Dual-Axis Current Control of Brushed DC Motors Application Report

ABSTRACT

This application note presents a solution to control two, brushed DC motors using TMS320F2803x microcontrollers and the DRV84x2 Dual Full Bridge PWM Motor Driver. The TMS320F2803x devices belong to the C2000 microcontroller family. The devices enable cost-effective design of intelligent motor controllers by reducing the number of system components and increasing the system efficiency. With these devices it is possible to achieve more precise digital control algorithms. The DRV84x2 devices are high-performance, integrated, dual-full-bridge motor drivers with an advanced protection system.

This application note covers the following topics:

- Incremental build levels based on modular software blocks.
- Experimental test results

1 Benefits of Using C2000 Controllers for Digital Motor Control (DMC)

Devices that belong to the C2000 family posses the computation power to execute complex control algorithms, along with the right mix of peripherals to interface with the various components of the DMC hardware (like ADC, ePWM, QEP, eCAP and others). These peripherals have all the hooks needed to implement systems that meet safety requirements, like the trip zones for PWMs and comparators.

Along with these hooks, the C2000 ecosystem of software (libraries and application software) and hardware (application kits) help reduce the time and effort needed to develop a solution for digital motor control. The DMC Library provides configurable blocks that can be reused to implement new control strategies. The IQMath Library enables easy migration from floating-point algorithms to fixed-point algorithms, which accelerates the development cycle. Using devices from the C2000 family, developers can quickly and easily implement complex control algorithms for motor control.

Using the C2000 devices and the advanced control schemes provides the following system improvements:

- System cost reduction by using an efficient control in all speed ranges, and by applying the right dimensioning of power to device circuits.
- Decreases the number of look-up tables, which reduces the amount of required memory
- Improved performance by using real-time generation of smooth, near-optimal, reference profiles and move trajectories
- Allows generation of high-resolution PWMs by using the ePWM peripheral for controlling the power-switching inverters
- Provides a single-chip control system

For advanced controls, C2000 microcontrollers can also perform the following:

- Control multi-variable and complex systems by using modern intelligent methods, such as neural networks and fuzzy logic
- Perform adaptive control. C2000 controllers have the speed capabilities to concurrently monitor and control the system. A dynamic control algorithm adapts itself in real-time to variations in system behavior.
- Provide diagnostic monitoring with spectrum analysis. By observing the frequency spectrum of mechanical vibrations, failure modes can be predicted in early stages.
- Produce sharp-cut-off notch filters that eliminate narrow-band mechanical resonance. Notch filters remove energy that would otherwise excite resonant modes and could make the system unstable.

2   Texas Instruments Documentation and DMC Library

The Digital Motor Control (DMC) library is composed of functions, represented as blocks. These blocks are categorized as one of three categories: Transforms & Estimators (Clarke, Park, Sliding Mode Observer, Phase Voltage Calculation, Resolver, Flux, and Speed Calculators and Estimators), Control (Signal Generation, PID, BEMF Commutation, Space Vector Generation), and Peripheral Drivers (PWM abstraction for multiple topologies and techniques, ADC drivers, and motor sensor interfaces).

Each block is a modular software macro that is separately documented with source code, use, and technical theory. Check the folder directories below for the source codes and explanations of the macro blocks:

- C:\TI\controlSUITE\libs\app_libs\motor_control\math_blocks\fixed
- C:\TI\controlSUITE\libs\app_libs\motor_control\drivers\f2803x

The library supports the five motor types: AC induction (ACI), Brushless DC (BLDC), Permanent Magnet Synchronous (PMSM), Brushed DC, and Stepper Motor and comprises both peripheral-dependent (software drivers) and target-dependent modules. The DMC Library components have been used by Texas Instruments (TI) to provide system examples.

At initialization, all DMC Library variables are defined and interconnected, and the macro functions are called in order at run time. Each system is built using an incremental build approach, which allows a few sections of the code to be built at a time. By using incremental builds, the developer can verify each section of their application one step at a time. This verification is critical in real-time control applications, where many different variables can affect the system and many different motor parameters need to be tuned.

Note: TI DMC modules are written in the form of macros for optimization purposes (refer to SPRAAK2 for more details). The macros are defined in the header files, and the macro definitions can be changed in the respective header file, if needed.

In the macro definitions, there should be a backslash (\) at the end of each line, as shown in the code snippet below, to show that the code continues on the next line. Ensure the backslash is the last character in the line. Any character after the backslash, including "invisible" characters like a space, causes a compilation error. In terms of code development, the macros are almost identical to C functions, and the user can easily convert the macro definition to a C function.

The following code example is a typical DMC macro definition

```
#define PARK_MACRO(v)                                         \
                                                              \
v.Ds = _IQmpy(v.Alpha,v.Cosine) + _IQmpy(v.Beta,v.Sine);     \
v.Qs = _IQmpy(v.Beta,v.Cosine) - _IQmpy(v.Alpha,v.Sine);
```

For further information review the C2000 Motor Control Primer (link: SPRUGI6)

3 System Overview

This document describes the "C" real-time control framework used to demonstrate multi-axis current control of Brushed DC motors. The "C" framework is designed to run on TMS320C2803x-based controllers in Code Composer Studio.

The framework uses the modules listed in Table 1:

Table 1. Framework Modules[1]

Macro Names	Explanation
PID	PID Regulators
RC	Ramp Controller (slew rate limiter)
PWM / PWMDAC	PWM and PWMDAC Drives

[1] For deatils and theoretical background of each macro, see
C:\ti\controlSUITE\libs\app_libs\motor_control

This system demonstrates current control of a Brushed DC Motor. The examples start out with a single axis demonstration and end with a multi-axis demonstration.

The motor is driven by a H-bridge, provided by the DRV8412 Dual-Full-Bridge PWM Motor Driver IC. The Piccolo F28035 MCU controlCARD generates four pulse-width modulation (PWM) signals, two for each motor. Two phase currents of each motor are measured from the H-bridge and sent to the F28035 device through four analog-to-digital converters (ADCs). In addition, the DC-bus voltage is measured and sent to the F28035 through an ADC.

The 2xDC Motor project has the properties shown in Table 2, Table 3, and Table 4

Table 2. C Framework

System Name	Program Memory Use 2803x	Data Memory Use 2803x [1]
2xDC_Motor	2753 words [2]	1060 words

[1] Excluding the stack size
[2] Excluding "IQmath" Look-Up Tables

Table 3. CPU Use of 2-Axis, Brushed DC Current Control

Name of Modules [1]	Number of Cycles
2 x Ramp Controller	49
2 x Pid	96
2 x Pwm Drv	133
A/D Feedback scaling	40
Contxt Save etc.	53
Pwm Dac (optional)	
DataLog (optional)	
Total Number of Cycles	**371** [2]
CPU Utilization @ 60 Mhz	6.2% [3]
CPU Utilization @ 40 Mhz	9.3% [3]

[1] The modules are defined in the header files as "macros"
[2] 457 including the optional modules
[3] At 10 kHz ISR freq.

Table 4. System Features

Development /Emulation	Code Composer Studio v4.0 (or above) with Real Time debugging
Target Controller	TMS320F2803x
PWM Frequency	10kHz PWM (Default), 60kHz PWMDAC
PWM Mode	Symmetrical with a programmable dead band
Interrupts	EPWM1 Time Base CNT_Zero – Implements 10 kHz ISR execution rate
Peripherals Used	PWM 1 / 2 for motor control
	PWM 6A, 6B for DAC Outputs
	ADC A4 for DC Bus Voltage Sensing, A0, A1, A2 & A3 for Phase Current Sensing

Figure 1 depicts the overall system that accomplishes 2-axis brushed DC motor current control.

The brushed DC motors are driven by the conventional H-bridge configuration. The F28035 device generates the four pulse-width modulation (PWM) signals needed to drive the DRV8412 Dual-Full-Bridge PWM Motor Driver. Two input currents of each motor are measured from the H-bridge and 4 ADCs send these currents to the F28035 device .
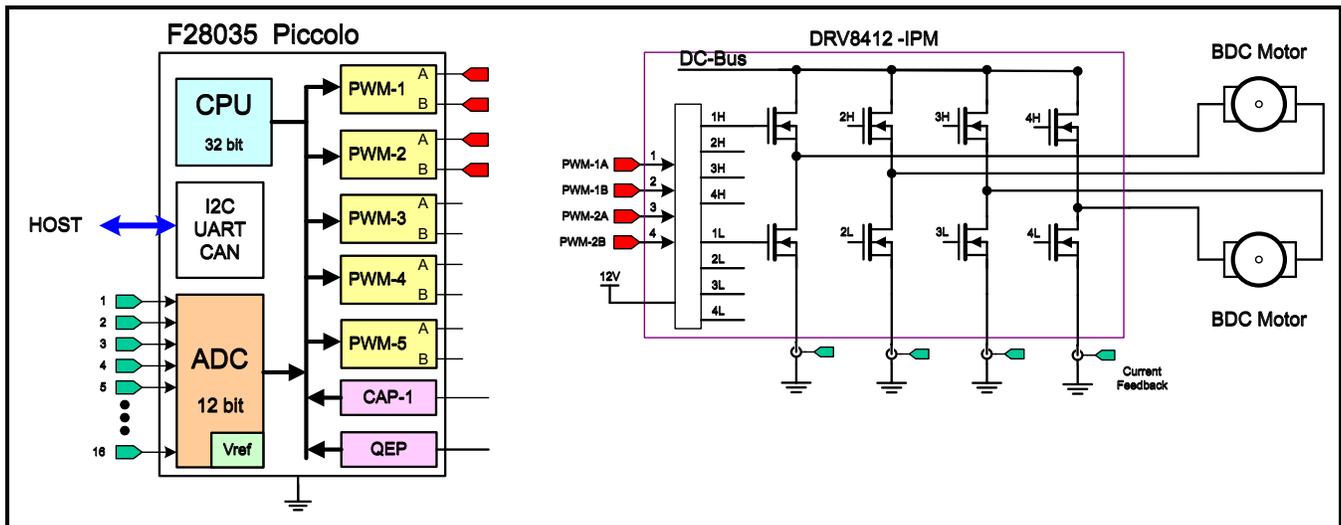

Figure 1. Dual-Axis, Brushed DC Motor Drive
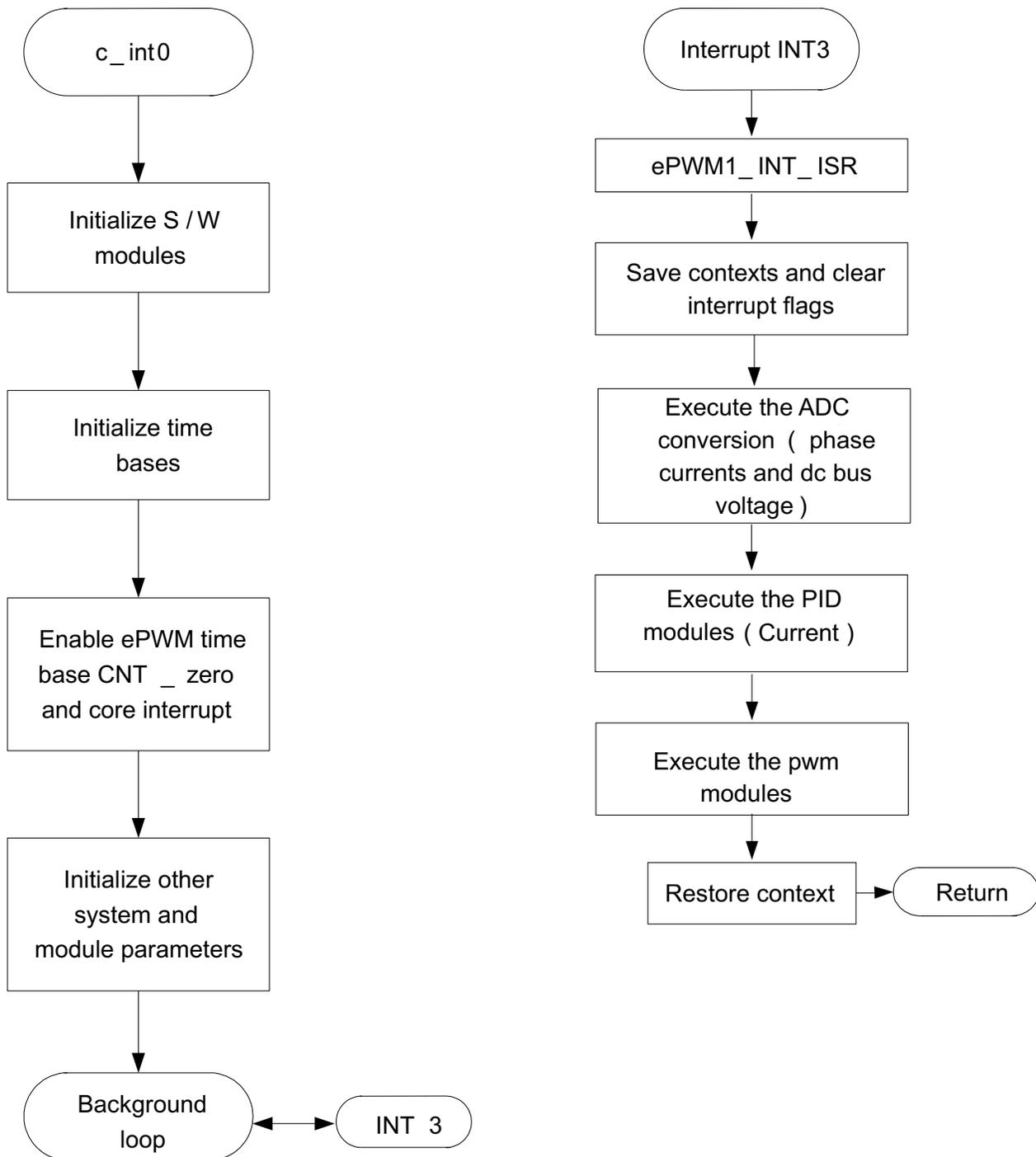
Figure 2 shows the software flow.

Figure 2. System Software Flowchart

4 Hardware Configuration (DRV8412-EVM)

For an overview of the kit hardware and the steps required to set up the kit, refer to the *DRV8412-EVM How to Run Guide* and the *DRV8412-EVM Hardware Reference Guide*, located in the following directory, :

`C:\TI\controlSUITE\development_kits\DRV8412-EVM\~Docs`

Some of the hardware setup instructions are captured below for a quick reference.

4.1 Hardware Setup Instructions

1. Unpack the DIMM-style controlCARD and verify that the DIP switch settings match those shown in Figure 3
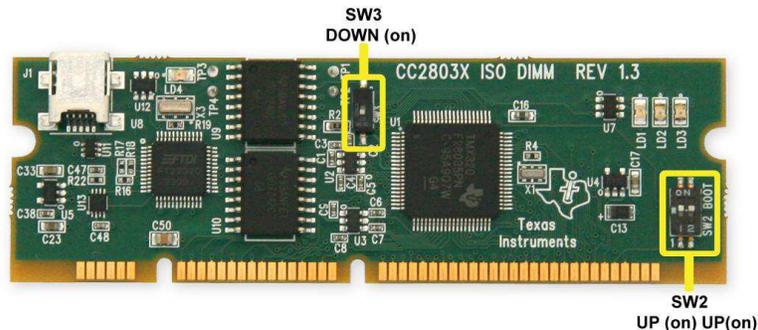

Figure 3. DIP Switch Settings

2. Place the controlCARD in the connector slot of J1. Push vertically down, using even pressure from both ends of the card, until the clips snap and lock. To remove the card simply spread open the retaining clip with thumbs

3. Ensure the DRV8412 mode jumpers and the +12V source jumper are set according to Figure 4.

4. Connect a USB cable to connector J1 on the controlCARD. This connection will enable isolated JTAG emulation to the C2000 device. LD4 should turn on.

   If the included Code Composer Studio is installed, the drivers for the onboard JTAG emulation will automatically be installed. If a windows installation window appears, try to automatically install drivers from those already on your computer.

   The emulation drivers are found at http://www.ftdichip.com/Drivers/D2XX.htm. The correct driver is the one listed to support the FT2232 device.

5. Connect a 24-V power supply to the PVDD and GND terminals of the DRV8412-EVM. Now, LED2 and LED3 should turn on. Notice the control card LED would also turn on, indicating the control card is receiving power from the board.

6. After completing the first incremental build step, motor 1 should be connected to the OUTA and OUTB terminals and motor 2 should be connected to the OUTC and OUTD terminals

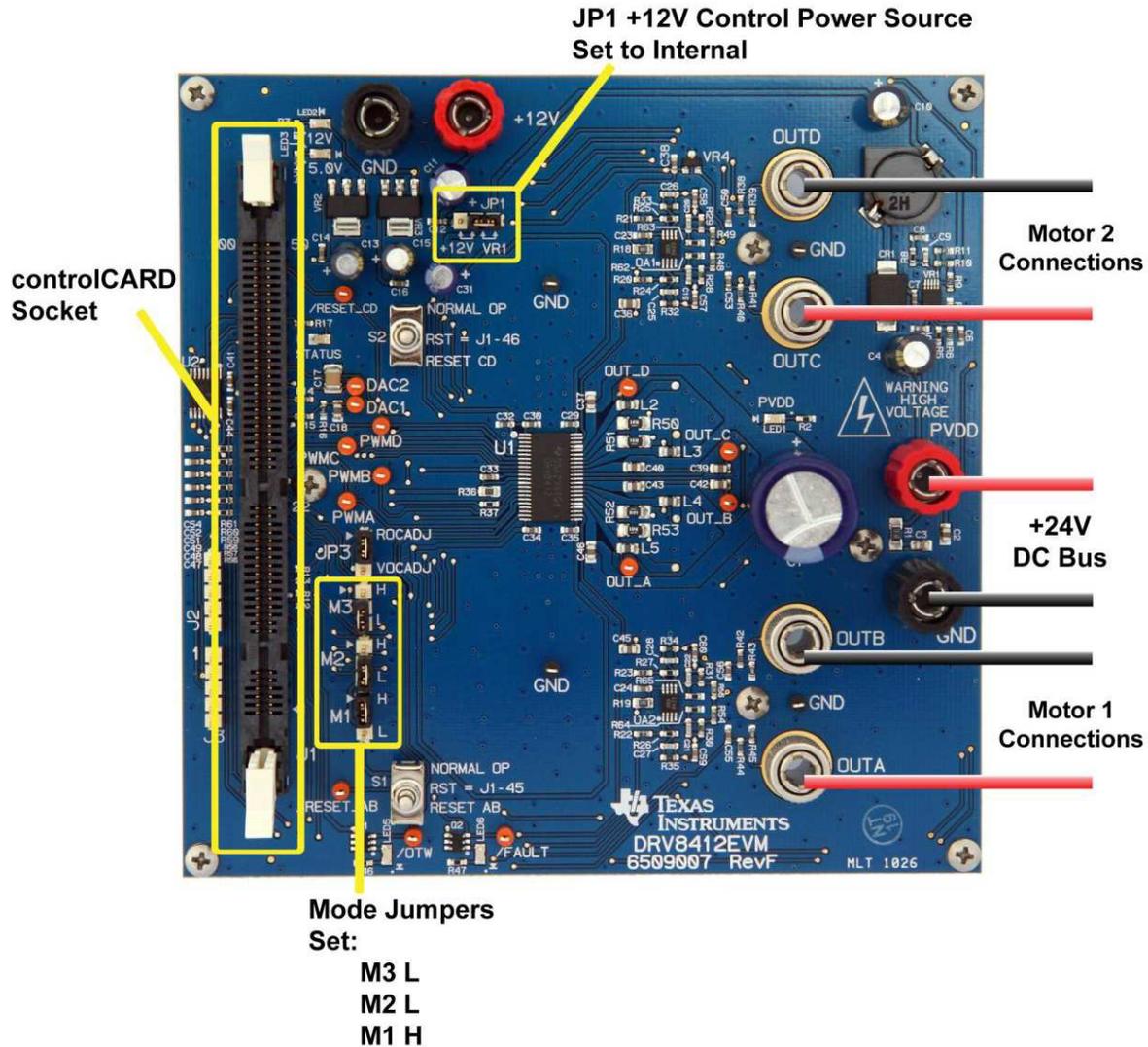For reference, Figure 4 shows the jumper and connectors that need to be connected for this lab.

Figure 4. EVM Connections

4.2 Software Setup Instructions to Run Dual-Axis Brushed DC Project

Please refer to the *Generic Steps for Software Setup for DRV8412-EVM Projects* section in the *DRV8412-EVM How To Run Guide*.

```
C:\TI\controlSUITE\development_kits\DRV8412-EVM\~Docs
```

This section instructs how to install Code Composer Studio (CCS) and how to set CCS to run with this project.

1. Select the 2xDC_Motor as the active project.
2. Verify that the build level is set to 1
3. Right-click on the project name and select "Rebuild Project".

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4. Once the build completes, launch a debug session to load the code into the controller.

5. Open a watch window and add the critical variables as shown in Figure 5and select the appropriate Q format for them.

Figure 5. Watch Window Variables

6. Setup time graph windows by importing *graph1.graphProp* and *graph2.graphProp* from the following location `C:\TI\ControlSUITE\developement_kits\DRV8412-EVM\2xDC_Motor\`. These graphs will operate similar to a strip chart. The update rate for these graphs is configurable in CCS.

7. To check the Continuous Refresh rate, click Window -> Preferences.

8. In the Preferences setup window, expand CCS and click on Debug. The window in Figure 6 will appear.
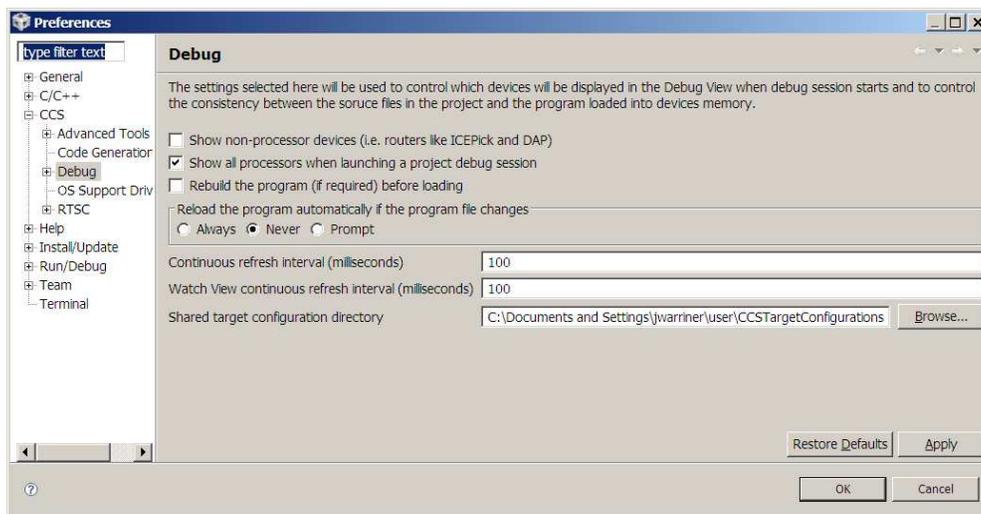

Figure 6. Continuous Refresh Interval Configuration

9. Set the Continuous refresh interval to a suitable value (typically 100ms is a good choice).

10. To enable periodic capture of data from the microcontroller, Click on the Continuous Refresh button in the top-left corner of the graph tab .

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5 Incremental System Build for Dual-Axis, Brushed DC Motor Project

For the final system to be confidently operated, we gradually build the system over 4 phases. The four phases (builds) of the incremental system build are designed to test and verify the correct operation of the major software modules used in the system. Table 5 summarizes the modules tested and used in each incremental system build.

Table 5. Modules Used in the Incremental System Build

Software Module	Phase 1	Phase 2	Phase 3	Phase 4
PWMDAC_MACRO	(1)	(1)	(1)	(1)
RC_MACRO	(1)	(1)	(1)	(1)
PWM_MACRO	(2)	(1)	(1)	(1)
A/D Conversion		(2)	(1)	(1)
PID_MACRO			(2)	(1)

(1) This module is used in this phase
(2) this module is tested in this phase.

5.1 Level 1 Incremental Build

In this build, keep the motor disconnected. Assuming the load and build steps described in the *DRV8412-EVM How To Run Guide* are completed successfully, this section describes the steps for a "minimum" system check-out, which confirms operation of the system interrupt and the peripheral-dependent PWM_MACRO (PWM initializations and update) modules.

1. Open the *2xDC_Motor-Settings.h* file
2. Select the level 1 incremental build option by setting the BUILDLEVEL to LEVEL1 (#define BUILDLEVEL LEVEL1).
3. Right-click on the project name and click Rebuild Project.
4. Once the build is complete, click on debug button
5. Reset the CPU and restart
6. Enable real-time mode
7. Run.
8. Set "EnableFlag" to 1 in the watch window. The variable named "IsrTicker" will now continue to increase, confirm this by watching the variable in the watch window. This confirms that the system interrupt is working properly.

In the software, the key variables to be adjusted are summarized below.

- **VRef1 (Q24):** for changing the motor voltage in per-unit.
- **DRV_RESET:** for holding the DRV8412 chip in reset.

5.1.1   Level 1A (PWM_MACRO Test)

In this level, we will test the PWM Generator Macro (PWM_MACRO). The VRef1 value is specified to the PWM_MACRO through RC_MACRO module. The rate of change for the PWM duty cycle is limited by the slew rate and will not change instantly with changes to VRef1.

Check the PWM test points on the board to observe PWM pulses (PWMA and PWMB for Motor = 1 and PWMC and PWMD for Motor = 2).

Ensure that the PWM module is running properly. When VRef1 is positive, PWMA (PWMC for Motor = 2) should show a 10 KHz square wave with a duty cycle corresponding to the magnitude of VRef1. When VRef1 is positive, PWMB (PWMD for Motor = 2) should be held low.
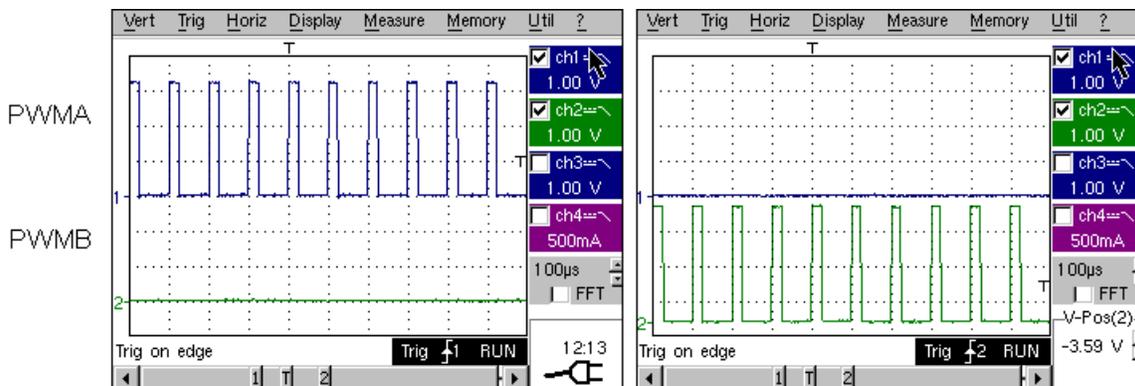

Figure 7. PWMA and PWMB for VRef1 = 0.25 and -0.25

5.1.2   Level 1B (testing The PWMDAC Macro)

PWM DACs are useful tools to monitor internal signal values in real time. PWM DACs on the DRV8412-EVM board use an external, low-pass filter to generate the waveforms (Test point is labeled DAC2). A simple, 1st–order, low-pass filter RC circuit filters out the high-frequency components.

Select the value of R and C (or the time constant, t) according to the value of the cut-off frequency (f_c). For this type of filter; the relation is as follows:

$$t = RC = \frac{1}{2\pi f_c}$$

(1)

For example, if R=470Ω and C=0.47uF, the result is f_c = 720.5 Hz. This cut-off frequency has to be below the PWM frequency. Using the formula above, one can customize the low-pass filters used for a signal being monitored. Refer to application note SPRAA88 for more details.

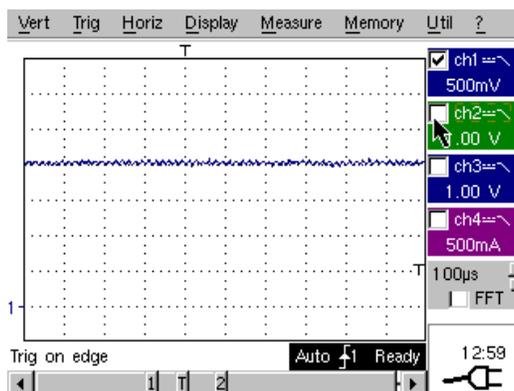The PWM DACs should represent an IQ range of ±1.0 with an analog range of 0-3.3V.

Figure 8. PWM DAC2 output for VRef1 = 0.25

5.1.3 Level 1C (DRV8412 Test)

After verifying PWM_MACRO module in level 1a, the dual-full-bridge hardware in the DRV8412 device are tested by looking at the low-pass filter outputs..

1. Set the variable DRV_RESET to 0 through the watch window
2. Check the ADC_Vhb1 and ADC_Vhb2 schematic nodes with an oscilloscope.
3. Observe that the phase-voltage dividers and the waveform-monitoring filters (R42 to 45 & C55 to 56) enable the generation of the waveform and ensure that the DRV8412 device is working appropriately

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CAUTION

After verifying the DRV8412 device is working, set the variable DRV_RESET to 1, take the controller out of real time mode (disable), and reset the processor 🐞 (see *DRV8412-EVM How To Run Guide* for details).

Note, repeat this step after each test for safety purposes. Also, note that improper shutdown might halt the PWMs at certain states where high currents can be drawn, hence caution needs to be taken when performing a shutdown.

After verifying the first axis, repeat the same tests for the second axis. Open *2xDC_Motor-Settings.h*, set the variable "Motor" to 2, and repeat the same steps.
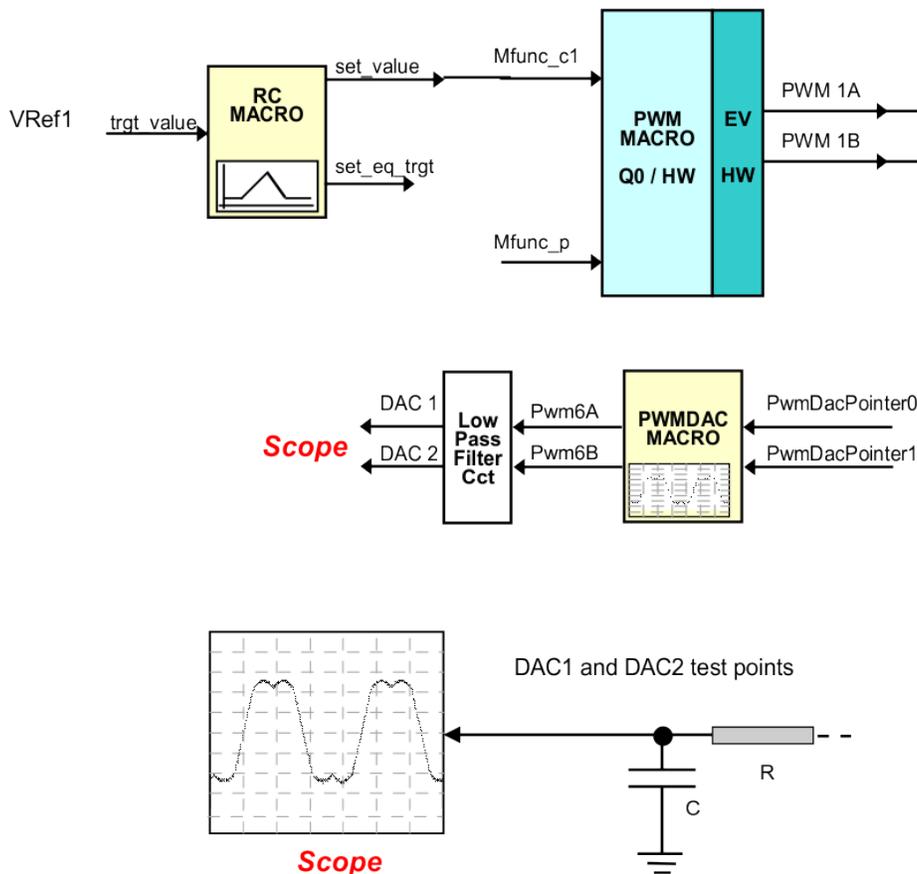
(1) Level 1 verifies the target independent modules, duty cycles, and PWM updates. The motors are disconnected at this level.

Figure 9. Level 1 – Incremental System Build Block Diagram

5.2   Level 2 Incremental Build

Assuming the Level1 incremental build is completed successfully, this phase verifies the analog-to-digital conversion. For this build, connect the motor to the board. In the software, the key variables to be adjusted are summarized below.

- **VRef1 (Q24)**: for changing the motor voltage in per-unit.

How to adjust the key variables:

1. Open *2xDC_Motor-Settings.h*
2. Select the level 2 incremental build option by setting the BUILDLEVEL to LEVEL2 (#define BUILDLEVEL LEVEL2)
3. Save the file.
4. Right-click on the project name and click Rebuild Project.
5. Once the build is complete click on the debug button.
6. Reset the CPU and restart
7. Enable real-time mode and run.
8. Set "EnableFlag" to 1 in the watch window. The variable named "IsrTicker" will be incrementally increased as seen in watch windows to confirm the interrupt working properly.

5.2.1   Testing the A/D Conversion

In this step, the A/D conversion will be tested.

1. Using the Watch Window, set VRef1 to 0.2 pu. The motor should start turning slowly.
2. Enable Continuous Refresh 🔄 for the graph window and you should see a relatively small value for IFdbk1.
3. Put a load on the motor (i.e. grab the motor shaft) and the value of IFdbk1 increases (see Figure 10)
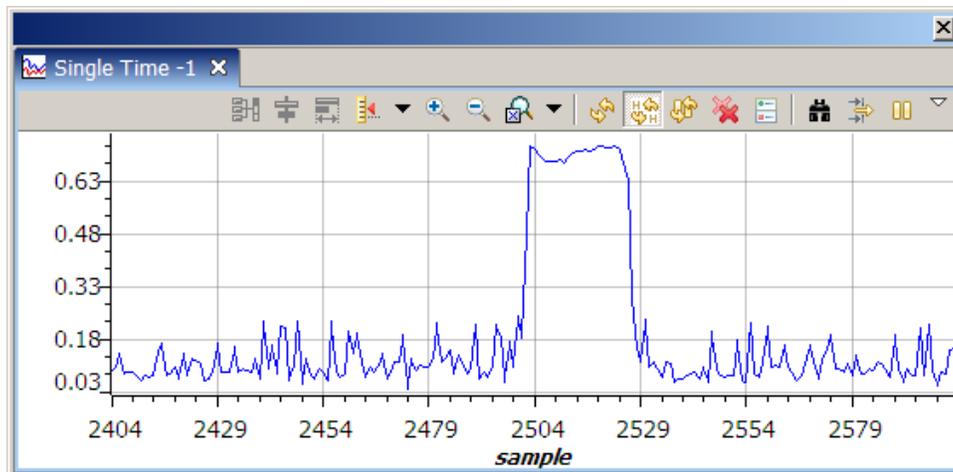

Figure 10. Build Level 2 Graph – Current Feedback under Free Running and Stalled Conditions

Note, the open-loop experiments are meant to test the ADCs, the DRV8412 device, the software modules etc., so running the motor under load or at various operating points is not recommended.

Bring the system to a safe stop, as described at the end of build 1, by setting DRV_RESET to 1, taking the controller out of realtime mode, and resetting.

After verifying the first axis, repeat the same tests for the second axis. Open *2xDC_Motor-Settings.h*, set the variable "Motor" to 2, and repeat the same steps.
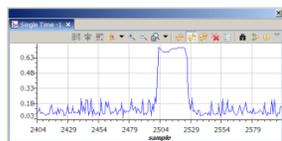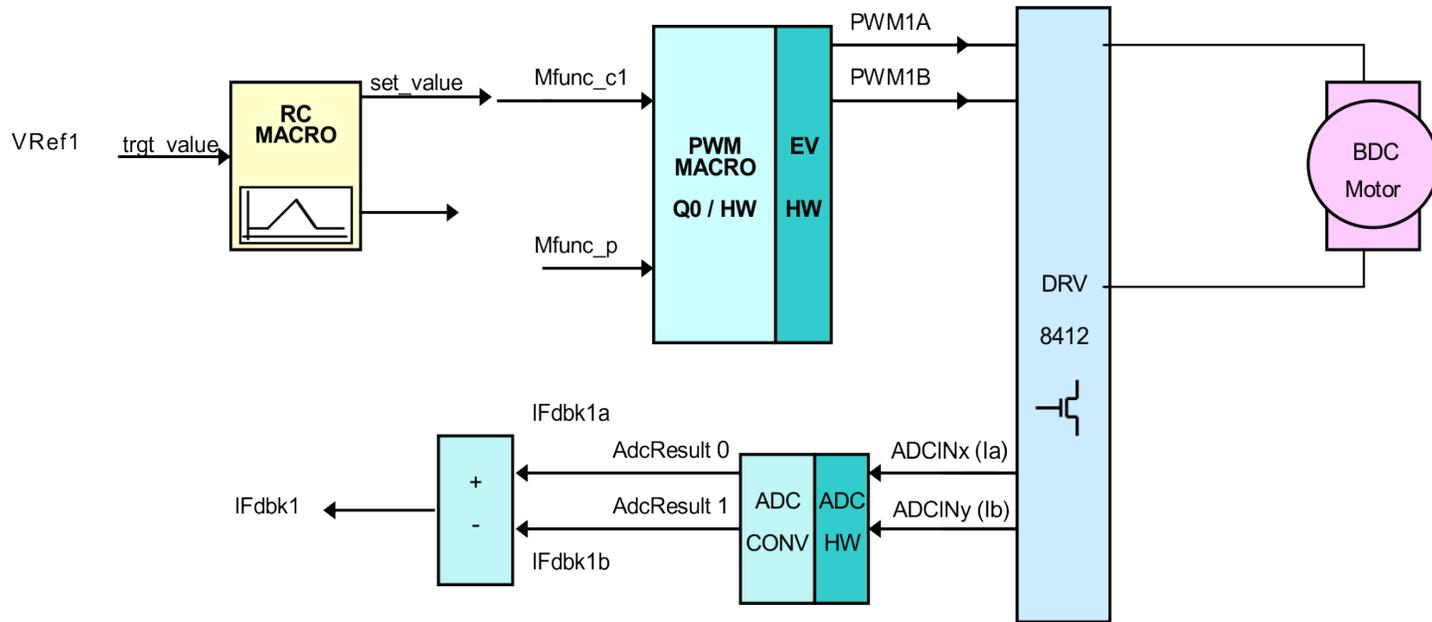
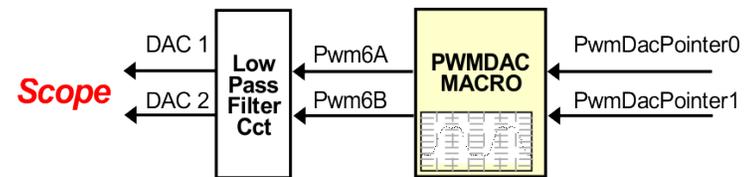(1)   Level 2 verifies the analog-to-digital conversion

Figure 11. Level 2 – Incremental System Build Block Diagram

5.2.2   Level 3 Incremental Build

Assuming the previous build is completed successfully, this build verifies the current regulation performed by the PID_REG3 module. To confirm the operation of the current regulation, the gains of these two PID controllers are necessarily tuned for proper operation.

1. Open *2xDC_Motor-Settings.h*
2. Select the level 3 incremental build option by setting the BUILDLEVEL to LEVEL3 (#define BUILDLEVEL LEVEL3).
3. Right-Click on the project name and click Rebuild Project.
4. Once the build is complete click on debug button
5. Reset the CPU and restart
6. Enable real-time mode and run.
7. Set "EnableFlag" to 1 in the watch window. The variable named "IsrTicker" will be incrementally increased as seen in watch windows to confirm the interrupt working properly.

In this build, the motor is supplied by DC input voltage and the (DC) motor current is dynamically regulated by using the PID_REG3 module.

In the software, the key variables to be adjusted are summarized below.

- **IRef1(Q24):** for changing the motor current in per-unit.

The steps are explained as follows:

1. Launch a debug session
2. Enable real-time mode and run the project.
3. Set IRef1 to 0.25 pu (or another suitable value if the base current is different).
4. Put a load on the motor (i.e. Grab the motor shaft). An unloaded motor will rapidly accelerate to the maximum speed allowed by the DC bus voltage and will not regulate current.
5. Check IFdbk1 in the graph window with the continuous refresh feature. The graph window should keep track of IRef1 for PID_REG3 module. If not, adjust its PID gains properly.
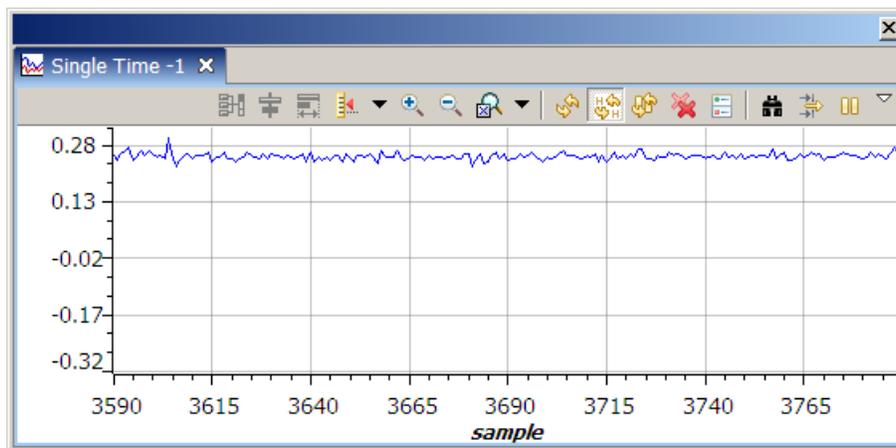

Figure 12. Build Level 3 Graph of Regulated Motor Current

- To confirm proper function of the PID module, try different values of IRef1.
- For the PID controller, the proportional, integral, derivative, and integral correction gains may be re-tuned to have the satisfied response.
- Bring the system to a safe stop, as described at the end of build 1, by setting DRV_RESET to 1, taking the controller out of real-time mode, and reset.

After verifying the first axis, repeat the same tests for the second axis. Open *2xDC_Motor-Settings.h*, set the variable "Motor" to 2, and repeat the same steps.
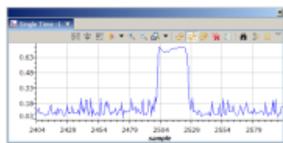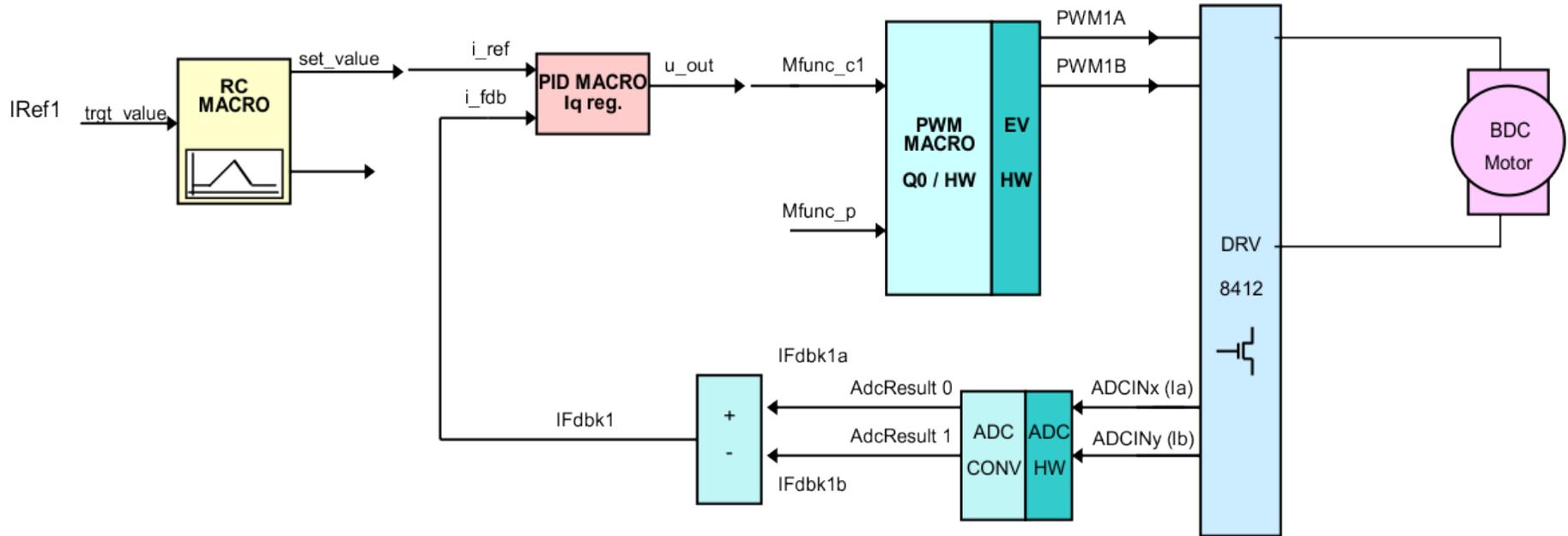
(1)   Level 3 verifies the close-loop current regulation performed by pid_i module

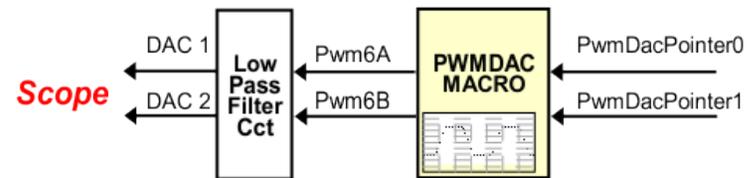**Figure 13. Level 3 – Incremental System Build Block Diagram**

5.2.3   Level 4 Incremental Build

Assuming two motors are connected to the device, and the previous build was completed successfully. This build verifies the multi-axis concept; which is two DC motors running simultaneously with current control.

1. Open *2xDC_Motor-Settings.h*
2. Select the level 4 incremental build option by setting the BUILDLEVEL to LEVEL4 (#define BUILDLEVEL LEVEL4).
3. Right-Click on the project name and click Rebuild Project.
4. Once the build is complete click on debug button
5. Reset the CPU and restart
6. Enable real-time mode and run.
7. Set "EnableFlag" to 1 in the watch window. The variable named "IsrTicker" will be incrementally increased as seen in watch windows to confirm the interrupt working properly.

In the software, the key variables to be adjusted are summarized below:

- **IRef1 (Q24):** for changing the motor 1 current in per-unit.
- **IRef2 (Q24):** for changing the motor 2 current in per-unit.
- **IFdbk1 (Q24):** for viewing motor 1 current feedback in per-unit.
- **IFdbk2 (Q24):** for viewing motor 2 current feedback in per-unit.

The key steps can be explained as follows:

1. Set IRef1 to 0.25 pu (or another suitable value if the base speed is different).
2. Put a load on the motor (i.e. Grab the motor shaft). An unloaded motor will rapidly accelerate to the maximum speed allowed by the DC bus voltage and will not regulate current.
3. Check IFdbk1 in the graph window with continuous refresh feature. It should track IRef1 for the PID_REG3 module.
4. Repeat the same tests for the second axis by modifying the value of IRef2 and viewing IFdbk2 in the second graph window.
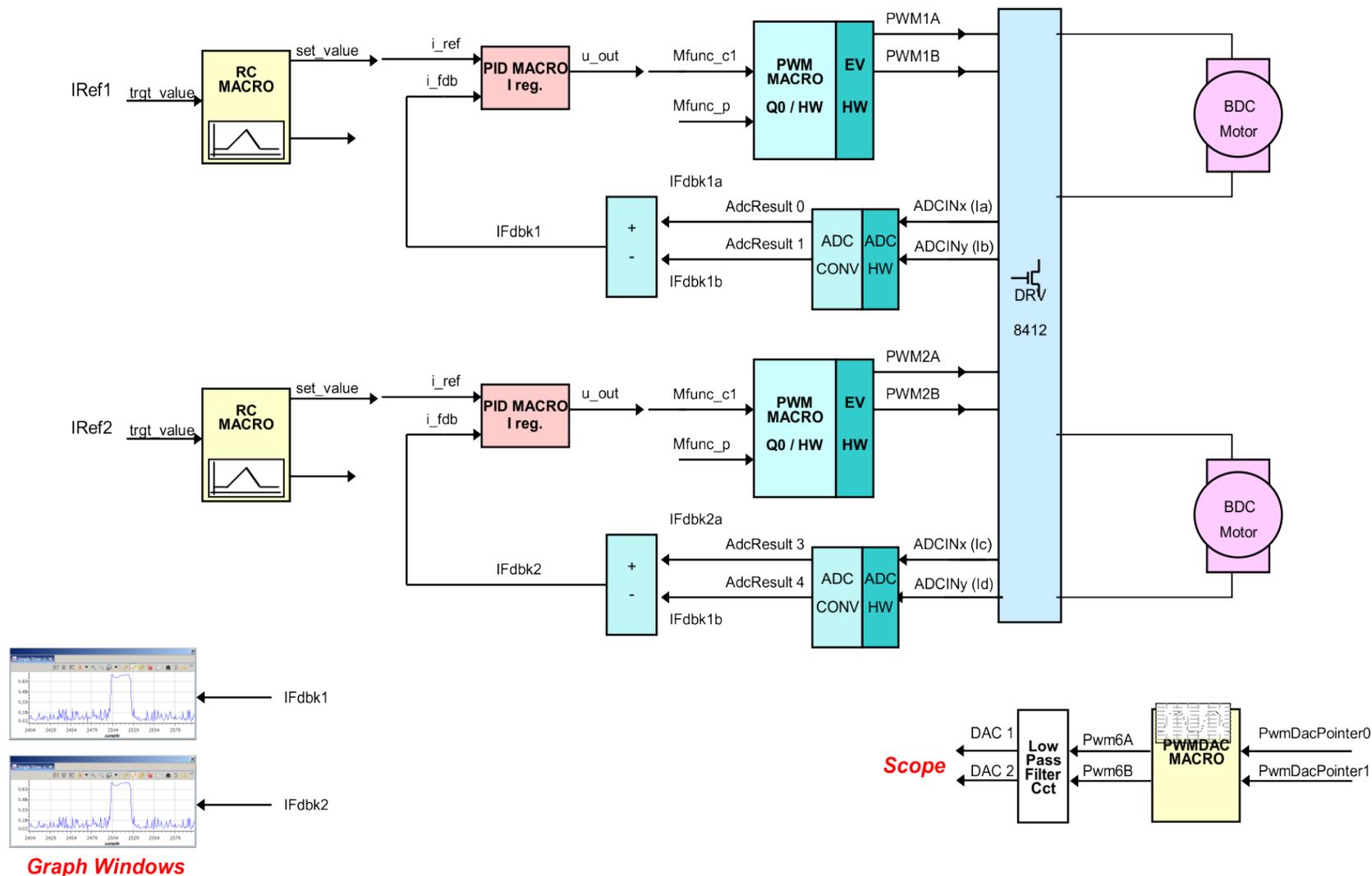
(1)   Level 4 verifies dual-axis closed-loop current control

Figure 14. Level 4 -Incremental System Build Block Diagram

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