Design and Implementation of Electric Drives Laboratory using Commercial Microcontroller Development Kits

Mr. Bhanu Babaiahgari, University of Colorado, Denver

Mr. Bhanu Babaiahgari received his M.S degree from University of Colorado Denver, Denver, in 2015. He is currently pursuing PhD at University of Colorado Denver supervised by Dr. Jae-Do Park. Since 2016, he has been teaching Electric drives and Energy conversion laboratory and Energy conversion laboratory as part-time graduate instructor. He is a research assistant at Dr. Park's Energy and Power lab under Energy Conversion Research Force (ECRF). His current research interests are DC shipboard power systems protection and stability analysis, power electronics and coordinated energy management.

Mr. Zizhuo Chen, University of Colorado, Denver

Mr. Zizhuo Chen received his bachelor's degree in Northeast Forestry University, China, in 2016. He is currently pursuing M.S degree at University of Colorado Denver supervised by Dr. Jae-Do Park. He is a research assistant at Dr. Park's Energy and Power lab under Energy Conversion Research Force (ECRF). His current research interest is BLDC motor speed control.

Dr. Jae-Do Park, University of Colorado, Denver

Jae-Do Park received his Ph.D. degree from the Pennsylvania State University, University Park, in 2007. Park is currently an Assistant Professor of electrical engineering at the University of Colorado, Denver. He is interested in various energy and power system research and education areas, including electric machines and drives, energy storage and harvesting systems, renewable energy sources, and grid-interactive distributed generation systems. Prior to his arrival at the University of Colorado, Denver, Park worked for Pentadyne Power Corporation in California as Manager of Software and Controls, where he took charge of control algorithm design and software development for the high-speed flywheel energy storage system. He also worked at the R&D Center of LG Industrial Systems, Korea, where he developed induction machine drive systems as a Research Engineer.

Design and Implementation of Electric Drives Laboratory using Commercial Microcontroller Development Kits

Abstract

A design and implementation of instructional electric drives laboratory at University of Colorado Denver using commercial off-the-shelf microcontroller kits and small motors is described in this paper. The main objective of this project is to provide senior level students with hands-on experience on electric machine drives and industrial microcontroller programming. This laboratory is associated with the electric drives lecture course to enhance their understanding of the theory taught in lectures with tangible examples. Moreover, the skills and experience on electric machines and drives that students gain in this laboratory can be readily applied in their senior design projects that are integrated with motion control components. Experiments, hardware components and instruments about the proposed laboratory course are presented.

Introduction

In recent studies, laboratory coursework is known to help students enhance theoretical understanding, interest on subjects, motivation to learn, practical skills, and problem solving abilities[1]. It also provides the understanding on how theory can be applied to actual systems by hands-on experience using practical equipment. The laboratory courses are usually taught associated with lecture courses to enhance students' mastery of the subject matter. While it is essential to keep the laboratory equipment up-to-date with the latest technologies[2], it is also important to design a cost-effective[3] and flexible solution[4] and a safe operating environment in the laboratory course.

Although the electric machine laboratory has been traditionally offered in Electrical Engineering curriculum in many of the engineering institutions, the laboratory for electric machine drives has not been common. While the electric machines have not changed much in their structure and operation, power electronic converters and machine drive technologies have been substantially improved. Recently, there have been efforts to implement electric drive laboratories[5], but the software and equipment required for that laboratory has not been so affordable.

Industrial microcontrollers have also advanced tremendously and now various experimental kits with versatile high-performance microcontrollers and power converters are available off-the-shelf at low cost. They are very well suited for real-time electric machine control applications and the software development tools for them are available for free of charge. Furthermore, these

Part	Description	Specifications
DC machine	BDD-36-49-12.0V-6630	12V, 150mA, 2-pole 6630 RPM, 1.49 oz-in, 6.2W
BLDC machine	BLY171S-24V-4000	24V, 1.8A, 8-pole 4000 RPM, 27 oz-in, 26W

Table 1: Specifications of DC and BLDC machines.

controllers can not only be used to control electric machines but also can be used for many other applications such as grid tied converters, electric vehicles, battery management systems, DC-DC converters, and so on. It will be a very realistic approach because the commercial full-fledged industrial electric machine drive systems would still use the same or similar microcontrollers and programming skills.

Although the various sample codes are available from the experimental kit manufacturers, it is still a very challenging task for students to understand and use them without putting in significant amount of effort and proper guidance. Typically, students get to gain experience and training when they work as entry-level engineers or graduate students. It would be beneficial if these tools, skills, and ideas can be taught systematically earlier, so that students can expand and evolve while they are in undergraduate program. This paper presents the design and implementation of a senior-level instructional electric drives laboratory using commercial off-the-shelf microcontroller and driver kits that provides step-by-step projects from scratch. The paper will also discuss the hardware components and their design, laboratory equipment setup, and experiment sessions.

Hardware Design

The hardware design of the proposed laboratory has focused on cost-effectiveness and reliability, as well as providing realistic but safe setup. The hardware setup is designed so that the students can perform various control tasks without any modification.

1. Machines

In this laboratory, two machines, brushed DC (DC) machine (BDD-36-49-12.0V-6630, Anaheim Automation)[6] and brushless DC (BLDC) machine (BLY171S-24V-4000, Anaheim Automation)[7], have been selected; they are widely used motor types for various applications and available in small sizes. Both machines were mounted on an aluminum plate and coupled using flexible shaft couplers in motor-generator set fashion. The motor mounts were built by in-house machine shop. The DC machine can be operated by nominal 12V DC and provide a torque up to 1.49 oz-in. The BLDC machine comes in standard 8-lead configuration with three wires for the three-phase supply and five wires for the hall sensors. The brief specifications of the motors can be seen in

Part	Description	Specifications
Microcontrollers	MSP-EXP430G2	16 MHz CPU, 512B RAM, 16kB Flash 2 16bit timer, 10bit ADC
	LaunchPadXL TMS320F28027F	60MHz CPU, 12KB RAM, 64KB Flash 3 32bit timers, 12bit ADC
Drivers	BOOST-DRV8848	6-24V, up to 1A rms, 2A peak Dual H-bridge drive stage
	BOOSTXL-DRV8301	6-24V, up to 10A rms, 14A peak Complete three-phase drive stage

Table 2: Specifications of microcontrollers and drivers.

Table 1. Although each motor can run as a load to the other, all experiment sessions in this paper are performed in no-load condition.

2. Microcontrollers and Motor Drives

Texas Instruments (TI) has been manufacturing wide variety of microcontrollers suiting different applications including electric machine drive systems. In this work, Launchpad MSP-EXP430G2 [8] and Launchpad XL-TMS320F28027F [9] have been selected for DC and BLDC machine drive to use compatible motor drive booster packs BoostXL-DRV8848 [10] and BoostXL-DRV8301 [11], respectively. The microcontrollers are featured with various peripherals and brief specifications are shown in Table 2. The microcontroller launchpad boards can use other compatible booster packs.

The DC motor drive BoostXL-DRV8848 can drive two DC motor in parallel mode or provide higher current to a single machine. The BoostXL-DRV8301 provides a complete 3-phase drive stage for a BLDC machine and features individual phase voltage, low-side phase current and DC bus voltage sense amplifiers which can be an advantage in designing feedback applications. Both of the drivers can operate in wide power supply voltage range and are compact in size.

To accommodate the microcontrollers and associated driver boosterpacks on a single platform, a motherboard is designed in two-layer printed circuit board (PCB). It has additional control inputs (potentiometer, toggle switch, and pushbutton switch) to implement user control interface for speed, run/stop, and rotational direction, respectively. Furthermore, many testpoints were placed at different locations to easily access signals while it is in operation, so that students can troubleshoot if necessary. Insulated connectors have been placed to provide easier connections to the machine platform and also to avoid bad contacts. The complete system and the functional diagram of the setup is shown in Figs. 1 and 2, respectively, and the bill of materials is listed in Table 3.

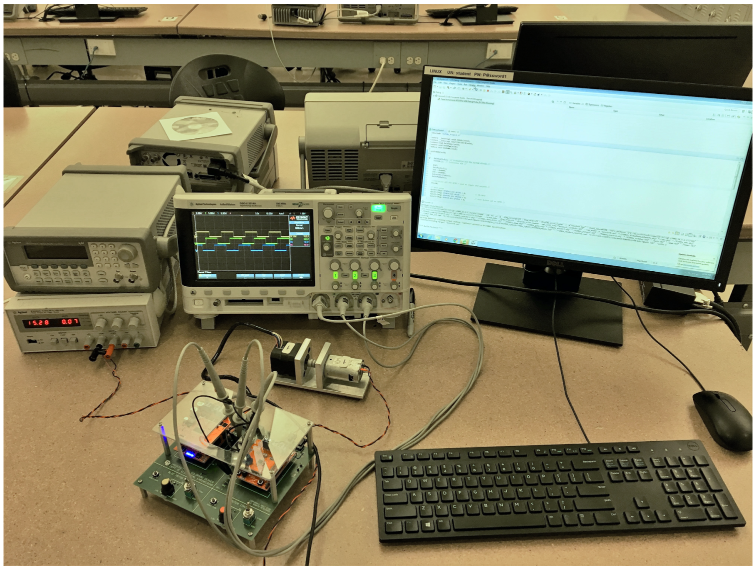

Figure 1: Experimental hardware setup.

3. Development Tools and Instruments

TI has a software called Code Composer Studio (CCS)[12], an integrated development environment (IDE) tool for their processors and controllers. The latest CCS 7.4 released in 2017 is used in this laboratory sessions. The software comprises a suite of tools such as optimizing C/C++ compiler, source code editor, project build environment, debugger, and many other features that are used to develop and debug embedded applications and is completely free of charge to download, install and use without any limitation for their development kits. The ControlSuite package contains example codes and other software infrastructure for C2000 microcontrollers, which is the one for BLDC machine.

A computer is provided to each student with pre-installed firmware development packages, as well as generic industrial instruments including digital multimeter and oscilloscope.

4. Safety and Protection

Safety and protection measures have to be taken at all times while students are performing experiments. The motor connections are pre-soldered and completely insulated to avoid short-circuit connections. In the board side, the connection is done using a polarized receptacle housing (Molex, 43645-0200) for fail-safe wiring. Moreover, the positive power supply rail is connected to the board through a diode to avoid damage to the circuit from a reverse power connection. The microprocessors and drives are covered with a transparent polycarbonate panel to avoid accidental contact. Furthermore, the motor drives have built-in measures against short-circuits, thermal, shoot-through, and under voltage.

Part Description	**Manufacturer**	**Quantity**	**Price($)**
Brushed DC machine	Anaheim Automation	1	6.00
Brushless DC machine	Anaheim Automation	1	56.00
MSP-EXP430G2 LaunchPad	Texas Instruments	1	10.37
Driver-DRV8848	Texas Instruments	1	25.96
TMS320F28027 LaunchPad	Texas Instruments	1	17.65
Driver-DRV8301	Texas Instruments	1	50.88
Socket Contact 20-24 AWG	Molex	20	2.72
2 Position Housing Connector	Molex	2	0.62
2 Positions Header Connector	Molex	2	2.64
3 Position Housing Connector	Molex	1	0.36
3 Positions Header Connector	Molex	1	1.24
8 Position Housing Connector	Molex	1	0.54
8 Positions Header Connector	Molex	1	2.00
Diode 60V 3A	Diodes Incorporated	2	0.94
DC-DC Converter	Recom Power	1	6.09
Resistor 330Ω 0.25W	Panasonic Electronic Components	2	0.22
Resistor 1KΩ 0.25W	Stackpole Electronics	7	0.7
Resistor 2KΩ 0.25W	Yageo	2	0.2
Resistor 10KΩ 0.25W	Panasonic Electronic Components	2	1.32
Potentiometer 5KΩ 0.1W	TT Electronics/BI	2	1.52
Capacitor 0.1μF 6.3V	Kemet	1	0.47
Capacitor 0.1μF 50V	Kemet	2	0.94
Capacitor 4.7μF 16V	Taiyo Yuden	1	0.81
Op-Amp LM358	STMicroelectronics	1	0.43
Pushbutton	Co-Rode	2	0.14
Toggle switch	Gadgeter	2	1.06
Test points	Uxcell	30	1.2
Banana plug connector	Cal Test Electronics	4	3.80
PCB	4pcb	1	33.00
Hex standoffS	Keystone Electronics	10	4.31
22 AWG wire	Remington Industries	1	10.00
Polycarbonate panel	Machine Shop	1	5.00
Total			**249.13**

Table 3: Bill of materials for one experimental setup.

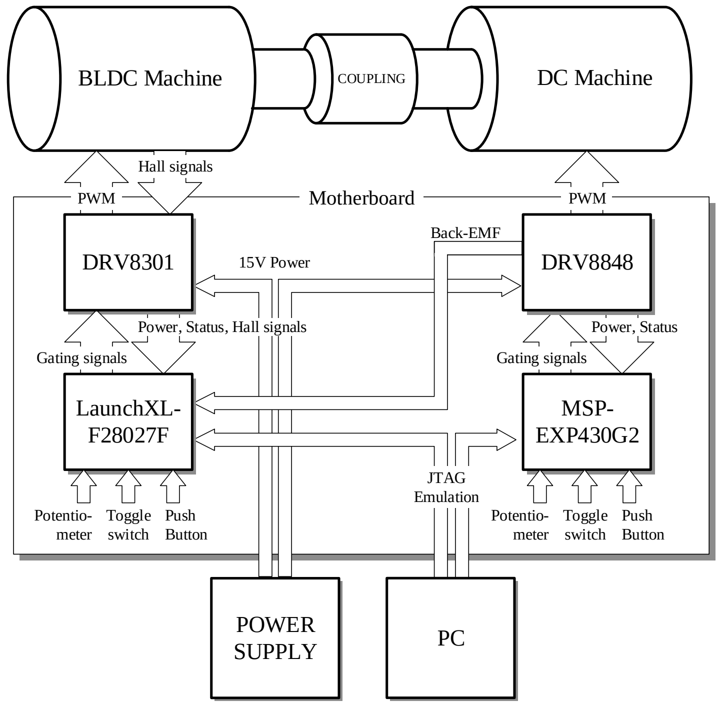

Figure 2: Functional diagram of the experimental hardware setup.

Experiments

The proposed electric drives laboratory comprises total eleven sessions including six and five allotted for DC and BLDC machine, respectively. Each experiment session would require students to build and debug the example C code that is provided at the beginning of the session. Troubleshooting would be done if necessary. At the end of chapter after the example sessions, development tasks are given expecting the students to analyze the problem and come up with a solution using the components from the examples. Students are asked to submit a report with the analysis of the example codes and the code and measurements for the development tasks at the end of the each chapter. An overview of the sessions can be seen in Fig. 3.

1. Initialization and Background Loop

As an introductory session, a ”Hello World” kind of code is provided as the first example to get students started with the microcontroller firmware programming; it toggles an LED on the board from the background loop in every 1,000 and 200,000 loops for MSP430 and C2000 microcontroller, respectively. In this session, students learn basic system initialization and how to configure a general purpose I/O (GPIO) as an digital output for both of the controllers.

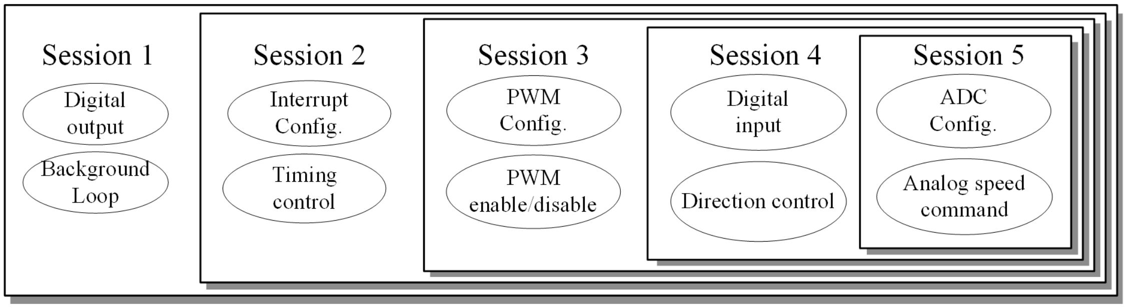

Figure 3: Session topics.

2. Hardware Interrupts and Interrupt Service Routines

The main objective of this experiment is to introduce peripheral hardware interrupts and interrupt service routines (ISR), which are critical components for embedded system programming. The ISR is a software module that is executed when the hardware requests an interrupt. The datasheets and user guides of all of the hardware components will be provided for further details. For the base of the firmware, a timer interrupt is introduced and another GPIO pin is set as a digital output to toggle an LED at a pre-defined frequency.

In this session, a timer interrupt is triggered with 1kHz frequency and the LED is toggled every 500ms in the timer ISR for both microcontrollers. Students learn timer configuration such as count mode and period, as well as interrupt enabling, nesting, and mapping the ISR to the interrupt vector table.

3. Pulse-Width Modulation

The pulse-width modulation (PWM) plays a critical role in power converters to control machines with arbitrary voltage. The two switches in each leg of the single- and three-phase full-bridge circuit in DRV8848 and DRV8301 are driven by the Capture/Compare unit in the associated microcontroller. Although gate driver circuits typically generate two complimentary gating signals for a switching power pole, one of the switches in each pole is kept constantly on at all times and hence only one PWM signal is required for both machines.

For the BLDC machine, the rotor position is provided by the hall sensor embedded in the machine placed exactly $120°$ apart from each other and each sensor generates logic high output (open collector) every time when the rotor of the machine crosses it. The three hall sensor signals are setup with GPIO digital inputs and read in 1ms timer ISR to determine the position of the rotor.

In these sessions, students can gain experience on PWM setup including carrier wave using timer, switching frequency, and compare output modes.

Figure 4: DC machine: bidirectional rotation. (a) Forward, (b) Reverse.

4. Motor Control

This experiment explains how one can change the direction of rotation of the DC and BLDC machine using an external pushbutton mounted on the motherboard. The objective of this experiment is to change the drive operation using the user input. For example, every time the pushbutton switch is pressed, the DRV8848 is driven between the states shown in Fig. 4. For the BLDC machine, the DRV8301 will be driven following the commutation sequence based on the hall-sensor feedback as shown in Fig. 5. It should be noted that only one switch in the switching pole is being PWM driven, while the other switch is constantly turned on as described in the PWM section.

5. Analog-to-Digital Conversion

Analog-to-Digital Conversion (ADC) is one of the most important features of electric machine drive systems as a lot of signals are in analog form. This session will introduce the built-in ADC of the microcontrollers for the purpose of generating the output voltage command to control the speed of motor using an external potentiometer mounted on the motherboard.

Both of the controller's ADCs are driven by start-of-conversion (SOC) signal. For the DC machine drive, the SOC is directly triggered at every 1ms by a software command in the timer ISR. The carrier wave counter is selected to generate the BLDC machine drive's SOC signal when the carrier wave reaches the peak value. The end-of-conversion (EOC) interrupts are enabled for both microcontrollers; they automatically jump to EOC ISR when the conversion is complete where the voltage of potentiometer is read. Considering the microcontrollers are fixed-point, the ADC readings (10-bit and 12-bit for MSP430G2553 and TMS320F28027, respectively) are directly fed to PWM compare register. It should be noted that the 12bit ADC reading may be shifted by one bit to limit the motor voltage in an appropriate range.

Conclusion and Future Work

In this paper, a design and implementation of the instructional electric drives laboratory has been presented. Inexpensive off-the-shelf TI microcontroller-based development kits and motor driver

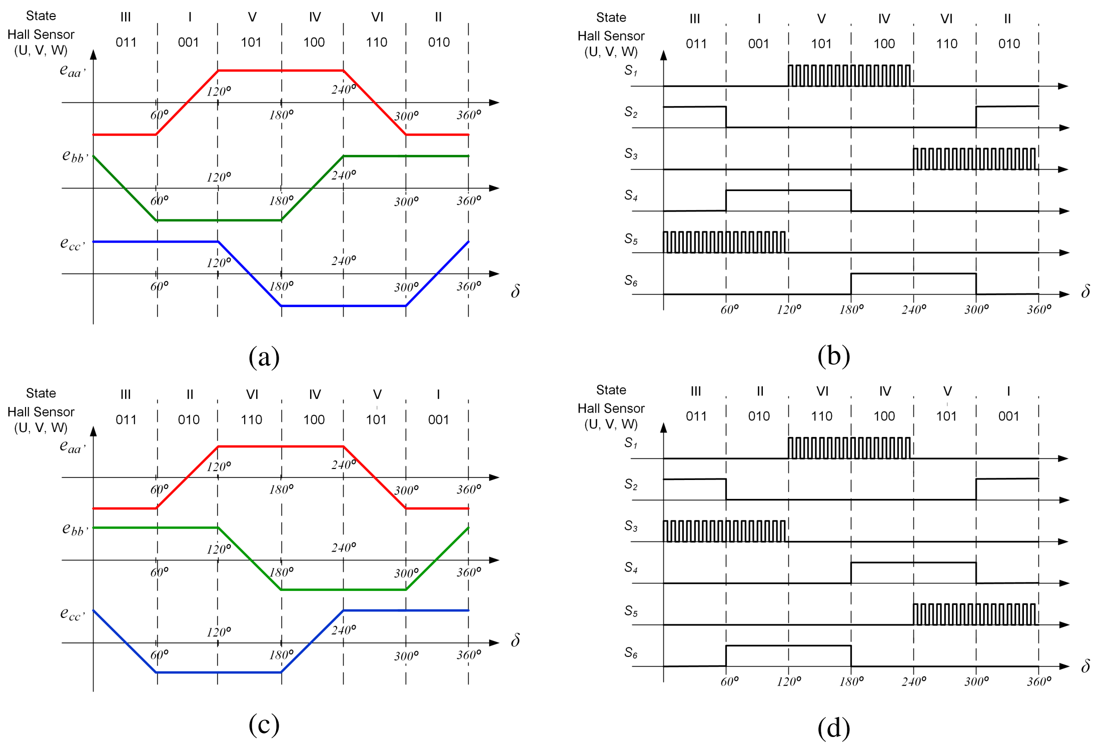

Figure 5: BLDC machine: (a) Forward: Back-EMF and hall-sensor outputs. (b) Forward: Commutation sequence. (c) Reverse: Back-EMF and hall-sensor outputs. (d) Reverse: Commutation sequence.

boards have been utilized with minimal custom addition to feature cost-effectiveness and reliability while offering complete hands-on experience on electric machine drive systems with up-to-date tools as well as embedded programming skills.

The laboratory was designed for senior students with entry level programming skill. For future work, widely used serial communication interface (SCI) and serial peripheral interface (SPI) can be considered for improved user interface and peripheral expansion, respectively, as well as the feedback speed control using motor's back-EMF.

References

[1] Avi Hofstein and Vincent N. Lunetta. The laboratory in science education: Foundations for the twenty-first century. *Science Education*, 88(1):28–54, 2004. ISSN 1098-237X. doi: 10.1002/sce.10106. URL `http://dx.doi.org/10.1002/sce.10106`.

[2] L. Zhao and F. Mak. Change the traditional way of teaching electric drives laboratory with design of experiment. In *2016 IEEE Frontiers in Education Conference (FIE)*, pages 1–6, Oct 2016. doi: 10.1109/FIE.2016.7757668.

[3] Vidmantas Macerauskas, Romualdas Masteika, and Arunas Lipnickas. Modernization of electric drives laboratory at kaunas university of technology (ktu) and new training potential. Jan 2004.

[4] Diamantino Freitas Rui Esteves Araujo, Vicente Leite. A low cost solution for laboratory experiments in induction motor control. In *Proceedings of 10th European Conference on Power Electronics and Applications*, Sep 2003.

[5] N. Mohan, W. P. Robbins, P. Imbertson, T. M. Undeland, R. C. Panaitescu, A. K. Jain, P. Jose, and T. Begalke. Restructuring of first courses in power electronics and electric drives that integrates digital control. *IEEE Transactions on Power Electronics*, 18(1):429–437, Jan 2003. ISSN 0885-8993. doi: 10.1109/TPEL.2002.807120.

[6] Anaheim Automation. Bdd-36-49 - face mount dc motors, . URL `www.anaheimautomation.com/manuals/brush/L01028720-20BDD-36-4920Series.pdf`.

[7] Anaheim Automation. Bly17 series - brushless dc motors, . URL `http://www.anaheimautomation.com/manuals/brushless/L01022820-20BLY1720Series20Product20Sheet.pdf`.

[8] Texas Instruments. *MSP-EXP430G2 LaunchPad™ Development Kit (SLAU318G)*, 2016.

[9] Texas Instruments. *LAUNCHXL-F28027 C2000 Piccolo LaunchPad Experimenter Kit (SPRUHH2A)*, 2014.

[10] Texas Instruments. *BOOST-DRV8848 Hardware User's Guide (SLVUAE1)*, 2014.

[11] Texas Instruments. *BOOSTXL-DRV8301 Hardware User's Guide (SLVU974)*, 2013.

[12] Texas Instruments. Code composer studio (CCS) integrated development environment (IDE). URL `www.ti.com/tool/CCSTUDIO`.