Lab #1

EE 452 / 532 - Power Electronics Design

Kevin Egedy
Luke Commins
David Babin

Description	Section	Score
Record all experimental results which are used to solve the parameters. Take oscilloscope screenshots as you test, which will later be used in your report to show explicitly how you arrived at the values you report. Explain, in your lab report, which parameters are solved in each test, why the test was chosen, and how the parameters were obtained from the test result (20 pts).	1A	
In order to determine the relationship between the hall sensors and winding phases, produce a time-aligned plot of the phase or line voltages and Hall sensor outputs. Divide your plot into six subintervals according to the state of each Hall output (15 pts).	1A	
Separate from the tests you ran to determine the parameters of the motor, design a single, continuous PLECS simulation test for the motor, which can be run both experimentally and in simulation, which will show the accuracy of your model as a whole. In your report, include details of the tests you used, and show the resulting experimental and simulation waveforms, side-by-side or overlaid on one another. You may use the starter PLECS file(s) provided. For the PLECS motor model, use Ke = λmP where P is the number of pole pairs. (10 pts)	1A	
What is the mechanical power required to meet both the top speed and gradeability requirements? (give one value) (5 pts)	1A	
What is the peak back-emf voltage that will be generated at a speed of 10 mph? (5 pts)	1A	
Consider and discuss, briefly, how each of these will inform the design of the power electronics in the ensuing experiments. (5 pts)	1A	
If VDC = 25 V, how large must CDC be so that VDC changes by less than 1 V during the time that imd(t) = 0 in either of the performance metric cases?	1A	

Description	Section	Score
A complete and labeled circuit diagram of the PWM IC along with labeled component names and values. (8pts)	1B	
Computation of switching frequency along with Rd included (2pts)	1B	
Capture 1 (20pts) D=25%: Noninverting input pin (PWM Reference Voltage)	1B	
Capture 1 (20pts) D=25%: Oscillator output pin voltage	1B	
Capture 2 (20pts) D=25%: PWM A Output	1B	
Capture 2 (20pts) D=25%: PWM B Output	1B	
Capture 3 (10pts) D=25%: PWM 'OR' output	1B	
Capture 1 (20pts) D=75%: Noninverting input pin (PWM Reference Voltage)	1B	
Capture 1 (20pts) D=75%: Oscillator output pin voltage	1B	
Capture 2 (20pts) D=75%: PWM A Output	1B	
Capture 2 (20pts) D=75%: PWM B Output	1B	
Capture 3 (10pts) D=75%: PWM 'OR' output	1B	
EE532 students to use a range of RD($33 - 500\Omega$) and record Capture 2 for different RD values (2 values other than 33Ω and be sure to include deadtime measurement.	1B	

Description	Section	Score
A complete and labeled circuit diagram of the driver IC along with labeled component names and values.(5pts)	1C	
A detailed computation of your boot resistance and capacitance. (10pts)	1C	
Capture 1 (10 pts): Capture the input LO signal of the driver.	1C	
Capture 2 (10 pts): Capture the output LO signal of the driver.	1C	
Capture 3 (10pts): Include a zoomed in capture of an on/off transient	1C	

Lab #1 - A

1. Motor Characterization Experiments

EMF Shape

To determine the shape of the induced EMF, we connect the oscilloscope probes to any two of the three hub motor winding terminals (denoted as $V_A, V_B, and\ V_C$ in the schematic) and observe the generated waveform as the wheel spins. The captured waveform is shown below:

Figure 1. EMF induced in a winding of the motor hub

From the signal displayed, it is evident that the shape of the induced EMF is sinusoidal.

Number of Poles (P)

Using an oscilloscope to measure the induced winding EMF, we can extrapolate the number of pole pairs (PP) present in the hub of the bike's wheel.

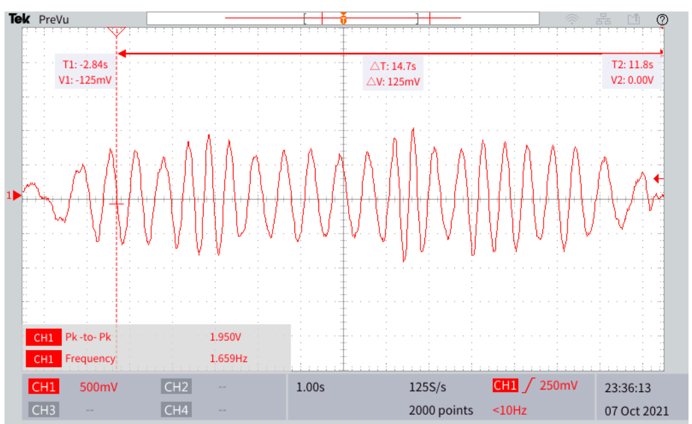


Figure 2. EMF induced in a single phase winding from a complete revolution of the wheel

The magnetic field generated by the permanent magnets in the wheel's hub will have a corresponding flux that will link with the phase windings inside the motor's hub. As we begin to rotate the wheel, the flux linking the motor hub windings changes with time; this, as a direct result of Faraday's Law, will induce an electo-motive force (i.e., EMF) in the windings. As observed in the previous section, this EMF will be sinusoidal in shape due to the time-varying flux resulting from the spinning motion of the magnets in the wheel (as the wheel itself is spun). We know that a single cycle of the sinusoidal EMF waveform corresponds to our phase winding passing over a single pole-pair. Rotating the wheel exactly by one complete revolution, we can observe the number of sinusoidal cycles in the induced EMF and accordingly, extrapolate the number of pole pairs in the hub of the wheel by counting the number of sinusoidal cycles. From the oscilloscope screenshot above, we see that there are 24 complete cycles which our EMF undergoes. As such, the number of pole-pairs our winding has seen as it made one complete revolution is $PP = 24$. This then means that the number of poles P in the wheel hub is:

$$P = 2 \cdot PP = 2 \cdot (24) = 48 \rightarrow P = 48$$

Winding DC Resistance (r_w) and Low-Frequency Inductance (L_w)

As stated in the lab procedure, the motor is 3-phase Wye-connected; because of this Wye configuration, if we connect an LCR meter to any two of the three hub motor windings (denoted as $V_A,\ V_B,\ and\ V_C$ in the schematic) we will in fact be measuring 2 times the actual resistance or inductance value. To get the single-phase equivalent value, we must divide the measured value by 2. The resulting values for the DC winding resistance (r_w) and low frequency inductance (L_w) are:

$$2 \cdot r_w = 585\ m\Omega \rightarrow r_w = 292.5\ m\Omega$$

$$2 \cdot L_w = 859.3\ \mu H \rightarrow L_w = 429.65\ \mu H$$

Peak Flux Linkage ($\lambda_m = N \cdot \Phi_{pk}$)

Before we can compute the peak flux linkage λ_m, we must find the phase (line-to-neutral) voltage magnitude V_m for a corresponding electrical angular frequency ω_r. To obtain this data, we examine the EMF induced in the hub motor windings by connecting oscilloscope probes to any two of the three hub motor winding terminals (denoted as $V_A,\ V_B,\ and\ V_C$ in the schematic). After giving the wheel a good spin, we observe the following signal on the oscilloscope screen:

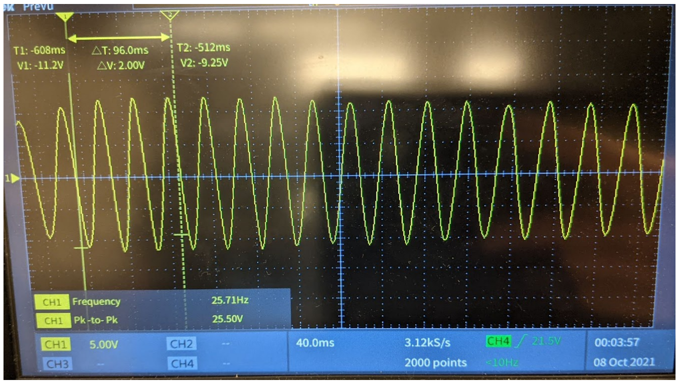


Figure 3. EMF induced in winding of motor hub

Using the oscilloscope's trace feature, we find the peak-to-peak, line-to-line voltage $V_{pp,\,LL}$ to be $V_{pp,\,LL} = 25.5\ V$. We can convert this peak-to-peak, line-to-line voltage to the corresponding phase (line-to-neutral) voltage magnitude V_m via:

$$V_m = \frac{V_{m,\,LL}}{2} = \frac{V_{pp,\,LL}\ /\sqrt{3}}{2} = \frac{25.2\ /\sqrt{3}}{2} = 7.275\ V$$

The electrical frequency is likewise found to be $f_r = 25.71\ Hz$. The corresponding electrical angular frequency ω_r is then:

$$\omega_r = 2\pi \cdot f_r = 2\pi \cdot (25.71) = 161.541\ rad/s$$

We can now proceed with the rest of the calculations. The single phase motor winding voltage is known to be:

$$v = ri + L\frac{di}{dt} + \lambda_m\ \omega_r\ cos(\theta_r)$$

No current was injected in any of the phases (i.e., $i = \frac{di}{dt} = 0$); as such, the single phase motor winding voltage equation simplifies to:

$$v = \lambda_m\ \omega_r\ cos(\theta_r)$$

Since we will be solving this expression for the case when the voltage is at a maximum (i.e., $v = V_m$), it must be true that $cos(\theta_r) = 1$. The expression now becomes:

$$V_m = \lambda_m\ \omega_r$$

Rearranging for λ_m and solving, we have:

$$\lambda_m = \frac{V_m}{\omega_r} = \frac{7.275}{161.541} = 0.045033\ V \cdot m$$

And so we have that the peak flux linkage is:

$$\lambda_m = 0.045033\ V \cdot m$$

Relation between phases and hall sensors

Using the oscilloscope probes along with a differential probe, we were able to measure the output signals of one of the phase windings inside the motor hub and the output signals of the Hall Effect sensors of each of the phases. When we spun the wheel, the following signals were observed on the oscilloscope:

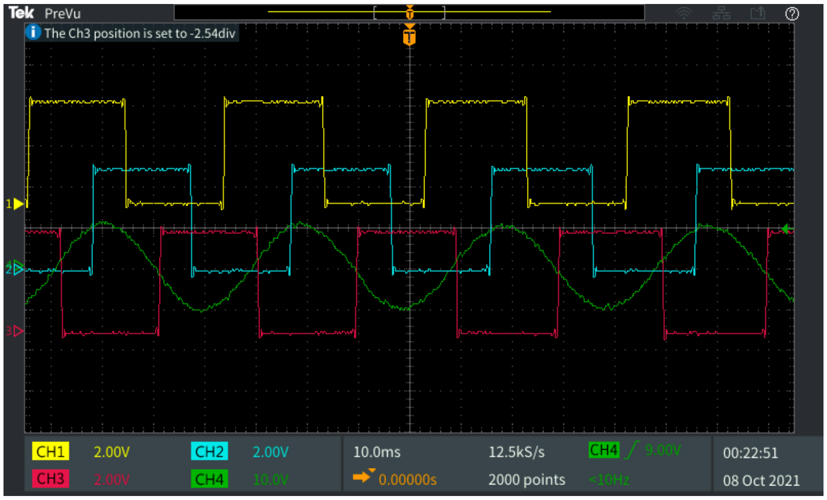


Figure 4. Time-aligned plot of a line voltage and the Hall sensor outputs

This test shows the relationship between the back emf and the density of the magnetic field captured by the hall sensors (for each of the phases). We can now look at the time-aligned plot over a single cycle, and subdivide it into six subintervals according to the state of each Hall sensor output:

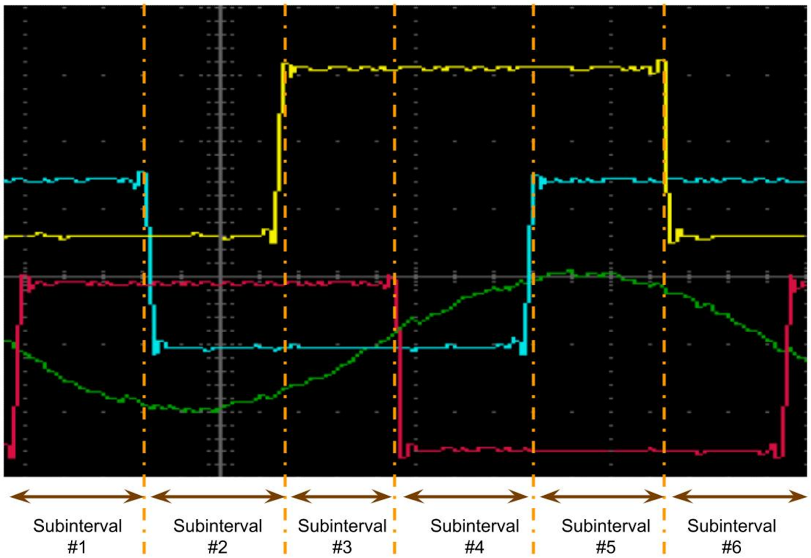


Figure 5. Time-aligned plot of the line voltage and Hall sensor outputs subdivided into six subintervals according to the state of each Hall output

2. Simulation and Modeling

2.1 Motor Simulation

PLECS Simulation Parameters	Description
PP = 24	Number of pole pairs
R = 292.5e-3	Stator resistance (Ohms)
L = 429.7e-6	Stator inductance (H)
KE = 0.045*PP	Amplitude of back EMF (Vs/rad) * pole pairs
M.T = 7.6	Applied torque impulse amplitude (Nm)

To build a simulation test, we first begin by finding the necessary torque that matches the experimental mechanical speed. The mechanical speed is a function of the electrical frequency.

$$\omega_m = \omega_r / PP = 161.54/24 = 6.71\ (rad/s)$$

The applied torque is tuned until the speed sensor reaches a max value of ~6.71 rad/s. The experimental speed was not captured but can be determined intuitively. A large torque was applied to the wheel and remained untouched until the wheel came to a complete stop.

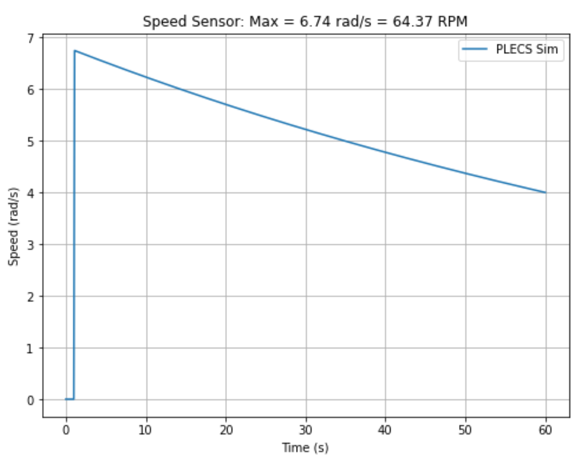


Figure 6. PLECS Speed Sensor: ω_m (rad/s)

The measured motor characteristics are applied to the PLECS motor to achieve a similar representation. Pole pairs, stator resistance, stator inductance, and back EMF amplitude (K_e) are updated in the model. The PLECS model obtains a back EMF voltage of 7.28V and is very close to the measured line-to-neutral voltage V_m of 7.275 V.

PLECS | **Experimental**

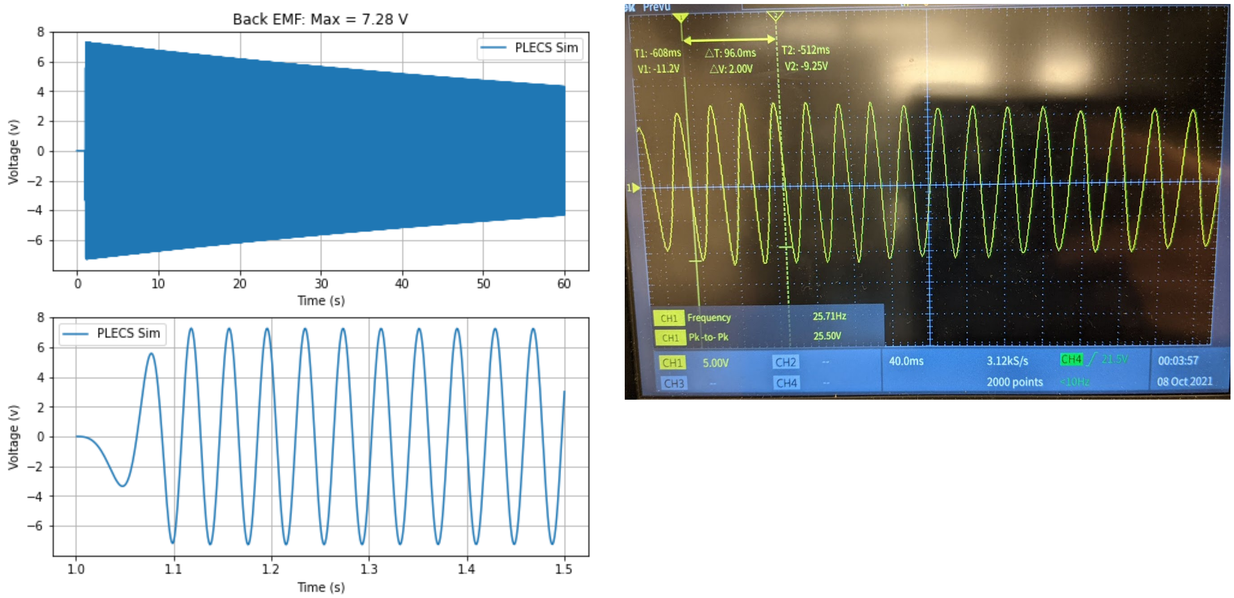


Figure 7. PLECS vs Experimental: Back EMF Voltage

Additionally, the PLECS' hall sensors agree with the experimental captures. The hall sensors define 6 intervals in the back EMF waveform. The period of the EMF waveform is ~40ms with ~7ms intervals. Also the PLECS model uses hall sensors with output voltages of 1V compared to the 5V outputs measured in the lab.

PLECS | **Experimental**

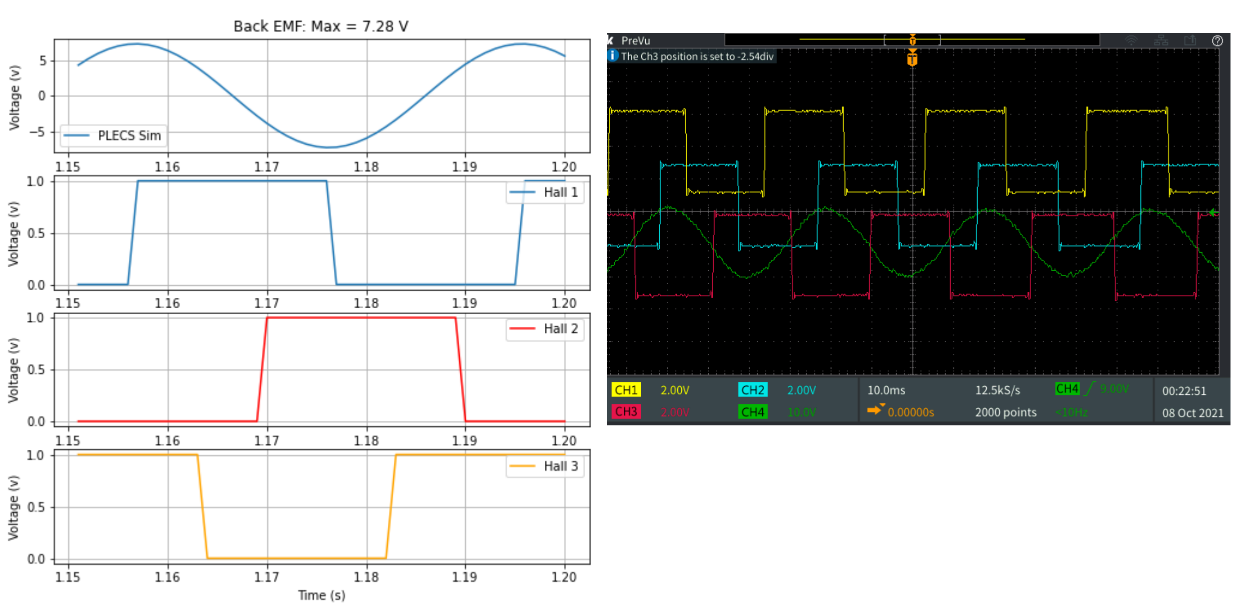


Figure 8. PLECS vs Experimental: Hall Sensors

2.2 Vehicle Dynamics

To determine the forces that act on our bicycle as it moves, we can use a free-body diagram. We know that the traction force is the sum of the gravity, friction (i.e., rolling resistance) and drag forces:

$$F_{traction} = F_{gravity} + F_{friction} + F_{drag} = Mg \cdot sin(\theta) + C_r Mg \cdot cos(\theta) + \frac{1}{2}\rho A_v C_d (V_{bike})^2$$

where: $M = M_{net} = M_{bike} + M_{rider} = (50\ lbs + 250\ lbs)\left(\frac{0.45\ kg}{1\ lb}\right) = 135\ kg \rightarrow$ net mass

$g = 9.8\ m/s^2 \rightarrow$ acceleration due to gravity

$A_v = 0.5\ m^2 \rightarrow$ frontal area of bike

$C_r = 0.013 \ \ || \ \ C_d = 0.65 \ \ || \ \ \rho = 1.204\ kg/m^3 \ \ || \ \ d_w = 2r_w = 700\ mm = 0.7\ m$

$$F_{traction} = 135 \cdot 9.8 \cdot sin(\theta) + 0.013 \cdot 135 \cdot 9.8 \cdot cos(\theta) + \frac{1}{2} \cdot 1.204 \cdot 0.5 \cdot 0.65 \cdot (V_{bike})^2$$

$$F_{traction} = 1323 \cdot sin(\theta) + 17.199 \cdot cos(\theta) + 0.19565 \cdot (V_{bike})^2$$

We find the mechanical power associated with this traction force by using the relationship:

$$P_m = P_{traction} = F_{traction} V_{bike} = V_{bike}\left[1323 \cdot sin(\theta) + 17.199 \cdot cos(\theta) + 0.19565 \cdot (V_{bike})^2\right]$$

The mechanical power required to meet the:

- Top speed requirement: $\theta = 0° \ \& \ V_{bike} = 10\ mph\left(\frac{0.447\ m/s}{1\ mph}\right) = 4.47\ m/s$

  $$P_m = 4.47 \cdot \left[1323 \cdot sin(0) + 17.199 \cdot cos(0) + 0.19565 \cdot (4.47)^2\right] = 94.434\ W$$

- Gradeability requirement: $\theta = tan^{-1}(3/100) = 1.718° \ \& \ V_{bike} = 5\ mph\left(\frac{0.447\ m/s}{1\ mph}\right) = 2.23\ m/s$

  $$P_m = 2.235\left[1323 \cdot sin(1.718) + 17.199 \cdot cos(1.718) + 0.19565 \cdot (2.235)^2\right] = 129.26\ W$$

So the mechanical power to meet both requirements (speed & gradeability) is:

$$P_m = 129.26\ W$$

It is also possible to find the peak back-emf voltage that will be generated at a speed of 10 mph. We know that the back emf e induced in a single phase of the coil is:

$$e = \lambda_m \omega_r \cdot cos(\theta_r)$$

The maximum of this back-emf occurs when $cos(\theta_r) = 1$; as such, the expression becomes:

$$max(e) = \lambda_m \omega_r$$

From the data gathered in lab, we know that:

$\lambda_m = N\Phi_{pk} = 0.04557\ V - s$ and is independent of the angular speed

$$\omega_r = \frac{P}{2}\omega_m = \left(\frac{P}{2}\right)\left(\frac{V_{bike}}{r_w = d_w/2}\right) = \left(\frac{48}{2}\right)\left(\frac{4.47}{0.7/2}\right) = 306.51\ rad/s$$

Solving for $max(e)$, we have:

$$max(e) = 0.04557 \cdot 306.51 = 13.966\ V$$

$$max(e) = 13.966\ V$$

The values we obtained will inform the design of the power electronics in the following way. The mechanical power P_m needed to meet the conditions imposed earlier will be produced as a direct result of the conversion from electrical to mechanical energy. As such, the mechanical power needed will proportionally determine the amount of electrical power we will need to generate. The amount of electrical power generated will in turn rely on the voltage level and the current drawn. The value of voltage, but more specifically current, will determine the sizing of our power electronic parts and their respective ratings. As such, the mechanical power P_m will determine the power rating of our electronic devices.

By employing similar analysis, the peak back-emf voltage $max(e)$ will determine the voltage rating of our electronic devices.

2.3 DC Bus Capacitance

We know that the expression for the current through a capacitor is of the form:

$$i_c(t) = C\,\frac{dv_c(t)}{dt}$$

Rearranging this expression for the value of capacitance C, we obtain:

$$dv_c(t) = \frac{1}{C} i_c(t)\,dt \;\rightarrow\; \Delta v_c(t) = \frac{1}{C}\int i_c(t)\,dt \;\rightarrow\; C = \frac{\int i_c(t)\,dt}{\Delta v_c(t)}$$

If $V_{DC} = 25\ V$, then the average current is $I_C = \frac{P_e = P_m}{V_{DC}} = \frac{P_m}{25}$. Given V_{DC} changes by less that $1\ V$ during the $0.01T$ time interval (for which the motor drive current pulses to 0), then C is:

$$C = \frac{\int_t^{t+0.01T} i_c(t)\,dt}{\Delta v_c(t)} = \frac{\frac{1}{2}(0.01T)(P_m/25)}{\Delta V_{DC}} = \frac{\frac{1}{2}(0.01T)(P_m/25)}{1} = 0.0002 \cdot T \cdot P_m$$

Using the same value for the period T as for the experimental results, we have:

$$T = T_r = \frac{1}{f_r} = \frac{1}{\omega_r/2\pi} = \frac{2\pi}{\omega_r}$$

It is now possible to find the the value of C_{DC} for either of the performance metric cases:

- Top speed performance metric requirement: $V_{bike} = 10\ mph = 4.47\ m/s$ ($P_m = 94.434\ W$)

  $$\omega_r = \frac{P}{2}\omega_m = \left(\frac{P}{2}\right)\left(\frac{V_{bike}}{r_w = d_w/2}\right) = \left(\frac{48}{2}\right)\left(\frac{4.47}{0.7/2}\right) = 306.51\ rad/s$$

  $$T = \frac{2\pi}{\omega_r} = \frac{2\pi}{306.48} = 0.0205\ s$$

  $$C = 0.0002 \cdot T \cdot P_m = (0.0002)(0.0205)(94.434) = 0.000387 \;\rightarrow\; C_{DC} = 387\ \mu F$$

- Gradeability performance metric requirement: $V_{bike} = 5\ mph = 2.23\ m/s$ ($P_m = 129.26\ W$)

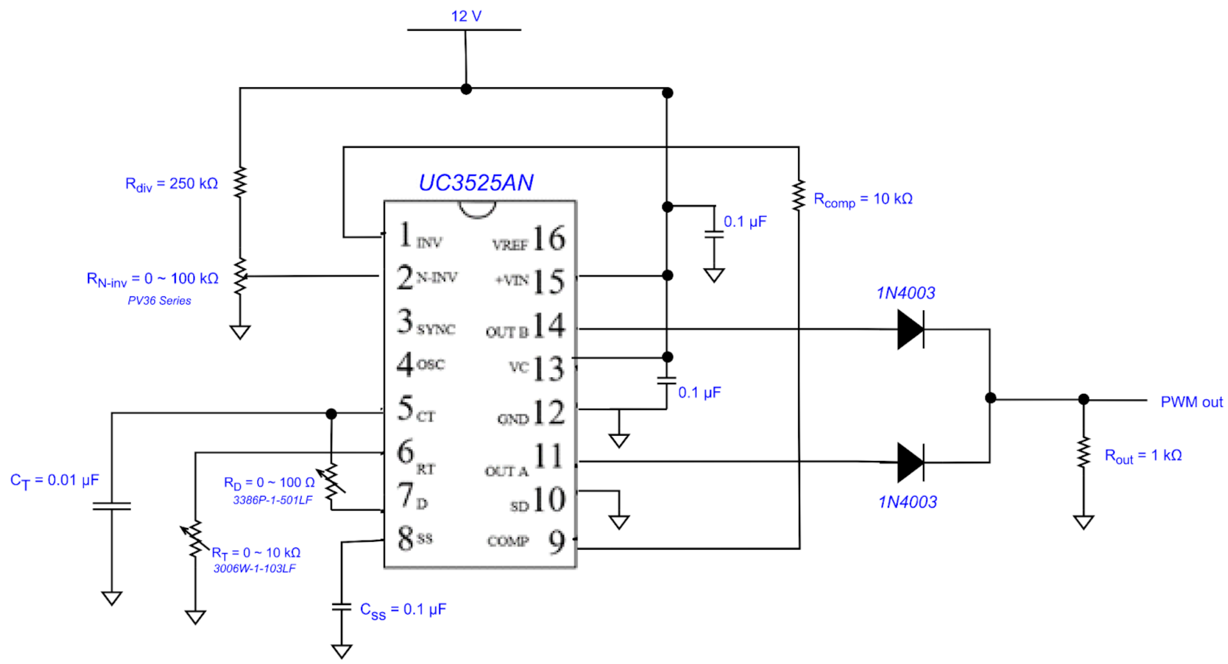
  $$\omega_r = \frac{P}{2}\omega_m = \left(\frac{P}{2}\right)\left(\frac{V_{bike}}{r_w = d_w/2}\right) = \left(\frac{48}{2}\right)\left(\frac{2.23}{0.7/2}\right) = 152.914\ rad/s$$

  $$T = \frac{2\pi}{\omega_r} = \frac{2\pi}{152.914} = 0.04109\ s$$

  $$C = 0.0002 \cdot T \cdot P_m = (0.0002)(0.04109)(129.26) = 0.001062 \;\rightarrow\; C_{DC} = 1,062\ \mu F$$

Lab #1 - B

PWM IC Diagram



R_{div}	voltage divider resistance
$R_{N\text{-}inv}$	non-inverting input resistance
R_D	dead-time resistor
R_T	oscillator timing resistor
C_T	oscillator-timing capacitor
C_{SS}	soft start capacitance
R_{comp}	compensation resistance

Switching Frequency along with R_D Computation

For the purposes of this lab, the oscillator timing capacitor was chosen to have a value of $C_T = 0.01\ \mu F$. As such, the switching frequency is:

$$f_{sw} = \frac{1}{C_T\ (0.7\ R_T + 3\ R_D)} = \frac{1}{(\ 0.01 \times 10^{-6}\ )\ (0.7\ R_T + 3\ R_D)} = \frac{10^8}{0.7\ R_T + 3\ R_D}$$

To obtain a switching frequency of $f_{sw} = 50\ kHz$ for the dead time resistor values of $R_D = \{0,\ 33,\ 100,\ 485\}\ \Omega$, the oscillator timing resistor, which has the general expression of $R_T = \left(\frac{1}{f_{sw}\ C_T} - 3R_D\right) / 0.7$, must be:

$$R_D = 0\ \Omega \qquad R_T = 2,857\ \Omega$$

$$R_D = 33\ \Omega \qquad R_T = 2,715\ \Omega$$

$$R_D = 100\ \Omega \qquad R_T = 2,428\ \Omega$$

$$R_D = 490\ \Omega \qquad R_T = 757\ \Omega$$

Note, if we were to keep the values $R_T = 4900\ \Omega$ & $R_D = 485\ \Omega$ fixed, then the switching frequency would be:

$$f_{sw} = 20.5\ kHz$$

75% Duty Cycle Waveforms

Capture 1: Non-inverting input pin (PWM Reference Voltage) & Oscillator output pin voltage

Figure 1. CH1 (Yellow): NINV || CH2 (Blue): Oscillator Output

Capture 2: PWM A & B Outputs. The deadtime was measured to be: $t_d = 4.96\ \mu s$

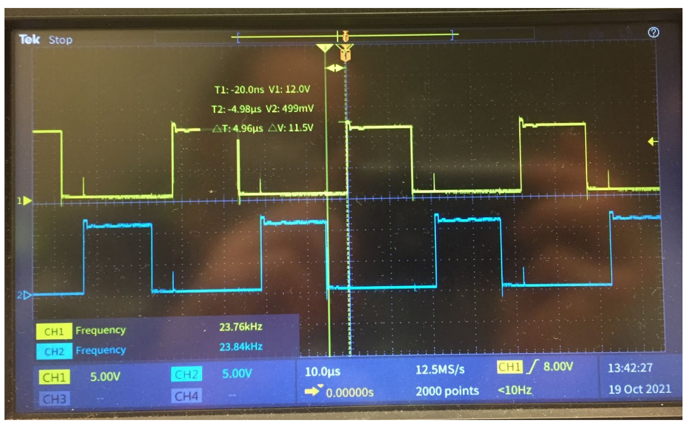


Figure 2. PWM A & B Outputs

Capture 3: PWM 'OR' Output

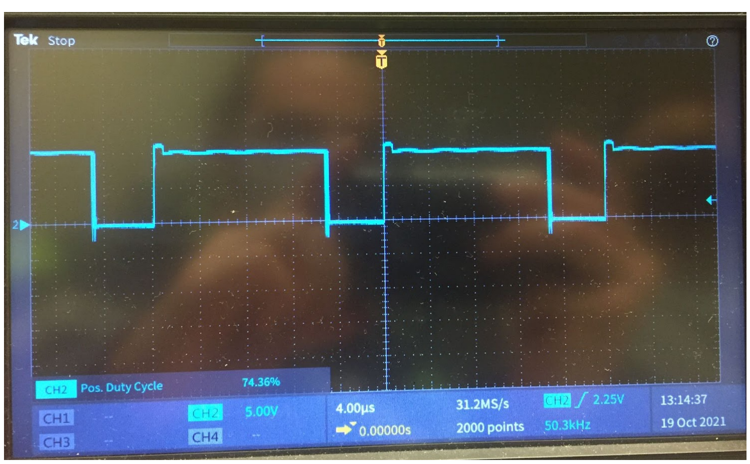


Figure 3. PWM 'OR' Output

25% Duty Cycle Waveforms

Capture 1: Non-inverting input pin (PWM Reference Voltage) & Oscillator output pin voltage

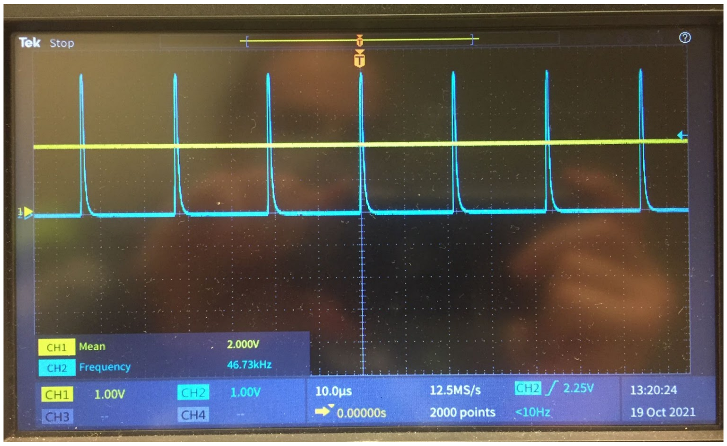


Figure 4. CH1 (Yellow): NINV || CH2 (Blue): Oscillator Output

Capture 2: PWM A & B Outputs. The deadtime was measured to be: $t_d = 14.9\ \mu s$

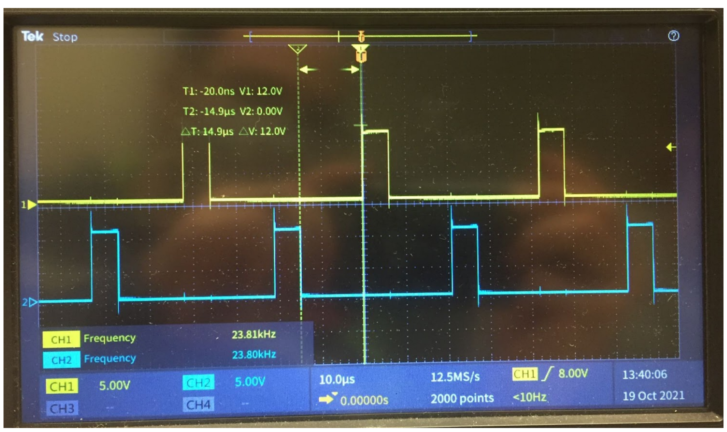


Figure 5. PWM A & B Outputs

Capture 3: PWM 'OR' Output

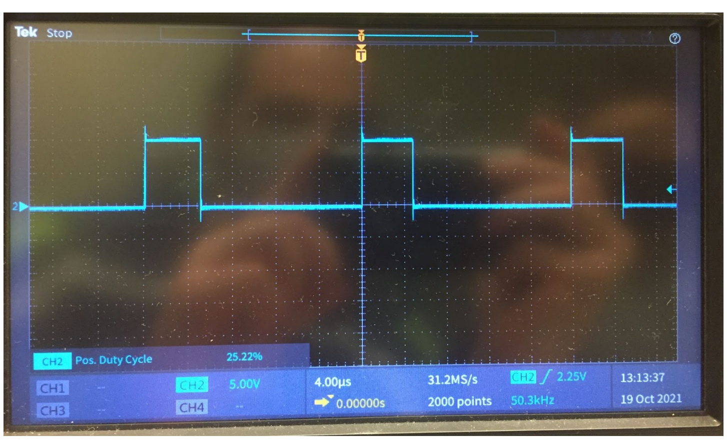


Figure 6. PWM 'OR' Output

Adjusting Deadtime

For a given frequency, different deadtimes are possible without changing the input of Pin 2 in the PWM circuit. This is done by changing R_D and tuning R_T until the desired frequency is measured (25kHz). Deadtime is denoted by t_d and increases with the value of R_D.

- $R_D = 33\ \Omega$. Deadtime is $5.84\ \mu s$.

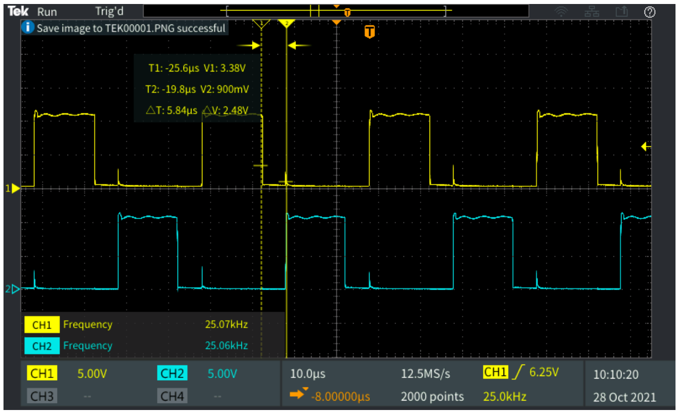


Figure 7. $R_D = 33\ \Omega$; $t_d = 5.84\ \mu s$

- $R_D = 100\ \Omega$. Deadtime is $6.64\ \mu s$.

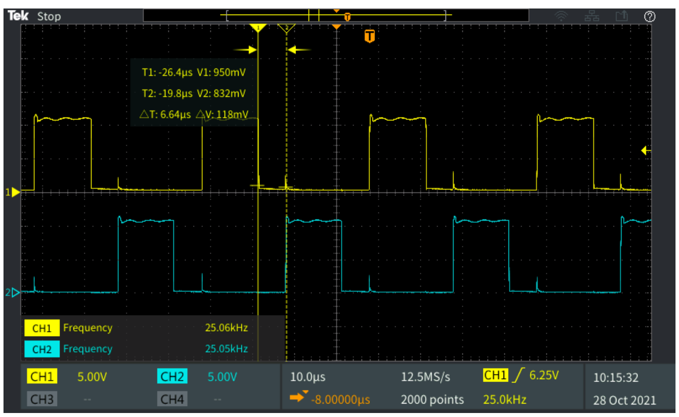


Figure 8. $R_D = 100\ \Omega$; $t_d = 6.64\ \mu s$

- $R_D = 200\ \Omega$. Deadtime is $8.44\ \mu s$.

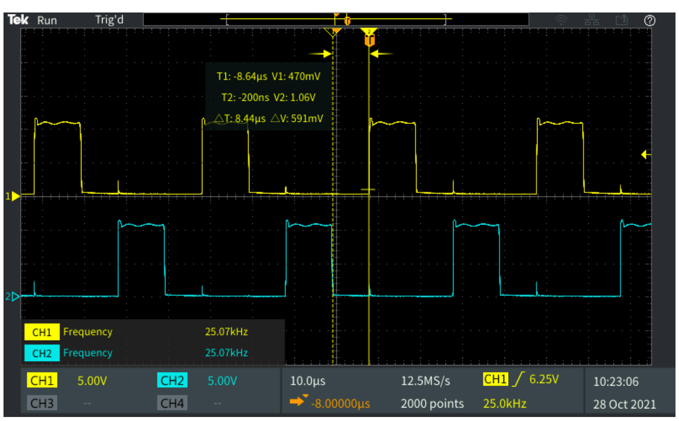
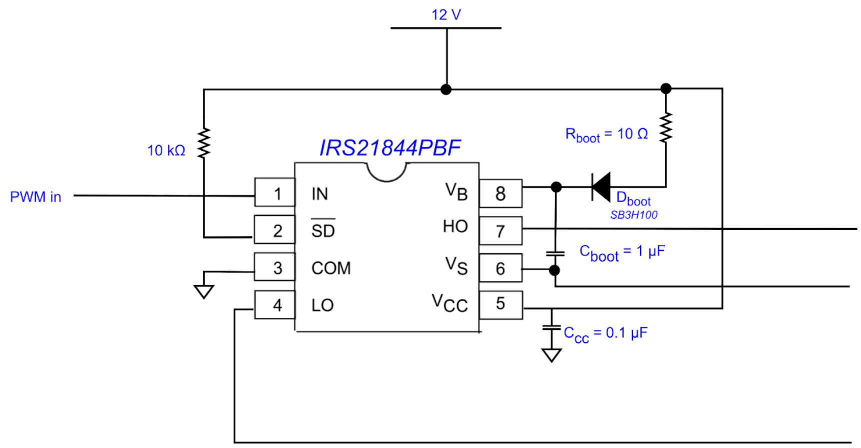


Figure 9. $R_D = 200\ \Omega$; $t_d = 8.44\ \mu s$

Lab #1 - C

Driver IC Diagram



R_{boot}	bootstrap resistance
C_{boot}	bootstrap capacitance
C_{cc}	common-collector capacitance

Boot Resistance and Capacitance Computation

Bootstrap capacitance C_{BOOT} is needed to limit the high-side voltage fluctuations to no more than 5% of $V_{CC} = V_{DD} = 12\,V$ (for a switching frequency of $f_{sw} = 50\,kHz$). Assuming the peak bootstrap diode current is $I_{DBOOT(pk)} = 3\,A$, we find the forward voltage drop of the of the SB3H100-E3/54 bootstrap diode to be $V_{DBOOT} = 0.8\,V$. For the specific IRS2184PBF Half-Bridge Driver, the Quiescent VBS supply current is known to be $I_{QBS} = 60\,\mu A$.

To find the bootstrap capacitance C_{BOOT}:

$$C_{BOOT} = \frac{Q_{TOTAL}}{\Delta V_{BOOT}} \qquad \textit{where: } Q_{TOTAL} = Q_G + \frac{I_{QBS}}{f_{sw}} \quad \& \quad \Delta V_{BOOT} = (\%\,fluctuation)(V_{DD})$$

- **CSD19535KCS** MOSFET ($Q_G = 78\,nC$):

$$Q_{TOTAL} = 78\,nC + \frac{60\,\mu A}{50\,kHz} = 79.2\,nC$$

$$C_{BOOT} = \frac{79.2\,nC}{(0.05)(12)\,V} = 132.0\,nF \rightarrow C_{BOOT} = 132.0\,nF$$

- **IRFB4615PbF** MOSFET ($Q_G = 26\,nC$):

$$Q_{TOTAL} = 26\,nC + \frac{60\,\mu A}{50\,kHz} = 27.2\,nC$$

$$C_{BOOT} = \frac{27.2\,nC}{(0.05)(12)\,V} = 45.33\,nF \rightarrow C_{BOOT} = 45.33\,nF$$

The corresponding bootstrap resistance R_{BOOT}, for both the **CSD19535KCS** and **IRFB4615PbF** MOSFETs can be found to be:

$$R_{BOOT} = \frac{V_{DD} - V_{DBOOT}}{I_{DBOOT(pk)}} = \frac{12 - 0.8}{3} = 3.733\,\Omega \rightarrow R_{BOOT} = 3.733\,\Omega$$

Although we found what C_{BOOT} & R_{BOOT} should be using numerical analysis, the actual values used for our gate driver were:

$$R_{BOOT} = 10\,\Omega \qquad \& \qquad C_{BOOT} = 10\,\mu F$$

Driver Input and Output LO Signal

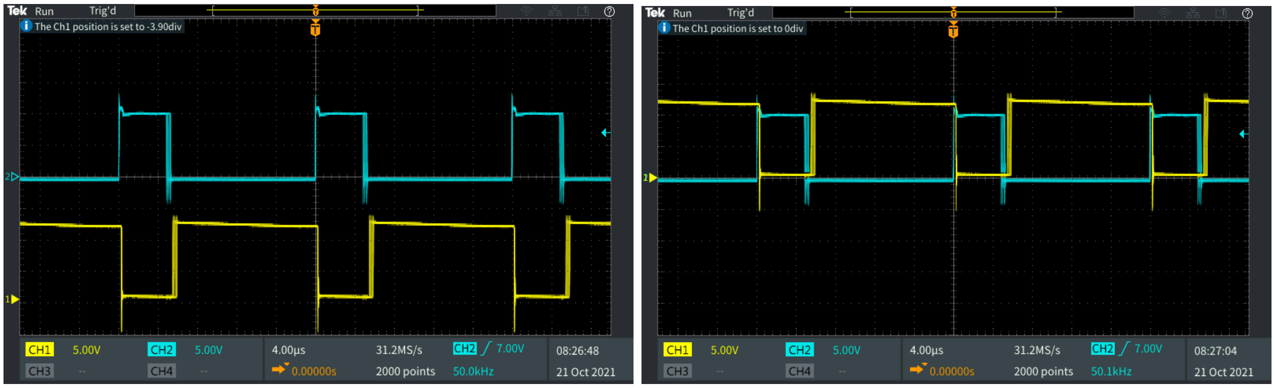


Figure 1. Driver LO signal (yellow) & PWM output signal (blue)

Left: Vertical offset introduced between signals

Right: Actual signals (no vertical shift introduced)

LO Signal on/off Transient

The following oscilloscope capture contains both the *on* and *off* transient of the LO output of the driver circuit.

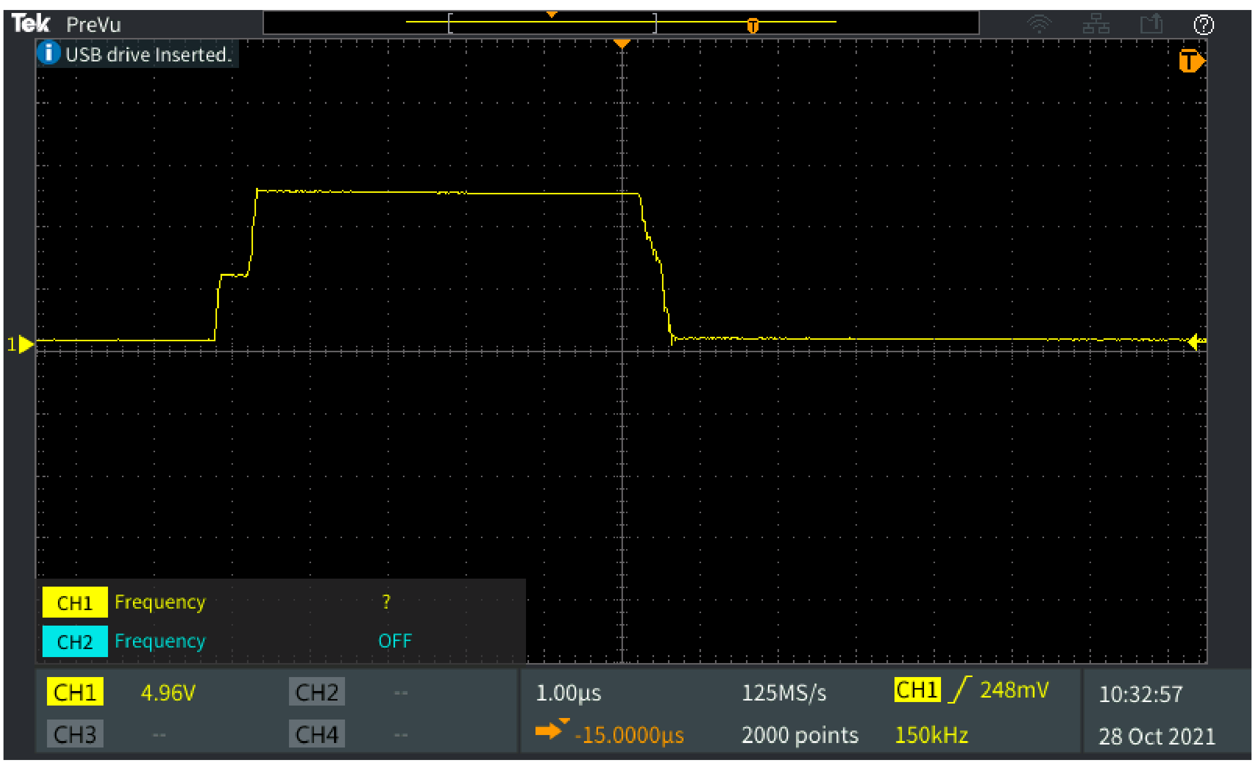


Figure 2. On/Off transient of Driver circuit's LO output

The following set of screenshots below shows the *on* and *off* transient of both the LO (BLUE) signal of the driver circuit and the logic OR (YELLOW) singal (of outputs a & b) of the PWM circuit.

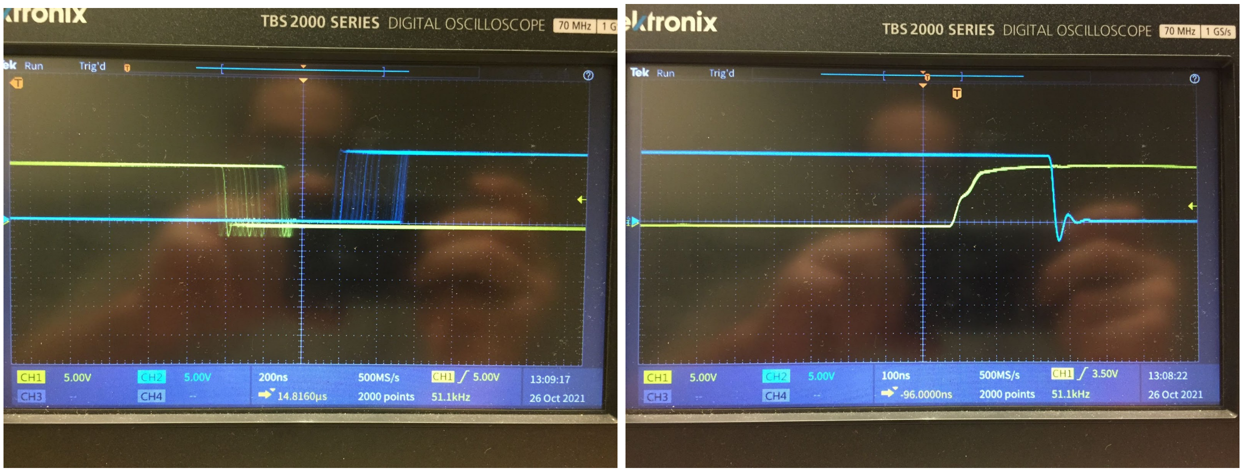
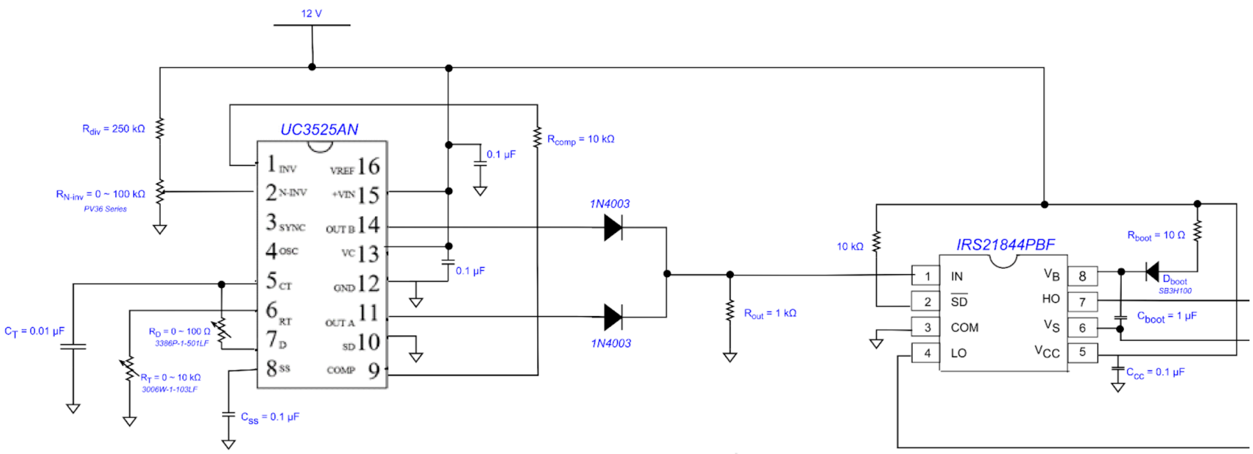


Figure 3. Yellow: PWM || Blue: LO

PWM & Driver IC Diagram



R_{div}	voltage divider resistance
$R_{N\text{-}inv}$	non-inverting input resistance
R_D	dead-time resistor
R_T	oscillator timing resistor
C_T	oscillator-timing capacitor
C_{SS}	soft start capacitance
R_{comp}	compensation resistance
R_{boot}	bootstrap resistance
C_{boot}	bootstrap capacitance
C_{cc}	common-collector capacitance