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The Design, Simulation, and Construction of an Electric Bicycle
An Undergraduate Independent Study Project

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Abstract

In the Fall 2011 semester, an undergraduate student at Northern Arizona University designed, simulated, and constructed an electric bicycle that he now uses reliably for the daily commute to and from school. The student began by researching several possible circuit designs. The buck converter was selected due to its high efficiency. The controller was originally based on an MSP430 microcontroller, and then converted to a high speed Pulse Width Modulation (PWM) controller. The original 10 Amp-hr Nickel-Metal Hydride (NiMH) battery was replaced over the winter holiday with a 13.5 Amp-hr Lithium Iron Phosphate (LiFePO4) battery to achieve the final powerful design. Thanks to manufacturers' sample programs, the university's electronics shop, and a propensity for collecting scrap electronics, the cost for the final design was less than $625, with the new battery accounting for the majority of that cost, approximately $515.

Design Choices, Technical Challenges

Aside from the existing bicycle, previously human-powered, one of the first design choices of this project involved the motor selection. Under federal law, an electric bicycle is exempt from classification as a motor vehicle when the following conditions are met: "a two-or three-wheeled vehicle with fully operable pedals and an electric motor of less than 750 watts (1 h.p.), whose maximum speed on a paved level surface, when powered solely by such a motor while ridden by an operator who weighs 170 pounds, is less than 20 mph." [Public Law No. 107-319, section 1, 116 Stat. 2776 (2002)]. Therefore, a qualifying 750 Watt scooter motor with an appropriate chain sprocket was selected, along with accessories to integrate the motor with the existing bicycle.

Originally, an MSP430F2012 microcontroller was chosen as the key component of the motor control circuit, primarily due to previous classroom experience with this device. A generic 10-Amp diode, two MOSFETs (model #IRF3710 with 100V, 57 Amp ratings), and line regulators were also used within this circuit. However, the high inrush current from the batteries fused the line regulators in this design, subsequently destroying the microcontroller.

The microcontroller was then replaced by a high speed PWM Integrated Circuit (Texas Instruments model #UC3823), and the MOSFETS were replaced by IGBTs (Mouser #40N60A4, 600 V, 75 A). In addition, a buck converter (Texas Instruments TL2575HV-15, 60 V) with an integrated switch was used in place of the line regulator to provide a constant 15 V for the controller and other circuit components. A few supporting circuit elements were also updated. The resulting circuit, shown in Figures 1 and 2, was much more efficient and reliable.

There were three iterations for the battery component in this design. Initially, two battery packs were composed of inexpensive NiMH batteries (1.2 V, 10 A-hr per cell, 3 A charge rate and 30 A discharge rate). Two packs of 25 cells were soldered together (after 6 hours) to create a 30 V input (Figure 3). Unfortunately, the batteries did not meet their manufacturer's ratings; they overheated at the rated 3 Amp charge, and the array voltage would fall from 30 to 7 Volts under the rated 10 Amp load. After a couple months, the batteries could no longer hold a charge.

A second battery pack was created with 8.6 V, 3.3 A-hr NiMH batteries. This pack performed well, holding its voltage with a current draw over 30 Amps. However, an LiFePO4 battery system was received as a Christmas present (13.5 A-hr, 52 V, 60 A current limited, with short circuit protection). Unfortunately, when the limits of the new battery system were tested, a diode failed, and IGBTs then failed under high voltage. The diodes were then upgraded to ultra-fast models (Mouser BYT79X-600-127, 600 V, 30 A, t_{rr} = 30 ns), the failed IGBTs were replaced, and the final version (Figure 4, Table 1) has worked well ever since.

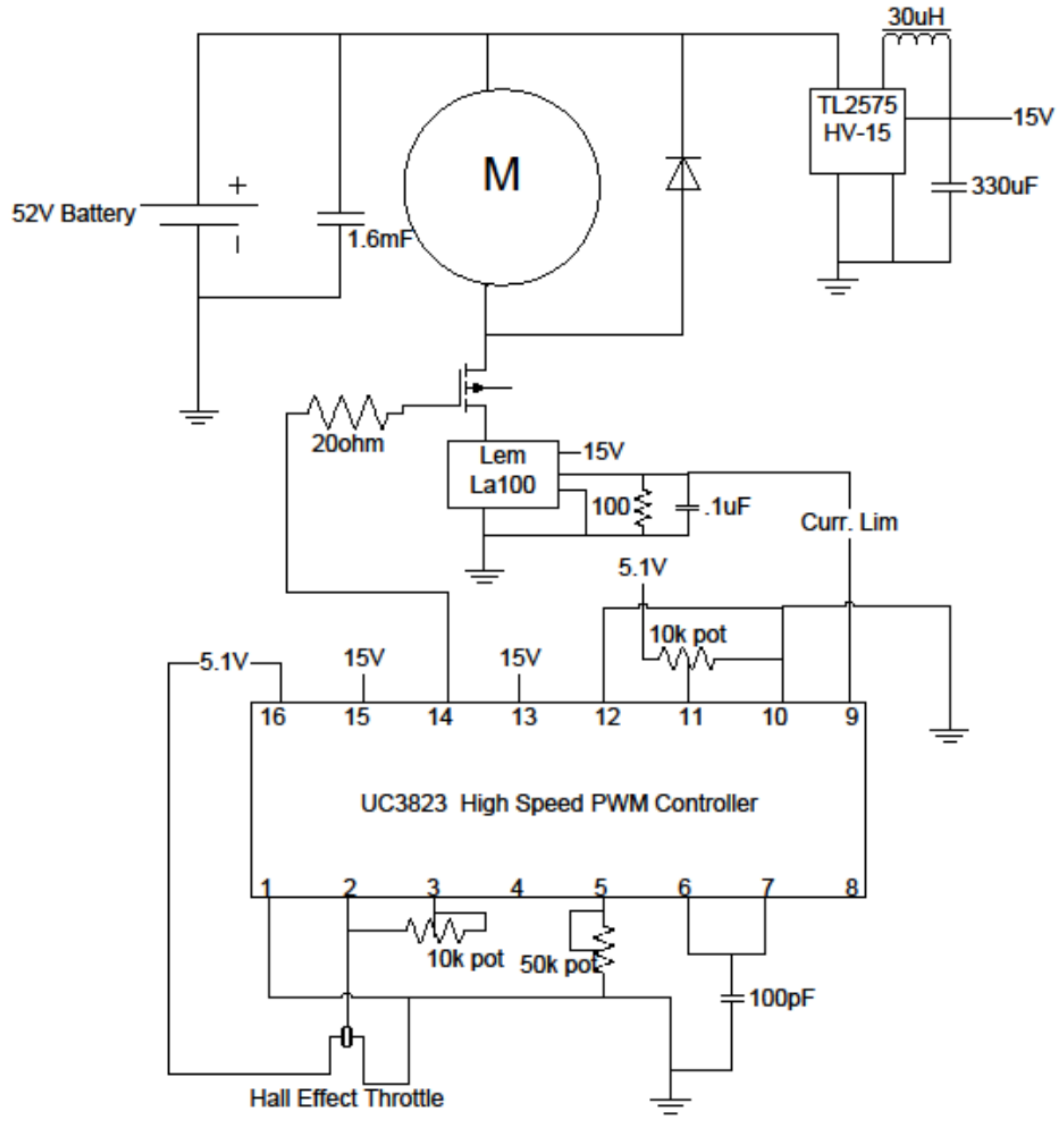

Figure 1. Final circuit schematic for the electric bicycle.

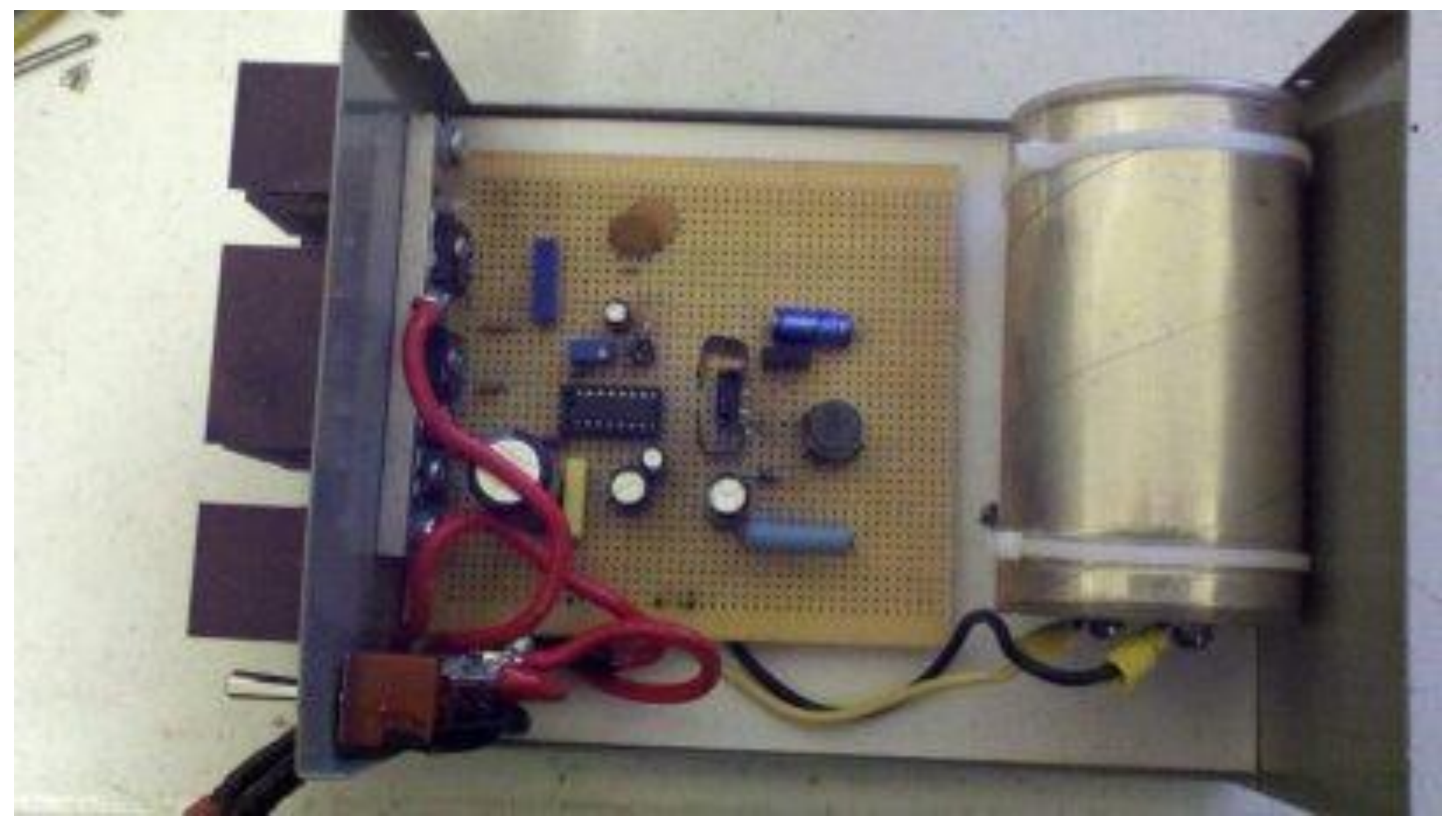

Figure 2. Physical circuit layout for the electric bicycle.

Figure 3. Original battery pack.

Figure 4. Final electric bicycle configuration.

Table 1. Final Bill of Materials.

Quantity	Description	Part Number	Provider	Cost
1	Buck converter 15V	TL2575HV-15	Texas Instruments	Free sample
1	High Speed PWM IC	UC3823	Texas Instruments	Free sample
2	Ultra fast diode	BYT79X-600,1	Mouser.com	2.5
2	IGBT 600V 75A	40N60A4	Mouser.com	10
1	13.5Ah 52V LiFePO4	LFP-51.2V13.6Ah	Batteryspace.com	514
1	36V 750W scooter motor	C80-8732	monsterscooterparts.com	74.99
1	#25 chain 132 link	W75-8293	monsterscooterparts.com	9.79
1	65t gear	N83-9034	monsterscooterparts.com	13.99
1	100 uF cap		NAU Electronics Shop	Free
1	330 uF cap		NAU Electronics Shop	Free
1	Schottky diode		NAU Electronics Shop	Free
2	0.01 uF cap		NAU Electronics Shop	Free
1	1 kΩ resistor		NAU Electronics Shop	Free
2	50 kΩ potentiometer		NAU Electronics Shop	Free
2	1 uF cap		NAU Electronics Shop	Free
1	220 uF cap		NAU Electronics Shop	Free
1	0.01 uF film cap		NAU Electronics Shop	Free
1	2.5 mF cap		NAU Electronics Shop	Free
1	AMD heatsink		Scrap Circuit Board	Free
1	TO220 heatsink		Scrap Circuit Board	Free
1	3 Amp switch		Scrap Circuit Board	Free
1	36 Ω 1W resistor		Scrap Circuit Board	Free
1	50 uH inductor		Scrap Circuit Board	Free
1	1000 uF cap		Scrap Circuit Board	Free

Total Cost: **625.27**

Circuit Simulation

A MATLAB Simulink model of the electric bicycle's final power system design was created. The motor spins at 50 rpm per volt, and the 36 V / 1800 rpm condition was simulated. A resistance of 0.2 Ω and inductance of 200 µH were assumed.

Although the simulation did a reasonable job of modeling the real world, the actual system behaved quite differently. For example, the physical system has far more noise and a large voltage ripple from the battery then the simulation would imply. This is caused by the equivalent series resistance (ESR) of the capacitor in parallel with the battery.

In addition, the current flowing through the MOSFET closely resembles an impulse response when the device is turned on, but the simulation did not predict this. The simulation also did not account for the rise and fall times of the IGBT when it was operating in a triode region, when the resistance would increase. Therefore, even though the simulations were educational and provided useful information, they did not completely represent the physical system.

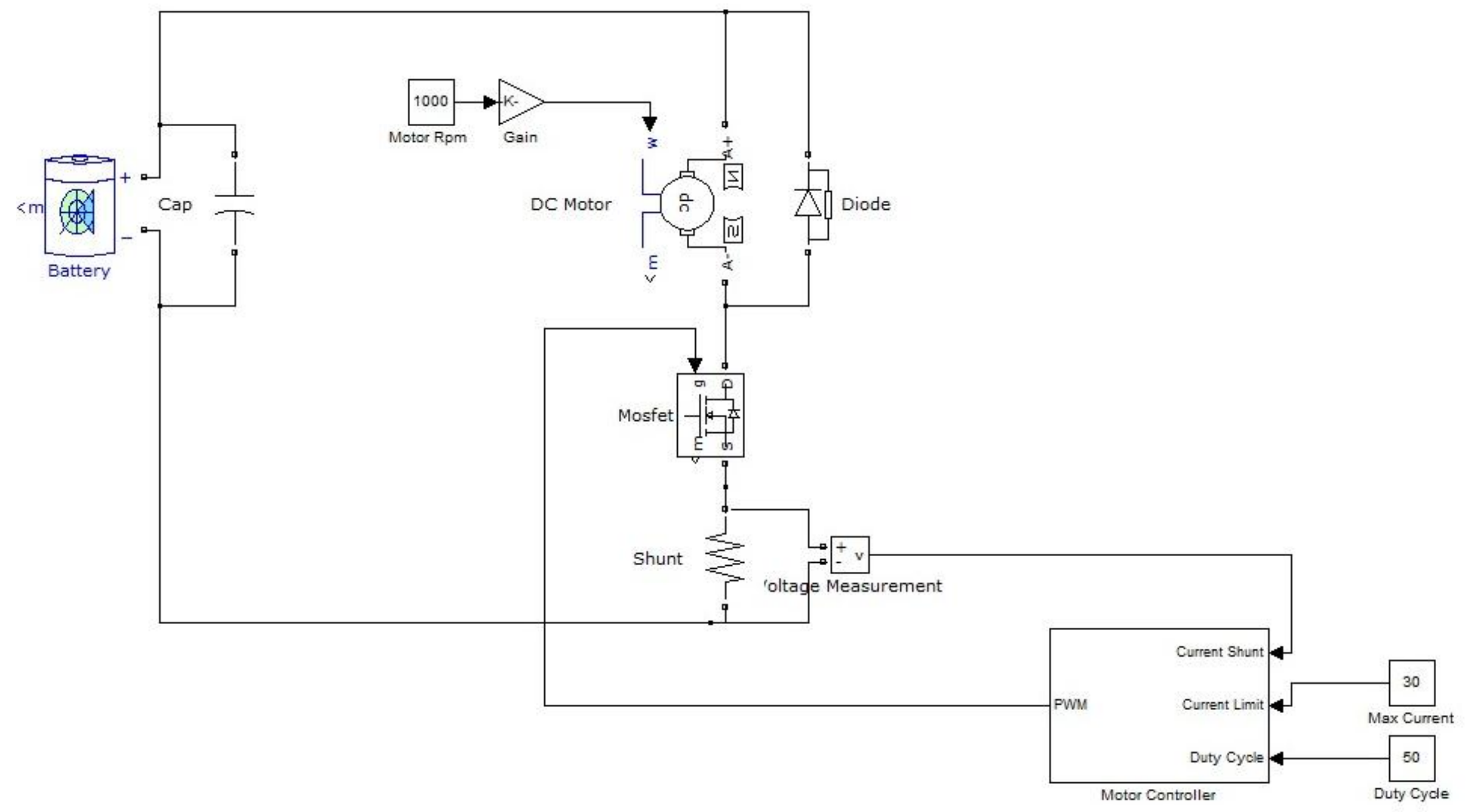

Figure 5. MATLAB Simulink model of the electric bicycle's power system.

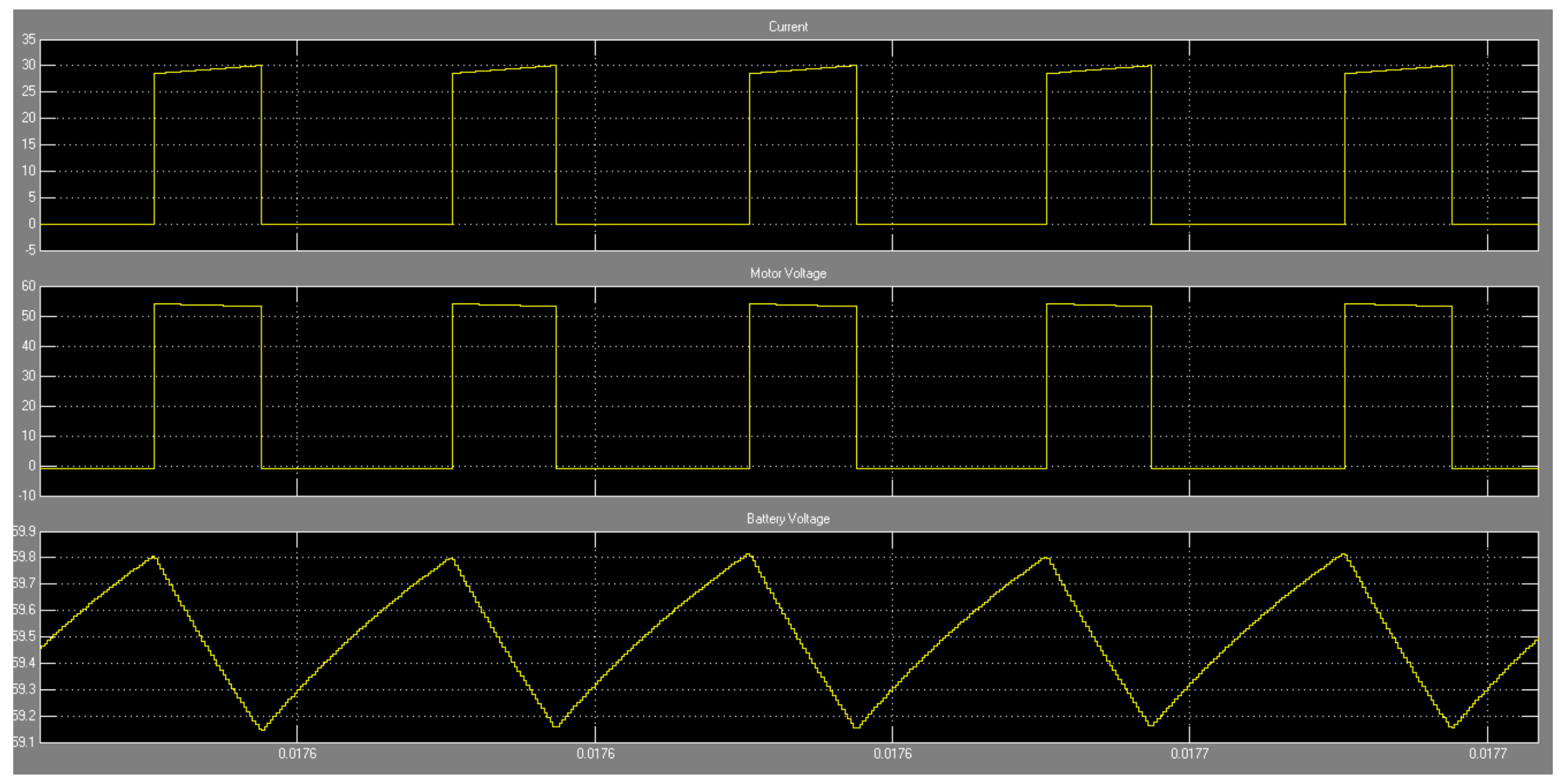

Figure 6. Current, Motor Voltage, and Battery Voltage waveforms output by the MATLAB Simulink simulation, showing pulse-by-pulse current limiting.

Acknowledgments

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