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ECE 492

Motor Controller + Modeling

4/7/16

Static Characterization Results

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I. Introduction

The purpose of this report is to characterize and understand the behavior of the Electric Vehicle motor operating at steady state conditions. Data was collected and analyzed to determine if the hypothesis of the motor model can be accepted or rejected. The aim of this study is to be able to relate inputs and outputs of the motor and controller system by either equation or lookup table.

II. Hypothesis

To understand the hypothesis made for this experiment and subsequent analysis, it is first important to understand the current test setup of all components in the motor system. The motor is connected to a Curtis Instruments (Mt. Kisco, NY) Controller which supplies three-phase AC current to the motor depending on two user-controlled inputs: Load % and Throttle %. Throttle percentage maps to a voltage which is used to determine the speed of the car at a given load. Load percentage maps to the position of a solenoid in the dynamometer which controls the amount of oil being circulated by the motor driven pump, therefore setting the speed that the motor spins at. The Curtis Controller is fed a DC current from a high voltage power supply which varies dependent on the parameters of the motor system. The relevant measurable outputs of this system are Motor RPM and Torque. The block diagram in Figure 0 gives a high level picture of this system:

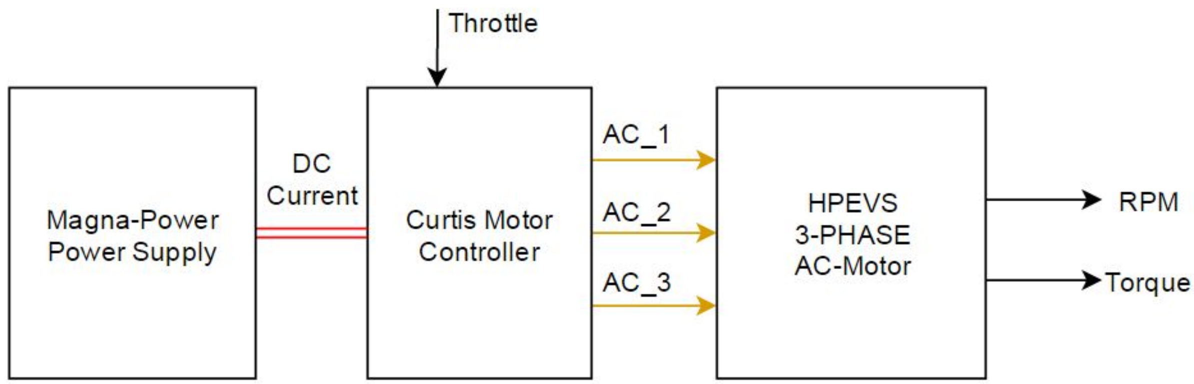

Figure 0.

For purposes of using the motor + controller system in a fully integrated car, it is not necessary to understand the intermediary signals between the controller and motor, so it is possible to model the whole system as a black box with the above described inputs and outputs.

The hypothesis for the experiment described below in Section III is that the findings from data collection will prove that the black box system of the motor and controller will exhibit the characteristics of a standard DC motor.

In order to prove this hypothesis true, it will be necessary to show that the data reflects the behavior detailed below in the **steady state** equation for a DC motor [1]:

$$T_L = K_T i - fw$$

where T_L is the load torque (hydraulic torque seen above)

K_T is the torque constant

i is the power supply current input

f is the friction constant

w is the motor speed in RPM

The aim of this report is to provide some way to relate the torque, power supply current, and motor speed I/O of this system.

III. Data Collection

After several preliminary data collection experiments were run in order to shape the hypothesis and direction of this report, a few large, final data collection experiments were formulated in order to obtain all data required for characterization.

The following experimental data was collected using the available dynamometer and sensors. All system operations are outlined and described in Appendix A.

A. Experiment 1

The aim of collecting this data was to illustrate a picture of the motor's behavior across the full range possible in its current setup. At a few set throttle settings, data measurements were taken for a number of parameters which the group determined would be useful in understanding the behavior of the motor at steady state. The sensors and setup for this experiment are detailed in **Appendix A** of this report. Likewise information on calibration and accuracy of the sensors and systems in this experiment are available in the reference section (**Appendix B**).

For each throttle setting (20% - 35% in increments of 2%), the team:

1. Set the load setting to 100% (no load)
2. Recorded the values of power supply current (A), Controller RMS Current (A), Motor RPM, hydraulic torque (ft-lb), power supply voltage (V), and motor controller and motor temperatures (deg C)
3. Decremented load setting by 2% (98, 96, 94…) and repeated step 2

This continued down to high load settings (40 – 60% setting) for each throttle setting resulting in the minimum motor speed to be near zero.

The analysis of this experiment is detailed below, and led the group to perform a second data collection experiment in order to obtain a more complete picture of the motor + controller's behavior.

B. Experiment 2

The aim of collecting this dataset was to choose torque as the static input for data collection rather than throttle setting, viewing motor response at low RPM values (<1000) at constant torque. The same parameters were measured as in the previous experiment. The sensors and setup for this experiment are detailed in **Appendix A** of this report.

For each torque setting (5.5, 7.8, 10.5, 11.8, 13.5, 16.2, 19, 22.1, 25, 26.4 ft-lb), the team:

1. Modulated the throttle and load percentages to obtain the given torque value at the highest setting below 1000 RPM.
2. Recorded the values of power supply current (A), Controller RMS Current (A), Motor RPM, hydraulic torque (ft-lb), power supply voltage (V), and motor controller and motor temperatures (deg C)
3. Decremented throttle setting by 1% and repeated step 2 (for a minimum of 6 total measurement steps)

The analysis of this experiment is also detailed below, and provided the group with the remainder of data required to characterize the motor + controller setup and determine if the hypothesis could be accepted or rejected.

IV. Data Analysis

The first set of graphs which were created from the data results of Experiment 1 was RPM vs Load setting for each throttle setting. A graph which includes all of these curves is shown below in **Figure 1.** The trend lines with shown equations highlight the linearity of RPM's variation with load at a constant throttle setting.

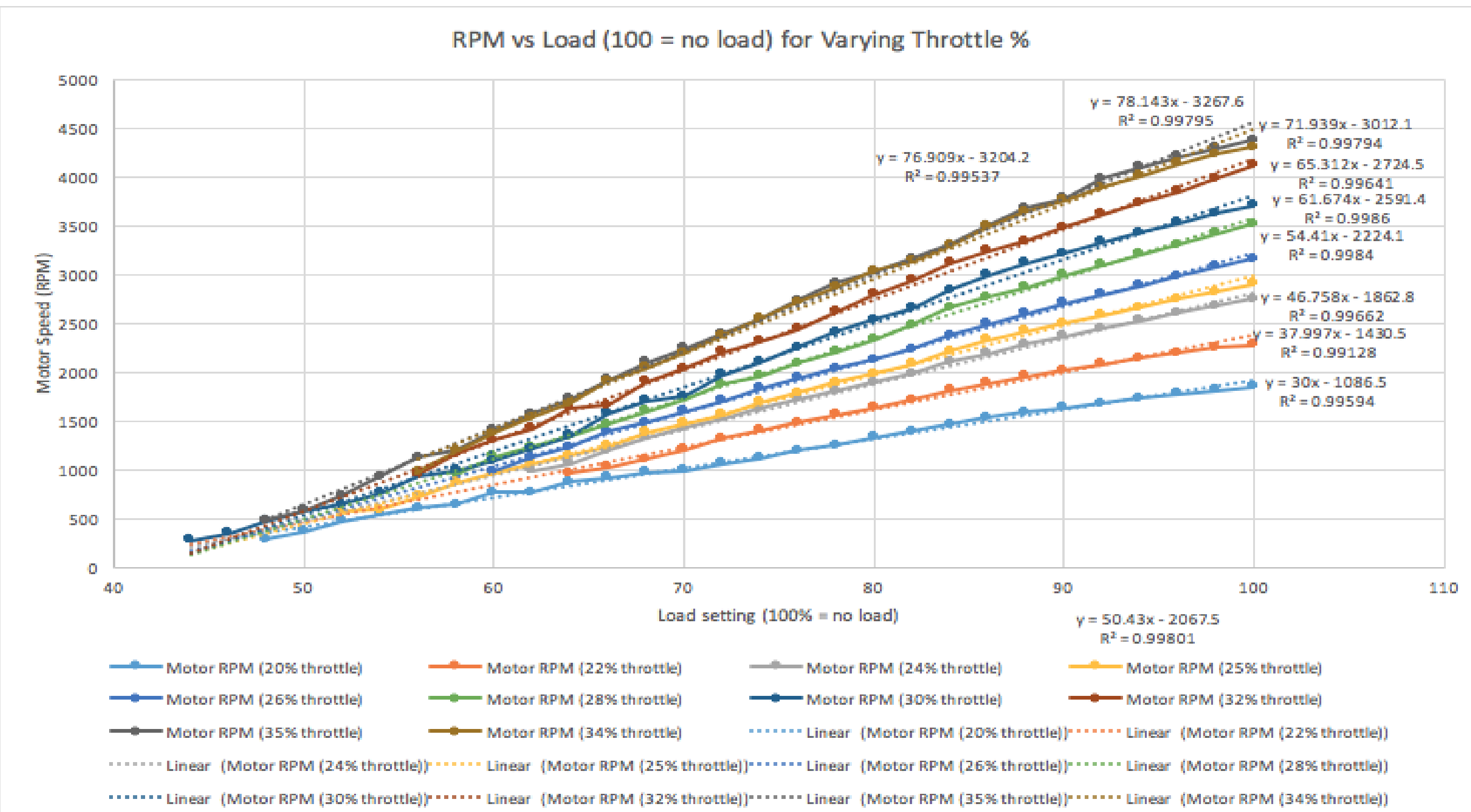

Figure 1.

It is important to note that the rate at which RPM varies is a function of throttle setting, with the maximum rate of change found at the highest recorded throttle setting. These ratios were also plotted versus throttle setting and can be seen in **Figure 2.** It is interesting to note that the the ratios have a linear relationship with throttle setting, but not immediately useful in the motor + controller characterization.

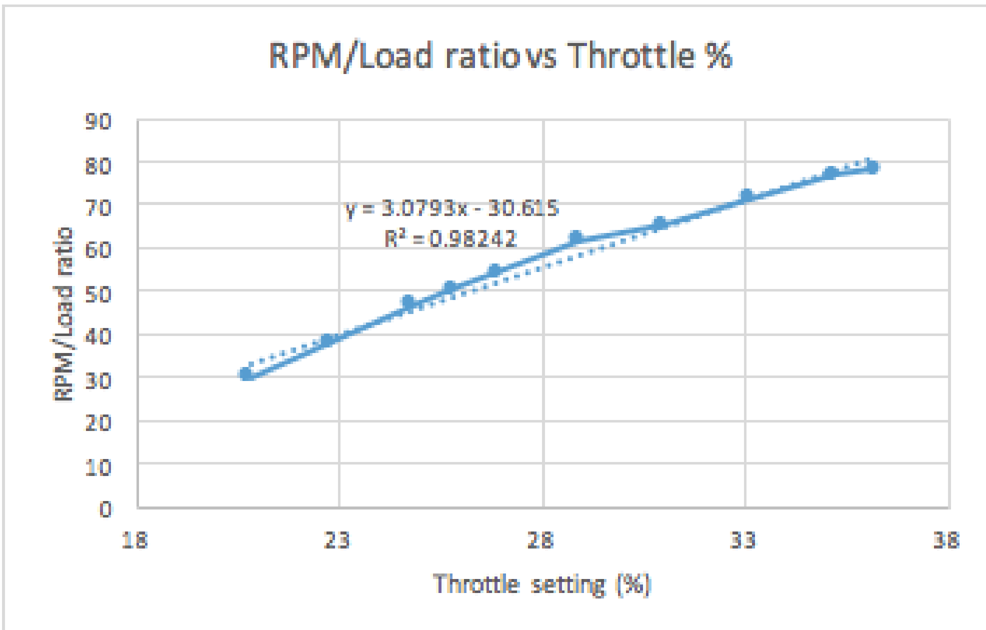

Figure 2.

The next set of graphs generated using the data from Experiment 1 were of motor RPM versus current drawn from the power supply. Once again, these curves were generated for each throttle setting used in the experiment. A graph which includes all of these curves is shown below in **Figure 3.**

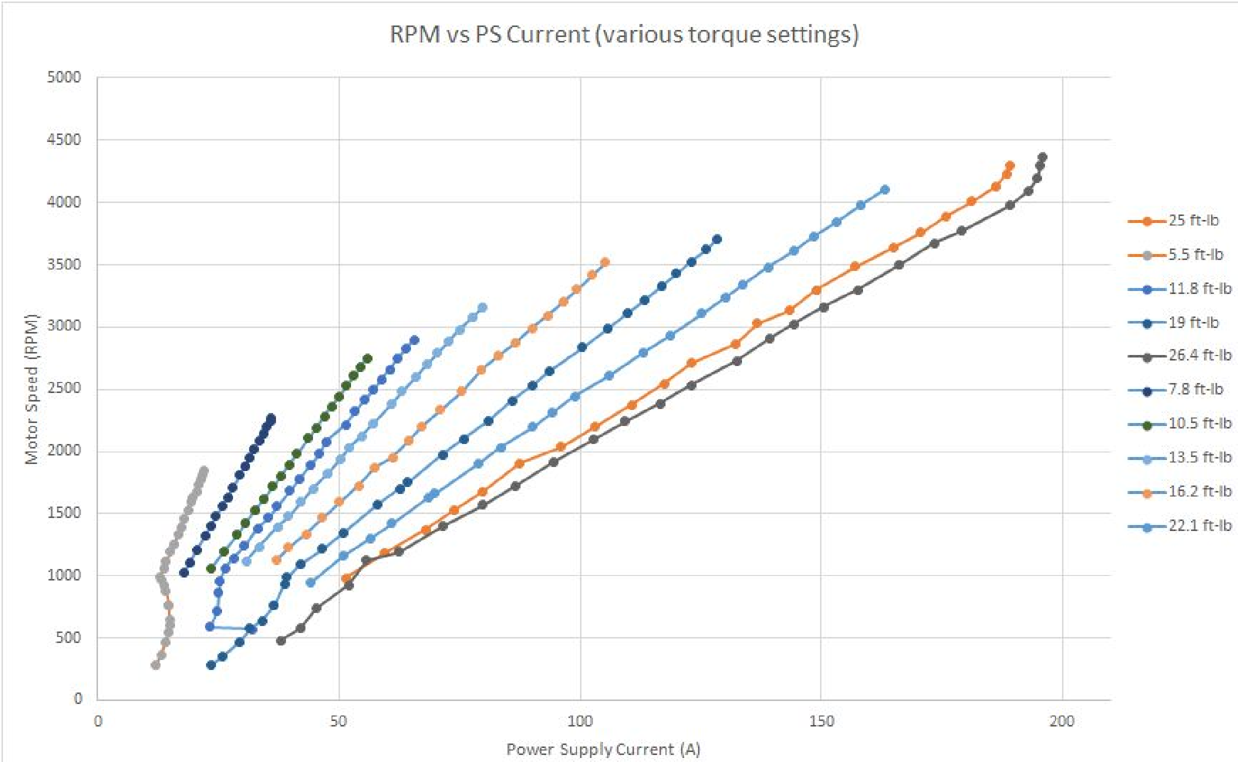

Figure 3.

One thing which can be seen clearly is in this collection of curves is that the linearity seems to fall off at the two extremes operation. It happens as power supply current nears 200A because a hard current limit was set at that point. It also happens less obviously as motor RPM goes below 1000 RPM. The group suspected that this was a symptom of the controller and dynamometer setup, and not the motor itself. Additionally, it was noted in another graphical analysis **(Figure 4**) of the same data that above this threshold of 1000 RPM torque is linear with throttle setting.

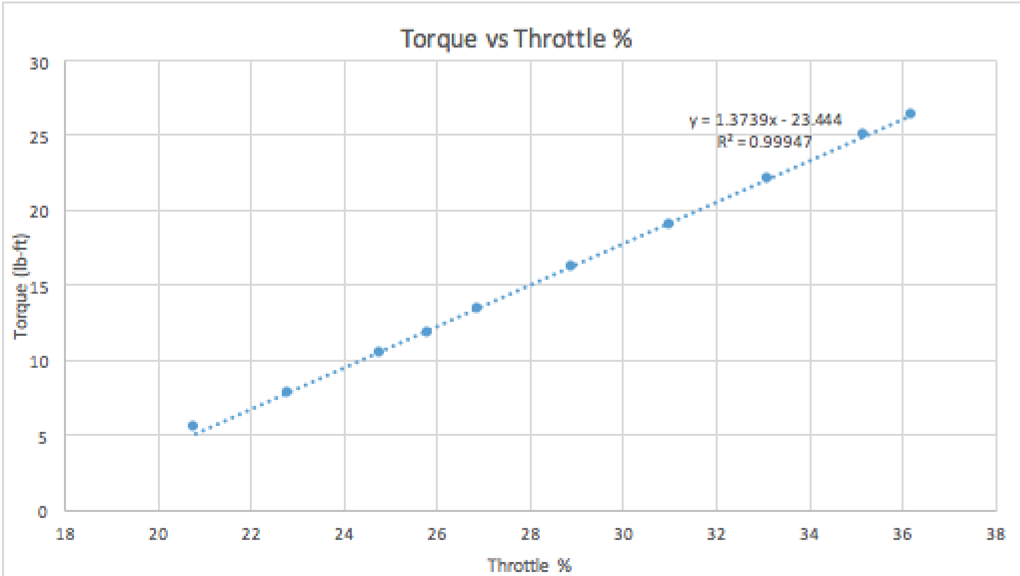

Figure 4.

For this reason, the team felt that it was necessary to run a second experiment (Experiment 2 described above) wherein the system response was recorded at constant torque below this threshold of 1000 RPM. The results of this experiment produced a new graph similar to **Figure 3** where the linearity continues below 1000 RPM to the absolute bottom of the motor's operating range. This data was combined with data collected during the first experiment in order to extend the original constant torque curves below 1000 RPM (see **Figure 5**). Trend lines were matched to each of these curves and once again a relationship was found between the ratio of RPM/power supply current and torque. The curve and trend line fitted to these results is displayed below in **Figure 6**, and a graph with logarithmic scales which proves the accuracy of the trendline is plotted in **Figure 7.** It was determined that it is worthwhile to analyze the x-intercepts of each of the graphs in **Figure 5**, because they represent a parameter which will hereinafter be referred to as the **0 RPM Current**. That is, the current value which must be "overcome" before the motor can start moving at a given torque value. A graph of these 0 RPM Current values versus torque are plotted below in **Figure 8.**

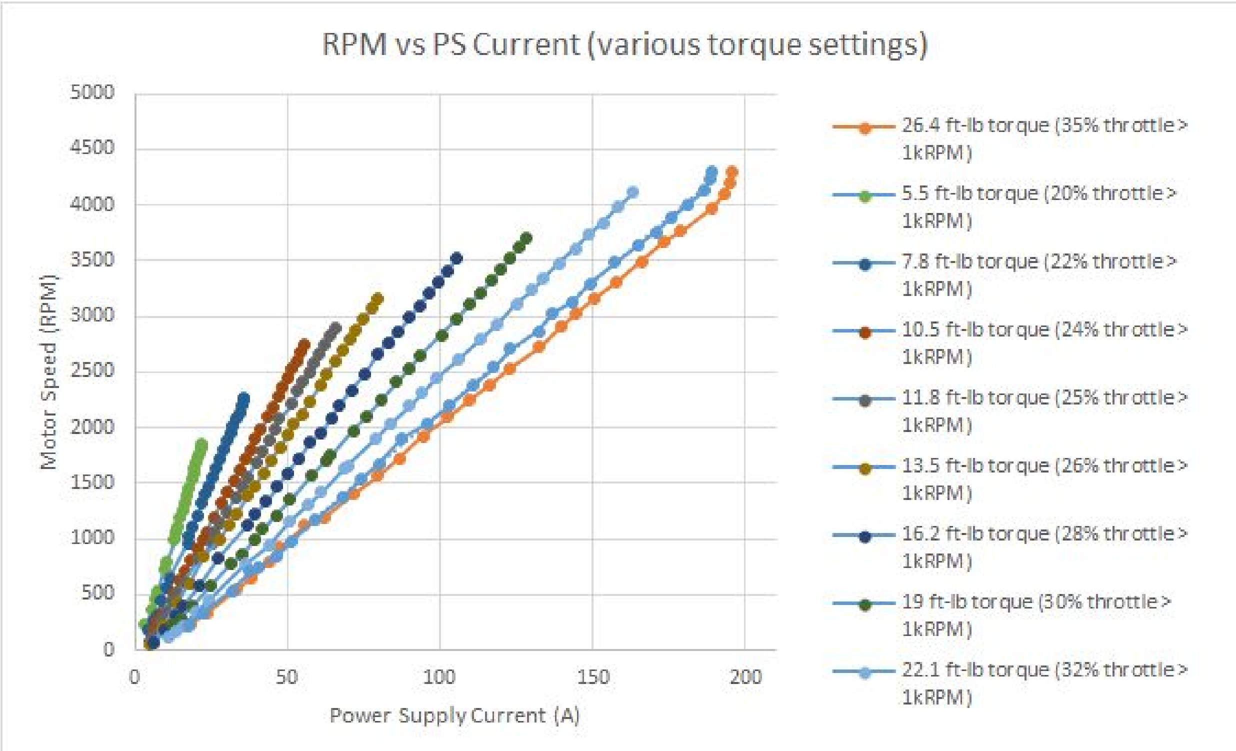

Figure 5.

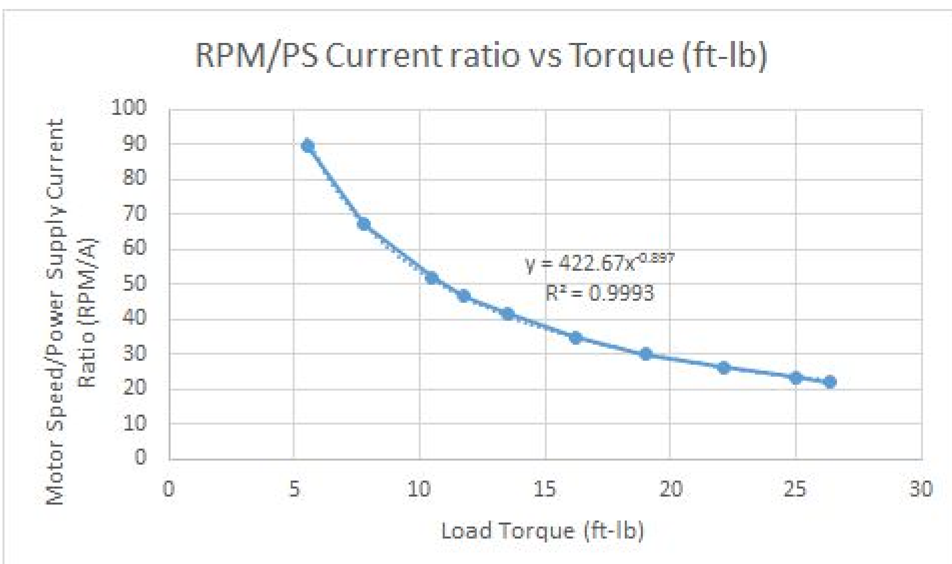

Figure 6.

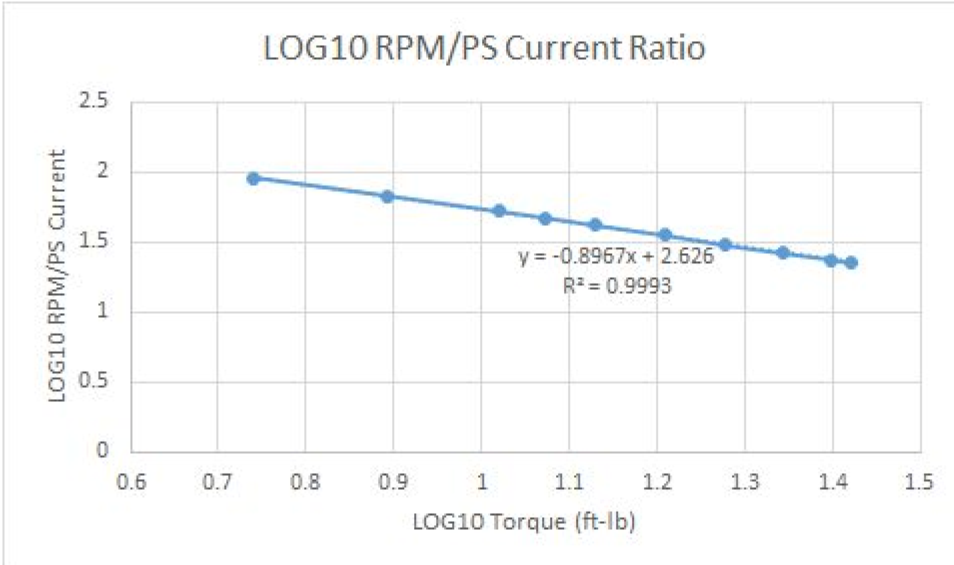

Figure 7.

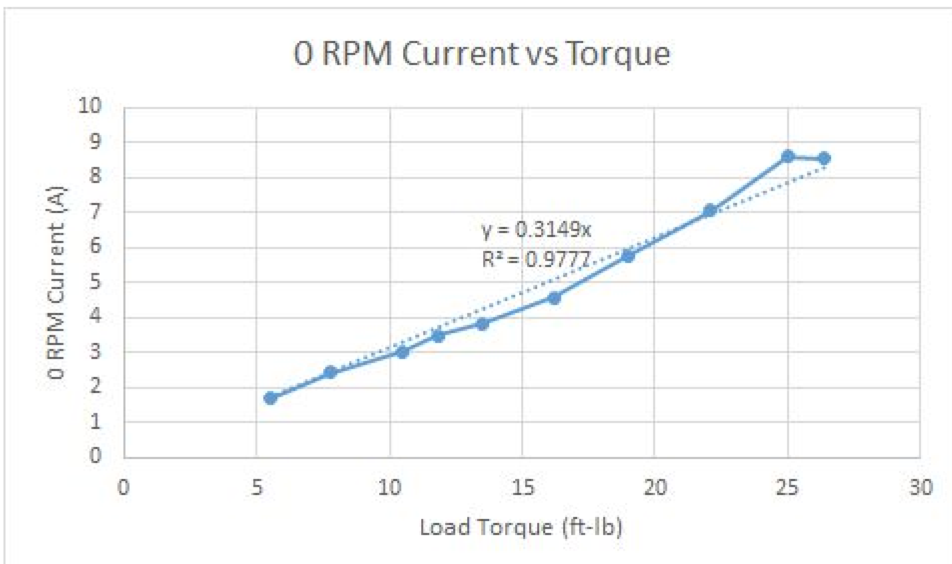

Figure 8.

All of these figures will be referenced in the results and conclusions section below which will determine if the hypothesis of this report can be accepted or rejected.

V. Results and Conclusions

As a reminder, the equation which must be satisfied in order to determine if the hypothesis can be accepted is the following equation [1]:

$$T_L = K_T i - fw$$

To start, as many variables will be removed as possible in order to find the value of one of the parameters K_T or *f*. One of the graphs listed above can be used to do this. Refer to **Figure 8** to see the values of 0 RPM current for different torque settings. The trend line fitted to this data provides the following equation:

$$i = 0.3149T_L$$

Converting to SI units (1 lb-ft = 1.3558 Nm),

$$i = 0.232258T_L$$

At $w = 0$, the above motor equation becomes

$$T_L = K_T i$$

or

$$i = \frac{T_L}{K_T}$$

Given these equations, we can find that KT = 1/(0.2322) = 4.305

Knowing this, it is now possible to calculate the friction constant *f* using another graph generated from the data collected in Experiments 1 & 2.

The new DC motor equation to work with will be

$$f = \frac{K_T i}{w} - \frac{T_L}{w}$$

Plugging in several values taken from the experimental data and calculating f for those values shows the results in **Table 1**:

PS Current	Motor RPM	Torque	f
19.8	1631	5.5	0.035183814
57.1	2496	11.7	0.06796859
81.1	2250	19	0.106032711
36.3	1718	10.56	0.060959721
65.9	2597	13.35	0.075451829
44.7	1703	13.49	0.075441691
163.2	4110	22	0.120759903
149	3295	24.91	0.136058877

Table 1

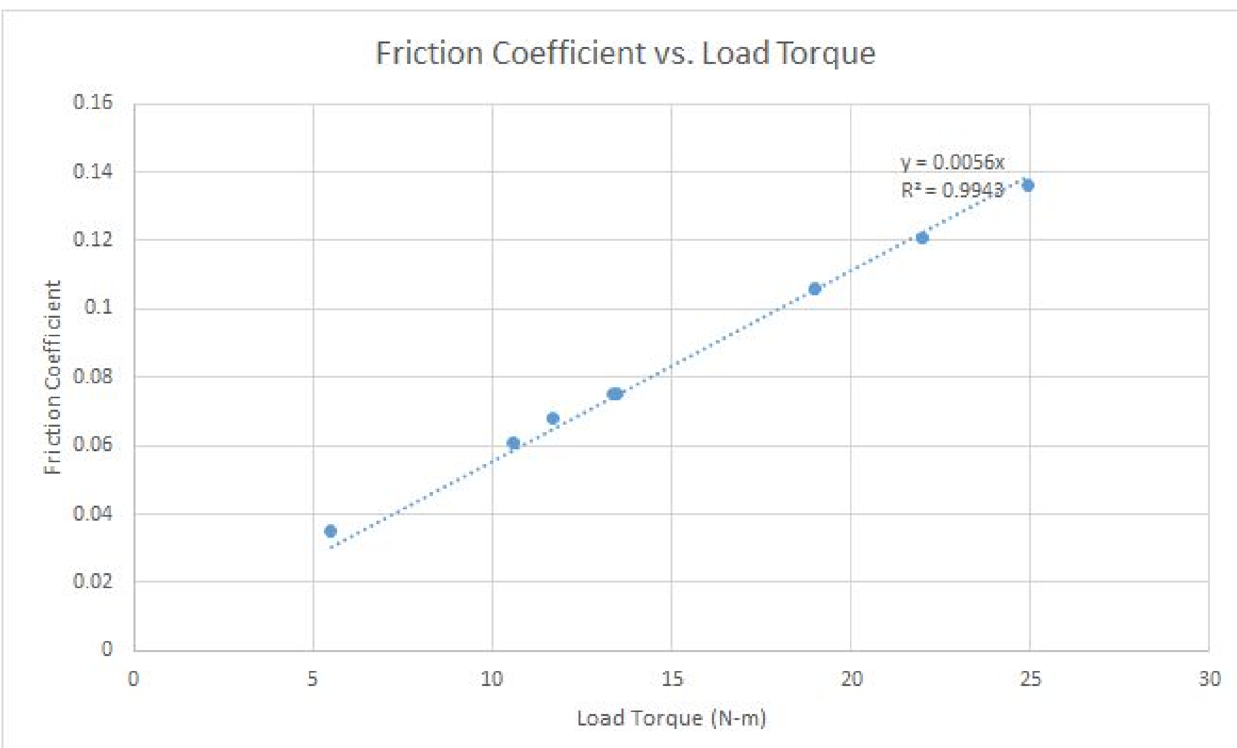

Figure 9

Figure 9 shows the relationship between friction and torque graphically.

This is an interesting relationship to find because it means that although the original hypothesis of modeling the motor+controller system as a single DC motor is rejected, the above-described motor equations can be modified in order to reflect these new findings. The new equation which describes this system is listed below:

$$.0056T_L = \frac{4.305i}{w} - \frac{T_L}{w}$$

This equation can be simplified to the following:

$$w = \frac{768.75i}{TL} - 178.57$$

Where the torque is in N-m. Comparisons of the results of this equation to the actual data found in experiments shows that this equation is able to predict motor speed to within +/- 200 RPM of the measured value. Given that the normal operating range of the motor will be between 1000 and 4500 RPM, this corresponds with an accuracy of **+/- 5.7%** of the operating range. The experiments performed and following data analysis do provide a way to relate the inputs and outputs of the overall system, meaning that the behavior of the motor + controller can be accurately predicted. Given any two of the three inputs to this system (power supply current, torque, RPM) one can calculate the third value as an output.

Appendix A - Dyno System Setup

Electric Vehicle Systems

- HPEVS AC50-51-5X Motor
- Curtis Instruments 1238R-7601 Controller

Battery Simulation - Magna-Power(TSD 100-250/208) D.C. Power Supply

- 20kW P.S. 200A max rms @ ~100 Vdc

Dynamometer System and Sensors - Huff HTH-100 Dyno

- Load Adjustment
  - Oil Valve(CAT HY14-3200)
- Torque Sensor
  - Load Cell (LCCE-250)
  - Strain Gauge Input Module (DataForth - SCM5B38)
- Tachometer
  - Frequency Input Module (DataForth - SCM5B45)
- Throttle
  - Voltage Output Module (DataForth - SCM5B49)
- Data Acquisition Board (MCDAQ-USB7204)

Data Acquisition Software

- Curtis 1314 Programming Software
  - Motor RPM data
- Dyno Software (Proprietary from Class of 2015)
  - Output Data: P.S. Current, Torque
  - Input Data: Load %, Throttle %

Computer

- Dell Precision T1700
  - Accessed through Windows TeamViewer
  - Dyno software is run using a deployment of OpenSuse in Oracle's Virtual Box

Detailed System Description

The Magna-Power power supply takes in 3-phase 208VAC power and is programmed to output 89.6Vdc. With a maximum current output of 200A RMS, it can accurately simulate four battery packs at normal operating conditions. The curtis controller takes in 89.6Vdc from the power supply at convert it to 3-phase AC voltage for the HPEVS AC-50 motor.

The motor is attached to the Huff HTH-100 Dynamometer system with a pump to motor gear ratio of 90:36 or 2.5:1. The Load Cell is attached at the pump and measures torque at the pump.

The signal is conditioned by the Strain Gauge Input Module. There are two tachometers measuring motor RPM, one is available through the Curtis 1314 Programming software, providing access to RPM information directly, while the tachometer provides RPM data at the pump. Load Cell data and RPM data (from the tachometer) is collected by the MCDAQ 7204 USB board. The MCDAQ interfaces with the computer using a USB connection. The Curtis Controller communicates over CAN and interfaces with the computer using a USB to CAN interface. The proprietary Dyno software interfaces with the MCDAQ, Curtis Controller and Magna-Power power supply.

Appendix B - References

[1] Golnaraghi, M. F., Benjamin C. Kuo, and M. F. Golnaraghi. "Chapter 4."*Automatic Control Systems*. Hoboken, NJ: Wiley, 2010. 199-205. Print.

[2] Calibration Memo:
https://sites.lafayette.edu/ece492-sp16/files/2016/04/CalibrationandAccuracyReport.pdf