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CY8CKIT-037

PSoC® 4 Motor Control Evaluation Kit Guide

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Contents

Safety Information

Regulatory Compliance

The CY8CKIT-037 PSoC® 4 Motor Control Evaluation Kit is intended for use as a motor control development platform for hardware or software in a laboratory environment. The board is an open-system design, which does not include a shielded enclosure. Therefore, the board may cause interference with other electrical or electronic devices in close proximity. In a domestic environment, this product may cause radio interference. In such cases, the user may be required to take adequate preventive measures. Also, this board should not be used near any medical equipment or RF devices.

Attaching additional wiring to this product or modifying the product operation from the factory default may affect its performance and cause interference with other apparatus in the immediate vicinity. If such interference is detected, suitable mitigating measures should be taken.

The CY8CKIT-037, as shipped from the factory, has been verified to meet with the requirements of CE as a Class A product.

	The CY8CKIT-037 contains ESD-sensitive devices. Electrostatic charges readily accumulate on the human body and any equipment, and can discharge without detection. Permanent damage may occur to devices subjected to high-energy discharges. Proper ESD precautions are recommended to avoid performance degradation or loss of functionality. Store unused CY8CKIT-037 boards in the protective shipping package.
	End-of-Life/Product Recycling The end of life for this kit is five years from the date of manufacture mentioned on the back of the box. Contact your nearest recycler to discard the kit.

General Safety Instructions

ESD Protection

ESD can damage boards and associated components. Cypress recommends that the user perform procedures only at an ESD workstation. If an ESD workstation is not available, use appropriate ESD protection by wearing an antistatic wrist strap attached to the chassis ground (any unpainted metal surface) on the board when handling parts.

Handling Boards

CY8CKIT-037 boards are sensitive to ESD. Hold the board only by its edges. After removing the board from its box, place it on a grounded, static-free surface. Use a conductive foam pad if available. Do not slide the board over any surface.

1. Introduction

Thanks for your interest in the CY8CKIT-037 PSoC$^®$ 4 Motor Control Evaluation Kit (EVK). This kit enables engineers to evaluate Cypress's PSoC family of devices for motor control applications. Based on this kit, customers can create control solutions for three dominant motor types: permanent magnet synchronous motor (PMSM), stepper, and brushless DC (BLDC).

The Cypress PSoC family of devices integrates abundant internal resources for motor control applications, such as Timer Counter Pulse Width Modulator (TCPWM), SAR-ADC, comparators, opamps, and universal digital blocks (UDBs). In addition, an ARM$^®$ Cortex™ core enables high-performance motor control solutions on PSoC devices. Headers provided on the EVK board allow you to connect it to the CY8CKIT-042 PSoC 4 Pioneer Kit board to create a complete motor control system.

This kit guide documents the circuit structure of the Motor Control EVK board and explains how to configure it to create a solution for different motor types. It provides five example projects that cover sensored and sensorless BLDC control, PMSM sensorless field-oriented control (FOC), and stepper motor microstepping control. It also introduces the Bridge Control Panel (BCP) as a debugging tool in the motor control development process.

1.1 Kit Contents

The CY8CKIT-037 PSoC 4 Motor Control EVK includes the following contents, as shown in Figure 1-1:

- CY8CKIT-037 PSoC 4 Motor Control EVK main board

- AC-DC 24 V/2.0 A power adapter

- BLY172S-24V-4000 BLDC motor with sinusoidal back electromotive force

- USB-A to mini-B cable

- Configuration Jumpers

- Fuse

- Screwdriver

- Related documents:

    □ Kit guide (this document)

    □ Quick start guide

    □ Release notes

Figure 1-1. CY8CKIT-037 PSoC 4 Motor Control EVK Contents

Visit www.cypress.com/shop for more information. Inspect the contents of the kit; if any parts are missing, contact your nearest Cypress sales office for help.

1.2 Additional Learning Resources

Visit www.cypress.com for additional learning resources in the form of datasheets, technical reference manuals, and application notes.

▪ *CY8CKIT-042 PSoC 4 Pioneer Kit _Schematic.pdf*

▪ *CY8CKIT-042 PSoC 4 Pioneer Kit_Layout.brd*

1.3 Documentation Conventions

Convention	Usage
Courier New	Displays file locations, user-entered text, and source code: C:\...cd\icc\
Italics	Displays file names and reference documentation: Read about the *sourcefile.hex* file in the *PSoC Designer User Guide*.
[**Bracketed, Bold**]	Displays keyboard commands in procedures: [**Enter**] or [**Ctrl**] [**C**]
File > Open	Represents menu paths: File > Open > New Project
Bold	Displays commands, menu paths, and icon names in procedures: Click the **File** icon and then click **Open**.
Times New Roman	Displays an equation: 2 + 2 = 4
Text in gray boxes	Describes cautions or unique functionality of the product.

2. Kit Installation

This section describes the installation of the CY8CKIT-037 PSoC® 4 Motor Control EVK software and prerequisites.

2.1 Prerequisite Software

You must install the PSoC Creator™ Integrated Design Environment (IDE) and USB-Serial Configuration Utility software before the kit can be used. All Cypress software installations require administrator privileges. Administrator privileges are not required to execute the software after installation. Close all other Cypress software that is currently running before you install the kit software.

2.2 Install Kit Software

Follow these steps to install the CY8CKIT-037 PSoC 4 Motor Control EVK software:

1. Download the CY8CKIT-037 software from the Cypress web page: www.cypress.com/CY8CKIT-037. The CY8CKIT-037 software is available in three different formats for download (see Figure 2-1):

Figure 2-1. Available Formats for Downloading EVK Software
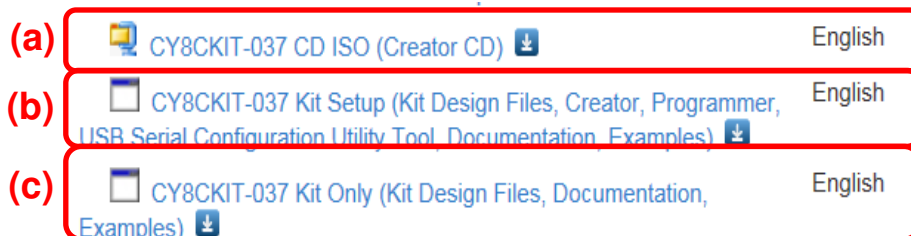
- **CY8CKIT-037 CD ISO**: This file is a complete package, stored in a CD-ROM image format, that you can use to create a CD or extract using ISO extraction programs, such as WinZip or WinRAR. The file can also be mounted like a virtual CD using virtual drive programs such as Virtual CloneDrive and MagicISO. This file includes all the required software, utilities, drivers, hardware files, and user documents.

- **CY8CKIT-037 Kit Setup**: This installation package contains all files related to the kit. However, it does not include the Windows Installer or Microsoft .NET framework packages, Internet Explorer, and Adobe Reader. If these packages are not on your computer, the installer directs you to download and install them from the Internet.

- **CY8CKIT-037 Kit Only**: This executable file installs only the kit contents, which include kit code examples, hardware files, and user documents. Use this package if the required software listed in step 4 is installed on your PC.

2. If you have downloaded the CD ISO file, mount it on a virtual drive. Extract the ISO contents if you do not have a virtual drive on which to mount. Double-click *cyautorun.exe* in the root directory of the extracted content or mounted ISO if "Autorun from CD/DVD" is not enabled on the PC. The installation window shown in Figure 2-2 will appear automatically.

    Note: If you are using the Kit Setup or Kit Only file, then go to step 3 for installation.

3. Click **Install CY8CKIT-037 EVK** to start the kit installation, as shown in Figure 2-2.

Figure 2-2. Kit Installer Startup Screen

4. Select the folder in which you want to install the CY8CKIT-037 kit-related files. Choose the directory and click **Next**.

    When you click **Next** button, the CY8CKIT-037 ISO installer automatically installs the required software, if it is not present on your computer. Following is the required software:

    ▪ PSoC Creator 3.2 or later version: Download the latest version from www.cypress.com/psoccreator.

    ▪ PSoC Programmer 3.23 or later version: Download the latest version from www.cypress.com/programmer.

5. Select the **Typical installation** type in the **Product Installation Overview** window, as shown in Figure 2-3. Click **Next**.

Figure 2-3. Product Installation Overview Window
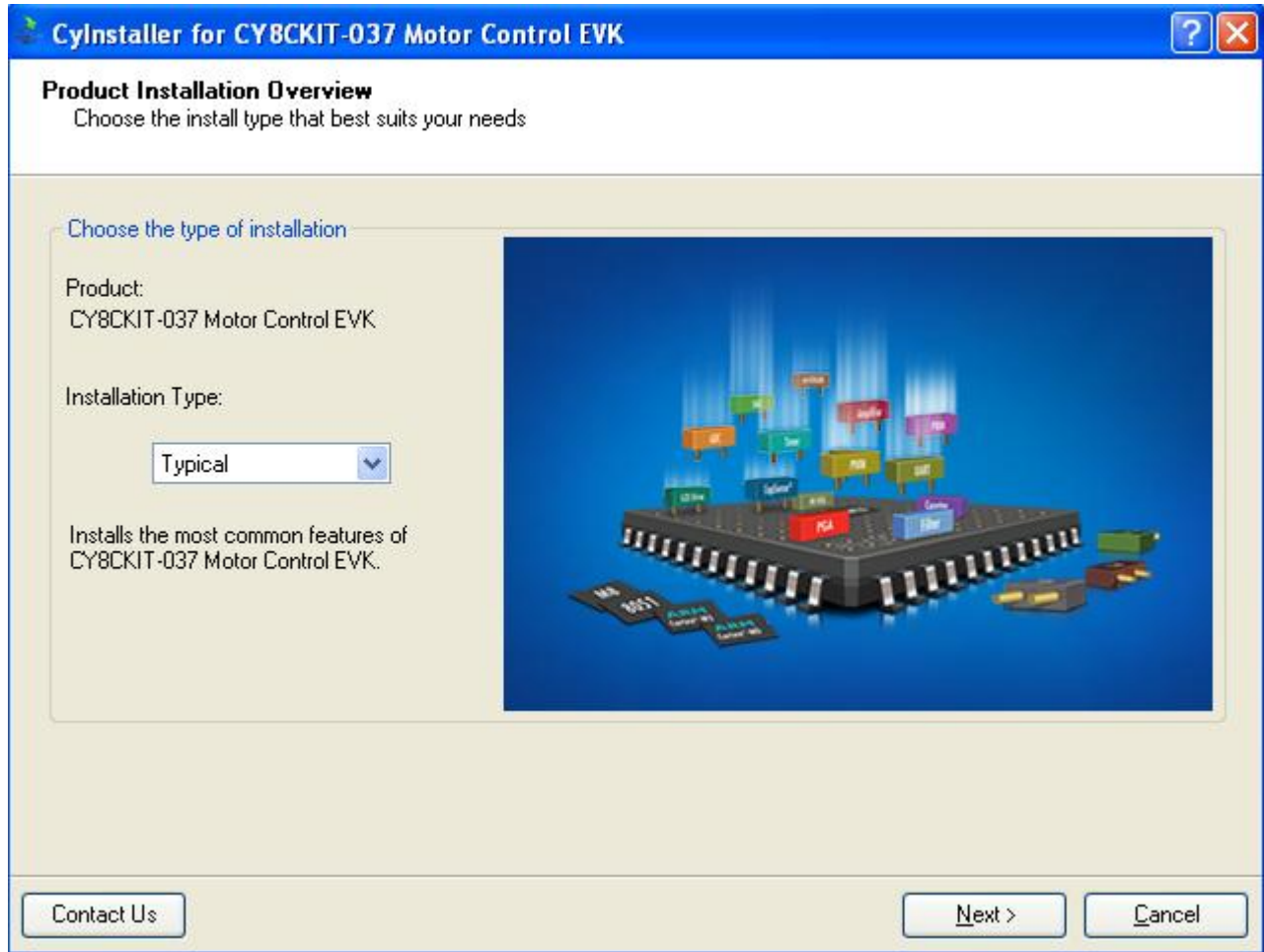
When the installation begins, a list of packages appears on the installation page. A green check mark appears next to each package after successful installation.

6. Enter your contact information or select the option **Continue without Contact Information**. Click **Finish** to complete the CY8CKIT-037 kit installation.

After the installation is complete, the kit contents are available at `<Install_Directory>\CY8CKIT-037 Motor Control EVK\1.0`. The default locations are as follows:

- Windows 7 (64-bit): `C:\Program Files (x86)\Cypress\CY8CKIT-037 Motor Control EVK\1.0`

- Windows 7 (32-bit): `C:\Program Files\Cypress\CY8CKIT-037 Motor Control EVK\1.0`

Note: For Windows 7/8/8.1 users, the installed files and the folder are read-only. To change the property, right-click the folder and choose **Properties** > **Attributes** and then disable the **Read-only** option. Click **Apply** and **OK** to close the window.

After the installation is complete, the following are installed on your computer:

- PSoC Creator 3.2 or later version

- PSoC Programmer 3.23 or later version

- USB-Serial Configuration Utility

- Kit documents

    - Quick start guide

    - Kit guide

    - Release notes

- Firmware

    - Sensored BLDC Motor Control example project

    - Sensorless BLDC Motor Control example project

    - Sensorless Foc Motor Control example project

    - SingleShunt Foc Motor Control example project

    - Stepper Motor Control example project

- Hardware

    - Schematic

    - Layout

    - Gerber

    - PCB assembly drawing

    - Bill of materials (BOM)

2.3 Uninstall Software

The software can be uninstalled using one of the following methods:

- Go to **Start** > **Control Panel** > **Programs and Features**; select the appropriate software package and click **Uninstall**.

- Go to **Start** > **All Programs** > **Cypress** > **Cypress Update Manager** > **Cypress Update Manager**; click **Uninstall** for the appropriate software package.

- Select the "CY8CKIT-037 Motor Control EVK 1.0 Rev **" row and click **Uninstall**. In the **Product Installation Overview** window, select **Remove** from the **Installation Type** drop-down menu. Follow the instructions to uninstall.

    Note: This method will uninstall only the kit software and not all the other software that may have been installed along with the kit software.
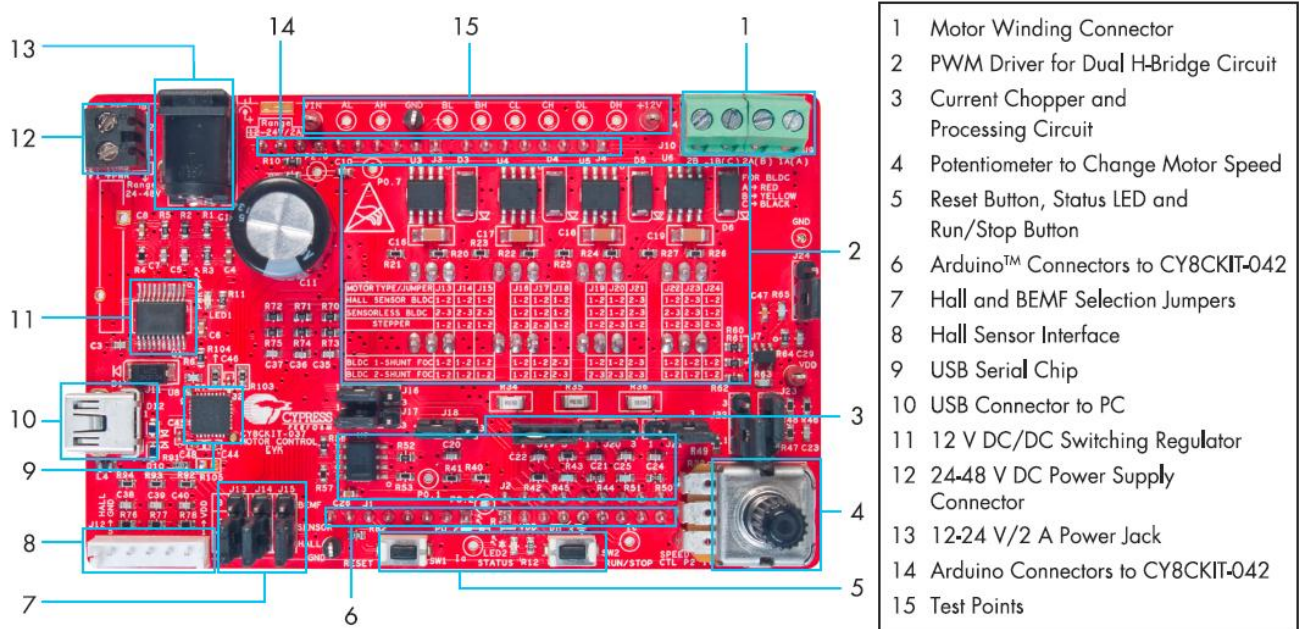
3. Kit Overview

3.1 CY8CKIT-037 Evaluation Kit Overview

The motor control system can be separated into two parts: the driver board and the controller board. The CY8CKIT-037 Motor Control EVK is the driver board, which contains the DC/DC power circuit, dual H-bridge circuit, motor current and bus voltage sampling and processing circuit, protection circuit, user configuration circuit, and connectors to the controller board. The controller board receives the signals, implements the proper algorithm to process them, and then generates control signals to the driver board to run the motor. Figure 3-1 shows the EVK board and its general description. CY8CKIT-037 EVK is the driver board; the CY8CKIT-042 kit works as controller board. They are interfaced with Arduino-compatible connectors.

Figure 3-1. General Description of EVK Board

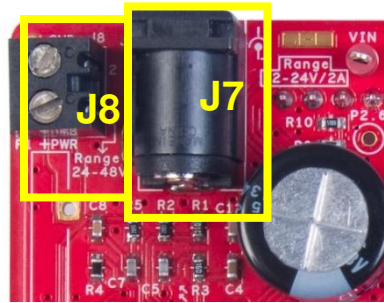| 1	Motor Winding Connector
2	PWM Driver for Dual H-Bridge Circuit
3	Current Chopper and Processing Circuit
4	Potentiometer to Change Motor Speed
5	Reset Button, Status LED and Run/Stop Button
6	Arduino™ Connectors to CY8CKIT-042
7	Hall and BEMF Selection Jumpers
8	Hall Sensor Interface
9	USB Serial Chip
10	USB Connector to PC
11	12 V DC/DC Switching Regulator
12	24-48 V DC Power Supply Connector
13	12-24 V/2 A Power Jack
14	Arduino Connectors to CY8CKIT-042
15	Test Points

3.2 Kit Operation and Configuration Guide

3.2.1 DC Power Supply Connector

There are two connectors for DC power input, J7 and J8, as Figure 3-2 shows. J7 is the standard power jack for DC adapters, with 12-V or 24-V DC output. J8 enables the kit to get input power from a general variable DC power supply with 24- to 48-V DC output voltage. The input current of both connectors can be up to 2 A. For schematic details, see Input Protection Circuit. CY8CKIT-042 gets 12 V from the DC/DC converter on CY8CKIT-037. The LDO on CY8CKIT-042 generates the 3.3-V supply for PSoC if the VDD on CY8CKIT-042 is configured as 3.3 V. If the VDD on CY8CKIT-042 is configured as 5 V, CY8CKIT-042 needs 5 V from the USB cable.

CAUTION	Do not connect power to both J7 and J8 simultaneously. Also, when using J7, connect the power cable to it before loading the AC supply at the AC/DC adapter to avoid a potential spark.

Figure 3-2. Connectors for DC Power Input

3.2.2 Motor Winding Connectors

J9 and J10 provide four pins for motor windings, as shown in Figure 3-3. The BLDC and PMSM motors use three pins, while the stepper motor application needs all four pins. Connection details are as follows:

For BLDC and PMSM:

- Pin 1–1A (A) → Motor winding A – Red

- Pin 2–2A (B) → Motor winding B –Yellow

- Pin 3–1B (C) → Motor winding C – Black

For the stepper motor:

- Pin 1–1A (A) → Motor winding 1 terminal A – Blue

- Pin 2–2A (B) → Motor winding 1 terminal B – Yellow

- Pin 3–1B (C) → Motor winding 2 terminal A – Red

- Pin 4–2B → Motor winding 2 terminal B – Green

For schematic details, see Connectors.

Figure 3-3. Connectors to Motor Windings
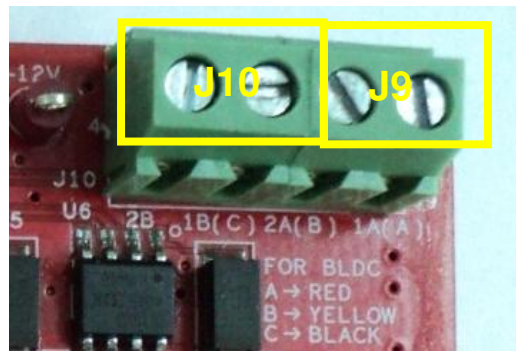
3.2.3 Hall Sensors Connector

J12 is the Hall sensors connector for the Sensored BLDC Motor Control example project, as Figure 3-4 shows. It is a five-pin connector. The details of each pin are as follows.

- 1 – VDD → Hall sensor board VDD – Red

- 2 – HALL A → Hall sensor A output – Blue

- 3 – HALL B → Hall sensor B output – Green

- 4 – HALL C → Hall sensor C output – White

- 5 – GND → Hall sensor board ground – Black

For schematic details, refer to Hall Sensors and BEMF Sensing Circuit.

Figure 3-4. Hall Sensors Connector
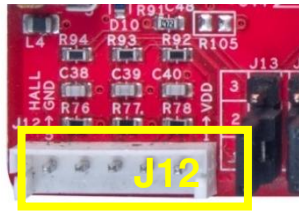
3.2.4 Connectors to CY8CKIT-042 Board

Figure 3-5 shows the Arduino-compatible connectors to the CY8CKIT-042 board: J1, J2, J3, and J4. You can plug the EVK board into the CY8CKIT-042 board through these connectors. For schematic details, refer to Connectors.

Note: Pin connectors J1, J2, J3, and J4 may become bent inadvertently when plugging the EVK board into CY8CKIT-042.

Figure 3-5. Connectors to CY8CKIT-042 Board
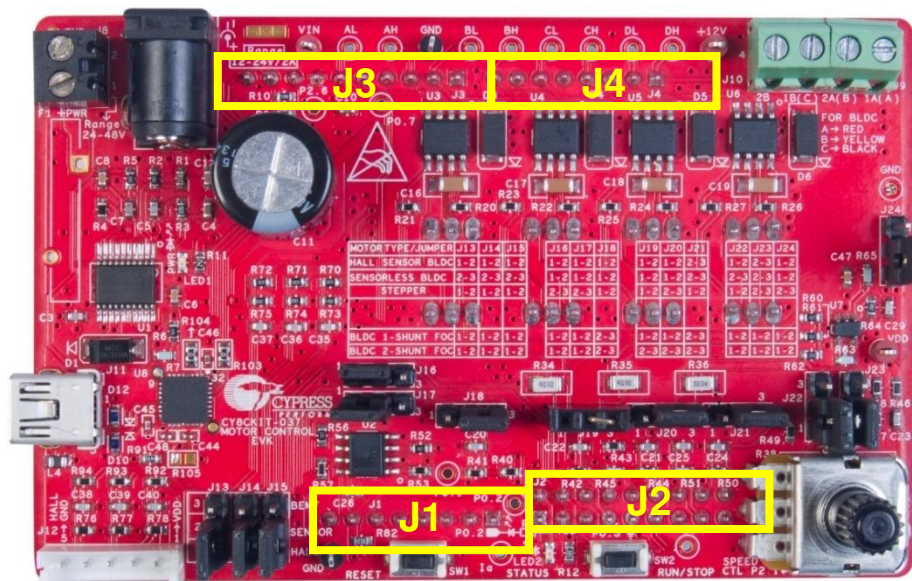
3.2.5 USB Connector

To monitor the real-time parameters while the motor is running, you can use the BCP (refer to Bridge Control Panel Monitor Tool Guide) to get data through the USB-to-UART bridge circuit on the EVK board during the debugging process. The USB-to-UART bridge circuit on the EVK board and PC can be connected by USB cable through the J11 connector, as Figure 3-6 shows. For schematic details of the USB-to-UART bridge circuit part, refer to USB-to-UART Bridge Controller Circuit.

Figure 3-6. USB-to-UART Bridge Controller Circuit
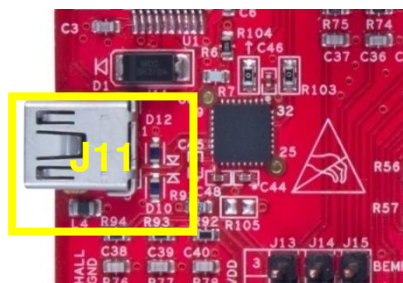
4. Kit Hardware Schematic Details

4.1 Block Diagram Overview

Figure 4-1 illustrates the CY8CKIT-037 hardware block diagram. The major features are as follows:

- Input protection circuit

- DC/DC switching regulator

- MOSFET dual H-bridge and dual H-bridge PWM drivers

- Phase current detecting and processing circuit

- Hall and back electromagnetic force (BEMF) sensing circuit

- USB-to-UART bridge controller circuit

- Connectors

- Test points and LEDs

Figure 4-1. CY8CKIT-037 Hardware Block Diagram
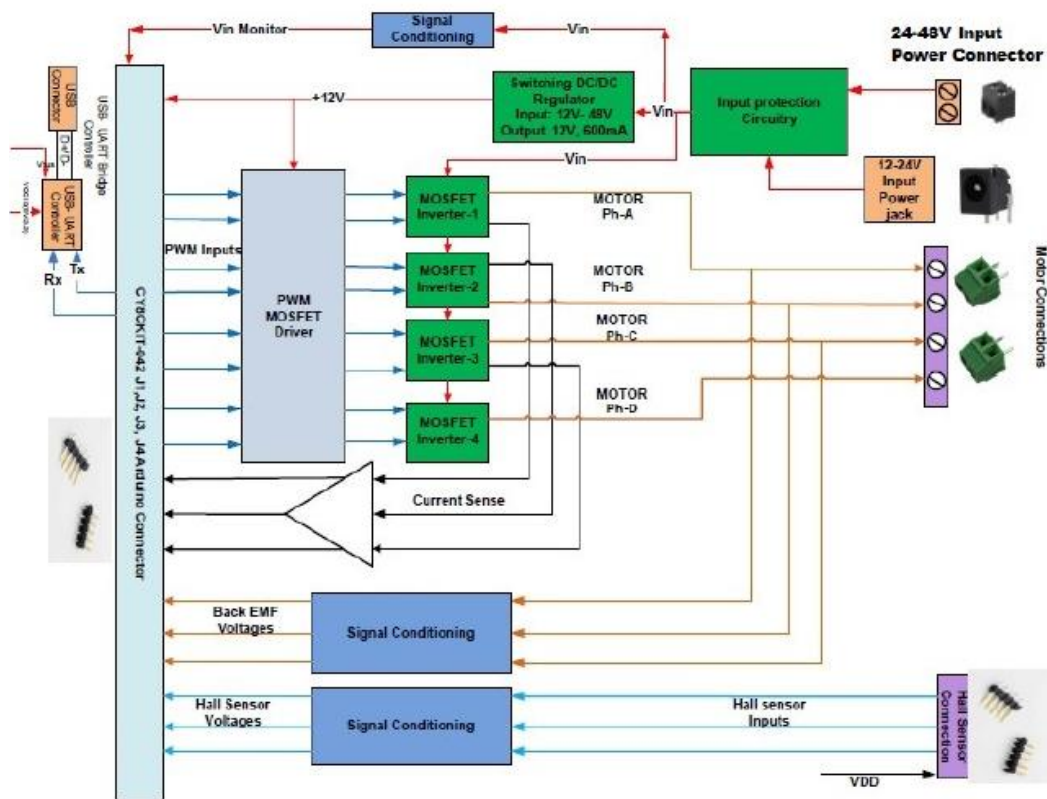
4.2 Input Protection Circuit

Figure 4-2 shows the input protection circuit that consists of three parts: overcurrent protection by fuse F1 or F2, power supply reverse protection by Schottky diode D2, and input voltage inrush protection by varistor VR1. Notice that there are two parallel fuses: F1 is a PTC resettable fuse, and F2 is the common thermal fuse. F2 is populated onboard by default. You can also use PTC fuse F1 to replace F2 according to your requirements.

Figure 4-2. Input Protection Circuit
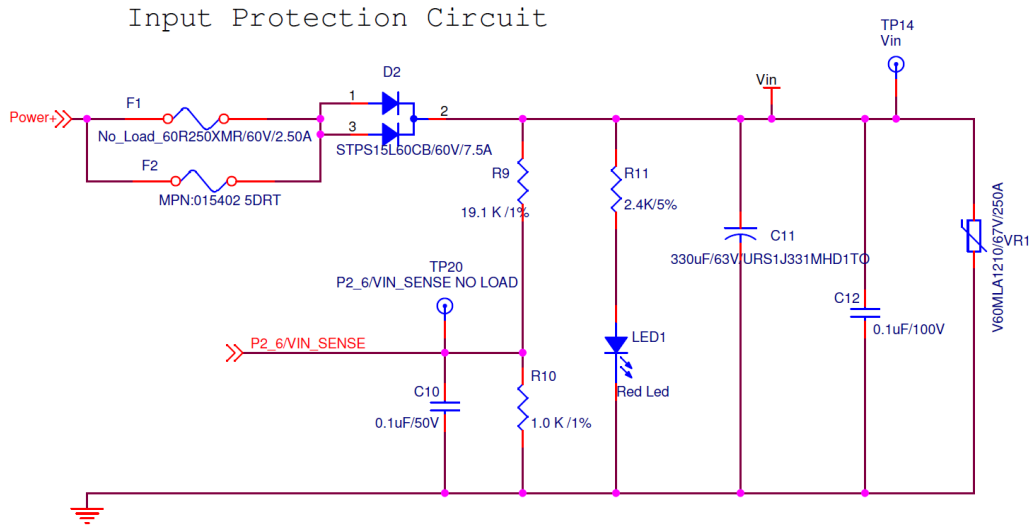
CAUTION	Do not populate both F1 and F2 on the board. Otherwise, when an overcurrent condition occurs. F1 and F2 cannot cut off the circuit, which will lead to component damage on the board.

4.3 DC/DC Switching Regulator

Figure 4-3 shows the DC/DC switching regulator circuit on the EVK board. It converts the voltage V_{in} (output of the input protection circuit, 0.5 V to 1 V lower than the input voltage) to +12 V. This switching converter is a buck regulator using LM5005. LM5005 has an internal 75-V N-channel buck switch with an output current capability of 2.5 A. It is designed to take an input in the range of 7–75 V and provides 12-V output with 1.5-A current capability when the input voltage is higher than 13 V.

Figure 4-3. Switching DC/DC Converter
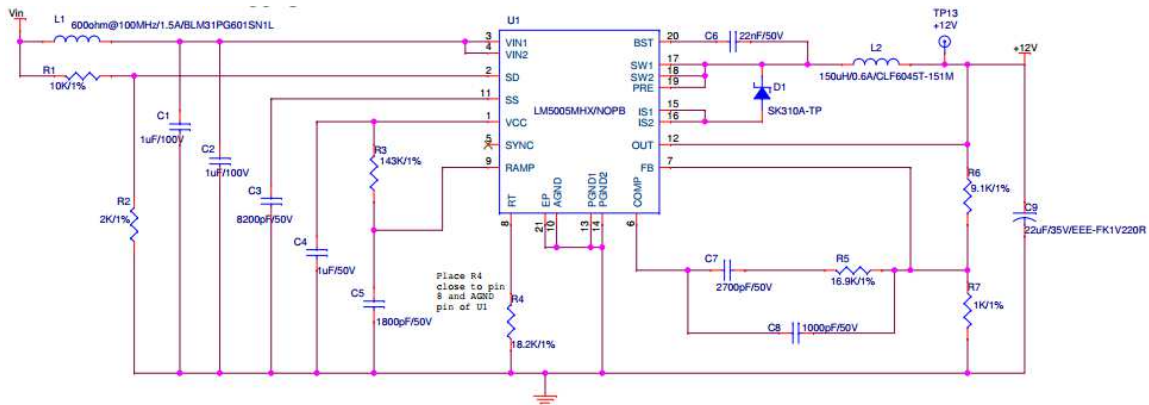
When the voltage at the SD pin of LM5005 is less than 1.225 V, the IC will go into an inactive state. The external R1 and R2 divider with 10 kΩ and 2 kΩ will give exactly 1.225 at 7.35-V input. If the input goes below 7.35 V, LM5005 will be in an inactive state.

The +12V output of the regulator provides power to the dual H-bridge driver chips and the PSoC 4 Pioneer Kit. The other circuits and chips on the EVK board also need a power supply in the range of 2.7 V to 5.5 V, which is VDD. But the EVK board does not contain this converter. It gets this power from the controller board through Arduino headers.

4.4 MOSFET Dual H-Bridge and Dual H-Bridge PWM Drivers

This part contains four half-bridge circuits and four driver circuits. For BLDC and PMSM control, you can use three half-bridge circuits to form a standard three-phase inverter. For the stepper motor, you can control two windings of the stepper motor separately via the dual H-bridge.

Figure 4-4 shows the driver circuit, containing four ASIC driver chips (IR2101) and relative peripheral components. IR2101 can source 100-mA or sink 210-mA current for MOSFETs. Each chip can drive two MOSFETs of a half-bridge, and its high-side PWM operates with a floating supply by a peripheral bootstrap circuit.

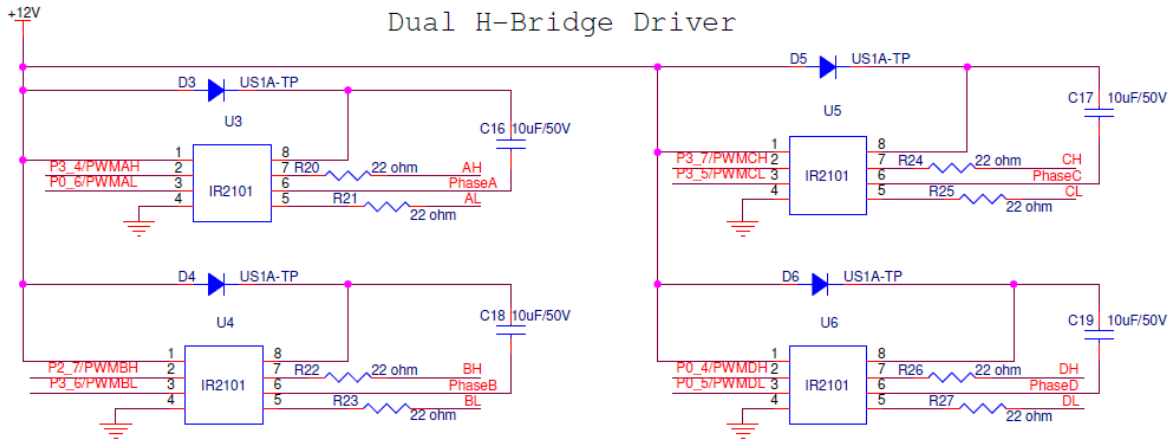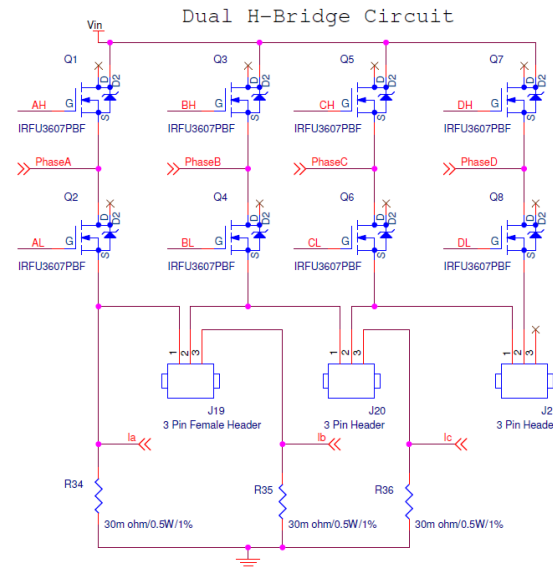Figure 4-4. Dual H-Bridge Driver Circuit

Figure 4-5 shows the MOSFET dual H-bridge. There are four half bridges in total, each one serving a motor phase or winding. Considering the compatibility for different motor control types, the population of components J19, J20, and J21 needs to be adjusted to fit different motor type applications.

Figure 4-5. MOSFET Dual H-Bridge

4.5 Phase Current Detecting and Processing Circuit

As Figure 4-5 shows, three sensing resistors, R34, R35 and R36, are inserted into three half-bridges. When the motor is running, the winding current floats through these resistors. So, detecting the voltage on the sensing resistors can get the phase current of the motor windings. Because of the sensing resistors' low value and the noise of the running motor, you need to amplify and filter the voltage signal. Figure 4-6 shows the current detecting and processing circuit for winding A and winding C.

The core of this part is the amplifier. You use PSoC internal opamps on the controller board. J18 and J23 are used only for PMSM FOC control because in the FOC application, the winding current can be both positive and negative. J18 and J23 add 1/2 VDD bias voltage to the sensing signal to make it always positive.

J22 is used only for the sensorless BLDC application, because the sensorless BLDC firmware uses an inside low-power comparator (LPComp). P1_1 is dedicated to its negative terminal, which needs to be connected to the Vin divider circuit (P2_6/Vin). R49 will change the divider proportion. You need to short pin 2 and pin 3 of J22 to remove R49 from the circuit in the Sensorless BLDC Motor Control example project.

Figure 4-6. Current Detecting and Processing Circuit

(Winding A)   (Winding C)
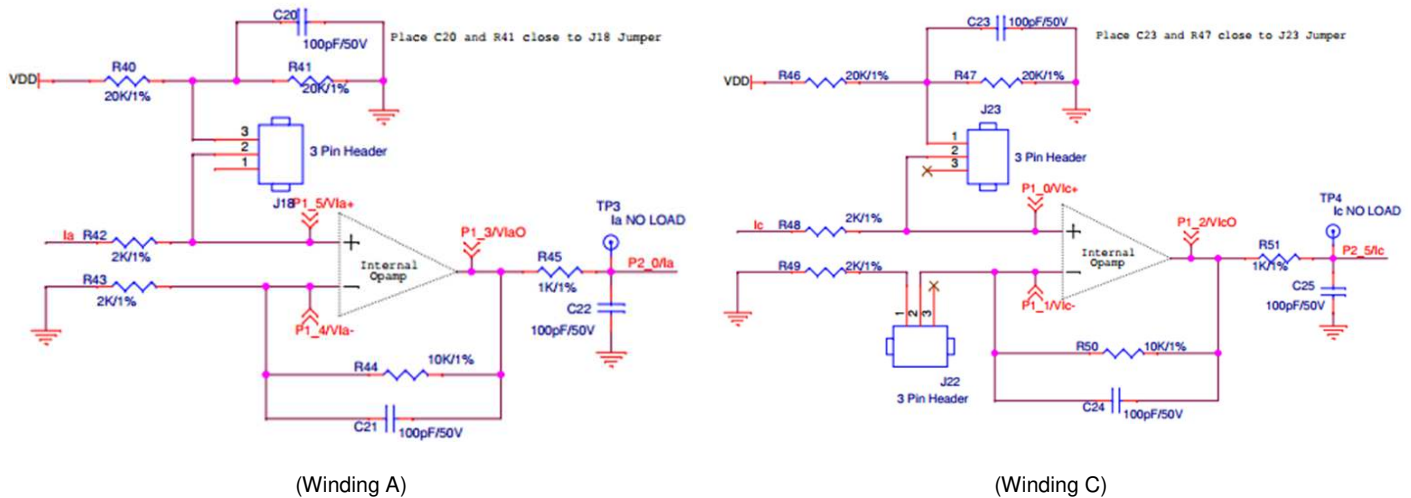
Figure 4-7 shows the external two-phase winding current comparing circuit, which is used only in the stepper motor application. The positive terminal input is the current sensing signal after amplifying and filtering, and the negative terminal input is the current reference set by the internal IDAC. The comparator output is routed to the PWM kill terminal to shut down the PWM output, forcing the winding current to follow the IDAC current reference.

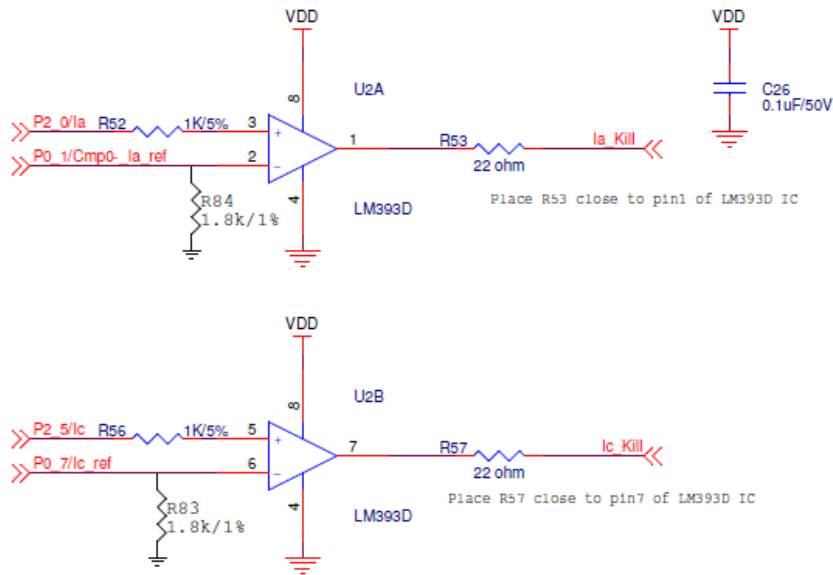Figure 4-7. Two-Phase Winding Current Comparing Circuit

Figure 4-8 shows the overcurrent protection circuit. R60, R61, and R62 add the three-phase winding current, and the external opamp U7 amplifies and filters the sum of the currents. Its output is routed to the positive terminal of the internal LPComp to be compared with the overcurrent threshold set by the IDAC.

Figure 4-8. Overcurrent Protection Circuit
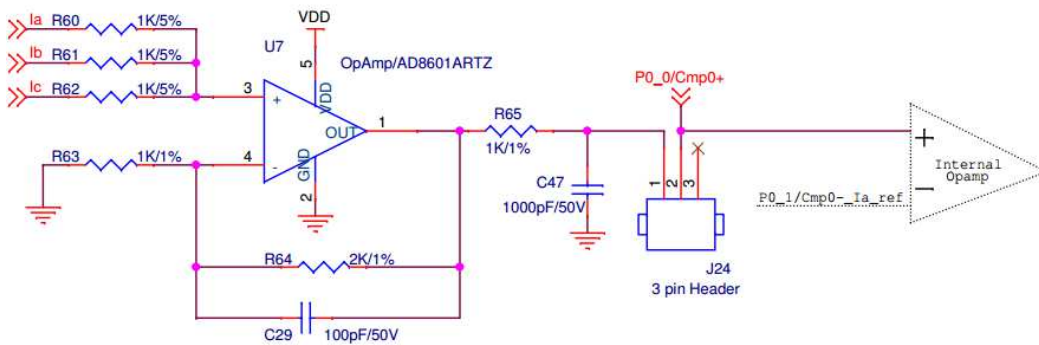
4.6 Hall Sensors and BEMF Sensing Circuit

Both sensored and sensorless BLDC motor can be rotated with the EVK board. The sensored BLDC gets its rotor position from the Hall sensors, and the sensorless BLDC gets its rotor position by detecting the BEMF signal from the stator winding. Figure 4-9 shows the Hall sensor interface. The Hall sensor output is in an open-collector structure, so the interface adds pull-up resistors to make the PSoC device receive the correct Hall sensor signal.

Figure 4-9. Hall Sensor Interface
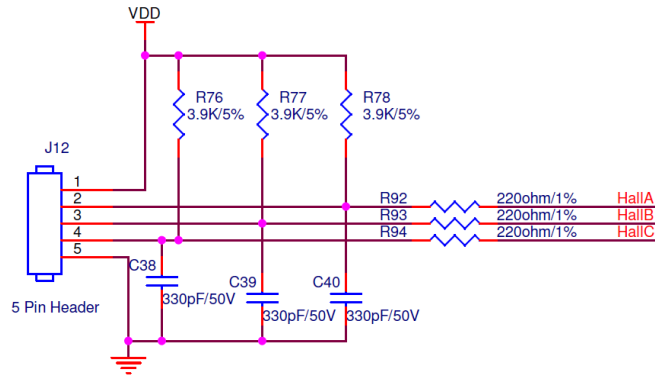
Figure 4-10 shows the voltage divider and filter circuit for BEMF detecting. Three phases of the Hall sensor and BEMF signals are routed to jumpers J13, J14, and J15, as shown in Figure 4-11. Users can select sensored or sensorless configuration via the three jumpers.

Figure 4-10. Sensorless BLDC BEMF Detecting Circuit
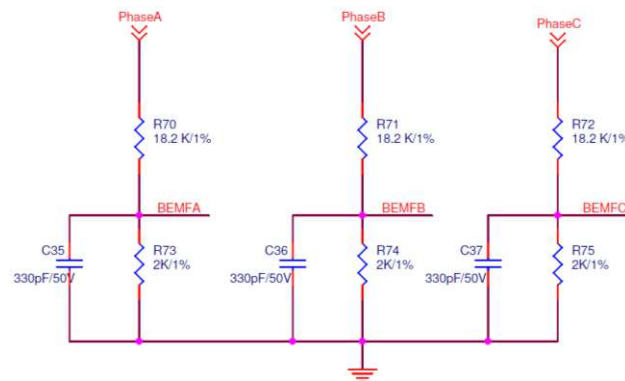
Figure 4-11 shows that the two Hall sensor and BEMF signals, as well as the two external comparator output kill signals of the stepper motor, are routed to J16 and J17. Since the GPIO pin numbers of PSoC 4 are limited, these signals need to share two GPIO pins. Be sure to configure J16 and J17 correctly for the BLDC and stepper motor applications.

Figure 4-11. Signal Configuration Jumpers
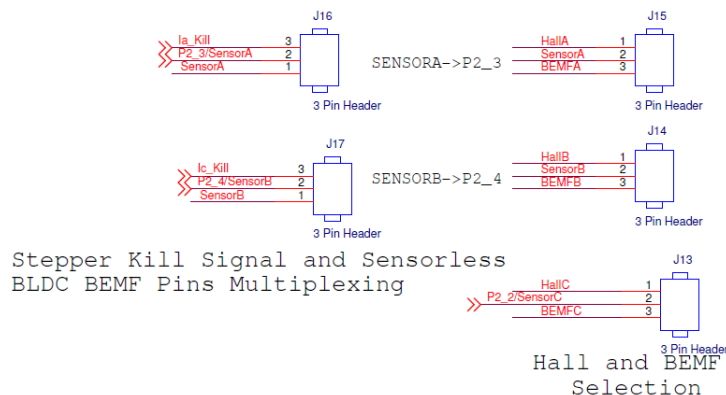
4.7 USB-to-UART Bridge Controller Circuit

Figure 4-12 shows the USB-to-UART bridge controller used for transferring data, such as speed and winding current, that you want to monitor on the BCP. The bridge controller receives the data from PSoC 4 on CY8CKIT-042 over UART and transmits it over USB to be monitored using BCP software.

Figure 4-12. USB-to-UART Bridge Controller
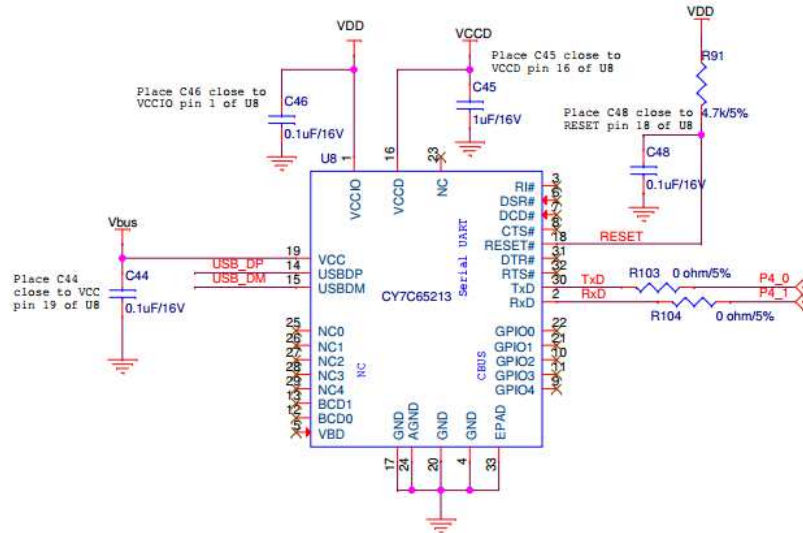
4.8 Connectors

There are several connectors on the EVK board. Figure 4-13 shows the input power connectors. J7 is the standard power jack for DC adapters, with an output from 12 V to 24 V. J8 can accept an input voltage from 24 V to 48 V through raw wire from a general variable DC power supply. The input current of both connectors can be as high as 2 A.
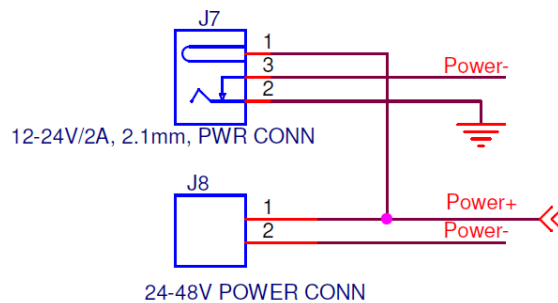
Figure 4-13. Input Power Supply Connectors

Figure 4-14 shows the motor winding connectors. The two connectors provide four pins in total. The BLDC motor contains three windings with a common neutral point inside the motor. It uses only three pins. The stepper motor contains two independent windings, so it needs all four pins.
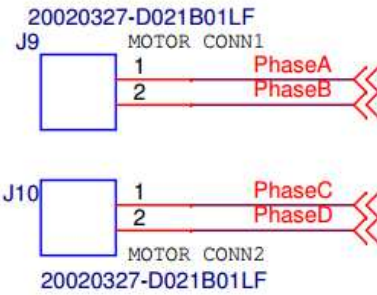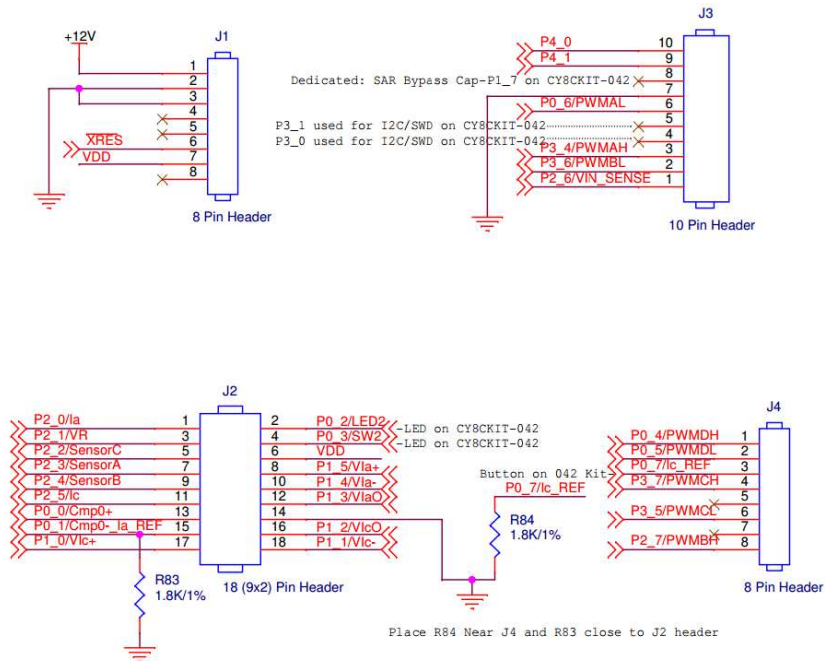
Figure 4-14. Motor Winding Connectors

Figure 4-15 shows the connectors to the CY8CKIT-042 board. The layout of J1, J2, J3, and J4 on the EVK board is designed pin-to-pin with J1, J2, J3, and J4 on the Pioneer Kit, so users can plug the EVK board directly into the Pioneer Kit.

Figure 4-15. Connectors to CY8CKIT-042

4.9 Test Points

The EVK board provides many test points of critical signals, making it convenient for users to debug in the development process. Test points cover driver PWMs, power output and ground, winding current, and IDAC reference output. You can observe and monitor these signals using probes. Figure 4-16 show some instances of test points.

Figure 4-16. Test Points
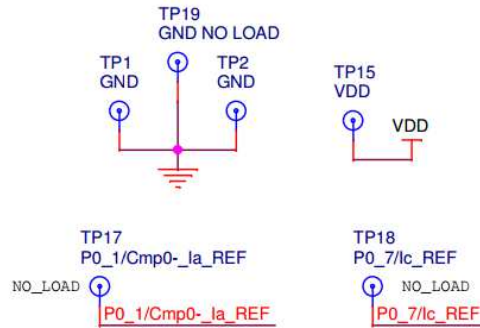
| CAUTION | **Do not power the kit through these test points to avoid damage to the board.** |

5. Example Projects

Cypress provides five example projects with the Motor Control EVK board package, which can help you accelerate the motor control development process based on PSoC 4.

5.1 Configuration Jumpers for Different Motor Types

CY8CKIT-037 supports three motor types: BLDC, PMSM, and stepper. When switching between different motor types or algorithms, the EVK board needs to be reconfigured via jumpers J13–J24. The jumper configuration table is printed on the top layer of the EVK board, as shown in Figure 5-1.

Figure 5-1. J13–J24 Configuration Table for Different Motors

MOTOR TYPE/JUMPER	J13	J14	J15	J16	J17	J18	J19	J20	J21	J22	J23	J24
HALL SENSOR BLDC	1-2	1-2	1-2	1-2	1-2	1-2	1-2	1-2	2-3	1-2	2-3	1-2
SENSORLESS BLDC	2-3	2-3	2-3	1-2	1-2	1-2	1-2	1-2	2-3	2-3	2-3	1-2
STEPPER	1-2	1-2	1-2	2-3	2-3	1-2	1-2	2-3	1-2	1-2	2-3	2-3
BLDC 1-SHUNT FOC	1-2	1-2	1-2	1-2	1-2	2-3	1-2	1-2	2-3	1-2	1-2	1-2
BLDC 2-SHUNT FOC	1-2	1-2	1-2	1-2	1-2	2-3	2-3	2-3	2-3	1-2	1-2	1-2

These jumpers are located in several different circuit parts. To learn about the principle of configuration, refer to Kit Hardware Schematic Details.

Note: When you prepare to change the configuration jumper settings for different motor types, ensure that all power sources are turned off; otherwise, the kits may be damaged.

5.2 Sensored BLDC Motor Control Example Project

5.2.1 Sensored BLDC Background

BLDC motors are widely used in industrial applications, home appliances, and vehicle systems. Such motors consist of a multi-pole permanent magnet placed on the rotor and several windings. In the BLDC motor, the commutation is controlled electronically. The motor requires the stator windings to be energized in a particular sequence. To implement this sequence, it is important to know the rotor position. The simplest way is to use rotor position sensors. The sensors can be optical, magnetic (Hall or magneto-resistance effect based), or inductive. The Hall sensor is selected in most applications for its high accuracy and low cost.

Hall sensors are embedded in the stator. When the rotor magnetic poles pass near the Hall sensors, they supply a high or low signal, indicating that the north or south poles are passing nearby. The rotor position is derived from the exact combination of the three Hall sensor signals. Three position sensors can provide six effective states (except 000 and 111) and separate a whole electrical space into six parts, each having a 60-degree electrical angle. Figure 5-2 gives a timing diagram of the sensor output and the required motor driving voltage. The optional use of a PWM provides speed or torque control as shown in phases A, B, and C. The duty cycle of the modulated output control signal (PWM) is varied to change the speed and torque of the motor.