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 2: Measuring DC Motor Characteristics & Creating DC Motor Speed Sensor
Date of Experiment: February 25th, 2024
Name: Connor Sorrell

Introduction and Objectives

Introduction:

In this lab, we continue in our realm of practical electronic design and now focus on motor control, RC, sensing applications, and real-world circuits. We dive into the construction and validation of variable motor supply circuits as well as the determination and validation of important motor parameters. Through the design of trigger, one-shot, and speed sensor circuits, we engage in even more simulation using SIMetrix and real-world breadboard testing. Doing so, we bridge our mathematical analysis with hands-on practice and are able to validate our measurements using an expected result. With an overarching goal of becoming proficient in motors, simulation software, scope probes, and hardware implementation, this lab consists of tons of groundwork which will be put to use in the future.

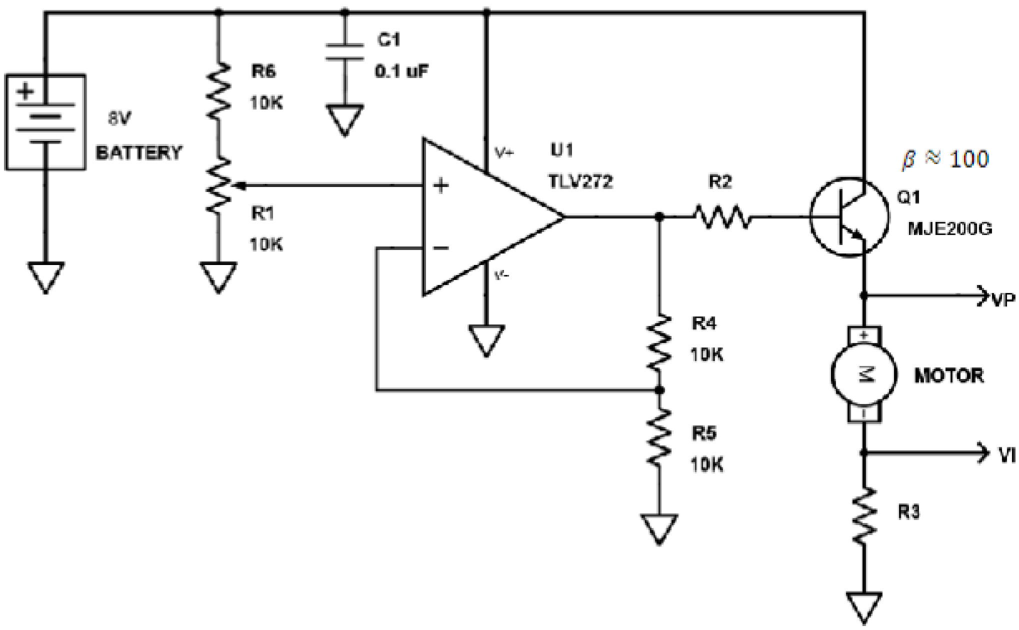
Objectives:

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

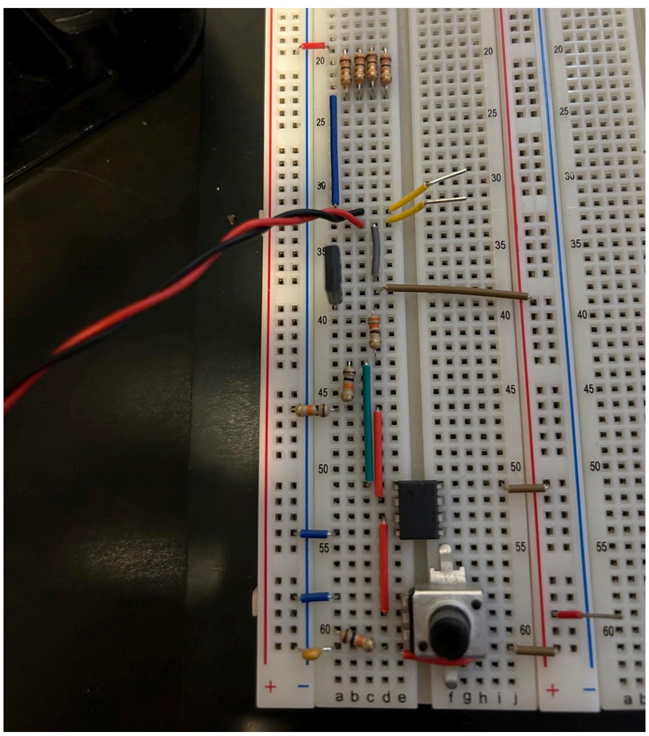
- Li-Ion batteries are introduced, as well as charged, prepared and inspected for future experiments.
- The variable motor supply circuit is built both on SIMetrix and on the breadboard and is simulated, tested, understood and validated.
- The motor and encoder is connected, and the measurements within it are understood.
- Motor parameters Rm, k, B, Tint, and J are all determined and validated, and so is the motor model as a whole.
- The speed sensor circuit is built, designed, tested, and understood.
- The trigger and “one-shot” circuits are built and understood.
- The RC filter and final speed sensor circuit is built and understood.
- The entire circuit is both simulated in SIMetrix and tested on the breadboard comprehensively, with trigger times, component values, time constants and more being adjusted to achieve expected results.
- The quality of all schematics and hardware circuit builds satisfy good experimental lab practice requirements.
- PWM and Vspeed outputs of simulation and hardware circuits are operational and produce reasonable values in agreement with one another.

Experiment 2A: Measuring DC Motor Characteristics

Experiment 2.A.2: Variable Motor Supply Circuit



Building this circuit on the breadboard:



- In your report explain the function of each component in the circuit and show your computations for R2 and R3.

  R_1 is a potentiometer that is used to vary the voltage.

  R_6 protects the potentiometer from a potential short.

  C_1 is a bypass capacitor that filters out AC noise to make our DC signal more pure.

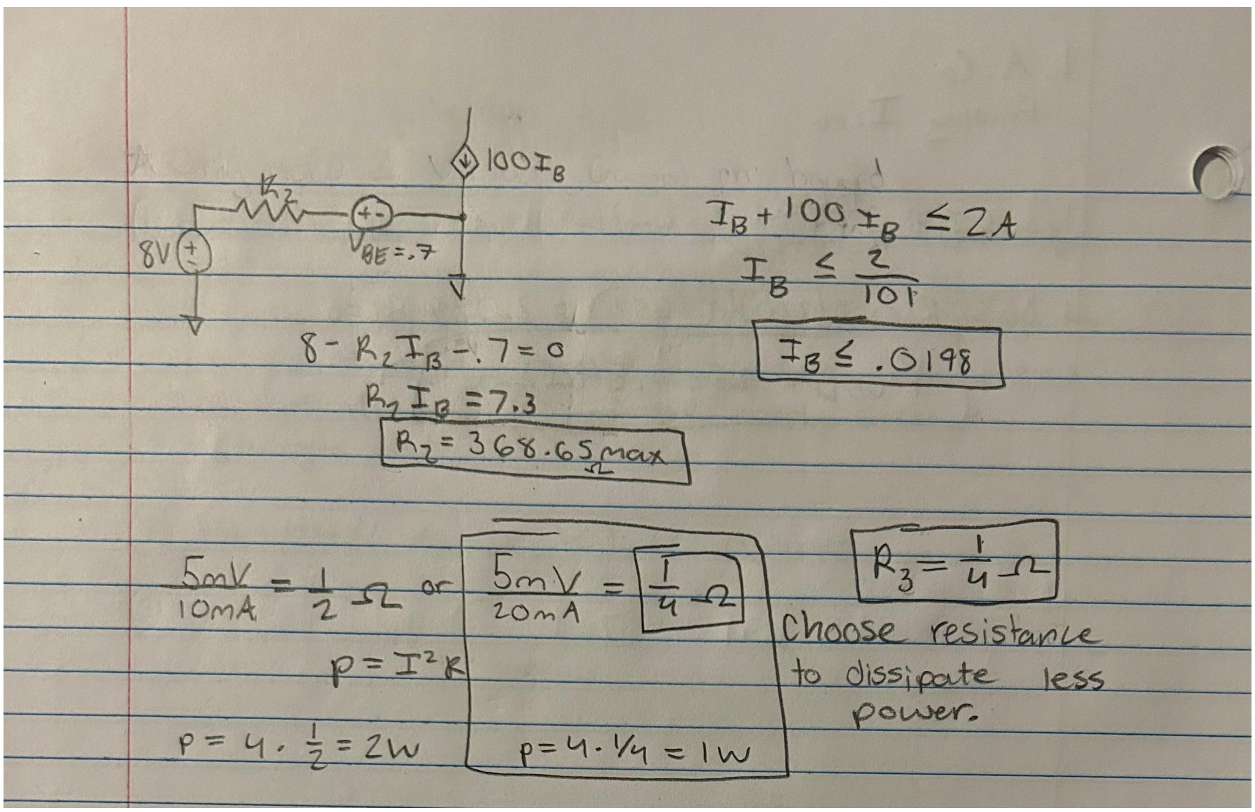
  U_1 is a TLV272 OpAmp. The output current of U_1 is amplified by transistor Q_1.

  R_2 limits the maximum motor current to about 2 Amps.

  R_3 is used to convert the motor current to a measurable voltage.

  R_4, R_5 provide a gain of 2.

  Q_1 is the MJE200G transistor. It is the equivalent of an emitter follower circuit.



- What is the expected maximum motor voltage V_M and what is the expected maximum motor Current I_M?

  $V_M = V_P - V_I$, max $V_M = 5.9\ V$

  $I_M = V_I/R_3$, max $I_M = 2\ A$

Experiment 2.A.3: Connect Motor and Encoder

We are able to measure $fenc$ by probing the green wire as shown below:

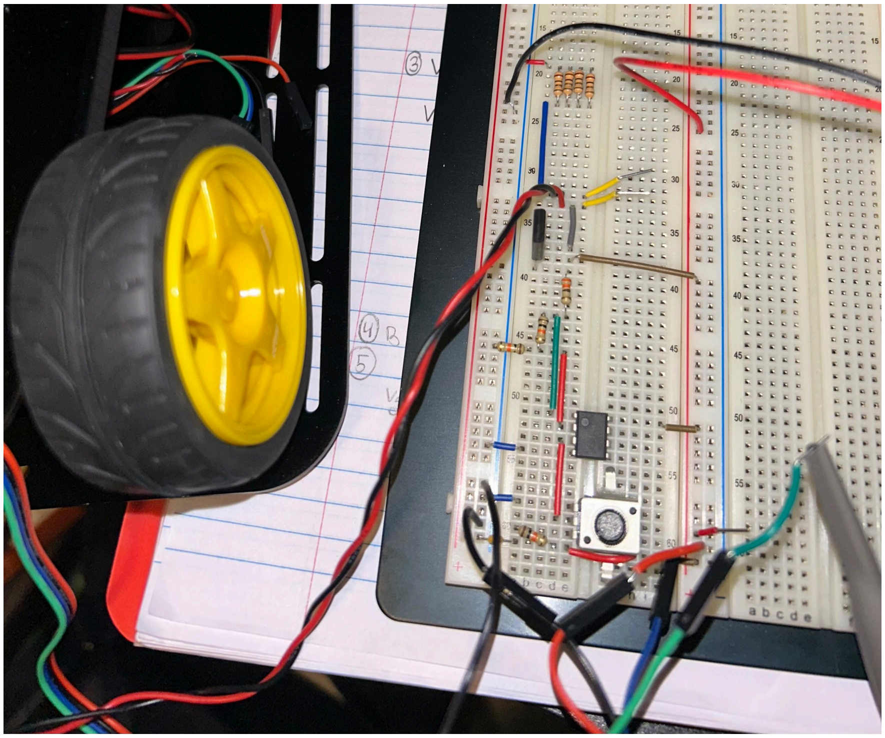


Figure: Variable motor supply with encoder

We will need to use this method of probing for all of the following steps. We can also probe (yellow wires) on either side of the motor wires to measure V_{dc} and V_{I}.

Experiment 2.A.4: Determine the Motor Parameter R_{M}

The Armature resistance, Rm, can be determined with a locked-rotor experiment. At three different values of supplied voltage, we held the motor wheel such that the speed of rotation was zero.

Vp (V)	1.3 V	3.2 V	3.7 V
Vi (V)	0.118 V	0.27 V	0.328 V
Vm (Vp - Vi) (V)	1.182 V	2.93 V	3.372 V

Idc (A)	0.472 A	1.08 A	1.312 A
Rm (Ohms)	2.50 Ohms	2.71 Ohms	2.57 Ohms

At three different voltage values, we found the voltage drop through the motor (Vm) by probing the voltage at Vi and Vp and solving for the difference. We then solved for Idc using I = V/R, where V = Vi and R = 0.25 Ohms, the resistance of R3.
Then, we solved for Rm simply just using R = V/I, in this case Rm = Vm/Idc, where we got an average Rm of 2.6 Ohms.

Experiment 2.A.5: Determine Motor Parameters k, B, and T_{int}

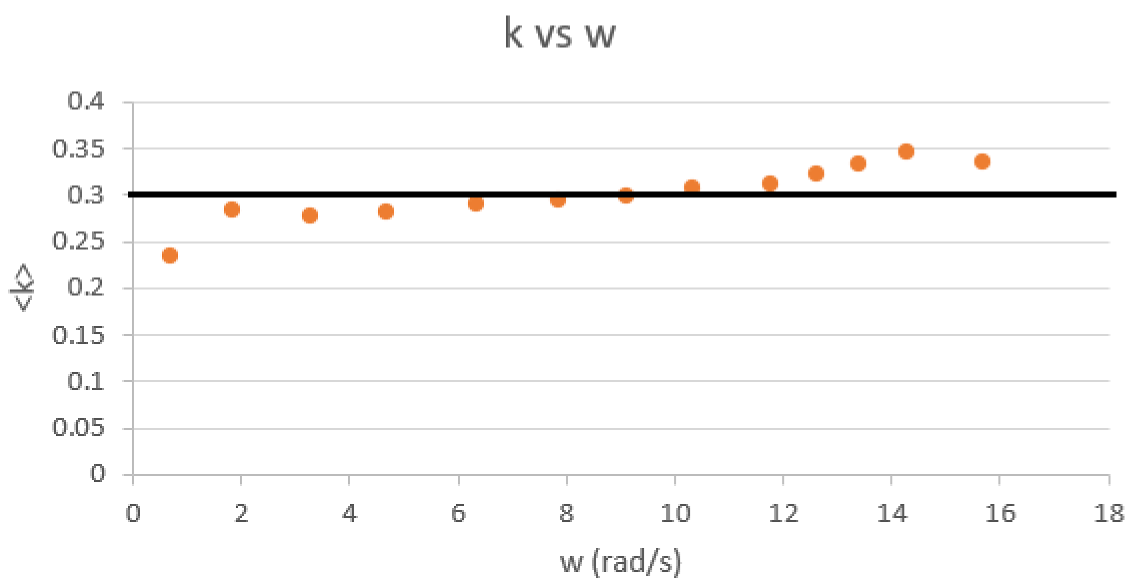
The motor constant k, the friction coefficient B, and the internal motor torque Tint can be estimated from an unloaded motor experiment.

Vp (V)	6.29	5.8	5.26	4.77	4.28	3.76	3.27	2.82	2.29	1.73	1.28	0.84	0.43
Vi (V)	0.089	0.076	0.069	0.061	0.054	0.051	0.048	0.044	0.04	0.036	0.033	0.028	0.025
fenc (kHz)	2.4	2.18	2.05	1.93	1.8	1.58	1.39	1.2	0.97	0.716	0.5	0.28	0.105
Vdc (V)	6.201	5.724	5.191	4.709	4.226	3.709	3.222	2.776	2.25	1.694	1.247	0.812	0.405
Idc	0.356	0.304	0.276	0.244	0.216	0.204	0.192	0.176	0.16	0.144	0.132	0.112	0.1
Rm (Ohms	2.6	2.6	2.6	2.6	2.6	2.6	2.6	2.6	2.6	2.6	2.6	2.6	2.6
w (rad/s)	15.7075	14.26765	13.41682	12.63145	11.78063	10.34077	9.09726	7.85375	6.348448	4.686071	3.272396	1.832542	0.687203
k	0.335852	0.345789	0.333417	0.322576	0.311053	0.307385	0.299299	0.295197	0.28889	0.281601	0.276189	0.284195	0.211
K avg	0.299419												
T	0.106444	0.090896	0.082524	0.072956	0.064584	0.060996	0.057408	0.052624	0.04784	0.043056	0.039468	0.033488	0.0299
SLOPE (B)	0.004458												
Tint	0.02179												

Letting the wheel rotate freely, we varied Vdc from maximum to minimum, the max voltage of the motor being ~6.3 V, and the minimum being the lowest voltage at which the motor still runs, 0.43 V. Due to the warming up of the motor and gears, it provided more consistent measurement results bny starting from a high speed and lowering it down, rather than the other way around.

To make our measurements, we first probed Vp and Vi, while simultaneously measuring the frequency using a multimeter. We were then able to calculate the difference between Vp and Vi, which we used to solve for Idc, once again using a value of R3 = 0.25 Ohms, found in the Prelab.

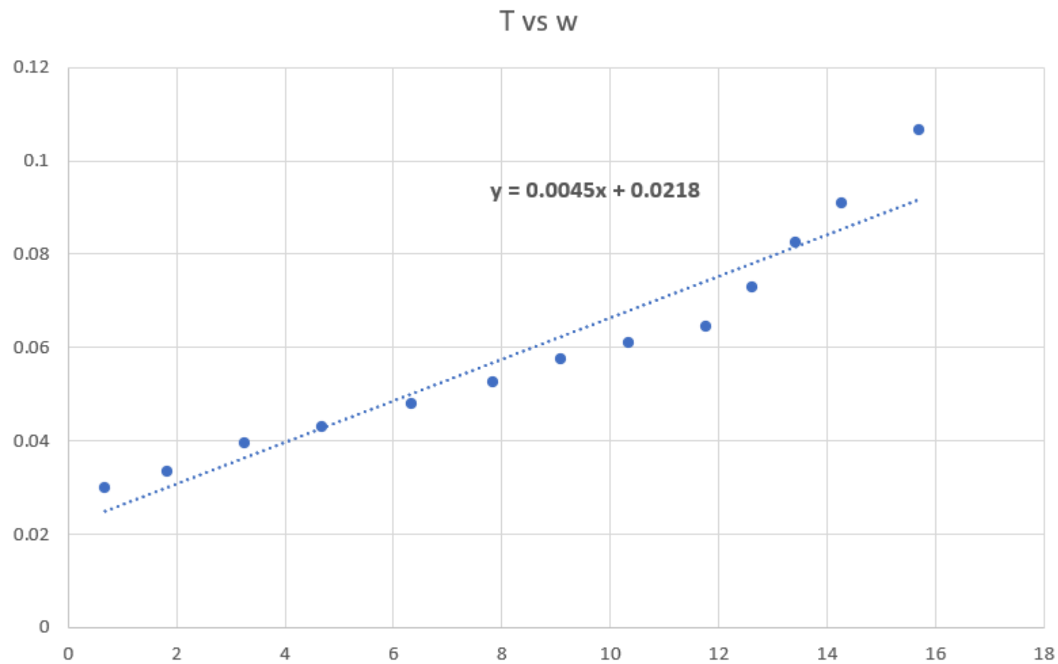
Maintaining the use of Rm = 2.6 Ohms, we then solved for w, the motor frequency using the equation $w = \frac{2\pi fenc}{960}$. Doing so, we were yielded 13 different values of w, in rad/s, for each voltage level we supplied.
To solve for k, we first had to solve for Vemf. In our case, $Vemf = Vdc - RmIdc$.
For each point, we solved for the Vemf and then used the equation $k = \frac{Vemf}{w}$. Solving for a k at each voltage level, we then averaged each of them, coming to an average k value of k = 0.30.



In our k vs. w graph, we would expect k to be constant, i.e., without slope. In our case, our solution for k matches closely enough with our expectations. The scatter plot is not perfect, however it does its purpose in validating our results, letting us move forward.

B and Tint:

To start, $Tload = Tint$ when there is no external load. With our rotor spinning at constant speed ($\frac{dw}{dt} = 0$), at a variety of w, we can calculate and form the scatter plot $T = kIdc$. Using k from the previous calculation, we solve for T at each interval, and form the following graph for T vs. w.



The scatter plot shows the T vs. w datapoints, and from here we perform linear regression of the line. The regression line has the form $T = kIdc = Bw + Tint$. So, from our graph we are yielded B = 0.0045 and Tint = 0.0218. These are lower than expected, but motors are all different and these measurements were completed with diligence, done multiple times, and all results were consistent and made sense.

Experiment 2.A.6: Determine the Motor Parameter J

The moment of inertia, J, can be estimated from the motor turn-off transient in an unloaded motor experiment.

- <u>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!)</u>
  There is noise in V_{dc} most probably because of basic electrical interference, and/or ripple in the voltage in the power supply that is out of our control. By adding the decoupling capacitor across V_{dc}, it would eliminate the noise would essentially be a low pass filter that just takes out all of the high frequency noise.

To find J:
In order to find J, we needed τ. This was estimated by supplying the motor with $\approx$ 7V and letting it rotate freely at full speed. Then, we turned off the voltage supply ($I_{dc} = 0$). After probing V_{dc} to measure the turn off transient, we received:

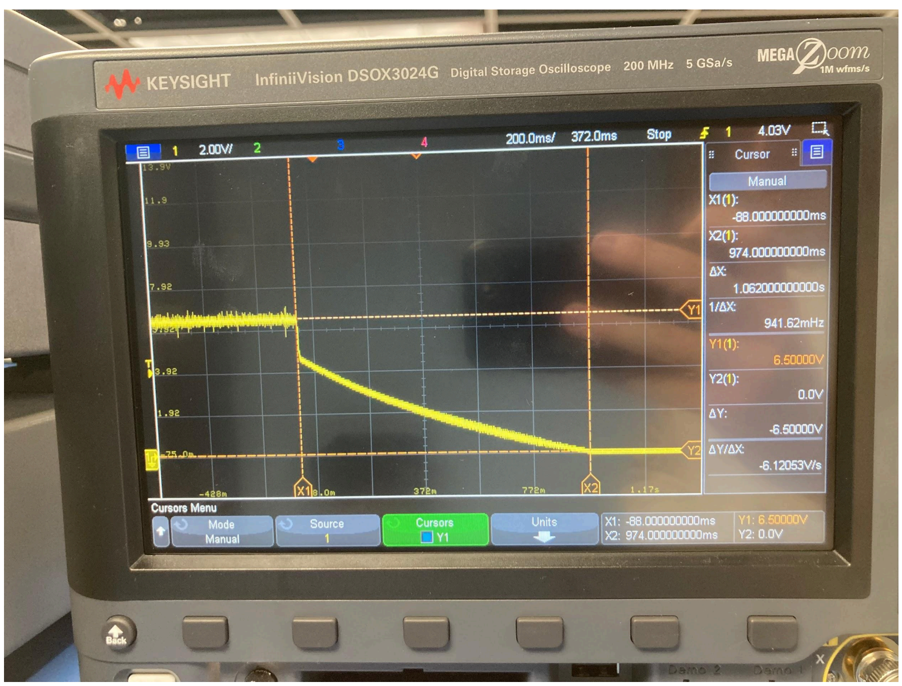


Figure: Turn-off transient of the motor

The spin down time in this experiment is $\tau = 1.062$ seconds.
The motor system is represented by the equation

$$J\frac{d\omega}{dt} + B\omega + Tint = 0 \rightarrow \frac{J}{B}\omega'(t) + \omega(t) = -\frac{Tint}{B}.$$

We can then separate the expression into its natural and forced solutions,

$$\omega?(t) = Ke^{st},\ t \geq 0,\ \omega f(t) = A,\ t \geq 0, \ \rightarrow A = -\frac{Tint}{B}.$$

The natural solution accounts for the inherent response of the system, while the forced solution represents impacts that external factors bring, such as an applied torque. The total solution is then expressed as

$$\omega(t) = \omega n(t) + \omega f(t) = Ke^{\frac{-Bt}{J}} - \frac{Tint}{B}$$

Previously, we found

$$k = \omega(0) + \frac{Tint}{B}$$

Substituting k into the total solution, we then get:

$$\omega(t) = (\omega(0) + \frac{Tint}{B})e^{-\frac{B\tau}{J}} - \frac{Tint}{B} \rightarrow (B\omega(0) + Tint)e^{-\frac{B\tau}{J}} = Tint$$

From here, we can conclude our analysis by solving for J. We do this by first manipulating our equation to place J alone on one side using natural logarithms and basic multiplication and division. Doing this yields

$$J = \frac{-B\tau}{ln(\frac{Tint}{B\omega(0)+Tint})}$$

After plugging in the values:

$$J \approx .00619$$

Experiment 2.A.7: Validate Motor Model

We validated our results in multiple ways. First, we simulated the spin down time:

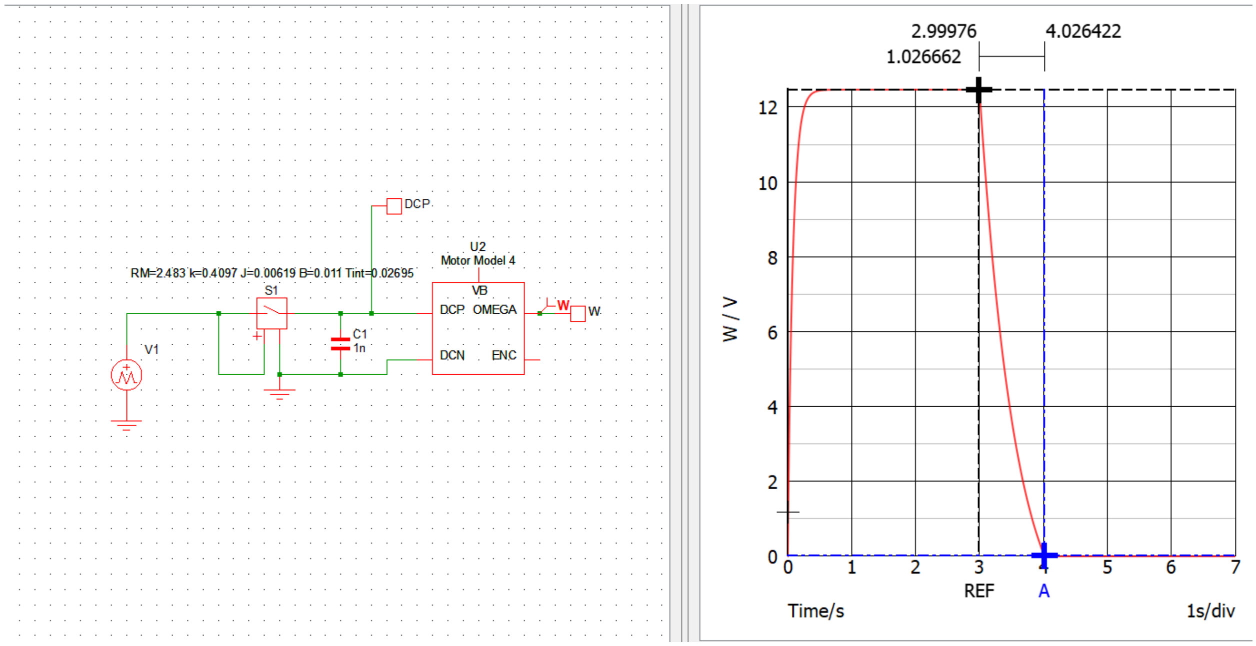


Figure: Simulated turn-off transient of the motor

The spin down time in the simulation is 1.027 seconds while the measured value is 1.062 seconds. Therefore, we can confirm that our J value is correct.

Next, we compared the measured and simulated k plots:

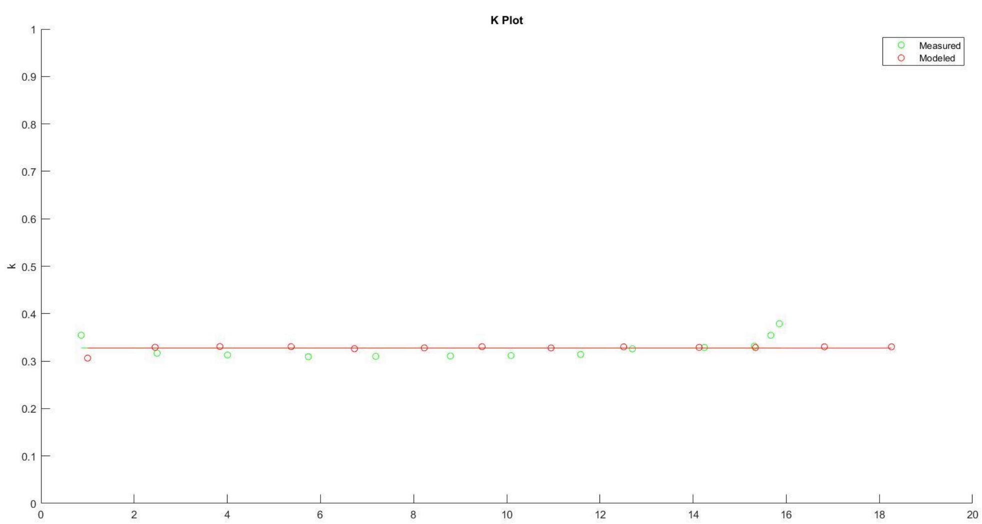


Figure: k measured vs. k simulated

The results are very similar meaning we can confirm that our k value is accurate.

Then, we plotted V_I $vs.$ V_{dc} for our measured values and our simulated values. These represent the locked-rotor experiments.

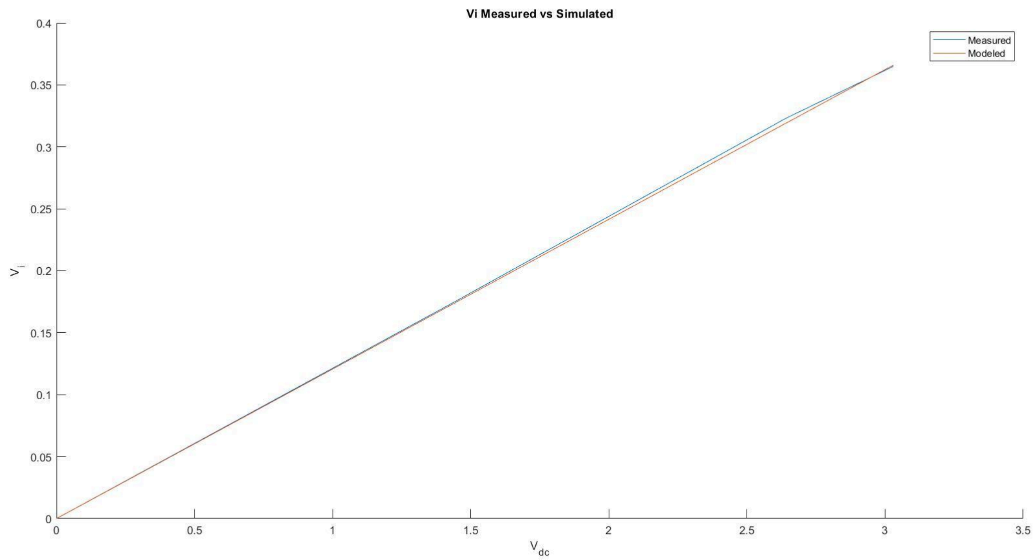


Figure: V_I $vs.$ V_{dc} measured vs. simulated

Once again, the results are extremely similar.

Finally, we plotted the measured vs. simulated data involving B and T_{int}.

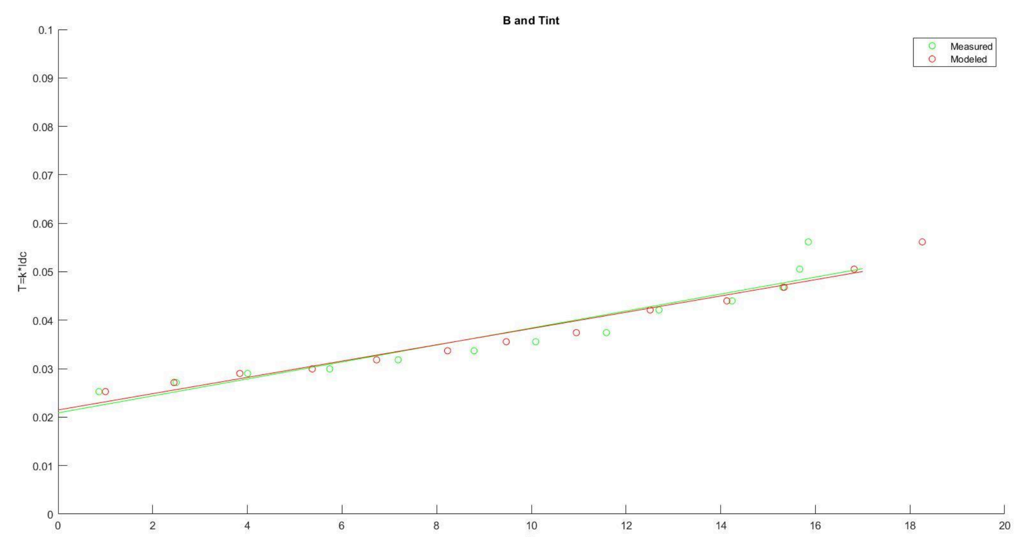
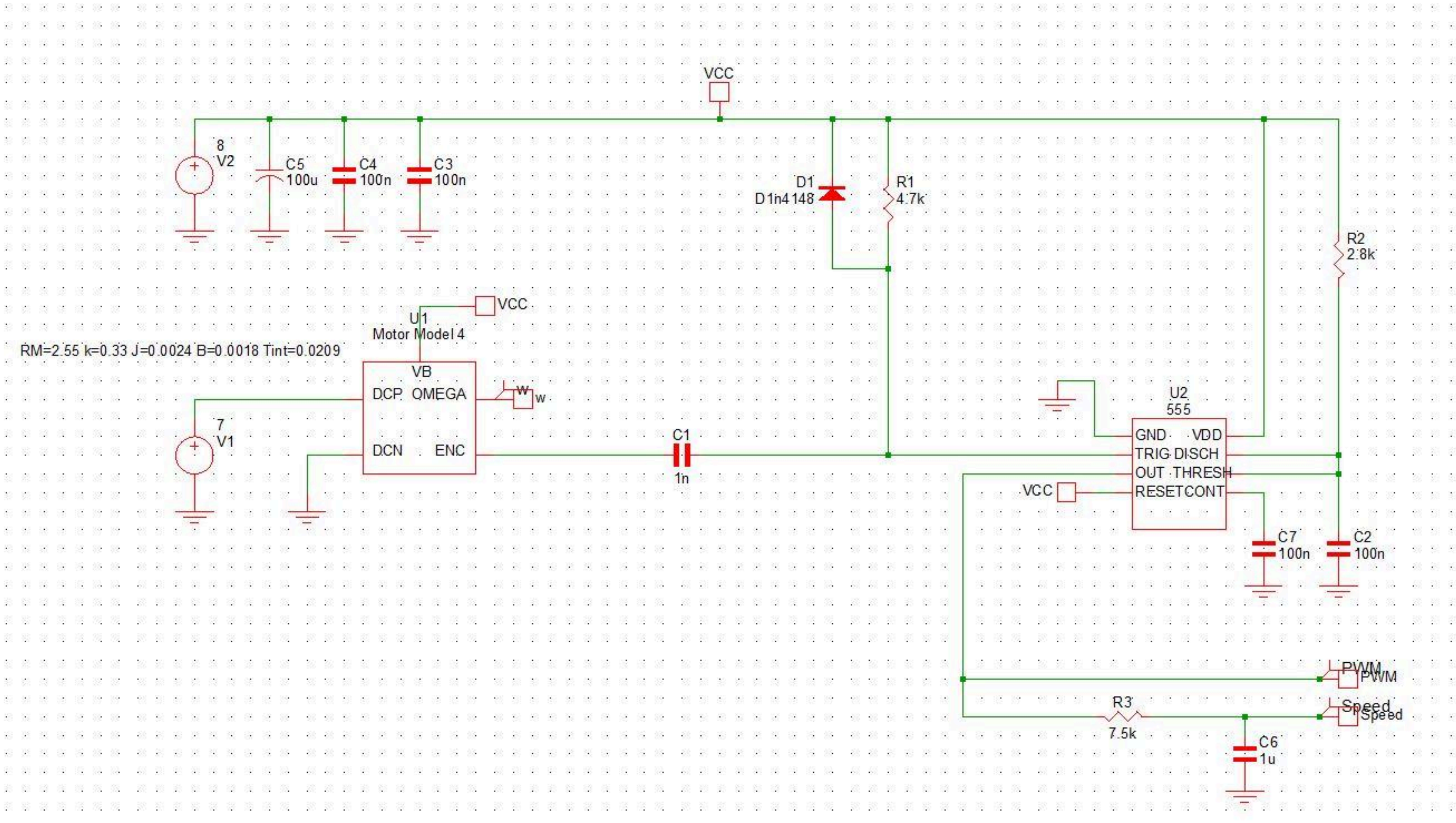


Figure: B and T_{int} measured vs. simulated

Due to all of these results being very similar, we can confirm that our measured parameters are correct and accurately model our motors.

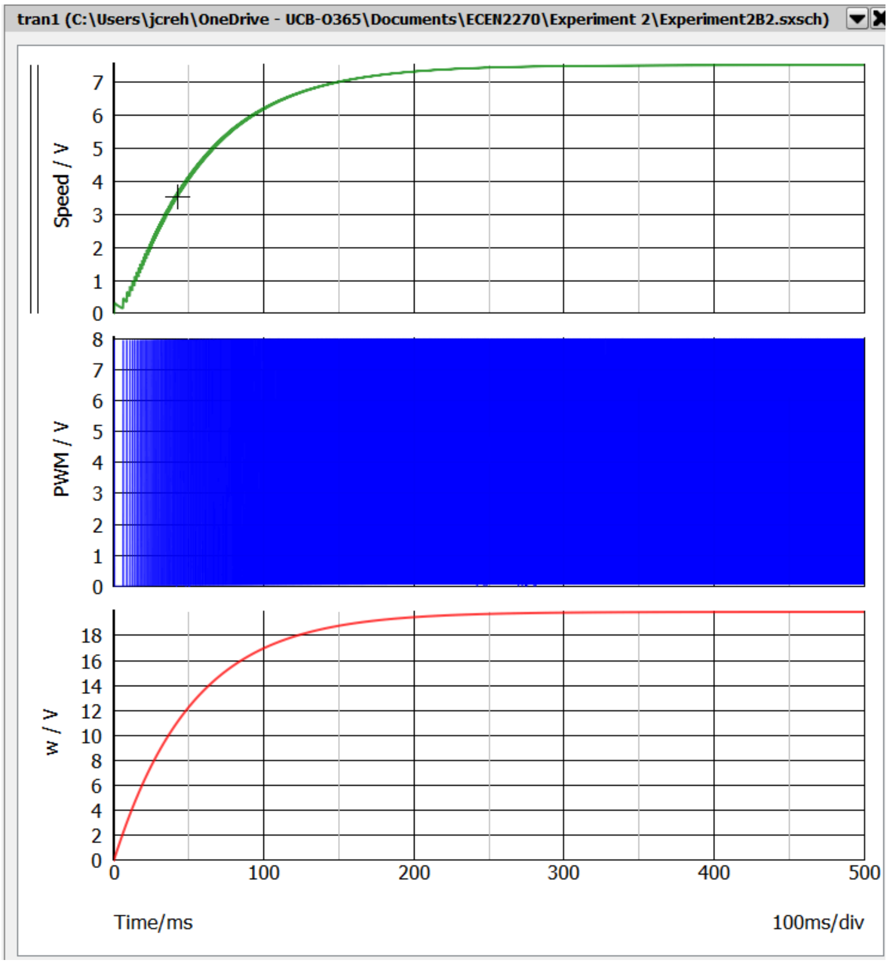
Experiment 2B: DC Motor Speed Sensor

Experiment 2.B.2: Speed Sensor Circuit Design, Simulation

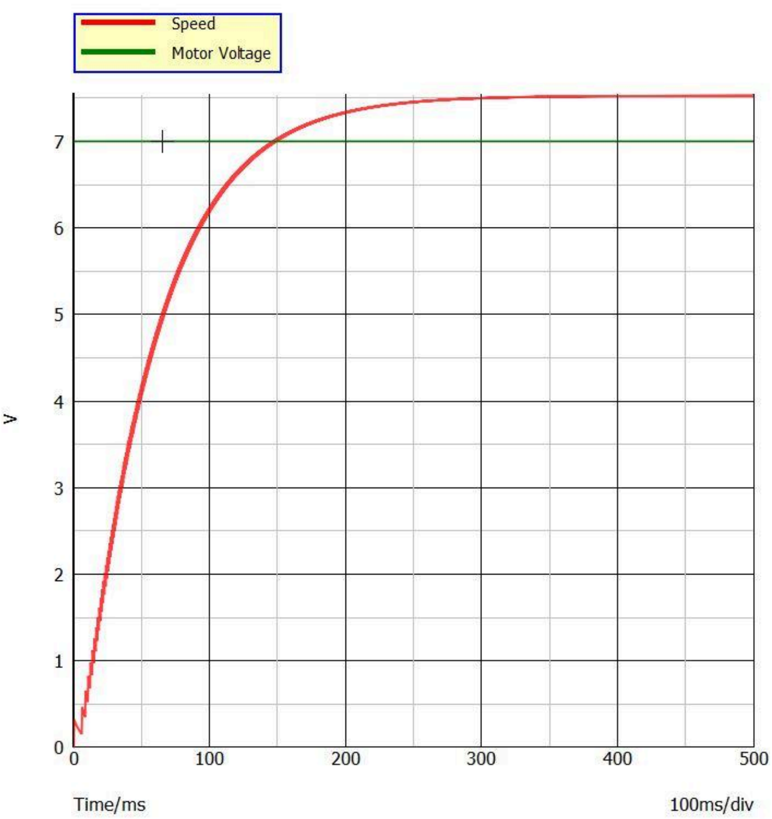


Above is the schematic for the Speed Sensor Circuit that we constructed. Based on the PreLab, our C1-C3 and R1-R3 values were decided. The only value modified was our R2 value, which decreased from 3.2k to 2.8k due to pulses skipping in the simulation. Decreasing this value lowered the time constant of the One-Shot circuit, preventing the skipping pulse problem.

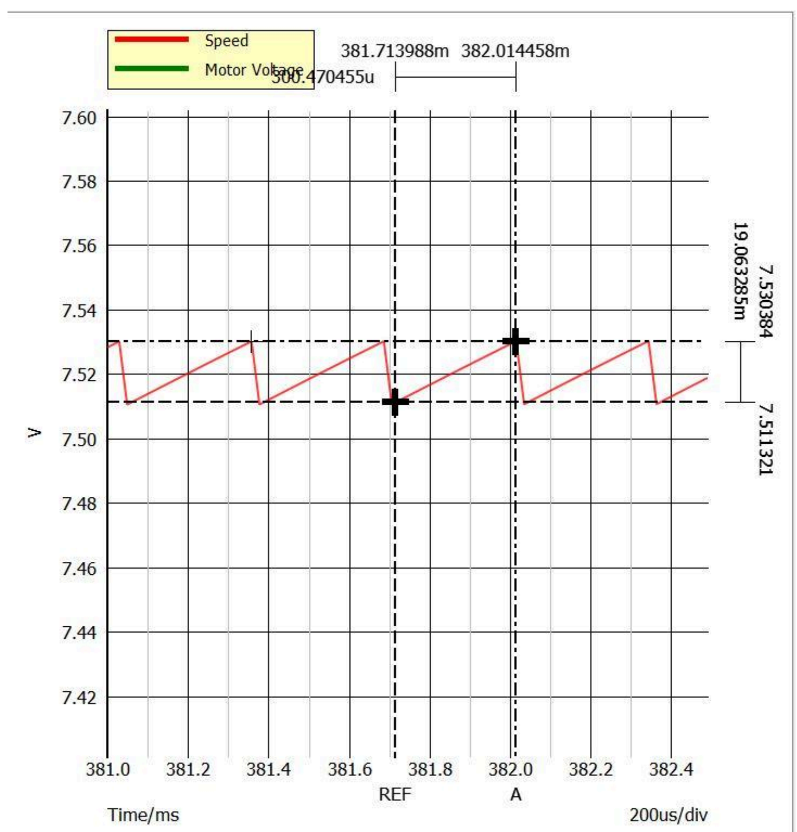
Below, the simulation for the speed sensor output voltage, PWM, and motor speed can be seen. This simulation, run for 500ms, clearly shows the steady state value of each signal at full motor speed $V_{dc} = 7V$. The final speed sensor output can be analyzed further in the plots following, showing the speed sensor output averaging a voltage of 7.51V. This value, while high, was verified accurate and acceptable by TAs due to the motor params calculated and used in this model. Furthermore, the ripple voltage can be seen to be 19mV, well under the 300mV requirement.



tran1 (C:\Users\jcreh\OneDrive - UCB-O365\Documents\ECEN2270\Experiment 2\Experiment2B2.sxsch)
Speed / V
PWM / V
w / V
Time/ms
100ms/div



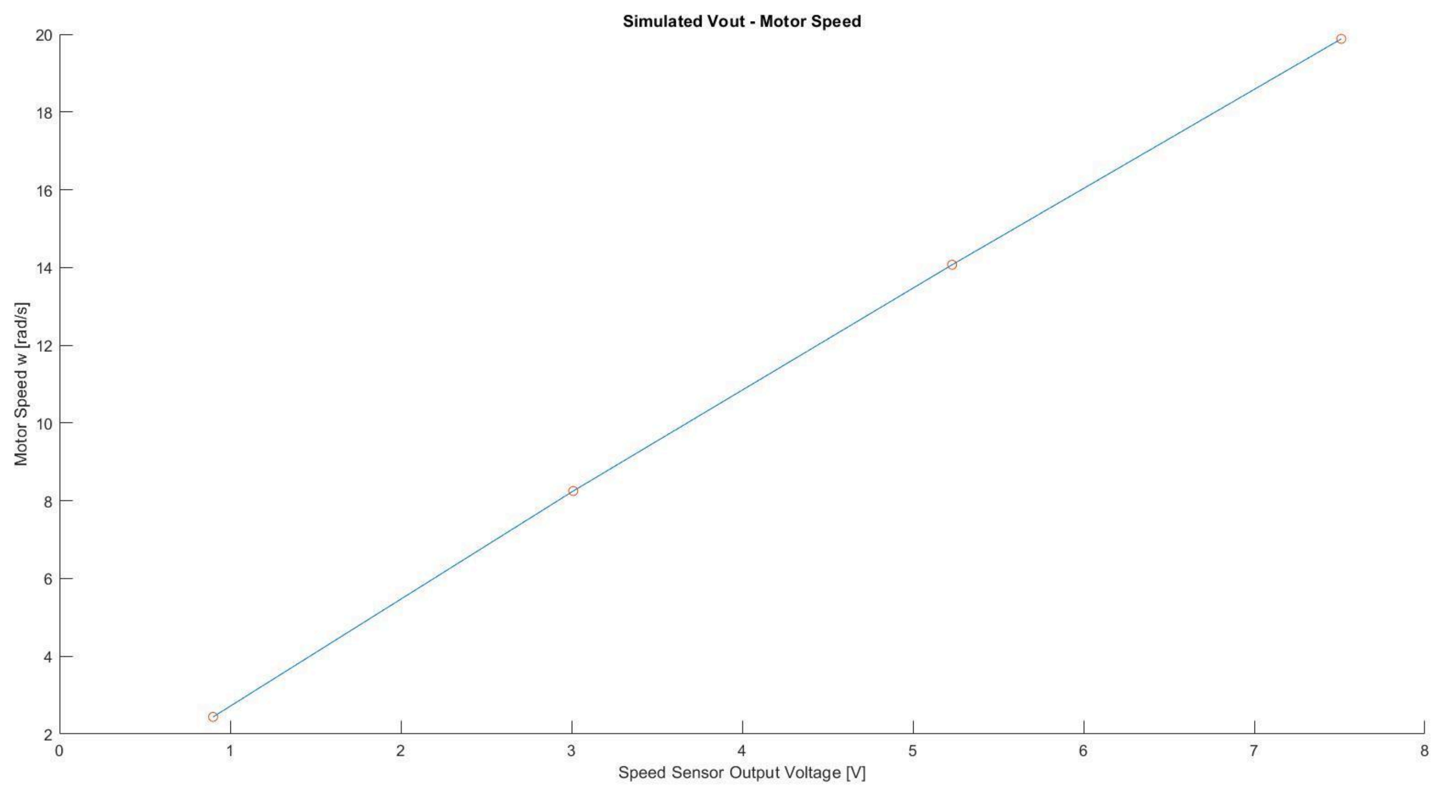
Speed
Motor Voltage
V
Time/ms
100ms/div



Speed
Motor Voltage
381.713988m
382.014458m
300.470455u
V
19.063285m
7.530384
7.511321
REF
A
Time/ms
200us/div

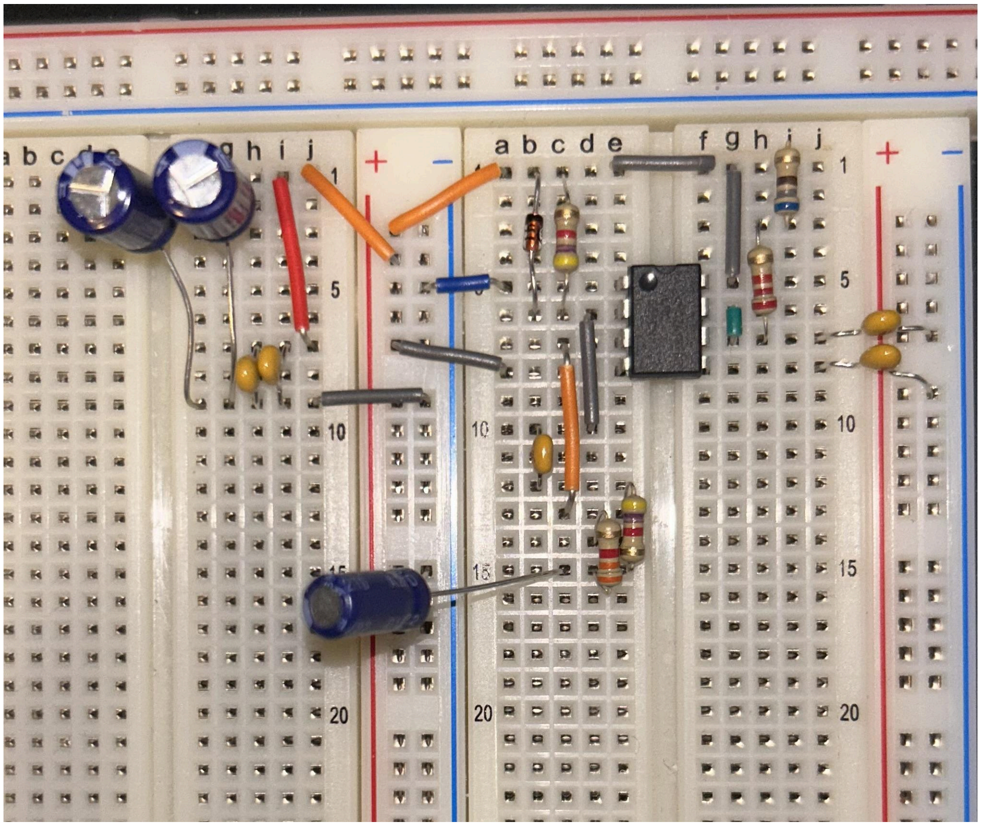
Next, the motor speed was varied to analyze the relationship between speed sensor output voltage, ***Speed***, and motor speed, ***w***. At the motor voltages of [7, 5, 3, 1] V, the following speeds and voltages were measured from the simulation. Visually from the plot, there is a clear, linear relationship between motor speed and speed sensor voltage output.

Motor Voltage [V]	7	5	3	1
Speed [V]	7.5	5.2	3.0	0.9
w [rad/s]	19.9	14.1	8.3	2.4

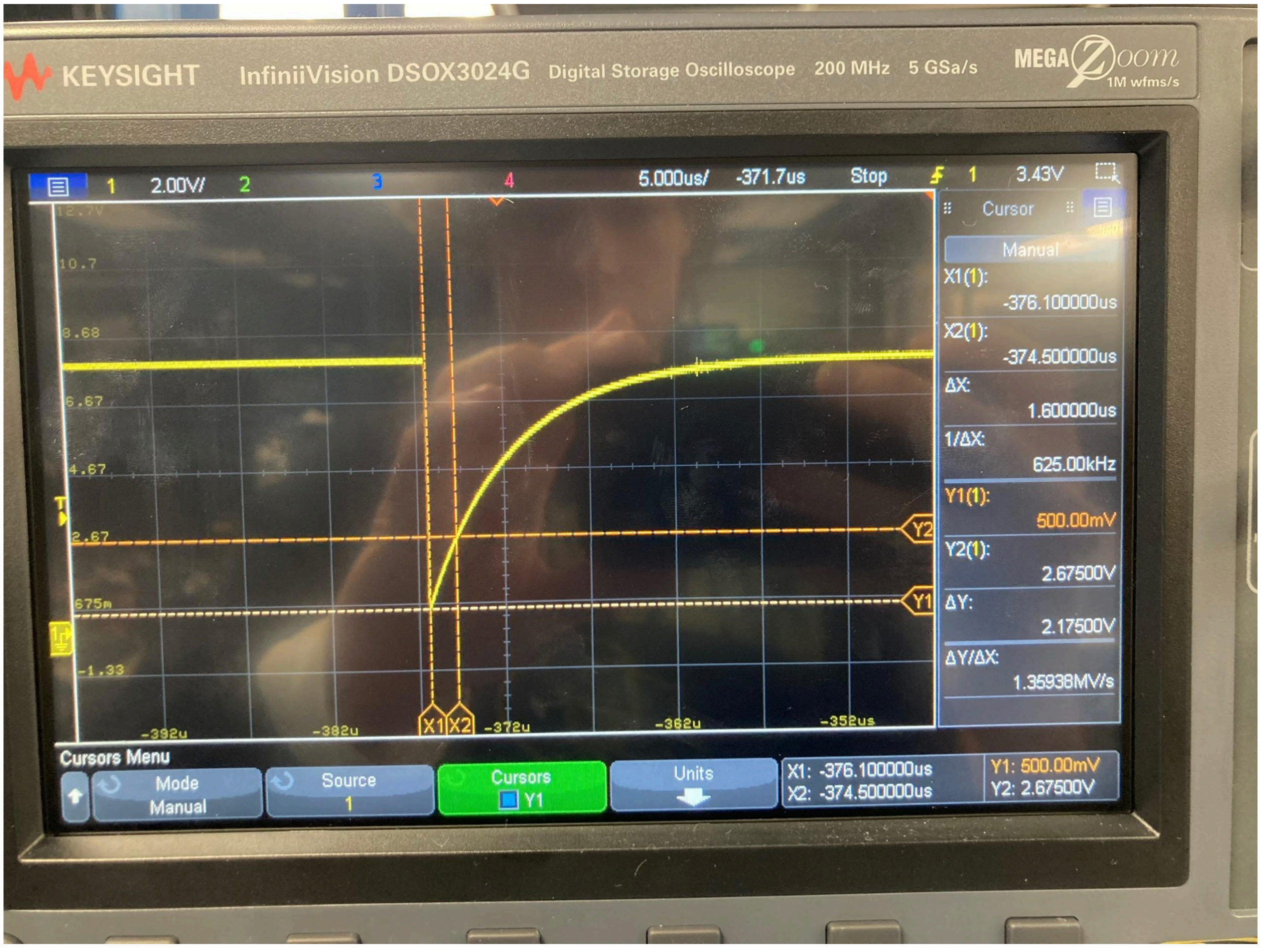


Experiment 2.B.3: Build Trigger and “one-shot” Circuits

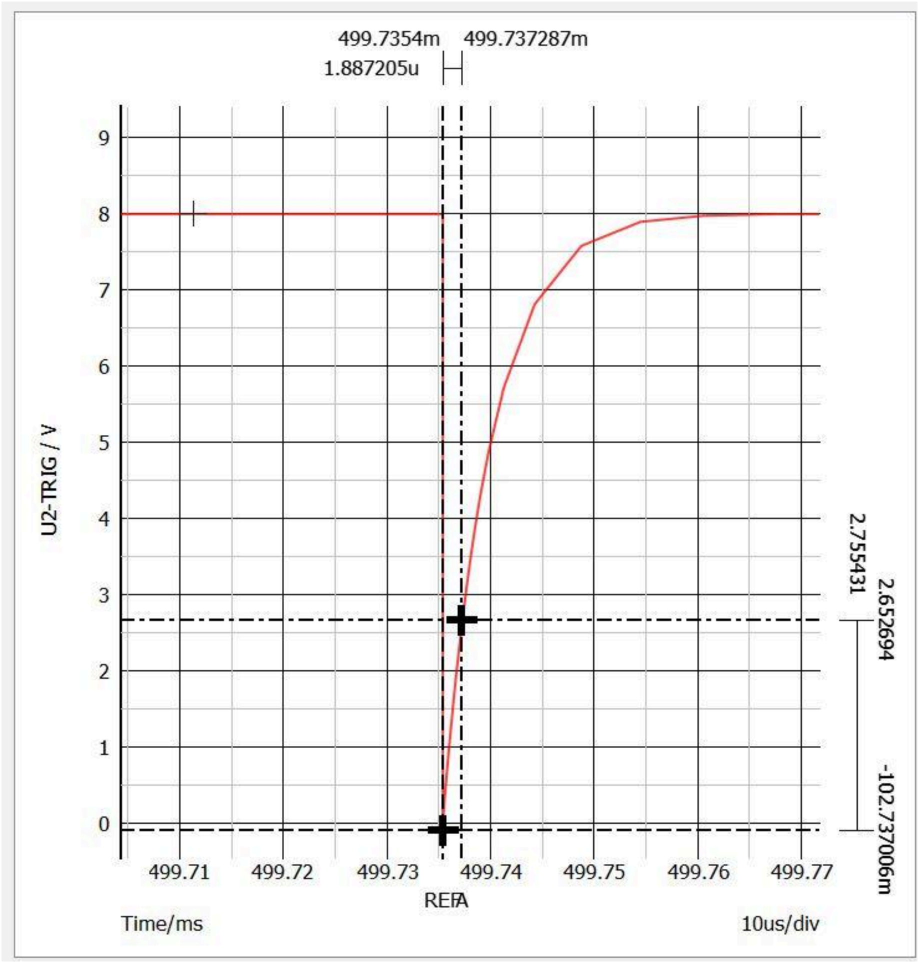
Below is an image of the actual speed sensor circuit built on a breadboard. This image includes the entire speed sensor circuit, not just the trigger and one-shot circuits.



t_{trig} **Comparison:**



The above plot shows the input to the TRIG pin of the LMC555 timer. The t_{trig} value was measured by finding the time between the low point and the $\frac{1}{3}V_{cc}$, ~2.67V. As can be seen above, $\Delta X = t_{trig} = 1.6\mu s$.

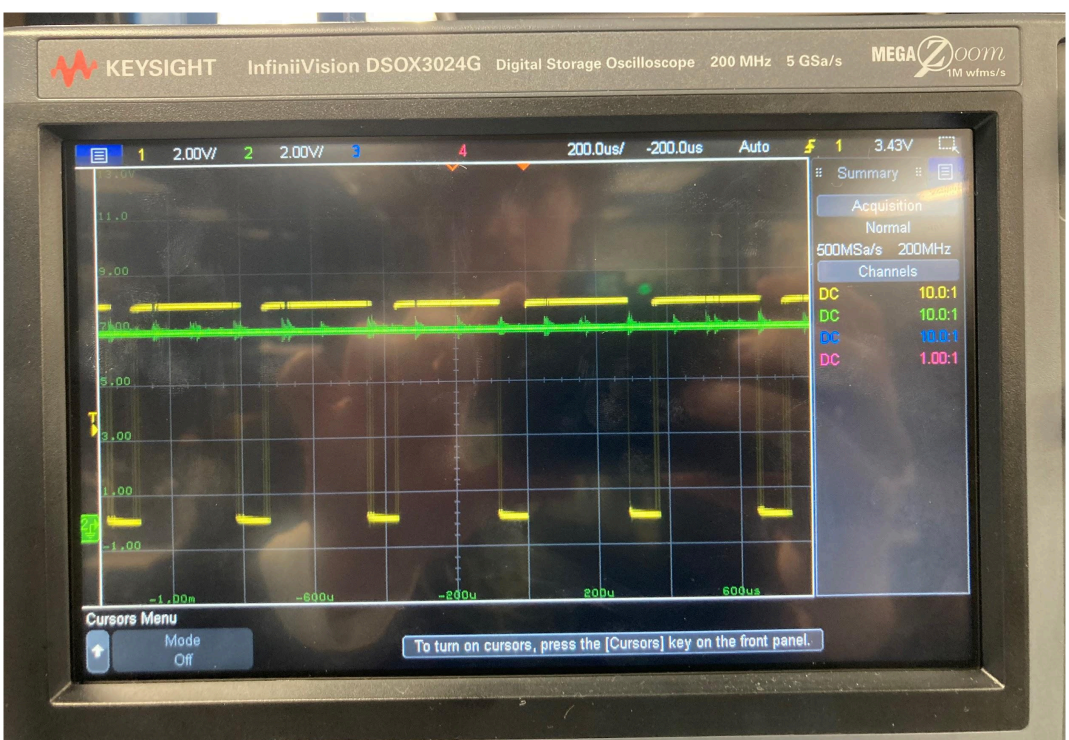


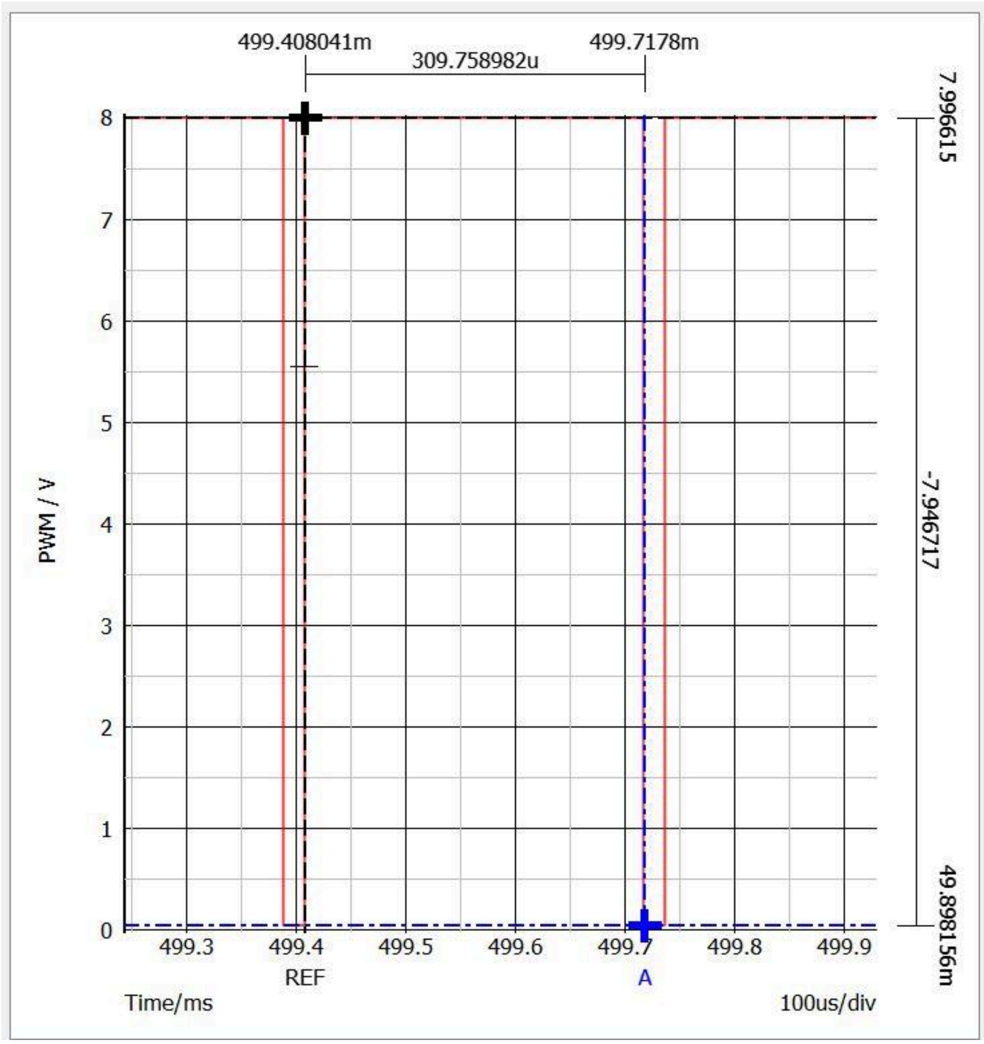
The below plot shows the simulation TRIG pin analysis. The t_{trig} value was measured in the same manner; by finding the time between the low point and the $\frac{1}{3}V_{cc}$, ~2.67V point. The t_{trig} value of the simulation was calculated to be $\Delta X = t_{trig} = 1.89\mu s$.

The difference between the simulated and actual trigger time values was calculated to be 0.29 microseconds, which is an 18% deviation. Given the errors that belong to actual circuitry and measurements, this deviation is very acceptable.

t_{on} **Comparison:**

The above plot shows the output of the LMC timer, which is the PWM output. To find the t_{on} time, we measured the positive width of the signal, which revealed: $\Delta X = t_{on} = 291\mu s$. The plot directly below shows the PWM above, with the max motor voltage (~7V) shown to verify the proper t_{on} value.





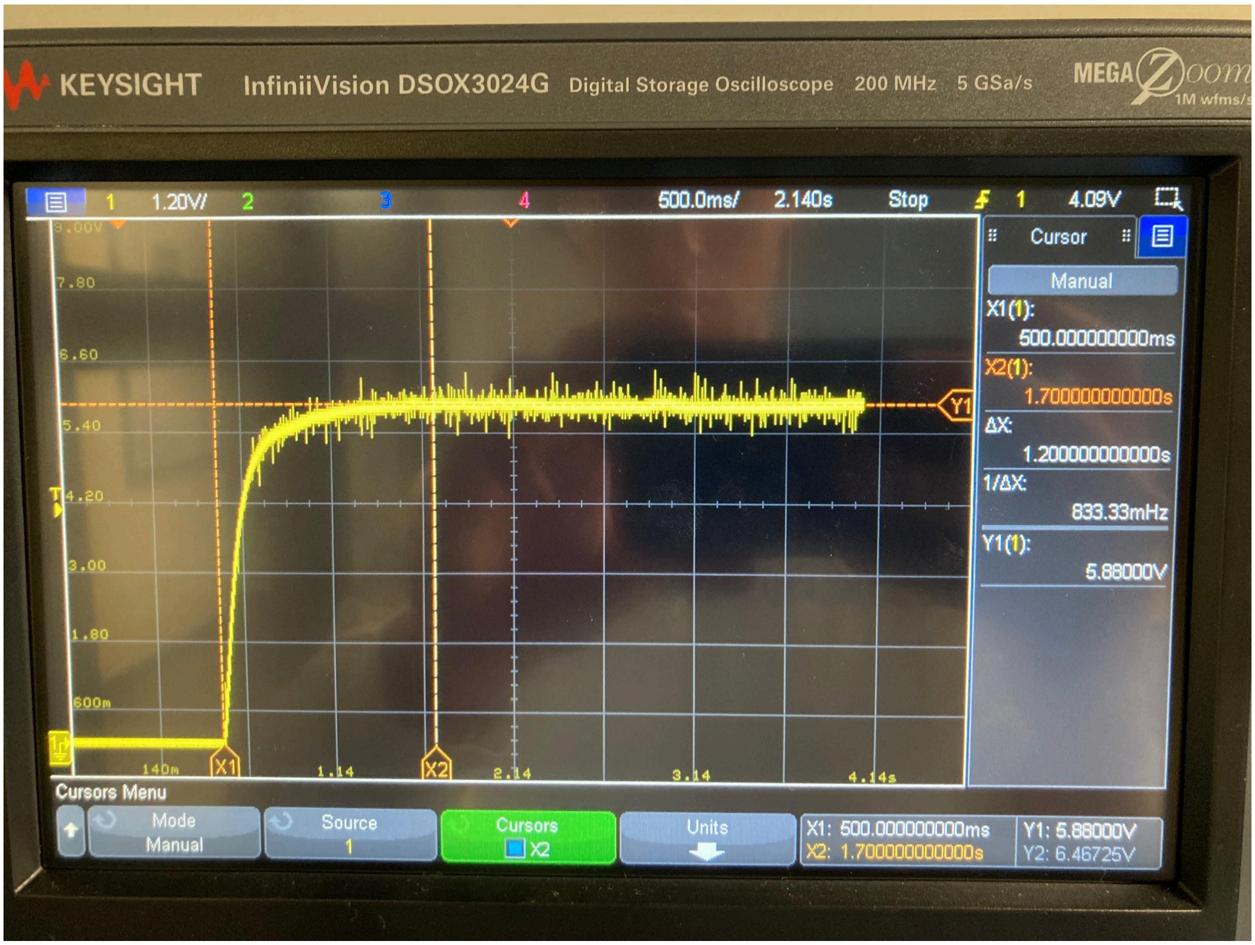
The above plot shows the PWM output during the steady state portion of the simulation. The t_{on} time was measured using the cursors to find the positive width time of the signal, $\Delta X = t_{on} = 310\mu s$.

The difference between the simulated and actual trigger time values was calculated to be 19 microseconds, which is a 6.5% deviation. Given the errors that belong to actual circuitry and measurements, this deviation is very acceptable.

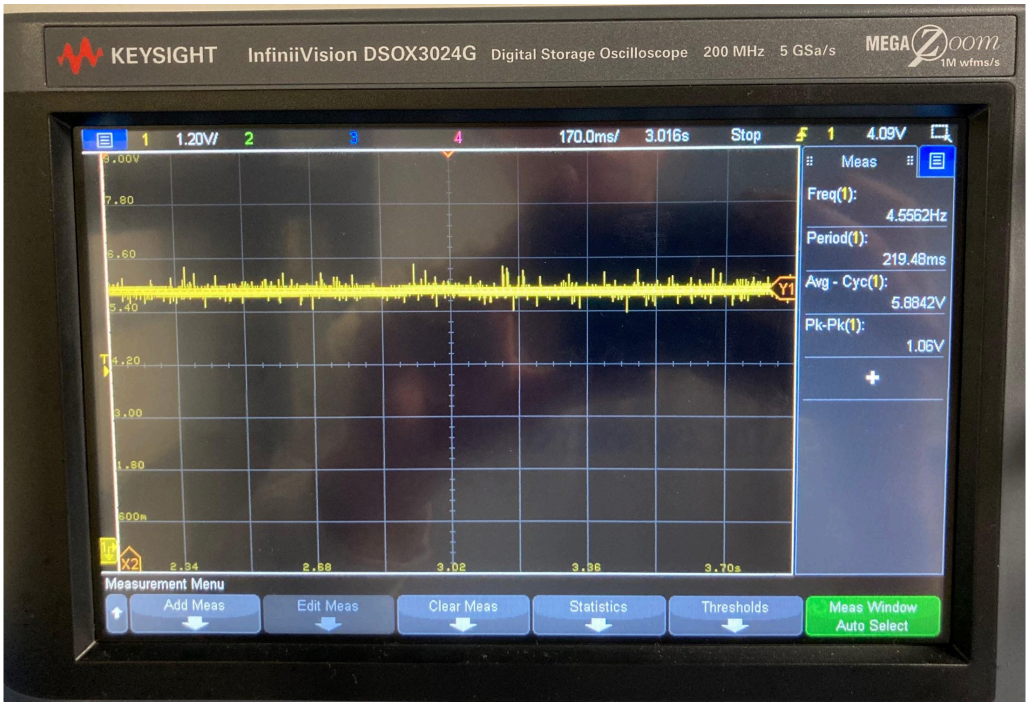
The necessary timing of this circuit was clearly upheld as $1\mu s < t_{trig} << t_{on}$. The inequality here with the values inserted appears as: $1\mu s < 1.6\mu s << 291\mu s$.

Experiment 2.B.4: RC Filter and Final Speed Sensor Circuit

In this portion of the lab, we added the LPF to the 555 timer output in order to complete the Speed Sensor Circuit. A picture of the whole circuit can be seen on the first page of section 2.B.3. The plot directly below shows the loading up transient of the speed sensor output voltage.

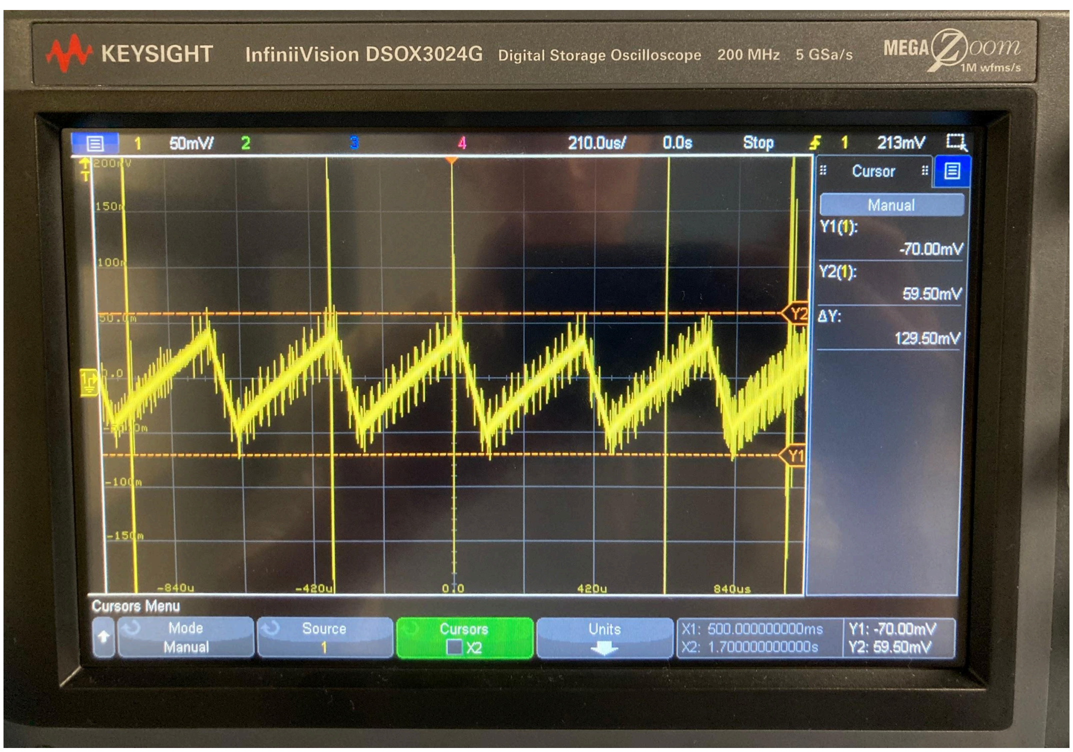


This plot matches the simulated loading-up transient of the speed sensor output voltage, providing confidence in the construction and measurement of this circuit. Seen below are two plots confirming the average *Speed* voltage, as well as the ripple voltage.



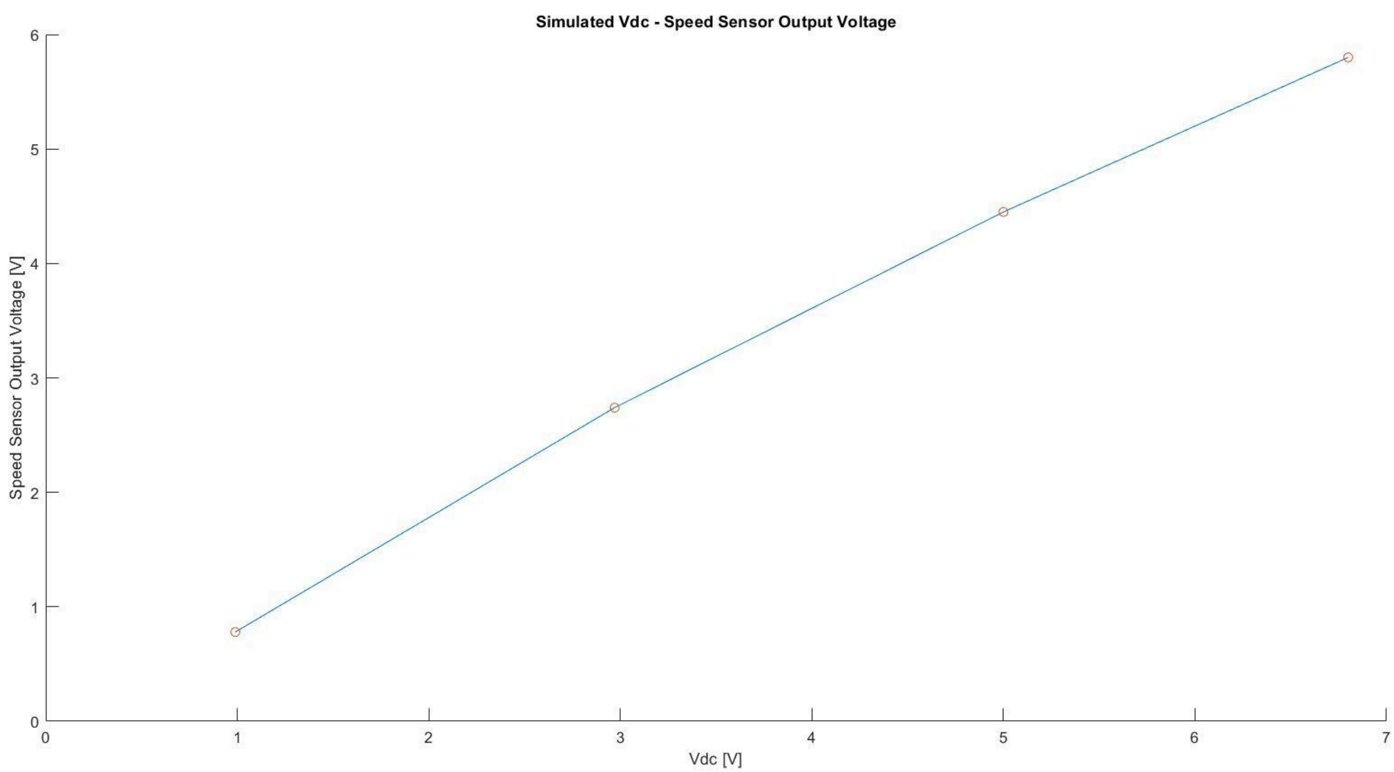
The above plot shows the average *Speed* voltage to be 5.88V, which is approximately 6V, as required by the lab doc.

The below plot shows the ripple voltage (ignoring the noise) to be 130mV, under the requirement of 300mV or less.



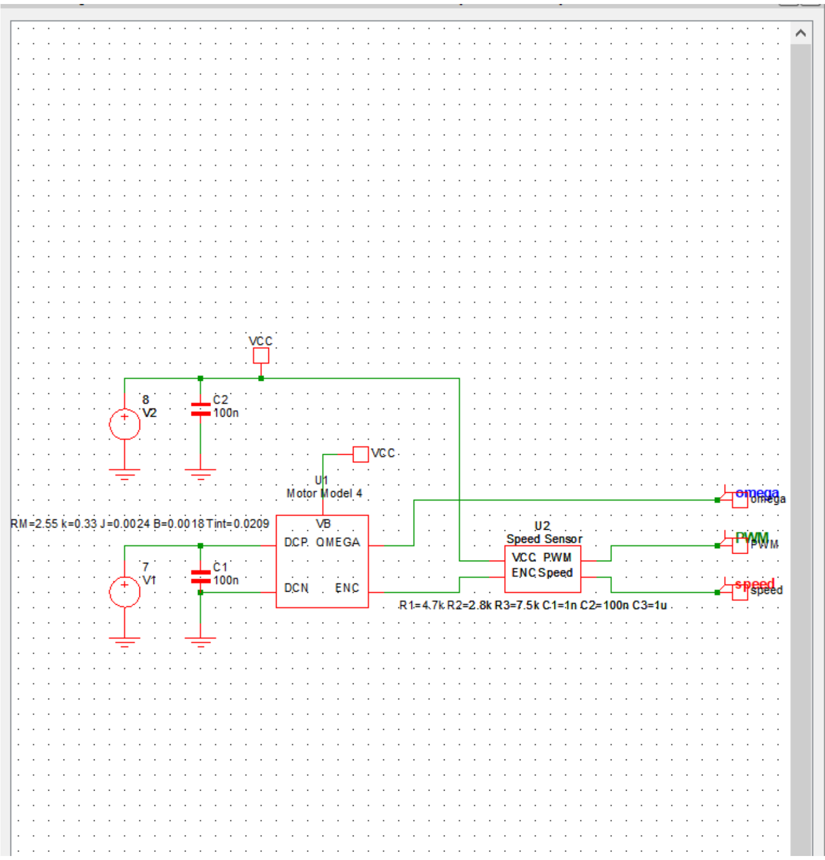
Next, the motor voltage was varied from 1V - 7V to verify the linear relationship between motor voltage and speed sensor output voltage. The data can be seen in the table and plot below:

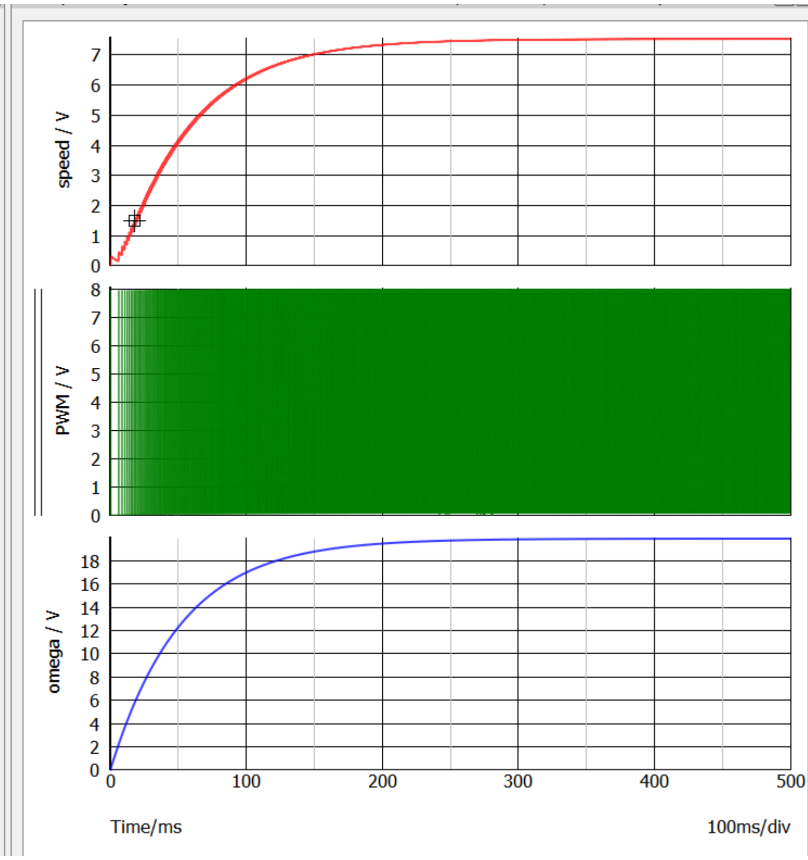
Motor Voltage V_{dc} [V]	6.80	5.00	2.97	0.99
Speed Sensor Output Voltage [V]	5.80	4.45	2.74	0.78



As can be seen from the data above, there is a clear, linear relationship between V_{dc} and *Speed*, which was expected. This verifies the integrity and accuracy of the physical circuit.

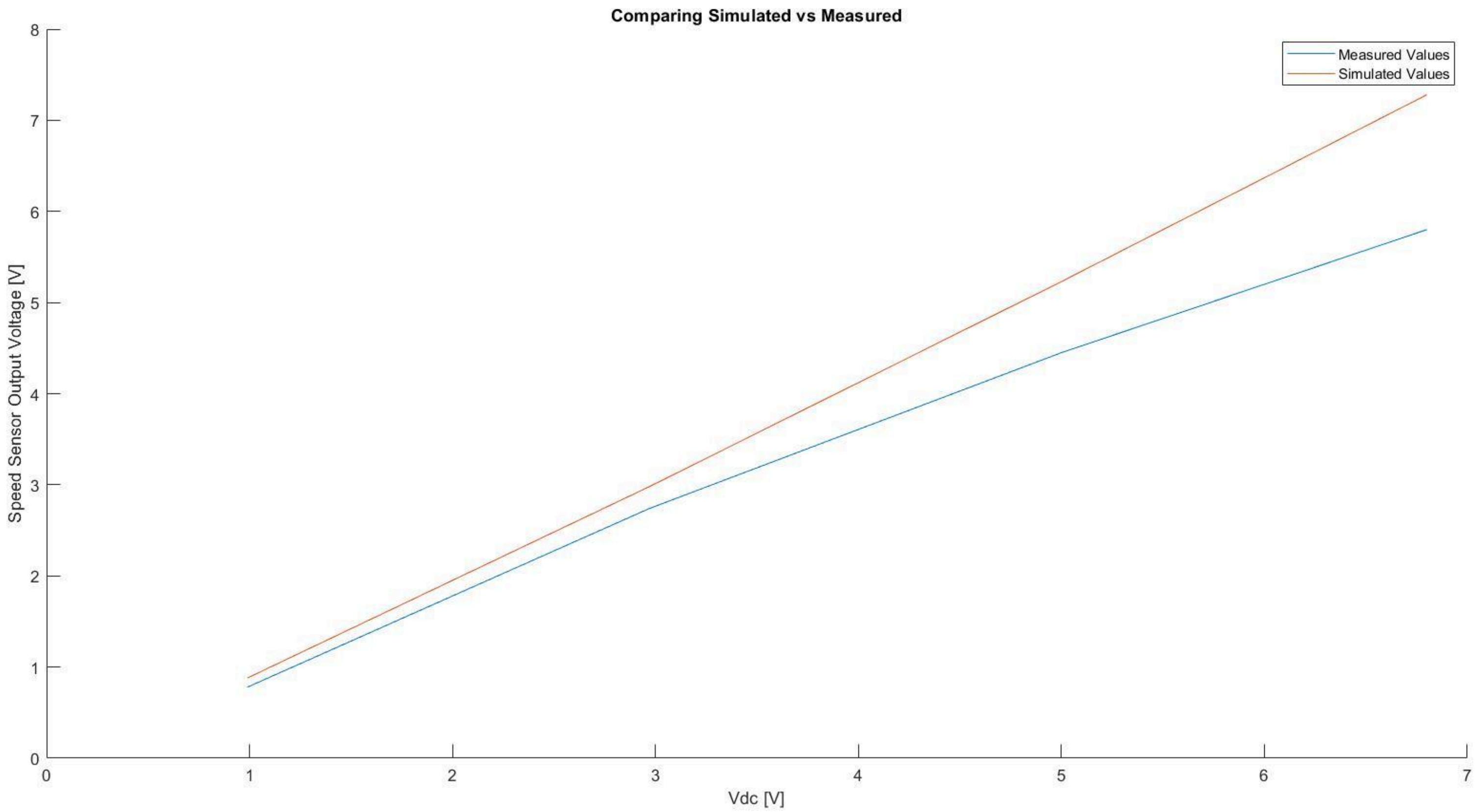
Experiment 2.B.5: Speed Sensor Sub-Circuit, Model Validation





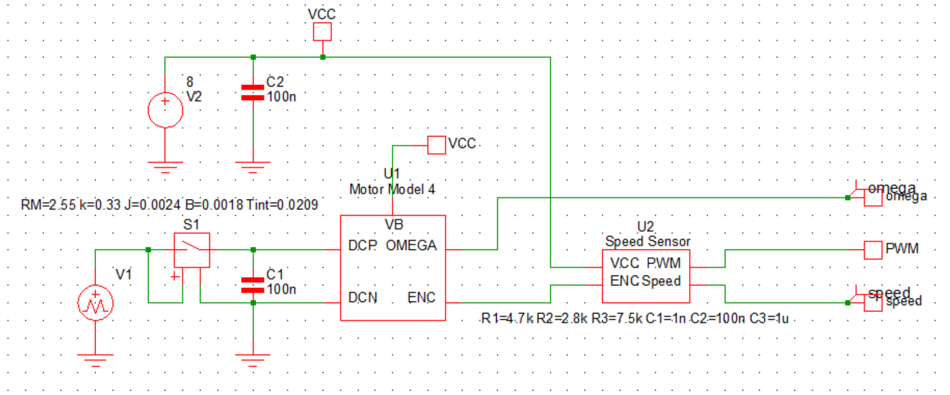
The above schematic and simulation show the same circuit and transient as 2.B.2, simply with the speed sensor as a sub-circuit. The transient and circuit operate identically.

The overall circuit correctness of the model to the actual was compared by plotting the data of their transients on the plot below. This plot compares the Speed Sensor Output Voltage per Motor Voltage of the simulation and actual circuits.

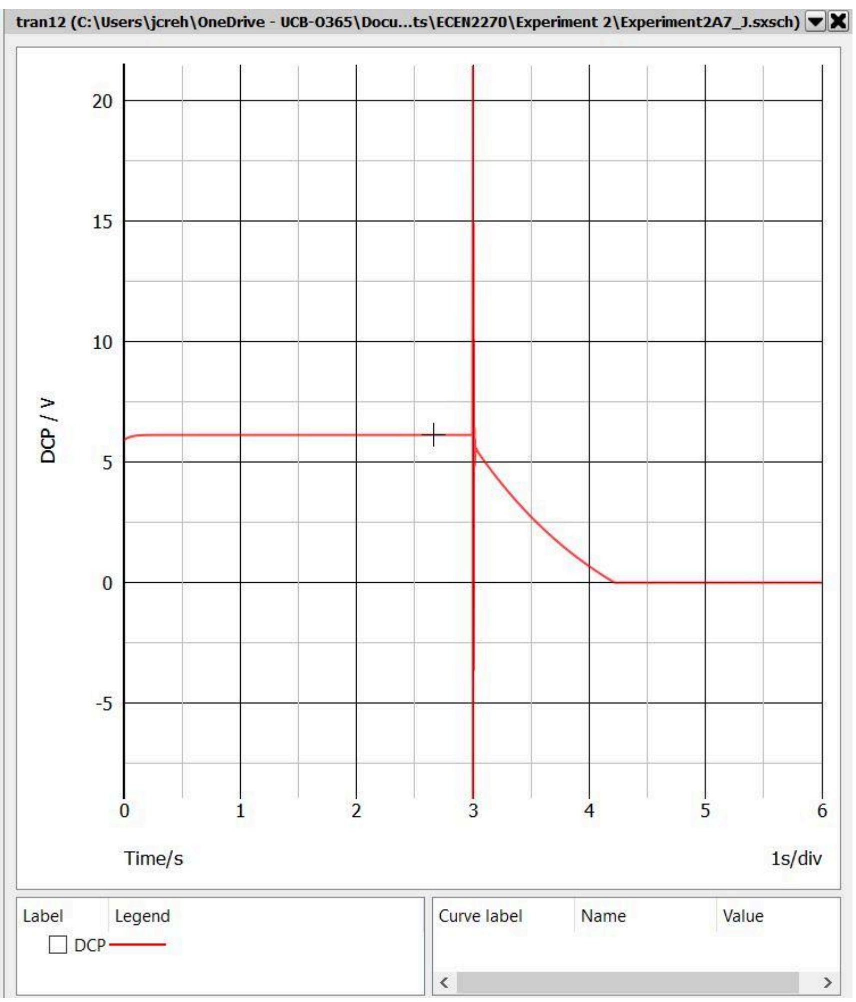


As can be seen, the simulation matches near perfectly for up to 3V on the motor. After this, there is a divergence in the model and the actual speed sensor output voltages. This must be due to physical imperfections within the circuitry or the motor itself. Given the simplicity of the circuit, the error most likely lies within the physical motor, which has internal frictions and max rotational velocities. This would lower the speed sensor output for the physical model that the simulation does not account for.

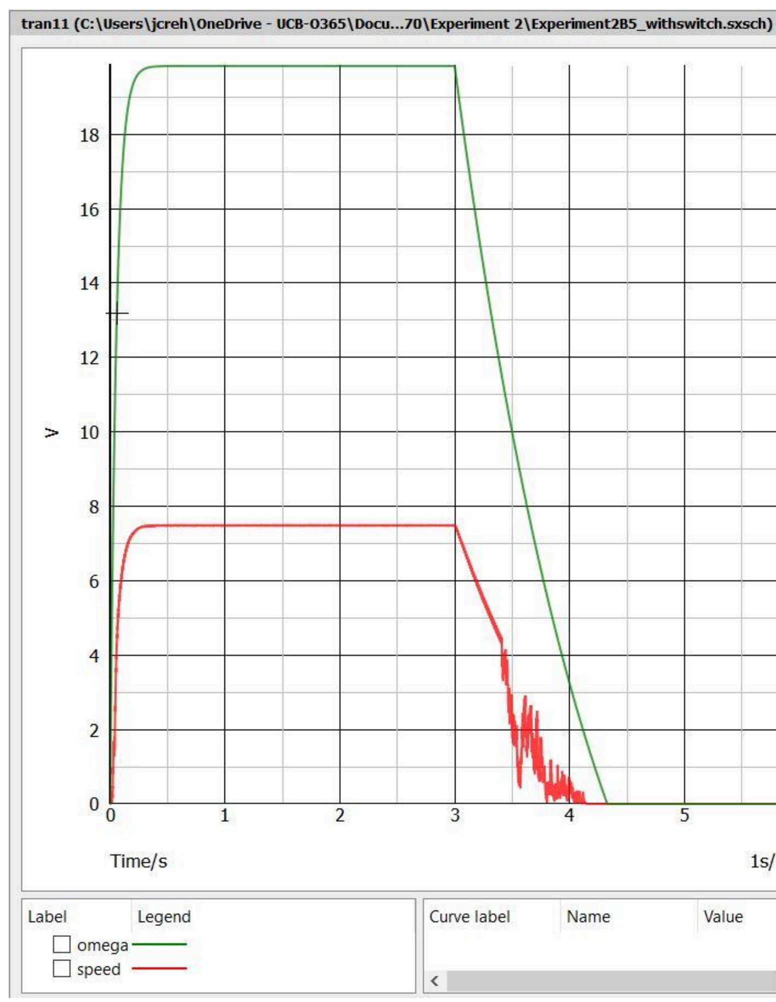
The transient of the unloaded motor turn-off of this circuit can be compared to the experiment performed in 2.A.6. Both plots can be seen below, with the experiment 2.A transient on the left, and the new transient on the right. The schematic for the new transient is also below.



VCC
8
V2
C2
100n
VCC
U1
Motor Model 4
RM=2.55 k=0.33 J=0.0024 B=0.0018 Tint=0.0209
S1
VB
DCP OMEGA
V1
C1
100n
DCN ENC
omega
U2
Speed Sensor
VCC PWM
ENC Speed
PWM
speed
R1=4.7k R2=2.8k R3=7.5k C1=1n C2=100n C3=1u



tran12 (C:\Users\jcreh\OneDrive - UCB-O365\Docu...ts\ECEN2270\Experiment 2\Experiment2A7_J.sxsch)
DCP / V
20
15
10
5
0
-5
0 1 2 3 4 5 6
Time/s
1s/div
Label
Legend
DCP
Curve label
Name
Value



tran11 (C:\Users\jcreh\OneDrive - UCB-O365\Docu...70\Experiment 2\Experiment2B5_withswitch.sxsch)
V
18
16
14
12
10
8
6
4
2
0
0 1 2 3 4 5
Time/s
1s/
Label
Legend
omega
speed
Curve label
Name
Value

The plots above reveal the similarities between the simple motor voltage turnoff of Experiment 2.A, and the more complicated turn-off of Experiment 2.B. In both plots, the motor voltage was set to zero at t=3s. In both cases, the wind-down takes approximately 1.2s. The new transient begins a smooth wind-down, similar to 2.A, then experiences the effects of the other components of the circuit. This causes a choppy wind-down, as the capacitors and inductors within the circuit and motor interact. The overall behavior of the system remains the same for the new circuit, compared to the circuit seen in Experiment 2.A.6.

The start-up transients were analyzed in a similar manner. The overall behavior of the start-up was the same, yet the load-up times were quite different. The 2.A motor started up faster than the new speed sensor circuit. This is most likely due to the additional components and complexity of the new speed sensor circuit. The extra capacitors and components caused a larger time to max voltage.

Conclusion

Throughout this lab, we delved deeper into practical electronic design, focusing on motor control, RC circuits, sensing applications, and real-world circuitry. By constructing and validating variable motor supply circuits and determining vital motor parameters, we got better at both theoretical analysis and hands-on experimentation. The design and testing of the trigger, one-shot, and speed sensor circuits allowed us to bridge the gap between mathematical analysis and practical implementation. We applied our knowledge yet again to dive deep into SIMetrix and breadboard testing, which helped us gain insight into some complexities of circuit behavior such as RC time constants, pulsing signals, timers, and sensing diodes. We spent countless hours constructing and validating variable motor supply circuits, fortifying our understanding of these concepts. Our attention to detail was tested and proven by the wheel encoder pulse to speed circuit, both in SIMetrix and on real hardware. Adhering to good practice requirements, we made sure the circuit looked good and matched our experimental expectations. Furthermore, we focused on the operational functionality and the resulting outputs of PWM and Vspeed, which we did so both by demonstrating circuit-building techniques but also troubleshooting and problem-solving techniques as well. In the end, we produced reasonable values which validated the effectiveness of our design and implementation. We can all agree that this lab has provided us with many new tools, experiences, and knowledge that will be necessary for our continued exploration.

Lab Exploration Topics

BJTs: (Part A)

1) What are BJTs made from?

Three layers of semiconductor material, each layer is either N-type or P-type.

2) What different types of BJTs are there?

NPN and PNP.

3) What are the inner workings of a BJT?

BJTs have three terminals: Emitter, Collector, and Base. They work by controlling the flow of electrons among these terminals.

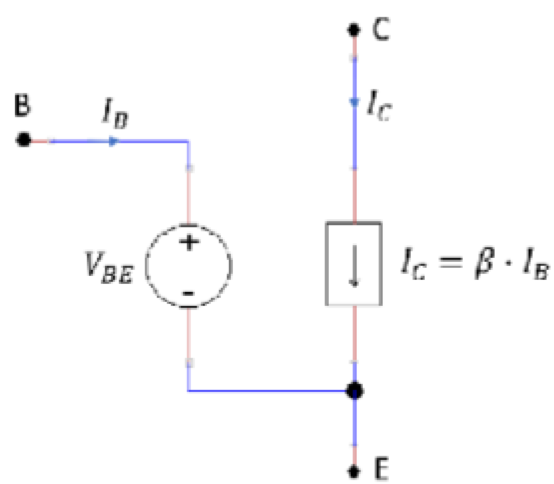
4) What are the key electrical parameters of BJTs (in particular power transistors)?

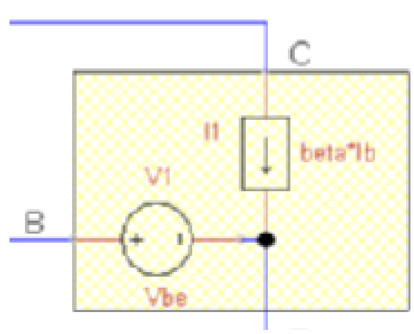
The current into the collector, the current into the base, the Collector-Emitter voltage, and the power dissipation.

5) What are the different modes of operation of BJTs?

BJTs have three different operational modes: Common Base mode, Common Emitter mode, and Common Collector mode.

6) What are simple equivalent circuits used to design BJT circuits?





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

Input to BJT is through the base terminal, the output is taken from the emitter terminal, and therefore the collector terminal is common to both the input and output. The main function of the CC circuit is to have a low input impedance and a current gain. It amplifies the current.

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

Input to BJT is through the base terminal, the output is taken from the collector terminal, and therefore the emitter terminal is common to both the input and output. The emitter circuit amplifies both the voltage and current.

Circuit Analysis: (Part B)

From your Circuits class knowledge, answer the following questions, assuming that Vs, RT, Cin, with RT $\ll$ Rin are given and that t1 = R1C1 should deviate as little as possible from its computed value:

1) How should R1 be chosen in relation to Rt and how should R1 be chosen in relation to Rin? If the requirements for the two cases are conflicting, what compromise should be chosen? How do the values of Rt and Rin affect t1 ?

R1 should be chosen to be much larger than Rt. We would do this so the voltage divider favors R1, which would be important for keeping our desired time constant. On the other hand, if R1 is too large, then the loading will be affected. For this reason, a middle ground needs to be found, where R1 is greater than Rt, but not too large where it would minimize the load. Both Rt and Rin affect the voltage divider, which affects the time constant, as the time constant is very dependent on the resistance at R1.

2) How should C1 be chosen in relation to Cin ? How does Cin affect T1 ?

C1 should be chosen with consideration to Cin to ensure that it has proper charging and discharging behavior to meet our specified time constant. If C1 is near or smaller than Cin, the input capacitance will have a more significant influence on T1. On the other hand, if C1 is way larger than Cin, it will dominate the process and primarily determine T1.

Cin is essentially adding more capacitance in parallel with C1. Since capacitors add in parallel, the total capacitance then becomes C1 + Cin, so T1 = R1(C1 + Cin).
As a result, Cin increases the capacitance seen by R1, leading to a longer time constant.

<u>3) 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.</u>

The source in this case would be the Hall Effect Sensor. This component is constantly detecting changes in the magnetic fields and providing an output signal when it does. Pin 1 is a +5V Vcc, pin 2 is Ground, and pin 3 is Output. If a magnet is detected, the output pin would go high. It has a typical operating voltage of 5V, an output current of 25mA, and turn off/turn on time is 2 microseconds. It also presumably has some output impedance.

The load in this case would be the LMC555 Timer. The timer is triggered by the output voltage coming from the output of the Hall Effect sensor into the trigger pin (pin 2) of the timer. It pushes 0.05 mA, can run from -40 to 125 degrees C, and has a supply voltage range from 1.5 to 15 V. It also has less than 1 mW typical power dissipation with a 5V supply.

<u>4) In the case where C1 is being charged and discharged through R1 (as is the case for the555 ‘one-shot’ timer circuit), how does R1 affect the maximum current drawn by the circuit? What if C1 is a ‘leaky’ capacitor, e.g., with a parallel resistance of 1 MΩ? How do these considerations constrain the choice of R1 ?</u>

You may also want to check on the Internet to see what practical rules of thumb engineers are using when selecting R and C to implement a specific time constant. Include your computations and findings in the lab report and use them for the selection of the R and C components for Experiment 2.B.

Effects of R1 on maximum current drawn:
During the charging phase, C1 will charge up through R1 until it reaches the threshold voltage which will then trigger the timer circuit. Charging current is just I = V/R1, so a larger R1 will result in a lower charging current, and a smaller R1 would result in a higher charging current. Then during discharge through R1 it will reach its other threshold, finishing the cycle, and the current will be discharging. So, there will be a higher maximum current with a lower resistance, and vice versa.

Effect of a “leaky” capacitor:

If C1 is leaky, meaning it has a parallel resistance of 1 M Ohm, it will lead to very fast discharge times which can heavily affect the circuit. A leaky capacitor can cause issues and lead to malfunction, instability or damage. It will make the timing inaccurate, the voltage unstable, and could cause a lot of heating.

Constrained choice of R1:
Choosing R1 should consider the desired charging and discharging currents, as well as the time constant and timing accuracy the circuit specifies.
If R1 is too large, it will lead to a longer time constant, and if R1 is too small, it could draw excessive current from the power supply and result in more power dissipation. If C1 is “leaky” the choice of R1 needs to take the added parallel resistance into account and its impact on the timing of the circuit.