A Smart Motor Controller for E-bike Applications

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Abstract

A smart motor controller for electric bicycle (e-bike) applications is described. The e-bike is a hybrid electric vehicle than can be powered by the cyclist and/or an electric motor. The controller is the first to provide automatic clutch control, which allows the cyclist to coast without the drag from the motor. The controller also supports regenerative braking and includes numerous safety features.

Sommaire

Une commande intelligente de moteur pour bicyclettes électriques e-vélo est expliquée. Le e-velo est un véhicule électrique hybride qui peut être propulsé par le cycliste et/ou le moteur électrique. La commande automatique de transmission de ce e-velo est la première en son genre et permet au cycliste de rouler sans le fardeau du couple du moteur. Le système de commande permet aussi d'avoir un freinage par régénération et renferme plusieurs dispositifs de sécurité.

1.0 Introduction

Hybrid vehicles are rising in popularity due to high fuel prices and growing environmental awareness. The electric bicycle (e-bike) is rapidly emerging as a new form of simple and cost-effective transportation for smog-infested urban areas. The e-bike is a hybrid light electric vehicle (HLEV) that can be powered both by pedals and/or an electric motor. Adapted from the standard bicycle, the additional components of an e-bike include a battery, a motor and an electronic controller. The primary role of the controller is to provide smooth power flow to the motor. There are currently a number of companies specializing in e-bikes such as Currie Technologies, EV Global Motors, and ZapWorld. It has been estimated that in China alone, approximately 300 companies sold over 1 million electric bikes in 2002 [1].

The efficiency of the e-bike is unquestionably superior to the automobile; a simple calculation shows that a typical e-bike requires 50 times less energy per kilometer than a standard car. In addition, as solar panel technology becomes more affordable, the net amount of energy required to power an e-bike can be reduced. For example, roof mounted solar panels could be used to charge spare batteries during the workday. Table 1 gives a perspective on current e-bike technology [2].

In the past, the majority of e-bikes were built by hobbyists, resulting in low-efficiency designs. However, with advances in power electronics and microelectronics, vast improvements have recently appeared on the market. These include the use of high efficiency motors, such as Brushless DC (BLDC) [3], regenerative braking and fault monitoring. A BLDC motor is conceptually similar to a traditional permanent magnet DC motor except that operates without brushes and a mechanical commutator [4]. The stator's magnetic field must be rotated electronically, which increases the motor drive complexity. However, when compared to DC motors, BLDC motors have higher efficiency, superior heat dissipation, increased power density and lower maintenance [5]. Regenerative braking refers to the use of the motor as a generator to capture kinetic energy from the bicycle during braking. The energy is redirected to the battery, increasing battery life and system efficiency.

This paper describes the design and implementation of a high performance BLDC motor drive controller and a test-bench for an e-bike. Our design demonstrates the first e-bike controller that incorporates all of the following features:

- BLDC motor control,
- Voltage, current, temperature and speed protection,
- Adaptive dead-time control in three-phase power-stage,
- Soft-start,
- Automatic clutch control for coasting and regenerative braking.

In addition to the hardware-based controller, the design includes both a mechanical setup to simulate realistic riding conditions and a software interface to allow comprehensive testing through a PC.

Table 1: Commercially Available E-Bike Technology

Characteristics	Min	Max	Units
Battery Voltage	12	36	V
Distance on One Charge	20	80	km
Motor Power	150	500	W
Price	300	2000	USD
Weight	25	40	kg
Recharge Time	4	10	Hours
Battery Capacity	10	30	Ah
Type of Drive	Friction/Belt/Chain/Hub		
Motor Type	AC Induction / Brushless DC / Switched Reluctance / DC Brush		

2.0 Design And Implementation

2.1 Overview

The complete e-bike system includes the controller hardware, as well as a mechanical test-bench. The controller hardware incorporates mixed-

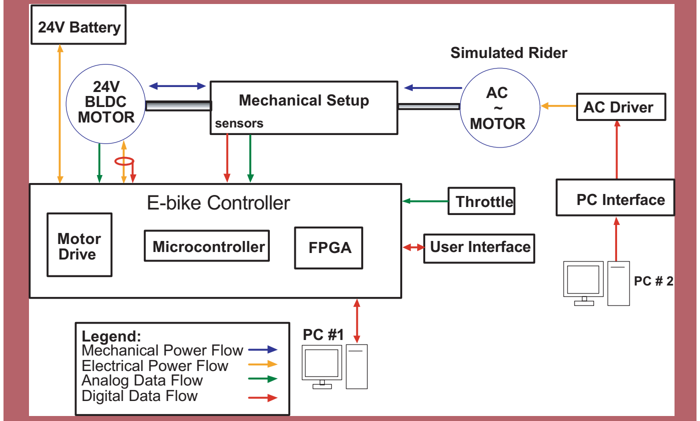


Figure 1: Controller and testbench system.

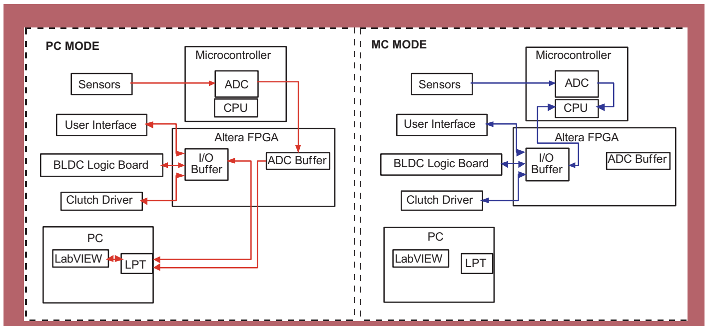


Figure 2: Data flow under PC and MC (microcontroller) mode.

signal circuits, sensors and a user interface for the e-bike cyclist. The mechanical setup, which includes a simulated rider interface, provides a versatile platform on which to test our controller. Figure 1 shows a representation of the e-bike controller and test-bench system.

For testing purposes our controller runs in 2 modes: PC mode and MC (microcontroller) mode. In PC mode the PC handles the controller duties while the microcontroller performs sensor data acquisition and transfers data between its various peripheral devices. This mode is used for testing the general functionality of our system and is essential for determining the effectiveness of the control algorithm. MC mode is the final form of the controller. In this mode the microcontroller acts autonomously to gather data from the sensors and implement the control algorithm. Figure 2 shows data flow under the two operation modes.

The major components of the e-bike system are listed below. Details are provided for several crucial components.

- Mechanical setup
- Rider simulation
- Three-phase BLDC motor drive
- FPGA design
- Speed, temperature and voltage sensor
- User interface
- Throttle filter
- Microcontroller and control algorithm

2.2 Mechanical Setup

A representative diagram of the mechanical setup is shown in Fig. 3. The flywheel simulates the inertia of the bicycle and a computer-controlled AC induction motor is used to simulate the power contribution of the cyclist. An electromagnetic clutch is used to isolate the BLDC motor from the drive-train for reduced friction during coasting.

The BLDC motor uses a three-phase synchronous buck topology that allows bi-directional current flow. The power switches are discrete HEXFETs from International Rectifier. SenseFETs are used as low-side switches to provide current-feedback. The pulse-width-modulated (PWM) gate drive incorporates adaptive dead-time control. This minimizes the dead-time while avoiding large punch-through currents. The three-phase gate drive signal is generated from a single phase PWM by a dedicated decoder as shown in Figure 4. The phases are synchronized using hall-sensor inputs from the BLDC motor.

2.3 Microcontroller and Control Algorithm

In order to model the typical demands of an e-bike, several drive-cycles were obtained in downtown Toronto using a traditional bicycle equipped with sensors and a portable data acquisition system. A drive-cycle is defined as a chart giving the instantaneous speed of a vehicle versus time for a particular terrain. Figure 5 shows an experimental drive-cycle.

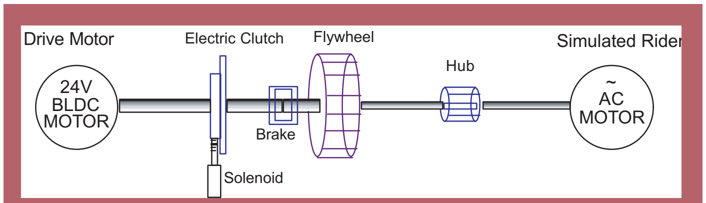


Figure 3: Mechanical setup.

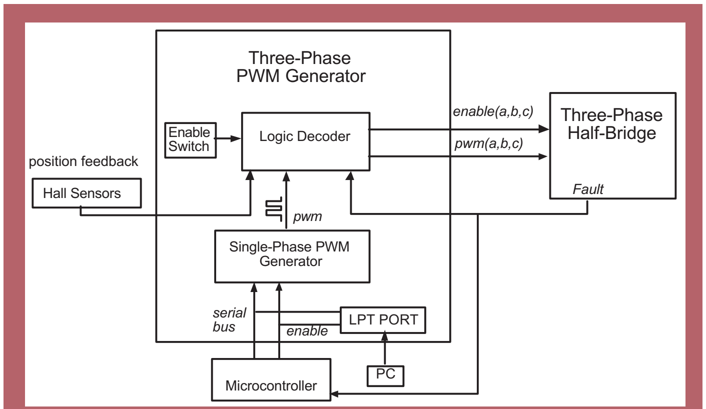


Figure 4: Three-phase PWM generation.

The control algorithm was developed in PC mode and then implemented in MC mode using a 68HC11 microcontroller. Using data from experimental drive-cycles the following drive stages were encoded in the drive algorithm:

- Regular driving
- Coasting
- Braking
- Low speed operation
- Motorless operation

During regular driving, the clutch is engaged and the throttle input controls the motor. During the coasting stage, our design allows the rider to coast just as one would on a traditional bicycle by disengaging the clutch. A free-wheel cannot be used as in other e-bike controllers [2] since it does not allow regenerative braking. Our design increases the length of coasting and thus saves valuable energy by disengaging the clutch. The user enters coast-mode by pressing the “clutch request” button, located on the user interface. When this button is pressed, the controller disengages the clutch and waits for the user to fully release the throttle. When the user resumes pressing the throttle, the controller ramps up the motor until the motor speed equals the bike speed and then engages the clutch. The speed control is then transferred back to the user. The rider can signal a braking event by lightly pressing on the brake levers. This signals the CPU to efficiently manage regenerative braking. At this point the CPU must disable the throttle; the PWM signal supplied to the motor is ramped down exponentially to maintain negative motor torque. When the brake is released, the user regains speed control. It should be noted that the e-bike user can also brake manually by fully pressing the levers.

Under all conditions, the PWM signal is disabled if the e-bike speed

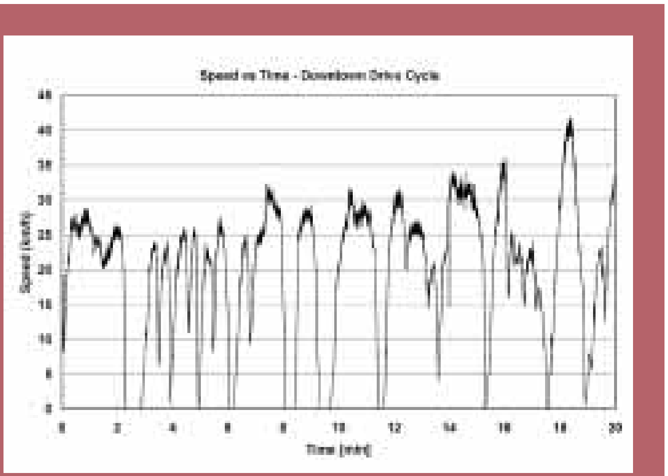


Figure 5: Experimental drive-cycle.

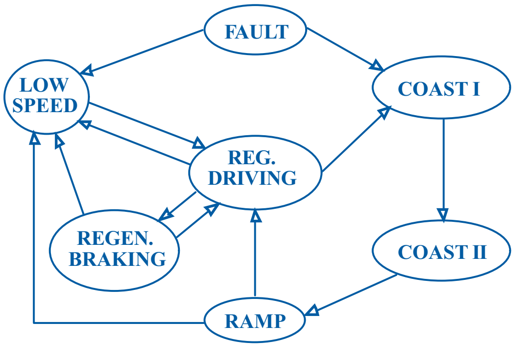


Figure 6: State diagram for control algorithm.

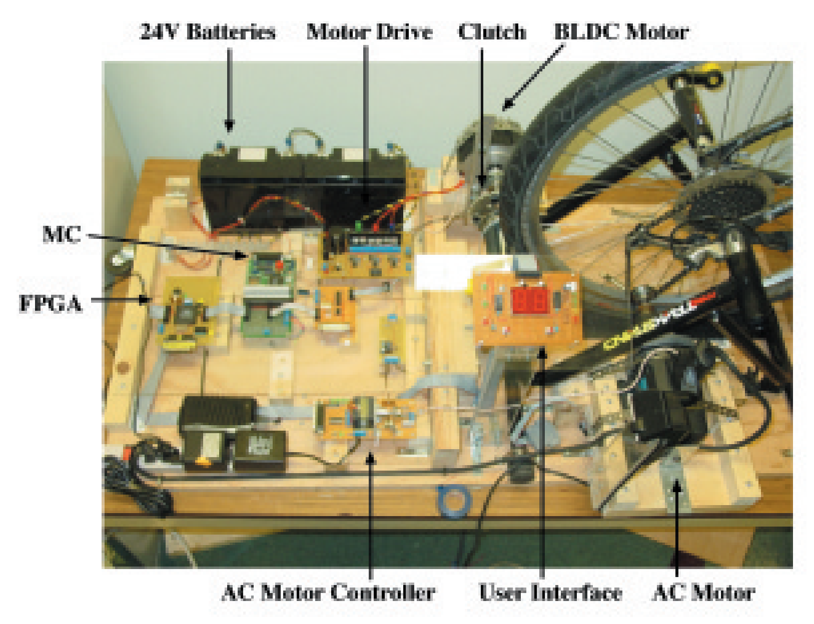


Figure 7: E-bike System.

falls below 5 km/h to prevent damage caused by high currents during low-speed operation. This also protects the motor if the wheel is jammed. A simplified state diagram for the controller algorithm is shown in Figure 6.

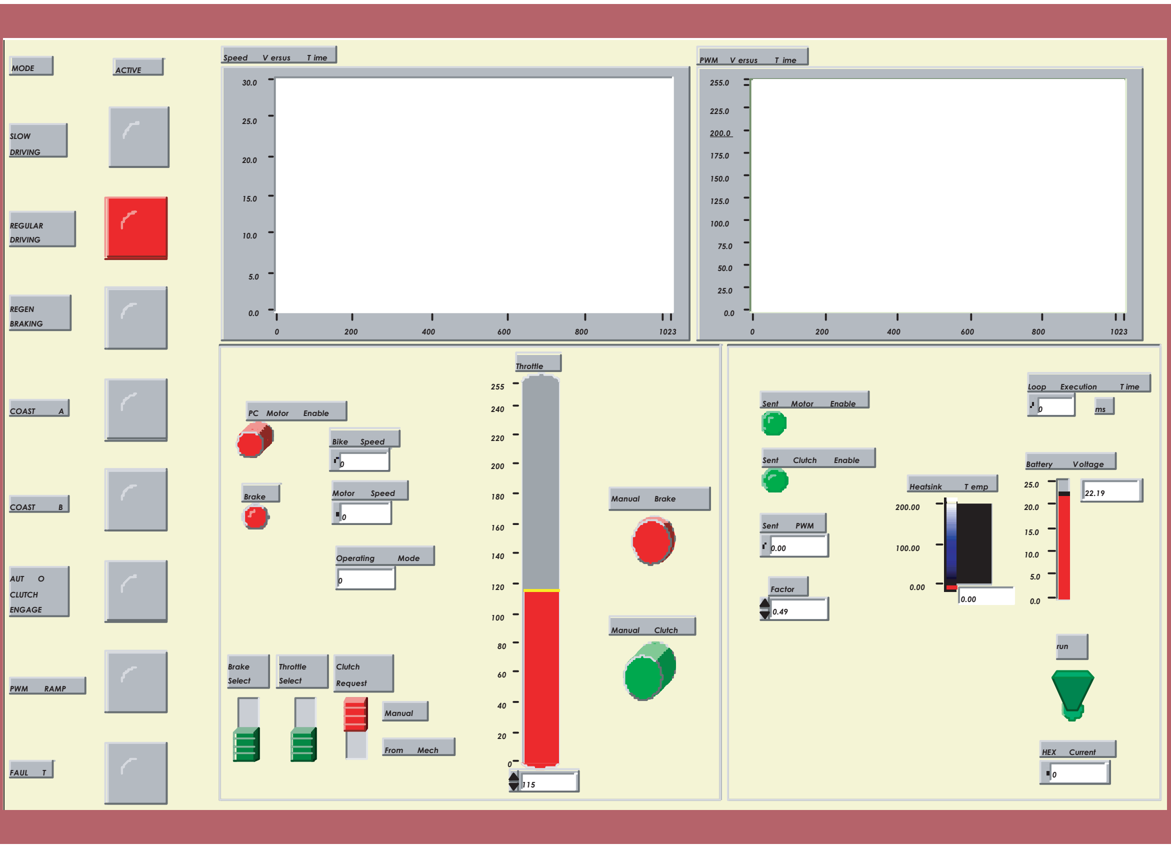
3.0 Results

Figure 7 shows the final e-bike controller and mechanical system. Tests have confirmed proper operation of the security features and the controller algorithm. This was demonstrated by programming the AC motor to simulate the behaviour of a cyclist while the e-bike controller carried out the algorithm described in the previous section. Figure 8 shows the GUI used in PC mode and Figure 9 shows the commutation of the motor phases. Final specifications are listed in Table 2.

4.0 Conclusion

An e-bike controller for a BLDC motor has been designed and implemented using low-cost off-the-shelf components. The design includes a versatile mechanical test-bench with a computer-controlled AC induction motor used to simulate the power contribution of the cyclist. The controller is the first to provide automatic clutch control, which allows the cyclist to coast without the drag from the motor. The controller also recharges the battery through regenerative braking for increased efficiency. Having completed the hardware development phase, current efforts are directed toward further algorithm development and system integration. A new research team is currently working on integrating the entire controller onto a single printed circuit board (PCB). Possible future algorithm improvements include adaptive control and battery management based on the terrain and cyclist habits.

Figure 8: PC-mode graphical user interface (GUI).



Bike Speed: 0
Motor Speed: 0
Operating Mode: 0
Throttle: 115
Sent PWM: 0.00
Factor: 0.49
Heatsink Temp: 0.00
Loop Execution Time: 0 ms
Battery Voltage: 22.19
HEX Current: 0

Table 2: Specifications

Module	Relevant Features	Specifications	Value	Units
Motor Drive	Adaptive non-overlap gate drives 3-Phase MOSFETs High-side charge pumps 3-Phase current feedback Temperature feedback Under/Over-voltage lockout Current limiting	Nominal battery voltage	24	V
		Electronic current limit	15	A
		Peak power	360	W
		Electronic heatsink temperature limit	120	C
		PWM switching frequency	25	kHz
		Minimum operating voltage	10	V
Buck Regulator		Output voltage	5	V
		Efficiency	77	%
		Rated current	1	A
		Switching frequency	56	KHz
BLDC Logic Board	Digital PWM LPT (PC) Interface	PWM generator clock frequency	17.4	MHz
		PWM resolution	8	Bits
Micro-controller	Multi-channel ADC Programmable interrupts Serial interface	Clock frequency	2	MHz
		ADC channels	8	
		ADC resolution	8	Bits

5.0 Acknowledgment

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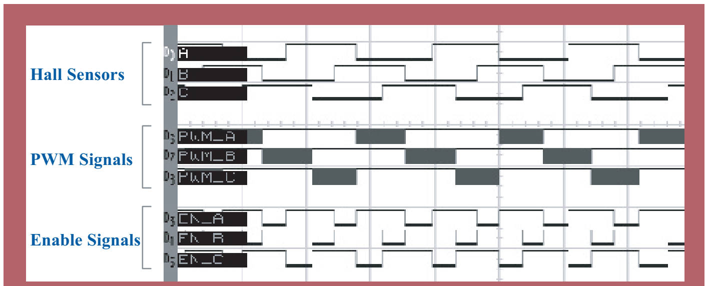

Figure 9: Commutation of motor phases

About the authors

Olivier Trescases was born in Paris, France. He received his B.A.Sc. degree in Electrical Engineering from the University of Toronto in 2002, where he is currently pursuing a M.A.Sc. His primary research interests include low-voltage DC/DC converters for microprocessor loads, hybrid vehicle motor controllers and audio amplifiers. He currently holds a Natural Sciences and Research Council Post-Graduate Scholarship. He was awarded the 2002 Gordon Slemon award for his E-bike motor controller prototype. In 2003 he received the IEEE Vehicular Technology Grant and the IEEE Hackbusch Student Paper Award.

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Wai Tung Ng received his B.A.Sc., M.A.Sc. and Ph.D. degrees in Electrical Engineering from the University of Toronto, in 1983, 1985 and 1990, respectively. In 1990 he joined the Semiconductor Process and Development Center of Texas Instruments, Dallas TX to work on LDMOS power transistors for automotive applications. His academic career started in 1992 when he joined the Department of Electrical and Electronic Engineering, University of Hong Kong, where his focus was on device models and circuit design. In 1993, Dr. Ng joined the University of Toronto, and was promoted to Associate Professor in 1998. His current work covers a wide spectrum, ranging from advanced MOS and RF BJT devices, analog circuits, smart power integrated circuits and fabrication processes.