Experiment 6
Complete System Implementation
ECE 482

The objectives of this experiment are:

- To aggregate the designs produced throughout the semester and design a coordinated control of each circuit
- To construct and demonstrate a functioning electric bicycle

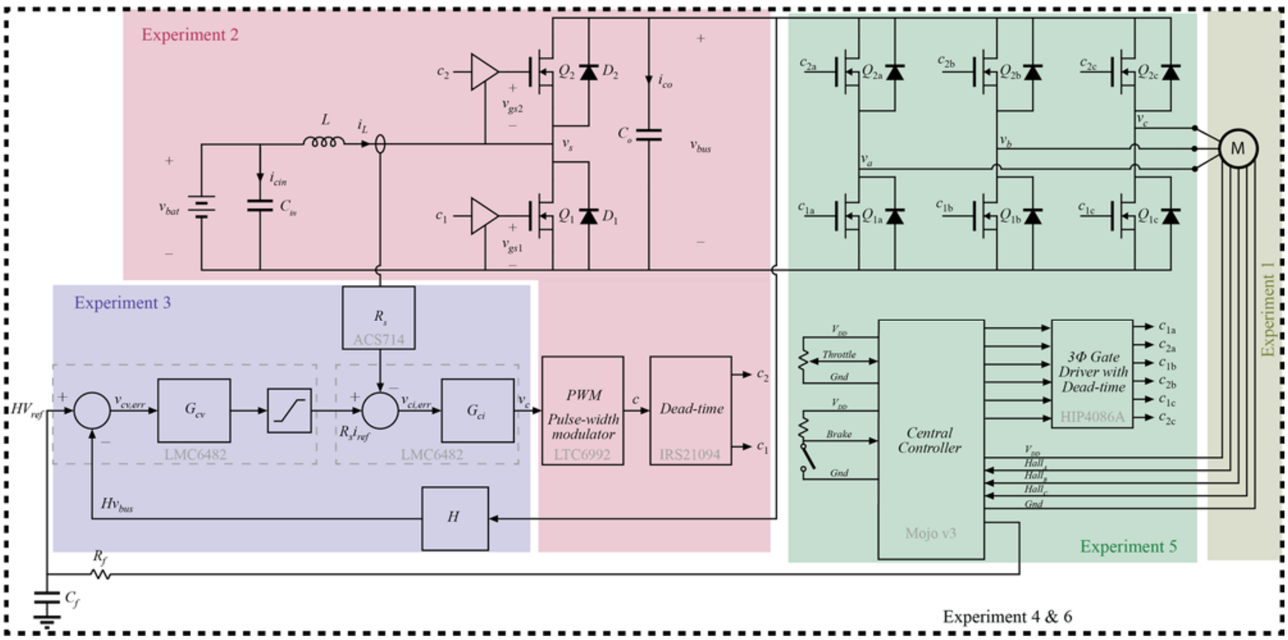

Figure 1: Motor drive power stage and control circuit schematic

In this final lab of the semester, you will complete the system you have designed and test ride the electric bicycle. You are *not* required to actually ride the bicycle, and should not do so if you are not entirely confident in the safety and reliability of the system you have constructed. It is sufficient to test the fully assembled bicycle on the stand only.

I. Boost Converter Population and Verification

Populate the boost converter and its control circuit on the PCB you designed. Using the same testing procedures developed so far in the course, populate one step at a time, testing as you go to ensure proper operation. Verify that the boost converter is able to regulate V_{bus} in the presence of a time-varying control signal, V_{ref} still supplied from a benchtop power supply.

Once you have confirmed that your circuit layout is correct and the boost converter is stable and functions correctly in closed loop, add the R-C filter in Fig. 1 composed of R_f and C_f. These two components will be used to low-pass filter a high frequency PWM output from the Mojo controller to generate an analog voltage from a digital output pin. You should design filter values and PWM frequency such that:

1. The filter cutoff frequency is at least two decades below the PWM switching frequency of the digital signal (this frequency does not need to match any other switching frequency in your circuit). This will help to ensure a low-ripple analog output.
2. The filter cutoff frequency is at least a decade above the closed-loop bandwidth of the boost converter. This ensures that the filter does not significantly adversely affect your designed closed-loop response.

3. The PWM switching frequency of the signal is at least three decades below the Mojo clock frequency. This ensures that you have a resolution of at least 0.1% in adjusting the analog reference voltage.

Beyond these tips, you can select the analog reference implementation as you see fit.

Once implemented verify that you are able to, adjust the duty cycle of the mojo digital output to control the boost converter voltage from V_{bat} to 75 V, when V_{bat} = 26 V.

II. **Throttle Dual Control**

At this point, we have two methods of controlling the power flow to the motor. First, as constructed in Experiment 5, it is possible to PWM the legs of the motor drive at high frequency to reduce the current to the motor. In this mode of operation, each leg of the inverter behaves as a buck converter were the output inductance is the motor winding inductance. Additionally, if the duty cycle of the high frequency PWM signal is kept constant, power flow to the motor can be increased by increasing the bus voltage.

In some commercial EVs, the boost converter is controlled to always boost to a maximum voltage (75 V in our baseline design), and the motor drive then does all of the “step-down” at low powers. However, this approach is inefficient. The switching devices exhibit switching loss according to the bus voltage, so stepping up this voltage when it is not required leads to greater-than-necessary power loss. Instead, we would like to keep V_{bus} at 26 V when the motor power is small (i.e. when the throttle command is small) and control the power with the motor drive high frequency PWM. Then, when this PWM reaches a duty cycle of 95%, we can adjust the reference voltage to the boost converter to increase V_{bus} while maintaining the motor drive duty cycle.

To implement this control, we will divide the throttle command into two sections. When the throttle is less than half of the way turned, V_{ref} to the boost converter should remain at its minimum output voltage, and the high frequency PWM duty cycle of the inverter should increase proportional to the throttle. This duty cycle should reach 95% when the throttle is twisted halfway (this will require modification of your Experiment 5 code). As the throttle is twisted beyond halfway, the duty cycle of the inverter should remain 95%, but the boost converter reference voltage should increase proportional to the throttle increase. When the throttle is fully twisted, V_{bus} should reach 75 V. This control is diagrammed in Fig. 2, where the analog voltage out of the throttle is given on the y-axis.

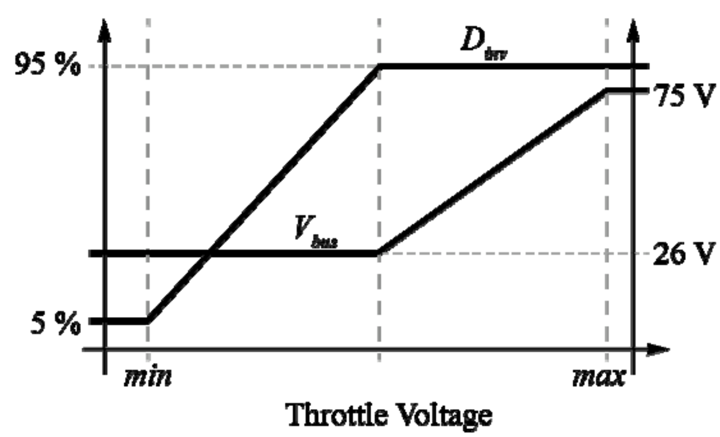

Figure 2: Steady-state diagram of dual throttle control

III. **Short-Circuit Protection**

It is necessary to prevent the motor drive from over-current issues when the wheel is at a stall. From experiment 5, you have implemented basic speed estimation code in Verilog, which used the hall signal period as an estimate of motor speed. Add Verilog to your controller which overrides the throttle and locks the PWM at a small value (e.g. 10 %) if the motor speed is less than 1 revolution every five seconds. This will prevent the motor drive from shorting the battery through the motor windings and boost inductor, which will saturate if the motor is stuck.

Extra Credit: This is a simple implementation, but is not ideal; in this control, a short is prevented but in exchange, the motor will have very small torque at startup, due to the limited duty cycle. If you would like, you may devise a new scheme for short-prevention *after* completing all other tasks. In one implementation, you may limit the time in which full duty cycle may be applied an estimate of the time it would take for this operating scenario to saturate the inductor. Extra credit will be given to *working* e-bikes with implementations which improve the starting torque while still preventing overcurrent issues.

IV. E-Bike Testing

Note: Do not resume testing on the motors until the instructor approves it.

Test your complete system indoors. In the final week of class, bicycles with batteries will be available. Connect, through the provided protection board (containing motor fuses, battery fuses, and hall sensor buffer, as well as +15V and +5V supplies) your circuit to the motor and battery. Verify that the motor spins with torque controlled by the throttle, and can be successfully started, brought to speed, and can coast down without issue. You may use the mechanical brake as necessary to slow the system down.

If you are confident in the system and would like to, you may test the e-bike off the stand, outdoors, with instructor present. Note that all Tennessee state bicycle safety laws still apply, and the 20 mph speed limiting code must be in place for the bike to be legal to ride. You are not required, and will not be penalized, if you choose not to complete this step. For full credit, you must only operate the complete system (with motor and battery) on the stand in the lab.

V. Deliverables

The deliverables for the final project of the semester are (1) demo of a functioning, complete system on or before April 25th and (2) a technical reference manual for your completed electric bicycle. The report should include the following:

- General Overview: highlighting the purpose and key features of the system
- System Description: block diagrams & (brief) description of functionality and use of your implementation, capabilities and operating ranges
- Implementation Details: block diagrams and descriptions of their internal operation
- Verification: simulations, and experimental results demonstrating the achieved operation of each block and the overall system
- Conclusions: including future steps, as you see them, to improve system performance and any comments on your system's successes, failures, or things you would do differently

Additionally, the following should be included as Appendices as well as additional supplemental files to the report:

- Schematics
- PCB Layout
- Parts List
- Microcontroller Codes

The technical reference manual and associated files should be sufficient to allow anyone with an appropriate background to reconstruct an exact copy of your system