ECE 5670/6670 – Project

Brushless DC Motor Control with 6-Step Commutation

Objectives

The objective of the project is to build a circuit for 6-step commutation of a brushless DC motor and to implement control algorithms for the regulation of the current and of the speed of the motor.

1. Introduction

A standard circuit for the control of a brushless DC motor is the three-phase inverter shown in Fig. 1.

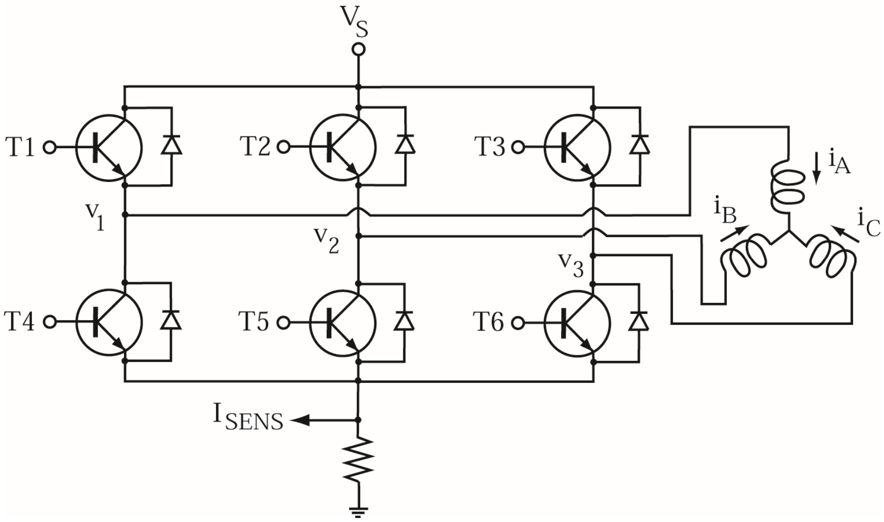


Fig. 1: Three-phase inverter and brushless DC motor

Transistors are turned on based on the following commutation table (other transistors are turned off). All transistors are turned off for zero torque command.

Step	$n_p\theta$	$\tau_e>0$	$\tau_e<0$
1	330° → 30°	T2, T6	T3, T5
2	30°→90°	T2, T4	T1, T5
3	90° →150°	T3, T4	T1, T6
4	150°→210°	T3, T5	T2, T6
5	210° →270°	T1, T5	T2, T4
6	270°→ 330°	T1, T6	T3, T4

The position of the motor is detected using Hall Effect sensors, and the current is measured through the voltage on the sensing resistor. Velocity is measured through an encoder, although it could also be reconstructed approximately from the Hall Effect sensors.

2. Implementation of the circuit and control systems

The implementation requires that all instructions be followed correctly. Read them carefully. If complications arise, see the Appendix for additional help.

You will need:

- Brushless DC motor,
- Brush DC motor,
- A metal frame to mount the motors on, with a box of screws and a screwdriver,
- Cable rack,
- Dual power amplifier,
- A breadboard, 6 - TIP 110 transistors, 6 - N1004 diodes, a 0.5 Ω resistor (1%, 3W), 2 - LM324 chips, 9 - 1k Ω resistors, 9 - 10k Ω resistors, wires,
- DC power supply to provide 5V to the Hall effect sensors,
- DC power supply to provide 6-12V to the inverter circuit,
- dSPACE breakout box with encoder cable,
- Digital I/O breakout cable (connects the dSPACE I/O connector on the breakout box to the breadboard circuit)
- Banana-to-pin-out cable (connects the Hall Effect sensors to the breadboard).

2.1 Hall Effect sensors and back-emf voltages

The brushless DC motor connections should be interpreted as follows:

Large gauge wires -

Yellow wire:	motor winding A.
Red wire:	motor winding B.
Black wire:	motor winding C.

Small gauge wires -

Red wire:	Positive DC power to Hall Effect sensors.
Black wire:	Ground power to Hall Effect sensors.
Blue wire:	Hall Effect sensor A.
Green wire:	Hall Effect sensor B.
White wire:	Hall Effect sensor C.

The first task is to connect a 5V power supply to the Hall Effect sensors. Next, use a breadboard and some wires to connect the Hall Effect sensor outputs (blue, green, white) to the three digital inputs labeled 6, 7, and 8 on the Digital I/O breakout cable. *Be sure to also hook up the ground '**GND**' lead from the breakout cable to the ground of the supply.*

Download the files *Project.mdl* and *Project.lay* from the lab web page. The layout should look similar to the one in Fig. 6 of the appendix. Gain blocks with a value of one are used in the Simulink models solely to generate a variable that can be used in dSPACE to observe and collect data.

Run the application and rotate the motor manually. Because the motor has two pole pairs, Hall Effect sensors should turn on and off twice over one rotation of the motor. Every 60 degrees, a different sensor should turn on or off. On the layout, observe whether the Hall Effect sensor outputs are consistent with the expected behavior.

For the second task, use BNC to banana plugs to connect the A, B, C windings of the brushless DC motor to channels ADCH2, ADCH3, and ADCH4 of the dSPACE system (tie all the common leads together to the ground of the breadboard). If you don't have access to BNC to banana plugs, you can use BNC to alligator clips, however, you must make sure that you have a solid connection to each winding and ensure that the alligator clips aren't touching the frame of the motor. Use a BNC to BNC cable to connect the DACH1 channel to the dual power amplifier. Couple the brushless DC motor to a brush DC motor and apply a positive voltage of 5V to the brush DC motor. Plot the Hall Effect sensor voltages h_A, h_B, and h_C and the back-emf voltages e_A, e_B, and e_C in Matlab. If the back-emf voltage sequence is ACB, reverse the voltage on the brush DC motor. If the Hall Effect sensor outputs are in the ACB sequence, reverse the B and C sensors (if this happens, talk to the TA, as it should not be necessary).

The commutation table of Fig. 1 assumes that the position is defined such that the back-emf voltages are as shown on Fig. 2.

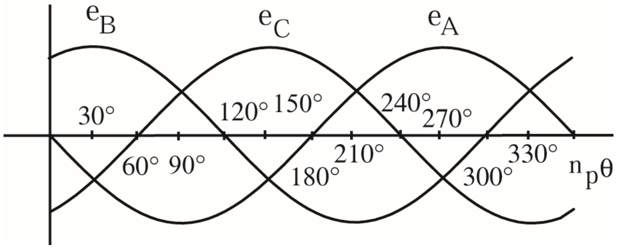


Fig. 2: Back-emf voltages as functions of position

Compare this figure with the plots of the back-emf voltages and, using the position inferred from the voltages, fill in the following table with the observed Hall Effect sensor values. Compare your results to the standard table from the course. Only a minor adjustment of the table should be needed.

$n_p\theta$	h_A	h_B	h_C
-30° → 30°			
30°→90°			
90° →150°			
150°→210°			
210° →270°			
270°→ 330°			

2.2 Transistor driver circuit and six-step commutation logic

Implement the driver circuit for the inverter using digital outputs of the dSPACE system as commands. Since the dSPACE digital output voltage is a 5V TTL signal, amplifiers are needed to connect the 6 digital outputs to the 6 transistor inputs. For example, one of the 4 op-amps of an LM324 chip can be used to connect the digital output D0 to the transistor input T1, as shown in Fig. 3. The digital outputs are numbered from 0 to 5 in the Simulink model and correspond to transistors T1, T2, T3, T4, T5, T6 respectively. For example, digital output 0 should be connected to transistor T1, digital output 1 should be connected to transistor T2 and so on.

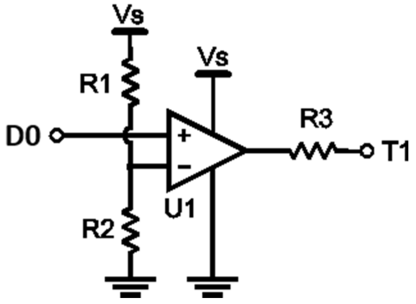


Fig. 3: Op-amp connection as a buffer between a digital output and a transistor

The resistor R3 is chosen to limit the current to drive the transistor. For the top transistors

T1, T2 and T3, use R3 = 1 kΩ. For the other transistors, a 10-kΩ resistor can be used. The resistors R1 and R2 are to provide a threshold voltage for the TTL signal coming from the digital output. By choosing R1 = 10kΩ and R2 = 1kΩ, a voltage of 1/11*V_s is provided.

Finish building the overall inverter circuit, being careful with the routing of wires and the polarity of the diodes. ***If you have any errors in your circuit it will not work properly.*** A suggested breadboard layout is shown in Fig. 4 and a schematic for the inverter circuit is shown in Fig. 5. ***Be sure that all ground connections are tied together (breakout I/O cable, op-amp circuit, driver circuit, and Hall Effect sensors). Also, secure unused pins of the digital I/O cable to unused slots on the breadboard to prevent accidental shorting.*** Disconnect the DC supply from the brush DC motor and connect it to the inverter circuit, setting the voltage at 6V. Replace the brush DC motor with a standalone encoder.

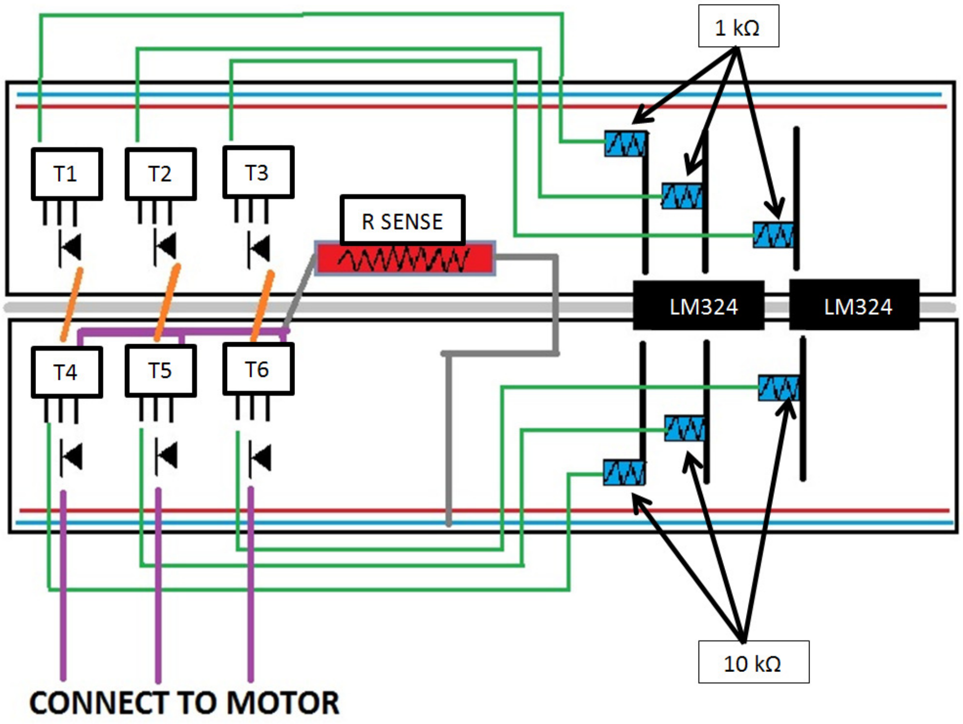


Fig. 4: Suggested breadboard layout

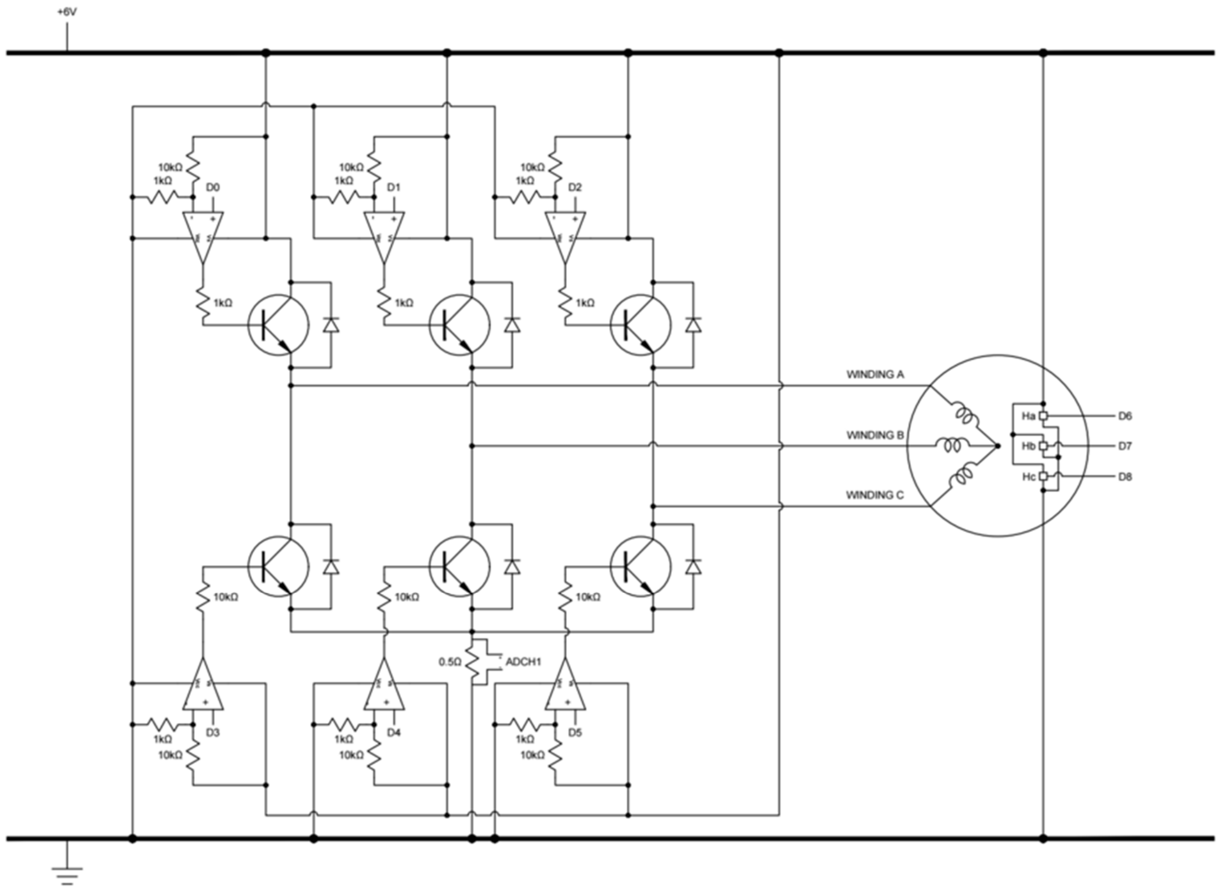


Fig. 5: Three-phase inverter and brushless DC motor w/ op amp detail

The project.mdl model as given is set up to increment through the six steps of the commutation table in the positive direction twice over 2.3 seconds. This will allow you to verify whether or not your circuit is correct. If you are not getting valid responses from your circuit you will need to troubleshoot. One way is to test the steps manually by replacing the step generator with a constant block and slowly incrementing through each step from 1 to 6 in dSPACE. This may help you narrow down which part of the circuit is causing problems.

Verify that the motor moves in the positive direction by increments of 30 degrees (the number of pole pairs is 2). In case of problems, test that the correct voltages appear at the output leads. Turn off the power if any component overheats. Monitor the voltage on the current sensing resistor and make sure that a similar current flows for every step. If not, check the related branch of the circuit. Turn off the power supply when done.

2.3 Six-step commutation logic

Let the variable *step* in the commutation logic be specified by the Hall Effect sensors instead of the layout. You will need to implement the decoding of the Hall Effect sensors in the commutation block as you did in Lab 7, but with the table derived in section 2.1. In Simulink, add the necessary elements for having a variable *dir* defining the sign of the torque (positive direction for *dir=1*, negative direction otherwise) and a variable *on* defining whether to turn on the transistors (all transistors off for *on=0*). Connect the two variables to new displays in the layout. Also, capture data for these two variables; they can be useful in troubleshooting errors. With the supply voltage still at 6V, run the application with dir=1 and on=1 and check that the motor accelerates to reach a constant speed. If the motor does not start, turn off the on-off button or the DC supply while you investigate the problem. If all is as expected, raise the inverter supply voltage to 12V and test again. The Hall effect sensors may be supplied by the higher voltage. *You only need to increase the supply to 12V if 6V wasn't sufficient*. If you have not done it yet, connect the voltage from the current sensing resistor to the A/D, the encoder cable of the standalone encoder, and the winding voltages v_1, v_2, v_3 (same connections as for e_A, e_B, e_C previously). Also add blocks in the Simulink model and dSPACE to process the current measurement as in Lab 7.

Collect data in the positive and negative directions. Produce plots of the transient responses of the motor velocity and of the motor current from standstill to steady-state. Also plot steady-state responses for the variables T1 to T6, v_1, v_2, v_3, h_A, h_B, and h_C, over a period covering the six steps of the commutation sequence. Keep the presentation compact by plotting complementary transistors (*e.g.,* T1 and T4) on a single plot, and using the subplot function in Matlab. The time scales should be the same on all steady-state plots.

Troubleshooting Tips:

If you run into any issues, you can also troubleshoot by analyzing the collected data from the experiment. Particularly, plot position vs. time and verify that the steps are all equal in size. You can also plot current vs. time and verify that there is current flow when your transistors are on at every step.

You must show the TA that the six step commutation phase is working appropriately before moving on.

2.3 Current and velocity control schemes

After testing the inverter circuit with the six-step commutation block, implement the current control scheme developed in Lab 7. Test the current control loop by applying a short pulse of current of 0.5-1A. It is recommended that you generate your current pulse automatically by implementing it in the Simulink model. Collect data in dSPACE and plot the current and the velocity as functions of time using Matlab. Compare to the results of the simulations. Begin with a supply voltage of 6V, and increase to 10-12 V as needed. To reduce the noise in the current measurement, you may lower the filter bandwidth, for example from 5000 rad/s to 1000 or 500 rad/s.

Next, implement the velocity control scheme developed in Lab 7, inserting a limit on the current reference I_{REF} of 4 A. The steady-state current should be less than 0.5 A with the brush DC motor as a load. Capture the step response of the system by stepping the reference signal from 0 to 40 rad/s, 80 rad/s, 40 rad/s and back to 0. Repeat in the negative direction. Comment on the time constant and any overshoot of the response. Compare to the results of the simulations.

Troubleshooting Tips:

If you run into any issues, analyzing collected data from the experiment is a good way to troubleshoot. Along with position, current, and the transistor values, the dir and on variables are also useful for troubleshooting. Common problems with this project are often due to errors in the wiring of the circuit or mistakes in the Simulink model. Rarely is it due to equipment failure. Be extra careful with the implementation of the circuit and model as accuracy is crucial to the success of this project.

To receive credit for the project, you must demonstrate the operation of your circuit to the TA. A passing grade may be received if everything is not working exactly as expected, but attempts to fix the problems must then be explained. In a team, both students must be able to answer questions about all parts of the design.

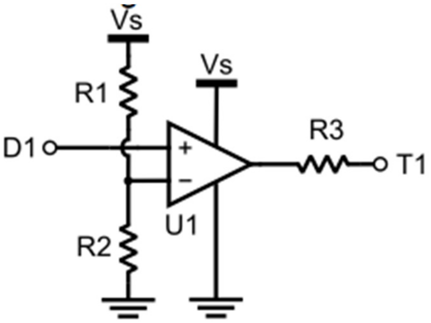
REPORT

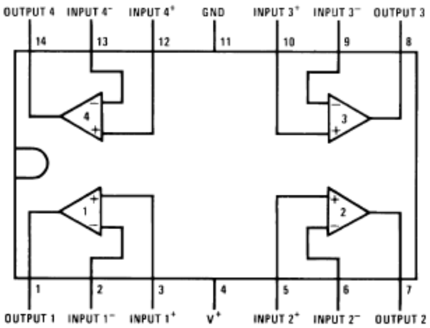
In the report, include the plots discussed in the handout, as well as a photograph of your circuit. Be sure to label and comment on all of your plots. Discuss the differences observed between the simulations of Lab 7 and the results of the experiments. Add any other interesting observation you may have made.

Appendix: Troubleshooting Guide

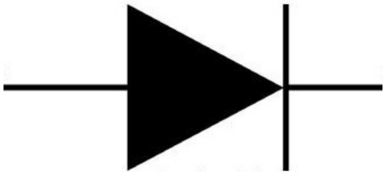
Below is a list that addresses common complications. Read and check each item on the list.

1. Verify that the dSPACE ribbon is inserted correctly and fully in the computer.
2. Verify that all grounds are tied.
3. Verify that Hall Effect sensors are connected properly, blue-green-white to 6-7-8 on the digital I/O breakout cable wires.
4. Verify that the motor lines are connected in the right order, yellow-red-black, to v_1, v_2, v_3 on your circuit. Note that black is not a ground, but one of the three lines. The digital output wires 0, 1, 2, 3, 4, 5 should correspond to transistors T1, T2, T3, T4, T5, T6 respectively.
5. Verify that resistor values are correct.
    a. R1 = 10k (Brown-Black-Orange) +12V to negative input on op-amp
    b. R2 = 1k (Brown-Black-Red) Ground to negative on op-amp
    c. R3 = 1k (Brown-Black-Red) op-amp output to transistor base

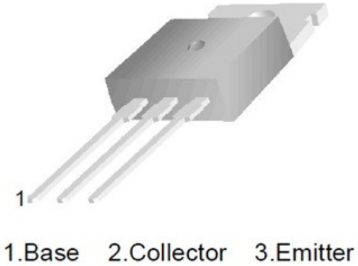




6. Verify that resistor leads do not touch. Because of compact design, this can be difficult – ***be careful.***
7. Verify that the transistors are connected via a common voltage at the top and bottom of the circuit (collector at top, emitter at bottom, see diagram on page 1).
8. Verify that transistors 4, 5, and 6 connect and feed through the 0.5Ω resistor to the ground.
9. Ensure that diodes are not touching transistors.
10. Verify the diodes are placed in the correct direction (see figure below). Improper directionality may create a large current draw and heating up of the diodes.

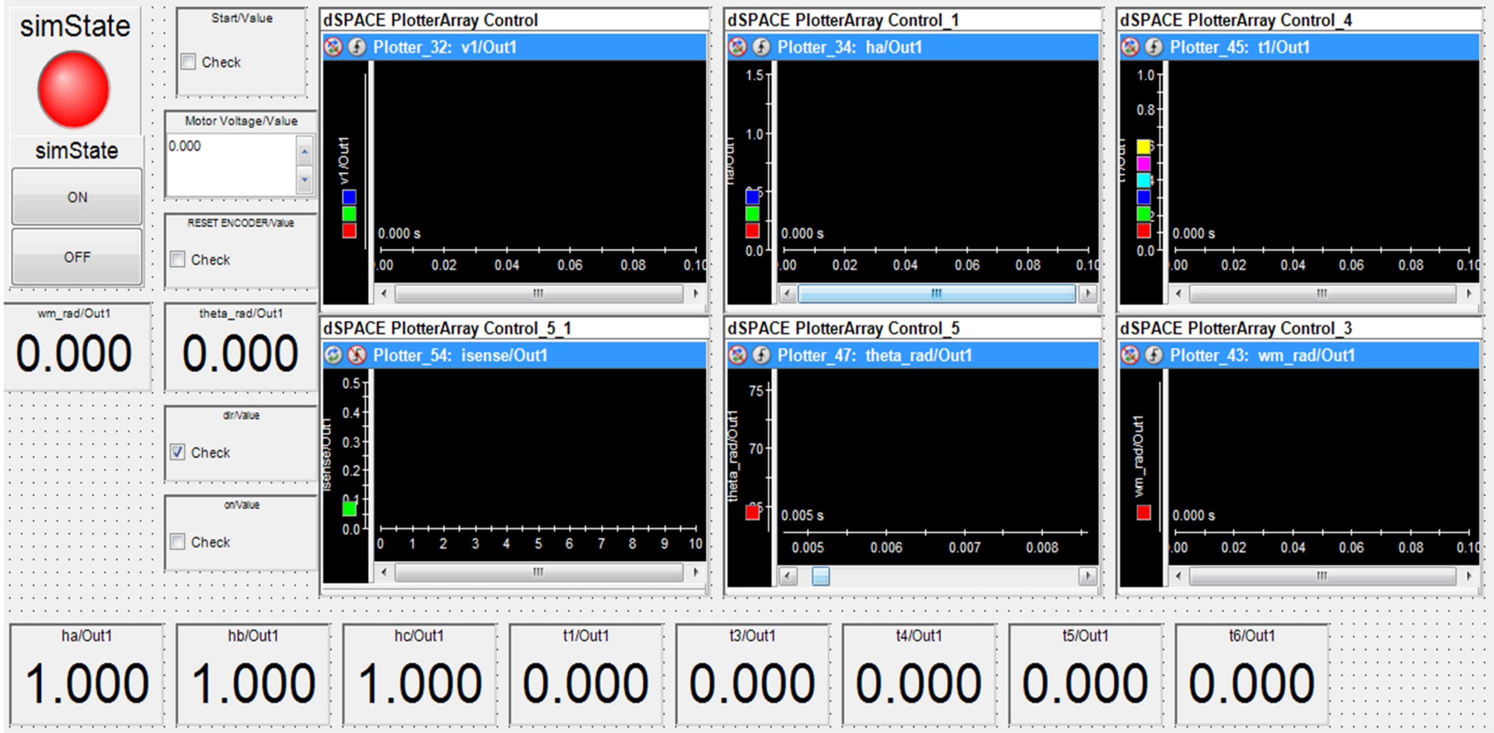


11. Verify that wires are connected to proper transistor locations.



Source: http://www.fairchildsemi.com/ds/TI/TIP110.pdf.

12. If components are heating up, check again that resistors are not touching, and diodes that are not touching transistors.
13. If the motor spins inconsistently or with no torque at certain locations, check again that the placement and values of the resistors are correct. Turn the motor slowly by hand and observe the output bits under positive commutation. Verify that the Hall Effect sensors are lighting up in the correct sequence.
14. Check your circuit and code with the TA.



Start/Value
☐ Check

Motor Voltage/Value
0.000

RESET ENCODER/Value
☐ Check

wm_rad/Out1
0.000

theta_rad/Out1
0.000

dir/Value
☑ Check

on/Value
☐ Check

ha/Out1
1.000

hb/Out1
1.000

hc/Out1
1.000

t1/Out1
0.000

t3/Out1
0.000

t4/Out1
0.000

t5/Out1
0.000

t6/Out1
0.000

Fig. 6: Project layout