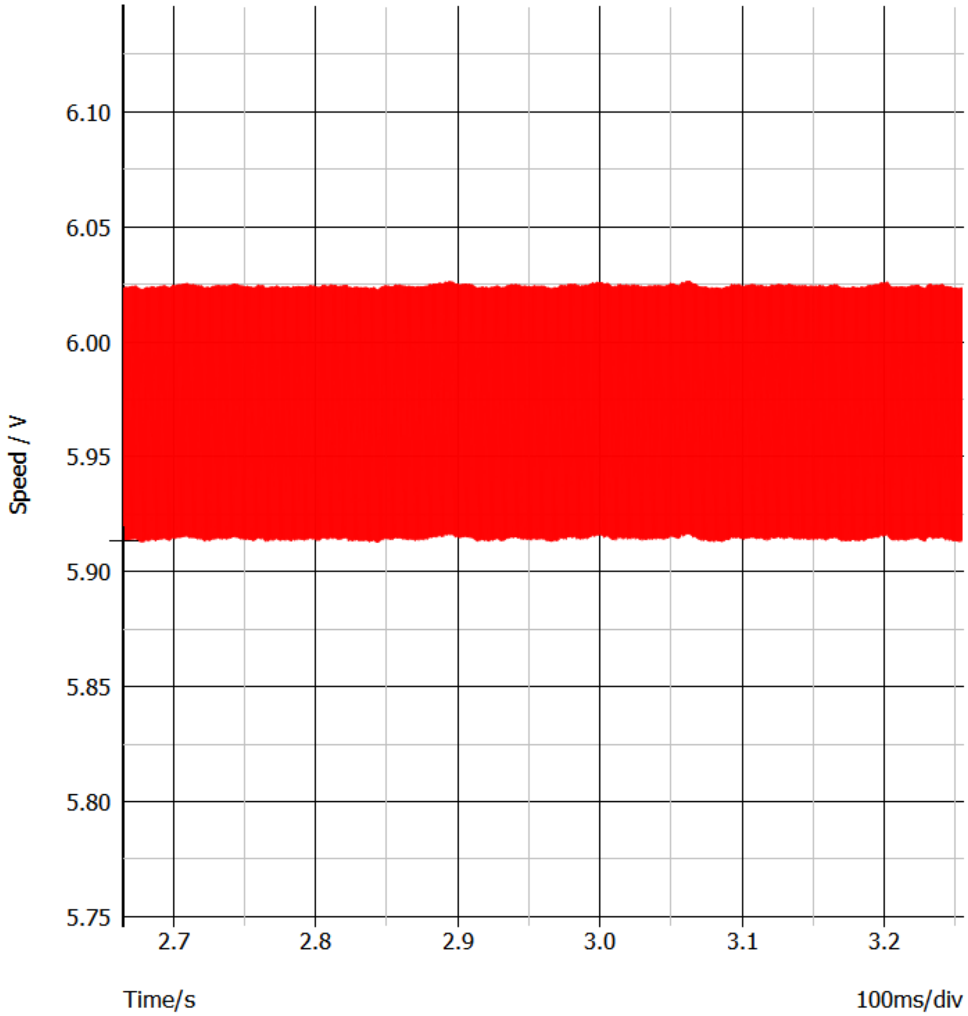


Fig. 14 Speed Sensor Output Peak-to-Peak Voltage

As seen in **Figures 13 and 14**, we average to about 6V as expected (and verified in a later section) and have a ripple voltage of about 100mV (less than the max allowed value of 300mV).

C. 2.B.3

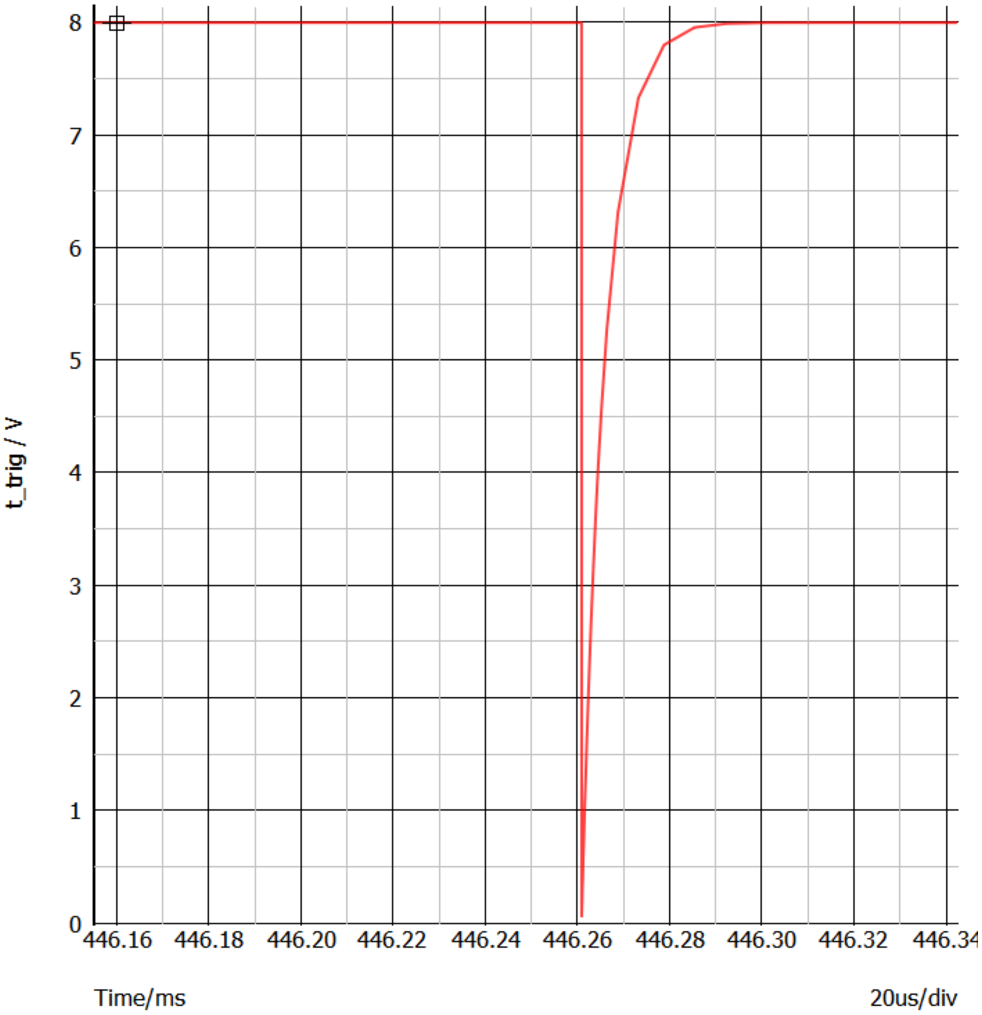
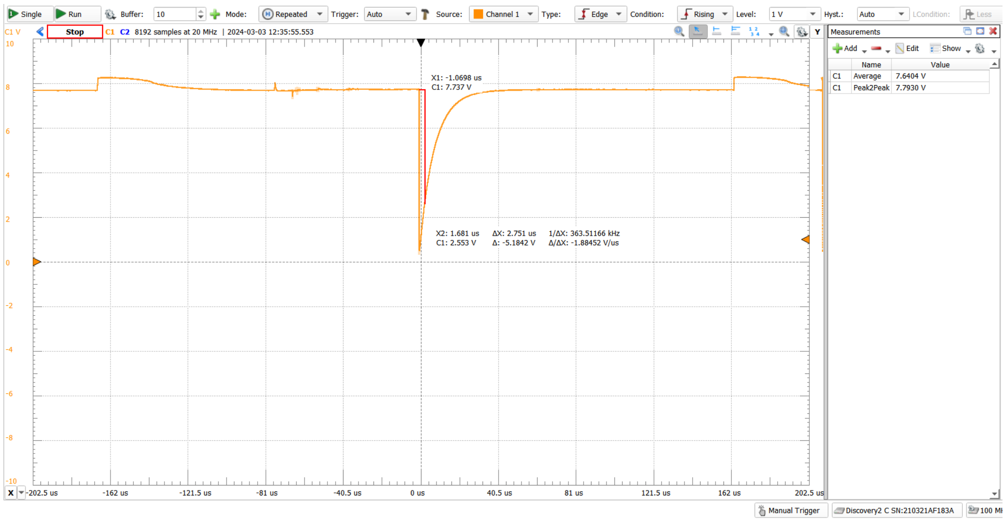


Fig. 15 Simulated t_{trig}



Buffer: 10
Mode: Repeated
Trigger: Auto
Source: Channel 1
Type: Edge
Condition: Rising
Level: 1 V
Hyst.: Auto
LCondition: Less

8192 samples at 20 MHz | 2024-03-03 12:35:55.553

X1: -1.0698 us
C1: 7.737 V

X2: 1.681 us
C1: 2.553 V

ΔX: 2.751 us
Δ: -5.1842 V

1/ΔX: 363.51166 kHz
Δ/ΔX: -1.88452 V/us

Measurements

	Name	Value
C1	Average	7.6404 V
C1	Peak2Peak	7.7930 V

Discovery2 C SN:210321AF183A

Fig. 16 **Experimental t_{trig}**

Method	Time [µs]
Simulated	2.05
Experimental	2.75

Table 3 **t_{trig} times for the Simulation and Experiment**

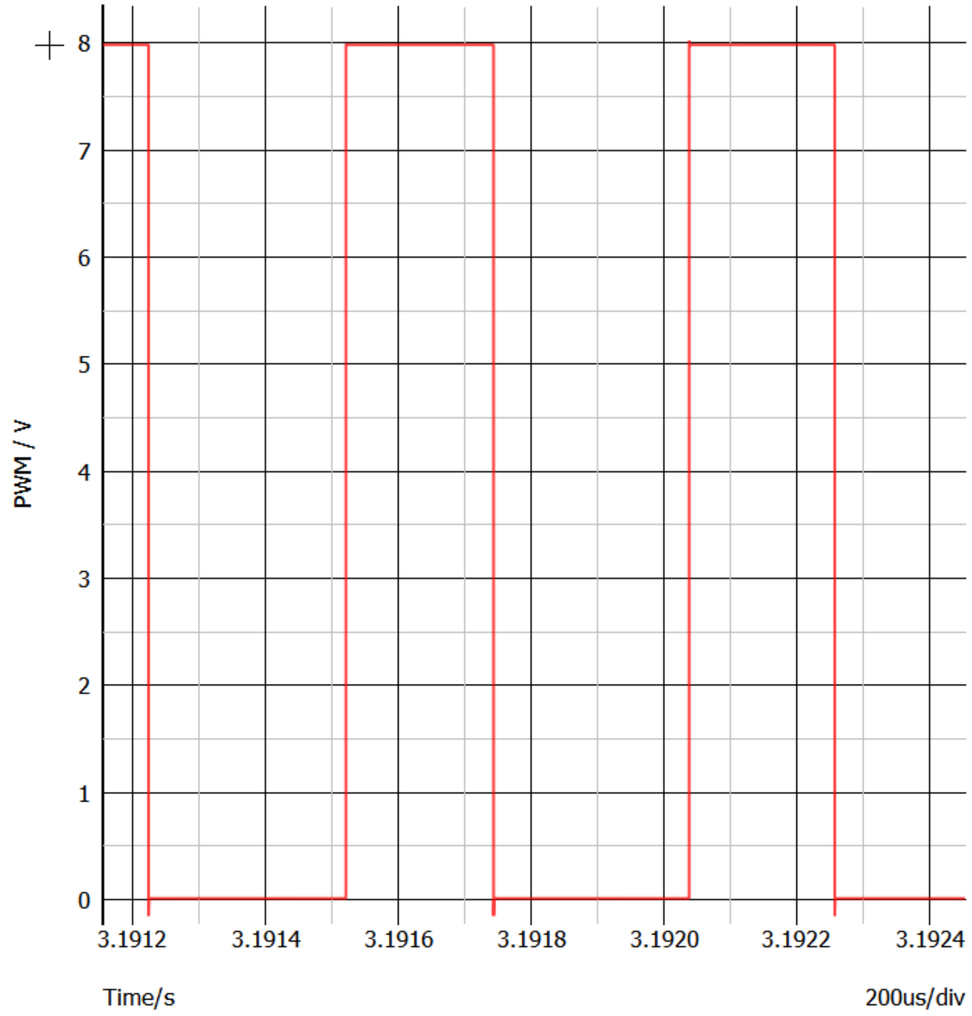
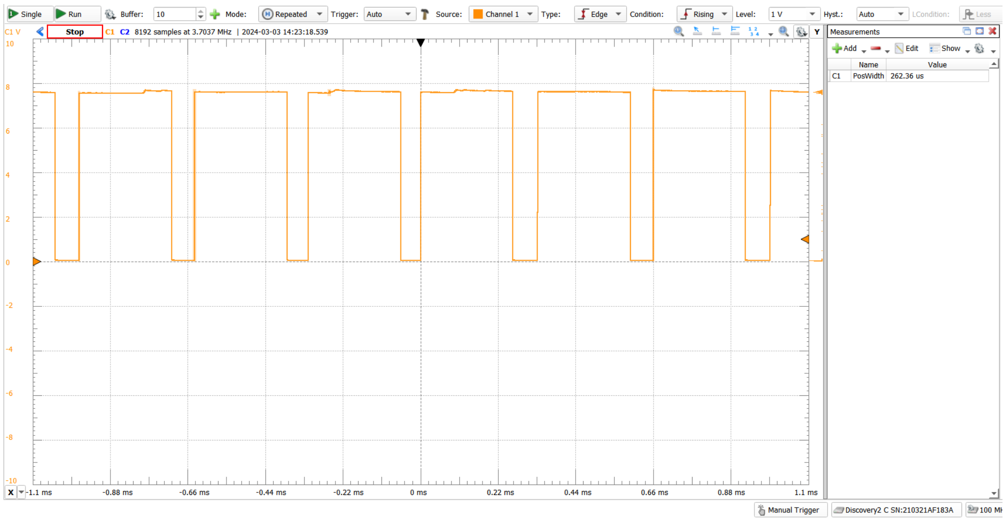


Fig. 17　Simulated t_{on}



Buffer: 10　Mode: Repeated　Trigger: Auto　Source: Channel 1　Type: Edge　Condition: Rising　Level: 1 V　Hyst.: Auto　LCondition:

8192 samples at 3.7037 MHz | 2024-03-03 14:23:18.539

	Name	Value
C1	PosWidth	262.36 us

Discovery2 C SN:210321AF183A

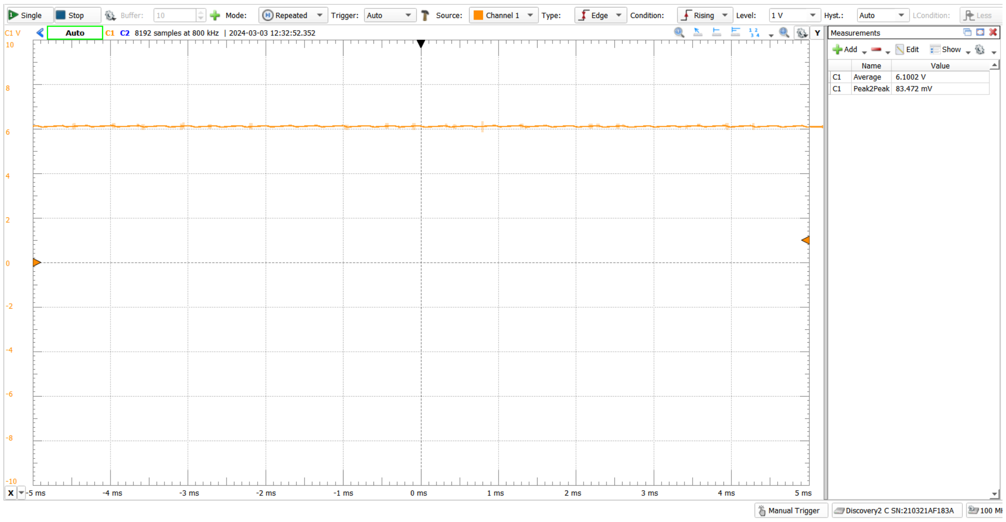
Fig. 18　Experimental t_{on}

Method	Time [μs]
Simulated	222.4
Experimental	262.4

Table 4 t_{on} **times for the Simulation and Experiment**

As required, both the simulated and experimental t_{trig} were greater than 1 μs and a lot less than t_{on}.

D. 2.B.4



Mode: Repeated
Trigger: Auto
Source: Channel 1
Type: Edge
Condition: Rising
Level: 1 V
Hyst.: Auto

8192 samples at 800 kHz | 2024-03-03 12:32:52.352

	Name	Value
C1	Average	6.1002 V
C1	Peak2Peak	83.472 mV

Fig. 19 Experimental V_{pp} Ripple Voltage

As seen in **Figure 19**, the speed sensor settles to about 6V with a ripple voltage of about 83.5mV. These values meet the requirements instated above and are similar to the simulated results.

E. 2.B.5

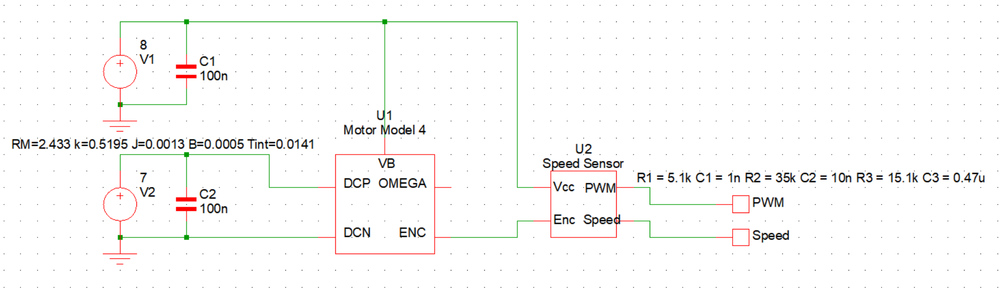


Fig. 20 Circuit Schematic

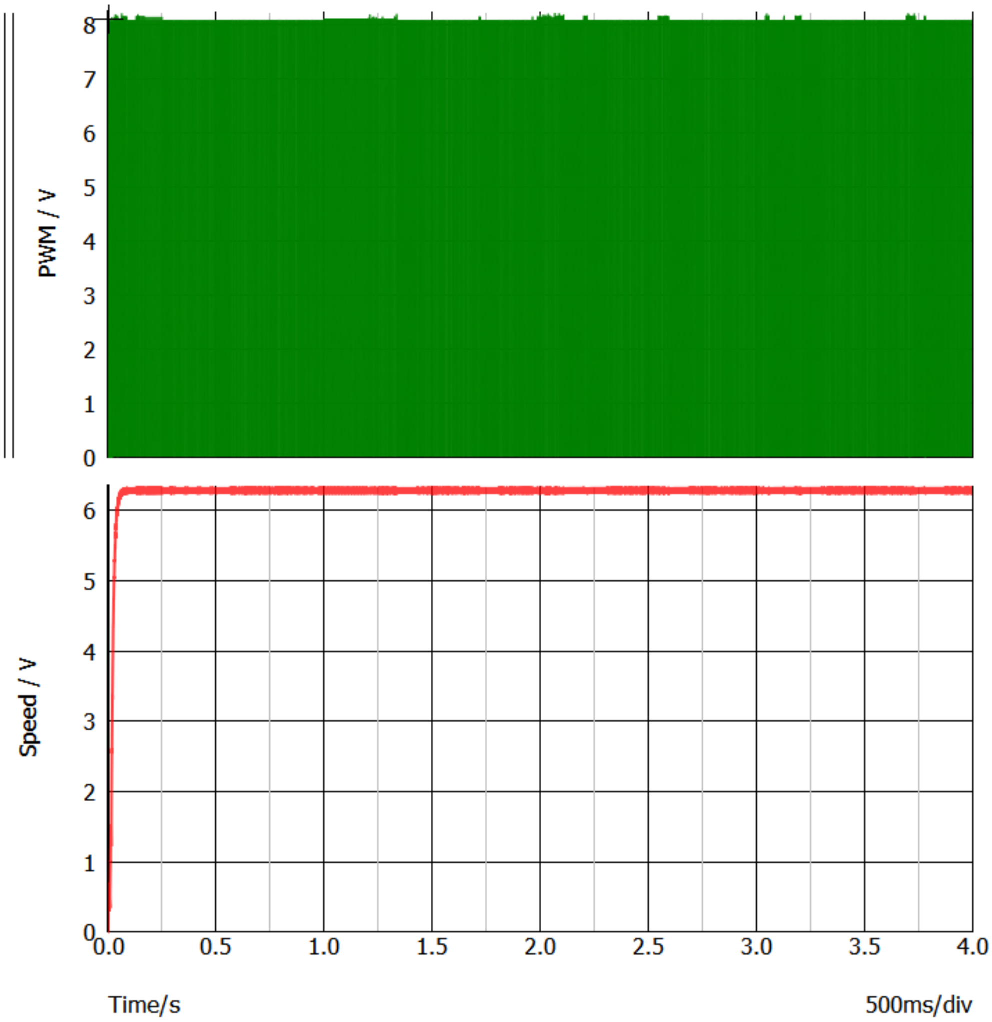


Fig. 21 Voltage and PWM Signals

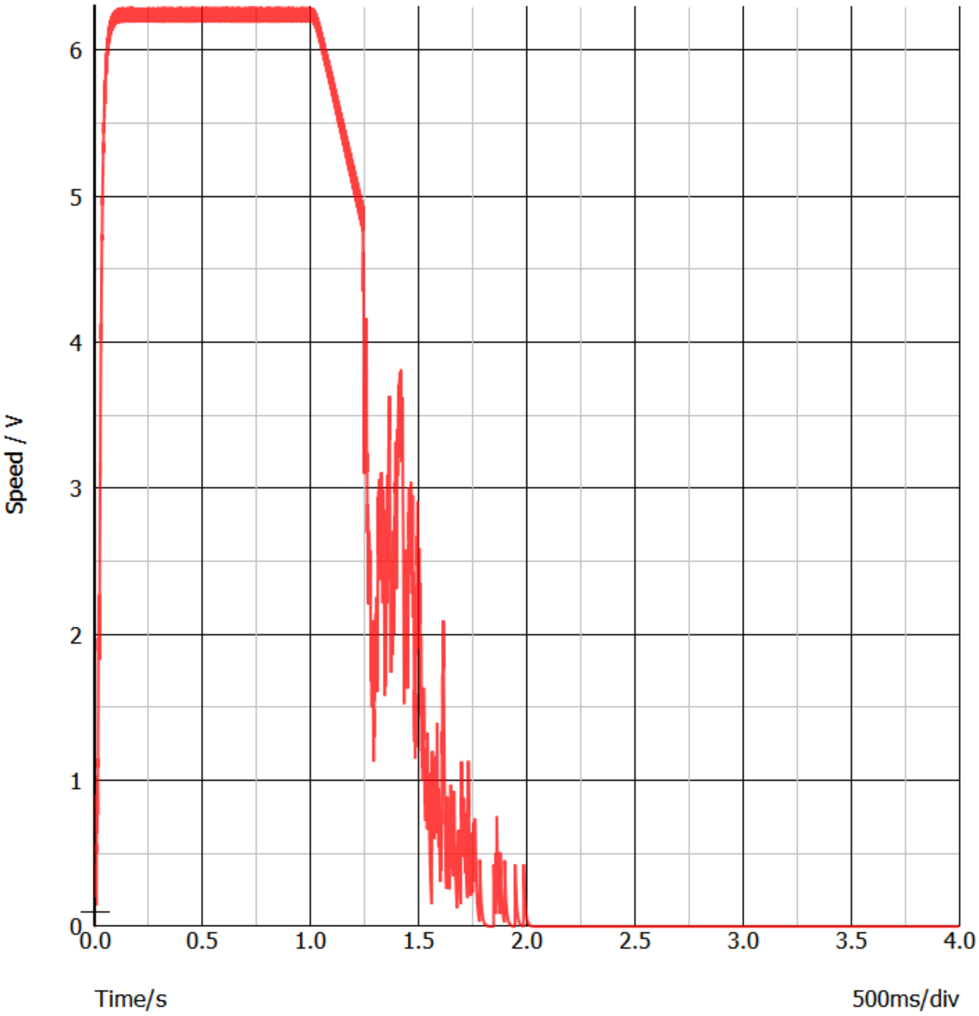


Fig. 22 Voltage Transient Fall

All values and graphs are similar to those seen earlier in this lab and their behavior is generally expected.

Not many inconsistencies existed between the LTspice model and the actual hardware circuit. One small issue came to light in the simulated model, that being the inconsistencies in R_2 for the model. The experimental hardware worked fine as expected with the R_2 = 20kΩ (as seen in **Figure 19**). However, the simulated model appeared to behave quite differently when the same R_2 value was used. In order to rectify this issue, R_2 was change to 35kΩ in the simulations and that result modelled the real system more closely as expected. We were not able to identify the cause of this problem as all simulated circuit schematics are correct (as far as we can tell). This means that (rather expectantly) the simulated circuit is not perfect and a designed should use a simulator only sparingly and not for high level processes as well as rely moreso on hardware for component output validation and testing.

III. Conclusion

The topic of this lab is to be able to design a variable voltage supply for motor parameter testing and a speed sensor for defining a voltage value for the speed of the motor.

For the variable voltage supply, we used an Op-Amp with a gain of 2 to vary the input voltage via a potentiometer and inputted that into a transistor. The transistor limits the current through the motor for safety. Lastly, the values of R_2 and R_3 were determined to meet the conditions we required. Their values are derived in **Appendix A**.

The second part of the lab is aimed at designing a circuit that takes the radial frequency of the motor and converts it into a variable voltage value between 0V and 6V that represents the speed of the motor and can be used for various applications. This is achieved by using a 555 Timer to trigger the circuit when the PWM encoder frequency experiences a falling edge and outputs a second PWM signal with a variable frequency. Using a Low Pass Filter and attenuating all resonant frequencies but the fundamental one, we can output a variable voltage that is essentially a Digital to Analogue value representing the speed of the motor. The values of these resistor and capacitor values were derived in **Appendix B**.

The aim of this lab was to be able to design multiple parts of a circuit in order to meet a specific purpose (primarily time requirements). The circuit built and testing in Experiment A is useful for testing many different applications. The circuit built and testing in Experiment B will be used to drive the motors of a robot and determine its speed.

IV. Appendix A

It should be noted that four 1.5Ω resistors were configured in parallel instead of 1Ω resistors as we did not have those resistor values. This results in a equivalent resistance of 0.375Ω.

ECEN 2270 Prelab 2A

1) a) $I_M = V_i / R_3$, $P_{R_3} = I_M^2 R_3 \leq 0.25$ W

$I_M \leq 2$ A (we'll use 2A as a tolerance)

$$R_3 \leq \frac{1}{4I_M^2} = \frac{1}{16} = \underbrace{0.0625 \text{ or } 62.5\ m\Omega}_{\text{by power constraints}} \geq R_3$$

check to see we meet AD2 res. req. =>

$I_M = V_i / R_3$ => assume $V_i = 0.005$ V =>

$I_M = 80$ mA (want to measure ~10-20 mA

MINIMUM) => Thus $R_3 = 0.25\ \Omega$ =>

Need to make $0.25\ \Omega$ resistor from standard values and ensure each meets power req. => 4 1Ω resistors in parallel =>

$i = 2/4 = 0.5$ A => $P = i^2 R = 0.25$ W =>

4 1Ω resistors in parallel meet req.!

b) $i_e = i_c + i_b = \beta i_b + i_b = i_b(\beta + 1)$ =>

$i_b = V_{R_2} / R_2 = \frac{V_{out} - 0.7}{R_2}$ =>

$2 = \frac{V_{out} - 0.7}{R_2}(101)$ where V_{out} from 0-8 V =>

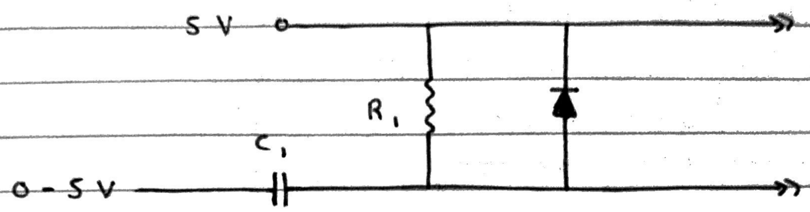
$$\left.\begin{array}{l} V_{out} = 8 \Rightarrow R_2 = 368.65\ \Omega \\ V_{out} = 1 \Rightarrow R_2 = 15.15\ \Omega \end{array}\right\} \text{must be b/w these values}$$

$R_2 = 330\ \Omega$

V. Appendix B

ECEN 2270 Prelab 2B Quiz

1) a)



find C_1, R_1 so $t_{trig} = 2 \mu s = 2e-6$ s ⇒

t_{trig} is time it takes to go from $0 \rightarrow V_{cc}/3$ ⇒

$v_c(t) = V_{cc}(1 - e^{-t/RC}) = V_{cc}/3$ ⇒

$\frac{1}{3} = 1 - e^{-t/RC}$ ⇒ $-\frac{t}{RC} = \ln\left(\frac{2}{3}\right)$ ⇒

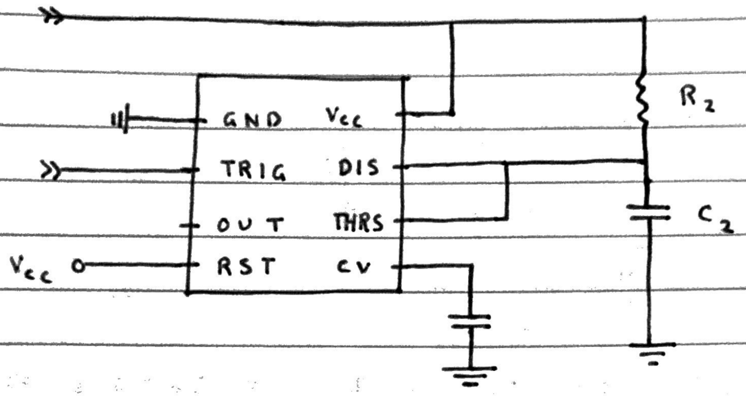
$RC = -t\left(\ln\left(\frac{2}{3}\right)\right)^{-1} = 4.933e-6$ s ⇒

if $R = 5.1 k\Omega$ ⇒ $C \approx 1 nF$

b) R_1 and C_1 are already standard values

c) $t \geq 1 \mu s = -RC \ln\left(\frac{2}{3}\right) = 2.068 \mu s$ ✓

2)



a) find R_2 , C_2 so $t_{on} = \frac{0.9}{f_{enc_{max}}}$

from LMC555 sheet $\Rightarrow$ $t_{on} = 1.1 R_2 C_2 \Rightarrow$

$RC = \frac{0.9}{1.1 f_{enc_{max}}} = 3.99e-4$ s ($f_{enc_{max}} = 2050$ Hz)

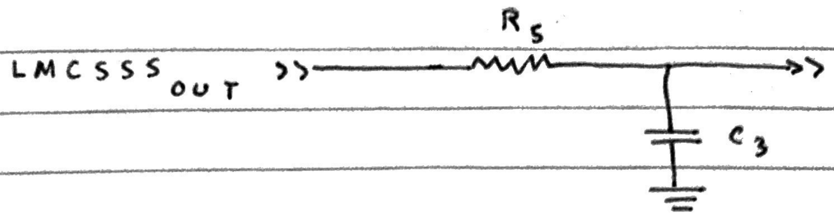
if $R_2 = 20 k\Omega \Rightarrow C_2 = 10 nF$

b) see above ⤴

$t_{on} < \frac{1}{f_{enc_{max}}} = 4.88e-4$ s

$t_{on} = 1.1 R_2 C_2 = 2.0e-4$ s ✓

3)



a) find R_3, C_3 so $f_{enc_{max}}$ is attenuated by

-40 dB ⇒ $f_{enc_{max}} = 2560$ Hz ⇒

$f_c = 25.6$ Hz ⇒ $\omega_c = 51.2\pi$ rad/s

-40 dB ⇒ 0.01 ⇒

$$0.01 = \frac{1}{\sqrt{1 + \omega^2 (RC)^2}} \Rightarrow$$

$$RC = \sqrt{\frac{9999}{\omega^2}} = 0.00776 \text{ s}$$

if $R_3 = 15.1\,k\Omega \Rightarrow C_3 = 0.47\,\mu F$

b) $\tau = RC = 0.0071$ s << 1 s