EE 452 – Power Electronics Design
Experiment 1 Procedure

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The objectives of this experiment are:

- To characterize and find numerical parameters for the modeling of bicycle hub motors
- To become familiar with use of lab equipment

Section 1 of this experimental procedure deals with the characterization of the motor. Section 2 covers simulation and hand analysis of electric bicycle mechanics.

1 Motor Characterization Experiments

In this portion of the experiment procedure, perform tests on the electric hub motor in order to determine the motor characteristics. Known characteristics of the motor are:

- Three Phase, Wye-connected
- Permanent Magnet
- Outer-rotor
- Non-geared, direct drive

The motor winding voltages can be modeled using the following (simplified) set of equations

$$v_a = ri_a + L\frac{di_a}{dt} + \lambda_m \omega_r \cos(\theta_r) \tag{1}$$

$$v_b = ri_b + L\frac{di_b}{dt} + \lambda_m \omega_r \cos\left(\theta_r - \frac{2\pi}{3}\right) \tag{2}$$

$$v_c = ri_c + L\frac{di_c}{dt} + \lambda_m \omega_r \cos\left(\theta_r + \frac{2\pi}{3}\right) \tag{3}$$

Note that ω_r is the electrical frequency, which relates to the mechanical frequency ω_m as

$$\omega_m = \frac{P}{2}\omega_m \tag{4}$$

where P is the number of poles. The following characteristics need to be determined, through any series of tests you find appropriate:

- EMF Shape (e.g. trapezoidal, sinusoidal, other)
- Number of Poles P

- Winding DC Resistance r_w
- Winding Low-Frequency Inductance L_w
- Flux Linkage λ_m
- Relation between phases and hall sensors

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)**.

As shown in Fig. 1, the motor may be tested while stationary or manually spun on its stand. In all tests, the hub motor windings (V_A, V_B, and V_C) are to remain open-circuited; their voltages may be measured, but no voltage or current may be applied to them.

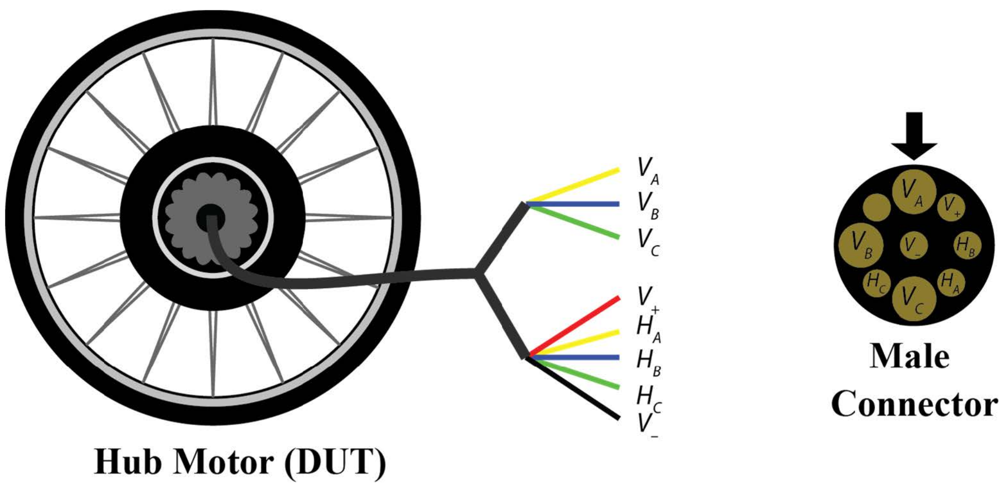

Figure 1: Motor connections diagram for Experiment 1-B.

The hub motor has a total of 8 electrical connections which may be made. The lower-gauge (larger diameter) wires comprise the three winding terminations of the motor. The higher-gauge wires connect internally to three digital-output hall sensors which may be used to determine rotor position. The hall sensors work by sensing the internal magnetic field generated by the rotating poles, with each of the three sensors outputting logic high when the magnetic field in its vicinity exceeds a predefined threshold. The three sensors are spaced 120° (electrically) apart. In this bundle of five wires, V_+ and V_- are 5 V compatible supply inputs which power the hall sensors, whereas H_A, H_B, and H_C are the outputs of each sensor. Note that, as shown in Fig. 2, the hall effect sensor outputs are open-collector type outputs, so an external resistor R_p is necessary to convert each signal to an observable voltage waveform. This resistor should be larger than 1 kΩ. The series resistance R_s protects the hall sensors, and should be (roughly) 33 Ω.

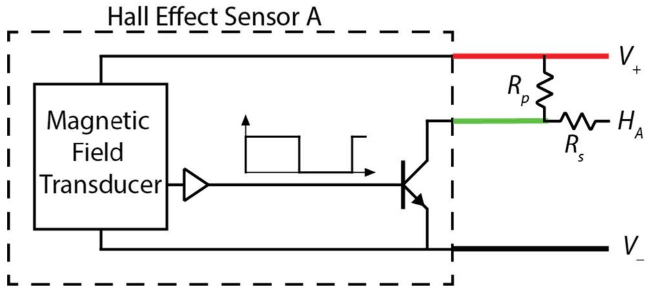

Figure 2: Motor hall sensor behavioral circuit model.

Important Note: It is very easy to destroy the internal hall sensor BJT by applying a voltage at its collector. Before connecting any signal to the hall sensor outputs, make sure that the signal has high impedance at its output.

The wiring of the hub motor and end connector are shown in Fig. 2. 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)**.

2 Simulation and Modeling

Below we outline the procedure to simulate your motor and give an overview of vehicle physics/mechanics.

2.1 Motor Simulation (10 pts)

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.

2.2 Vehicle Dynamics

The goal of this portion of this analysis is to determine the physical requirements of the electric bicycle drivetrain in order to meet specified performance metrics. The results of Experiments 1 are necessary to complete this section, but no further experimental measurements are needed.

- Top speed of 10 mph or greater on flat road
- Ability to travel up a 3% grade ($\tan(\theta)$) at a speed of at least 5 mph

The basic free body diagram of a bicycle, including effects of drag, rolling resistance, and the tactive force Ft applied by the motor is shown in Fig. 3.

You may use $A_v = 0.5\,\mathrm{m}^2$ or estimate your own frontal area on a bicycle. The bicycle weight is approximately 50 lbs (need to convert to grams). Additionally, for the rider weight, you

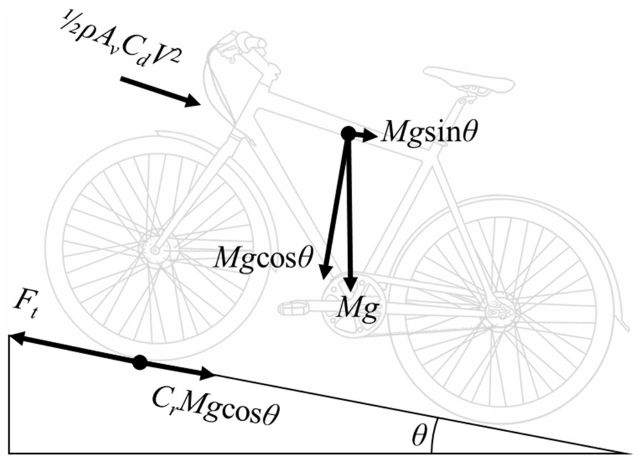

Figure 3: Bicycle free-body diagram.

may use your own weight or design for a 250 lb rider.

Additional characteristics of the bicycle and road conditions are:

- $Cd = 0.65$
- $Cr = 0.013$
- $\rho = 1.204\,\mathrm{kg/m^3}$
- wheel diameter $2rw = 700\,\mathrm{mm}$

Using the motor parameters found in section I, the mechanical power which is transferred to the rotor is

$$P_m = P_e = i_a \lambda_m \omega_r \cos(\theta_r) + i_b \lambda_m \omega_r \cos\left(\theta_r - \frac{2\pi}{3}\right) + i_c \lambda_m \omega_r \cos\left(\theta_r + \frac{2\pi}{3}\right) \tag{5}$$

If the currents ia, ib, and ic comprise a balanced three-phase system,

$$i_a = I\cos\left(\theta_r + \phi\right) \tag{6}$$
$$i_b = I\cos\left(\theta_r + \phi - \frac{2\pi}{3}\right) \tag{7}$$
$$i_c = I\cos\left(\theta_r + \phi - \frac{2\pi}{3}\right) \tag{8}$$

when $\phi = 0$, it can be shown that

$$\frac{P_m}{\omega_m} = \tau_m = \lambda_m \frac{P}{2}\frac{3}{2} I \tag{9}$$

Respond to each of the following in your report:

- What is the mechanical power required to meet both the top speed and gradeability requirements? (give one value) **(5 pts)**

- What is the peak back-emf voltage that will be generated at a speed of 10 mph? **(5 pts)**

Consider and discuss, briefly, how each of these will inform the design of the power electronics in the ensuing experiments. **(5 pts)**

2.3 Required for EE532 Students: DC Bus Capacitance (10 pts)

Finally, consider the design of the DC bus capacitance in the eventual system. Using a worst-case approximation, the DC capacitor can be designed using the equivalent circuit of Fig. 4, where $i_{md}(t)$ is the current going into the motor drive and I_{DC} is the output current from the boost converter, which is assumed to be constant over one electrical period of the motor revolution. The motor drive current will pulse to zero for as much as 1% of the electrical period during the commutation between phases. An example of this is shown in

- If $V_{DC} = 25\,\mathrm{V}$, how large must C_{DC} be so that VDC changes by less than 1 V during the time that $i_{md}(t) = 0$ in either of the performance metric cases?

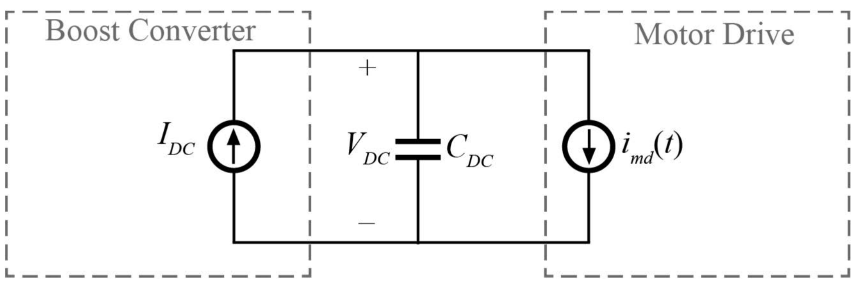

Figure 4: Equivalent circuit for DC capacitor design.

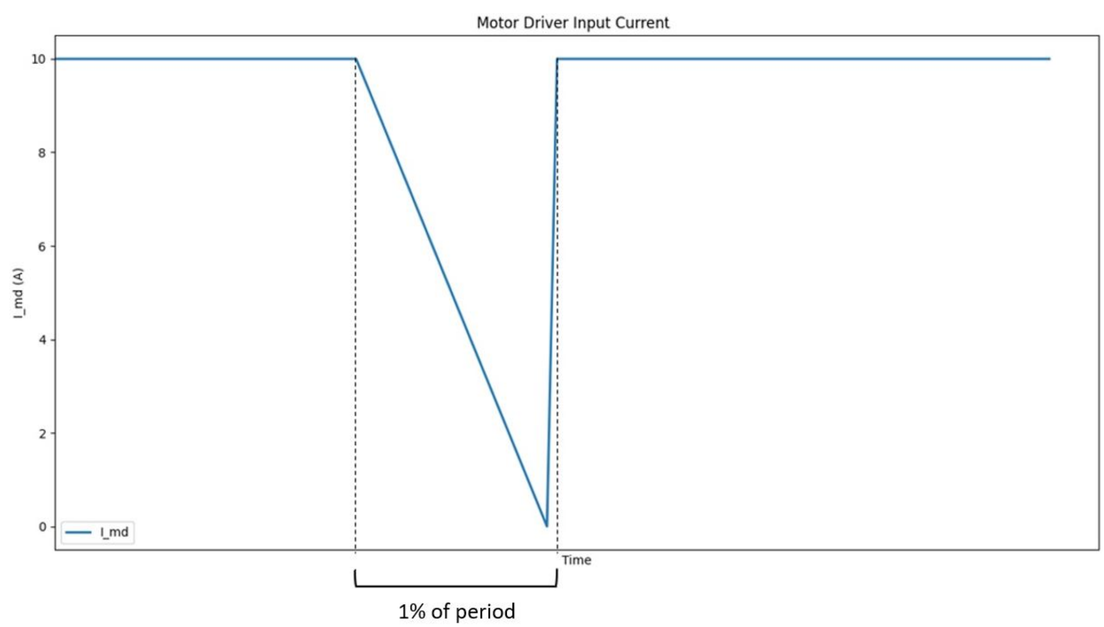

Figure 5: Motor Current