Application Report
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Dual-Axis Motor Control Using FCL and SFRA On a Single C2000™ MCU

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ABSTRACT

The latest C2000 family of microcontrollers supports fast current loop (FCL) implementation for high bandwidth control of motor drives over a wide speed range in high end multi axes industrial servo or robotics applications. Due to the stringent computational demands of the control algorithm and the demands of interfacing to various position feedback sensors used in these applications, traditionally FPGAs and discrete analog-to-digital converters (ADCs) have been widely used to implement the core control solution. However, recent C2000 MCUs can cost effectively replace FPGAs and external ADCs in these applications and exceed the functional requirements due to superior features. This design guide helps to evaluate the fast current loop (FCL) algorithm for high-bandwidth inner loop current control of dual-axis PM servo drives based on the TMS320F2837x or TMS320F28004x MCUs using TI's LaunchPad kit, inverter BoosterPack kit and the C2000Ware MotorControl SDK. The test bench used in this reference design consists of a motor-generator set (2MTR-DYNO), a TMS320F28379D LaunchPad or TMS320F280049C LaunchPad and TI's low voltage inverter module based on BOOSTXL-3PHGANINV.

This design guide describes the following topics:

- Set up development hardware platform
- Incremental build levels calling modular FOC, FCL and SFRA functions in software
- Experimental results on the hardware platform

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Trademarks

C2000 is a trademark of Texas Instruments.

1 Introduction

High performance motor drives in servo control and robotics applications are expected to provide high precision and high bandwidth control of current, speed and position loops for superior control of end applications such as robotic arm, CNC machines, and so forth. Since the current loop makes up the inner most control loop, it must have a high bandwidth to enable the outer speed or position loops to be faster. Hence, a high bandwidth FCL is needed in high performance industrial servo control applications. However, the delays due to ADC conversion and algorithm execution limit the current controller bandwidth to about a tenth of the sampling frequency.

Until recently, because of the time critical computational demand of the control algorithm and interface demands of various position encoders, FPGAs and external ADCs were needed to implement the fast current loop. However, with the advent of latest C2000 Delfino and Piccolo family of microcontrollers, it is now possible to replace FPGAs and external ADCs with these MCUs for a cost effective solution. This paper outlines the implementation of fast current loop on a C2000 platform running two motors, and verifies the frequency response of the control loops using TI's Software Frequency Response Analyzer (SFRA) software library. Dynamic frequency response analysis in real-time on a motor drive system is unique among MCU suppliers and is currently capable only on C2000 MCUs.

Using the released FCL algorithm for this device and the Software Frequency Response Analyzer (SFRA) library for C2000 MCUs from TI, the control bandwidth of fast current loop and the operating speed range of motor are experimentally verified. This design guide documents the test platform setup, procedure and the quantitative results obtained. It is important to note that when the PWM carrier frequency is 10 KHz, the current loop bandwidth obtained is 5 KHz for a phase margin of 45° over a wide speed range. Compared to the traditional MCU based systems, FCL software can potentially triple a drive system's torque response and double its maximum speed without increasing the PWM carrier frequency.

The Delfino F2837x and Piccolo F28004x series of C2000 microcontroller enable a new value point for dual-axis drives that also delivers very robust motion-control performance. The value comes not only from the achievable control performance and ability to drive two motors concurrently, but also from the high degree of on-chip integration of other key electronic system functions. Since both F2837x and F28004x devices support CPU and CLA cores, CPU offload encoder-feedback and torque control processing to the control law accelerator (CLA) to maximize the performance of dual-axis servo drive.

1.1 Acronyms and Descriptions

Table 1. Acronyms and Descriptions

Acronym	Description
ACIM	AC Induction Motor
ADC	Analog-to-Digital Converter
CLA	Control Law Accelerator (in C2000 MCU)
CLB	Configurable Logic Block (in C2000 MCU)
CMPSS	Comparator Subsystem Peripheral (in C2000 MCU)
CNC	Computer Numerical Control
DMC	Digital Motor Control
eCAP	Enhanced Capture Module
ePWM	Enhanced Pulse Width Modulator
eQEP	Enhanced Quadrature Encoder Pulse Module
FCL	Fast Current Loop
FOC	Field-Oriented Control
FPGA	Field Programmable Gate Array
INV	Inverter
MCU	Microcontroller Unit
PMSM	Permanent Magnet Synchronous Motor
PWM	Pulse Width Modulation
SFRA	Software Frequency Response Analyzer
TMU	Trigonometric Mathematical Unit (in C2000 MCU)

2 Benefits of the C2000 for High-Bandwidth Current Loop

The C2000 family of MCUs possesses the desired computation power to execute complex control algorithms along with the correct combination of peripherals such as ADC, enhanced pulse width modulator (ePWM), enhanced quadrature encoder pulse (eQEP) and enhanced capture (eCAP) to interface with various components of the digital motor control (DMC) hardware. These peripherals have necessary hooks to provide flexible PWM protection, such as trip zones for PWMs and comparators.

Both F2837x and F28004x MCUs contain additional hardware features such as the following:

- Higher CPU and control law accelerator (CLA) clock frequency
- Parallel processing floating point core (CLA) augmenting the main CPU
- Trigonometric Math Unit (TMU) to support high speed, precision trigonometric and math functions
- Four high speed precision 12bit and 16bit ADCs on F2837x, or three high speed precision 12-bit ADCs on F28004x.
- Configurable Logic Blocks (CLB) - using PM library from TI, a range of absolute encoders can be interfaced

Together, these features provide enough hardware support to increase computational bandwidth per CPU core compared to its predecessors and offer superior real-time control performance. In addition, the C2000 ecosystem of software (libraries and application software) and hardware (LAUNCHXL-F28379D, LAUNCHXL-F280049C, BOOSTXL-3PhGaNInv) help to reduce the time and effort needed to develop a high-end digital motor control solution.

3 Current Loops in Servo Drives

Figure 1 shows the basic speed control block diagram of a field oriented control (FOC) based AC motor control system used in servo drives. The current loop is highlighted here because this is the inner most loop and has a higher influence on the bandwidth of the outer speed and position loops. For the outer loop to have a higher bandwidth, the inner loop must have a far higher bandwidth, typically more than three times.

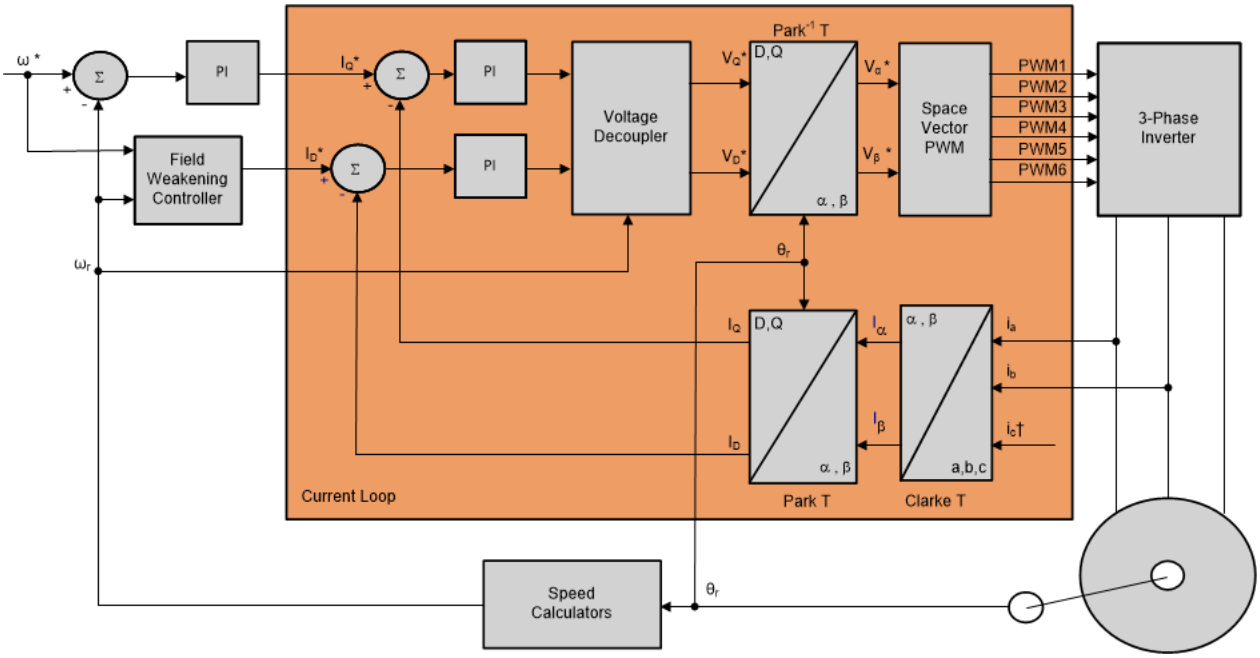


Figure 1. Basic Scheme of FOC for AC Motor

In the current loop, any two of the motor phase currents are measured, while the third can be estimated from these two sensing currents. These measurements feed the Clarke transformation module. The outputs of this projection are designated I_α and I_β. These two components of the current along with the rotor flux position are the inputs of the Park transformation, which transform them to currents (I_d and I_q) in D-Q rotating reference frame. The I_d and I_q components are compared to the references I_{dref} (the flux reference) and I_{qref} (the torque reference). At this point, the control structure shows an interesting advantage; it can be used to control either synchronous (PM) or asynchronous (ACIM) machines by simply changing the flux reference and obtaining the rotor flux position. In the synchronous permanent magnet motor, the rotor flux is fixed as determined by the magnets, so there is no need to create it. Therefore, when controlling a PMSM motor, I_{dref} can be set to zero, except during field weakening. Unlike PM motor, ACIM motors do not have a rotor flux by default. Since the flux need to be created, the flux reference current must be greater than zero.

The torque command I_{qref} can be fed from the output of the speed regulator. The outputs of the current regulators are V_{dref} and V_{qref}. These outputs are applied to the inverse Park transformation. Using the position of rotor flux, this projection generates $V_{\alpha ref}$ and $V_{\beta ref}$, which are the components of the stator vector voltage in the stationary orthogonal reference frame. These components are the inputs of the PWM generation block. The outputs of this block are the signals that drive the inverter.

Both Park and inverse Park transformations need the rotor flux position. Obtaining this rotor flux position depends on the choice of AC machine observer in sensorless control or the position encoder in the case sensored control.

4 PWM Update Latency for Dual Motor

The major challenge in implementing the current loop lies in reducing the latency between feedback sampling and PWM updates. In traditional control schemes, this latency is typically one sampling period, thereby, delaying the control action. In other words, it leads to one sampling period of inaction to any disturbances in the loop. For a fast current loop, this delay must be as small as possible to improve the loop performance over the wide operating speed range of the motor. Typically, a latency of one microsecond or less is considered acceptable in many applications that requires a controller with a fast compute engine, a fast ADC, low latency control peripherals and a superior control algorithm.

On a single F2837x or F28004x, it is possible to run two independent FCLs in less than 2 µs while still supporting the high control bandwidth and double sampling of each axis. In order to maintain the goal of measuring the currents of each motor during voltage transitions, the ADC double sampling is interleaved between each motor so that the sampling and subsequent FOC processing does not need to happen back to back. The motor 1 carrier lags motor 2 by a fixed 90°, then the ADC sampling period is consistent across both motors but interleaved between them as shown in Figure 2. Each ADC sample and conversion is followed by the C2000 CPU performing the FOC algorithm and updating the PWMs. In this way, the sample-to-PWM update remains very consistent for each execution, whether it's the first or second sample of motor 1 or motor 2.

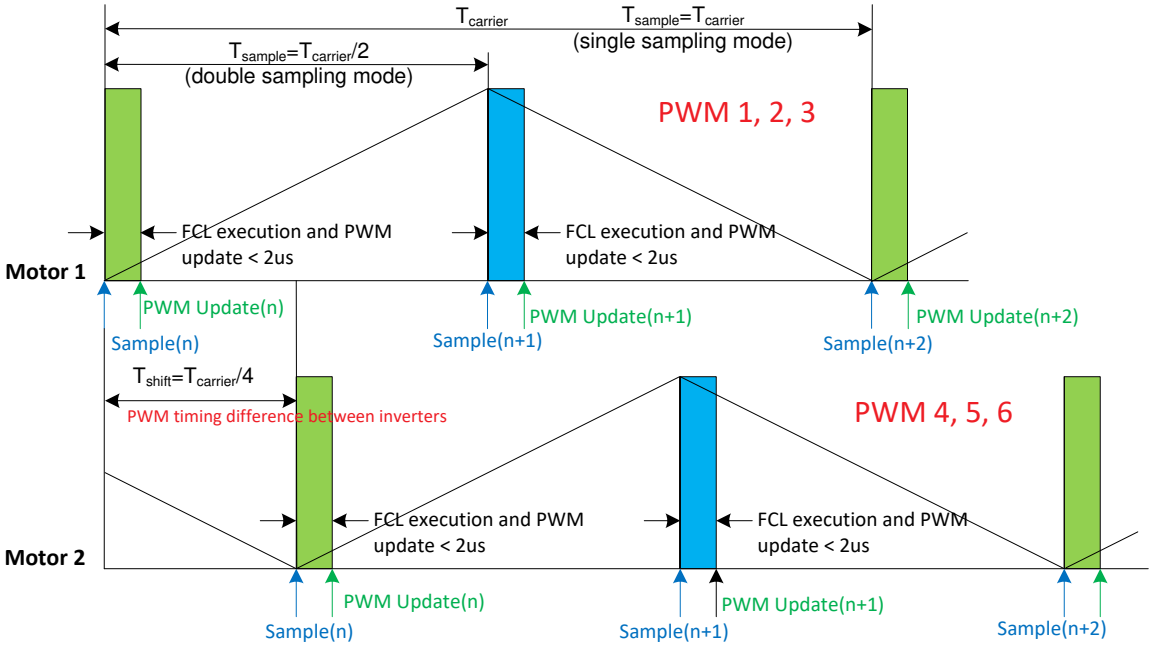


Figure 2. Motor Phase Current Sampling and PWM Update for Dual Motor

5 Outline of the Fast Current Loop Library

The major challenge in digital motor control systems is the influence of the sample and hold (S/H) , as well as transportation delay inside the loop that slows down the system, impacting its performance at higher frequencies and running speeds. A minimal current loop time not only helps to improve the control bandwidth, but it also enables a higher modulation index (M-I) for the inverter. A higher M-I translates into the higher phase voltage that the inverter can apply on the motor. Higher loop latency will reduce the maximum available voltage and can restrict the rate of current change in the motor, thereby, adversely impacting the controller performance.

To overcome these challenges, a controller with high computational power, right set of control peripherals and superior control algorithm are needed. The TMS320F2837x and TMS20F28004x provide the necessary hardware support for higher performance, and the FCL algorithm from TI that runs on the C2000 MCU provides the needed algorithmic support.

To improve the operational range of FCL, the latency between feedback sampling and PWM update should be as small as possible. Typically, a latency of 2 µS or less is considered acceptable in many applications. Traditionally, this task is implemented using a combination of high end FPGAs, external ADCs and MCUs.

The FCL algorithm utilizes the following features in the F2837x or F28004x MCUs.

- Floating-Point Unit (FPU)
- Trigonometric and Math Unit (TMU)
- Three high speed 12-bit ADCs
- Multiple parallel processing blocks such as Control Law Architecture (CLA)

Figure 3 shows the block diagram of FCL algorithm with its inputs and outputs. The FCL partitions its algorithm across the CPU, CLA and TMU to bring down the latency to under 1.0 µs compared to the acceptable 2.0 µs. Further optimization is possible if the algorithm is written in assembly.

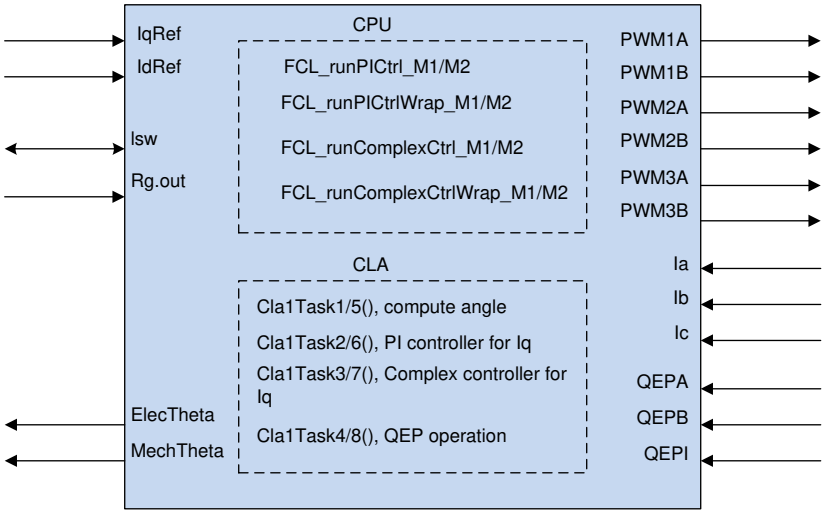


Figure 3. Fast Current Loop Block Diagram

The FCL algorithm supports two types of current regulators, a typical PI controller and a complex controller. The complex controller can provide additional bandwidth over the typical PI controller at higher speeds. Both current regulators are provided for user evaluation. In the example project, the current regulator can be selected by setting the FCL_CNTLR macro appropriately and studying how they compare.

Table 2 lists the FCL API functions and their descriptions.

Table 2. Summary of FCL Interface Functions

API Function	Description
uint32_t FCL_getSwVersion(void);	Returns a 32-bit constant and for this version the value returned is 0x00000008.
void FCL_initPWM(MOTOR_Vars_t *ptrMotor, uint32_t basePhaseU, uint32_t basePhaseV, uint32_t basePhaseW);	Initializes all motor control PWMs for FCL operation, this function is called by the user application during initialization process. Both motors call the same function, the difference is the passed parameters.
void FCL_initQEP(MOTOR_Vars_t *ptrMotor, const uint32_t baseA)	Assigned QEP base address of all motor control for FCL operation, this function is called by the user application during initialization process. Both motors call the same function, the difference is the passed parameters.
void FCL_resetController(MOTOR_Vars_t *ptrMotor)	Reset the FCL variables when user wants to stop the motor and restart the motor.
void FCL_runPICtrl_Mn(MOTOR_Vars_t *pMotor);	Function that performs the PI Control as part of the Fast Current Loop. (n=1 or 2 for motor 1 or motor 2)
void FCL_runPICtrlWrap_Mn(MOTOR_Vars_t *pMotor);	Wrap up function to be called by the user application at the completion of FCL in PI Control Mode. (n=1 or 2 for motor 1 or motor 2)
void FCL_runComplexCtrl_Mn(MOTOR_Vars_t * pMotor);	Function that performs the Complex control as part of the Fast Current Loop . (n=1 or 2 for motor 1 or motor 2)
void FCL_runComplexCtrlWrap_Mn(MOTOR_Vars_t *pMotor);	Wrap up function to be called by the user application at the completion of FCL in Complex Control Mode . (n=1 or 2 for motor 1 or motor 2)

For more information on the FCL algorithm, the source codes is available at : *\ti\c2000\C2000Ware_MotorControl_SDK_version\libraries\fcl\source*.

The algorithm is written in a modular format and is able to port over to user platforms using F2837x, F28004x, or F2838x devices if the following conditions are met:

- Motor phase current feedback are read into variables internal to the FCL functions. However, D-axis and Q-axis current feedback are available.
- PWM modules controlling motor phase A, B, and C are linked to the FCL.
- A QEP module connecting to the QEP encoder is linked to the FCL algorithm.
- CLA tasks one through eight are used by the FCL algorithm. This must be accommodated in the user application.

6 Evaluation Platform Setup

The example projects are evaluated on hardware kit that is readily available from TI. It consists of an F28379D- or an F280049C-based LaunchPad, inverter BoosterPack based on GaN+INA240, and a motor-dyno set for load testing the drive motor, their details are given in Section 6.1. This evaluation set up will use GaN+INA240 as the power stage to make use of line current sensing facility available in this hardware.

Example Project Features:

- Sensored FOC of PMSM motor
- FCL algorithm source code
- Position, speed and torque control loops
- Position sensor support: incremental encoder (QEP)
- Current sensing: analog feedback using ADC (from inline shunt resistor)
- SFRA tool for tuning current and speed loop

6.1 Hardware

The details of the evaluation hardware, most of which are available from the TI Store, and references to the user's guide are listed below:

- CPU - LAUNCHXL-F28379D - one unit - *LAUNCHXL-F28379D Overview User's Guide* or LAUNCHXL-F280049C - one unit - *C2000™ Piccolo™ F28004x Series LaunchPad™Development Kit*
- Inverter (INV) -BOOSTXL-3PhGaNInv - two units - *BOOSTXL-3PhGaNInv Evaluation Module User's Guide*
- Motor Dyno Set - 2MTR-DYNO - one unit (two motors)
- A variable DC power supply rated at 48V/5A

6.1.1 LAUNCHXL-F28379D or LAUNCHXL-F280049C

Figure 4 shows the layout of LAUNCHXL-F28379D. For further details, see the *LAUNCHXL-F28379D Overview User's Guide* .

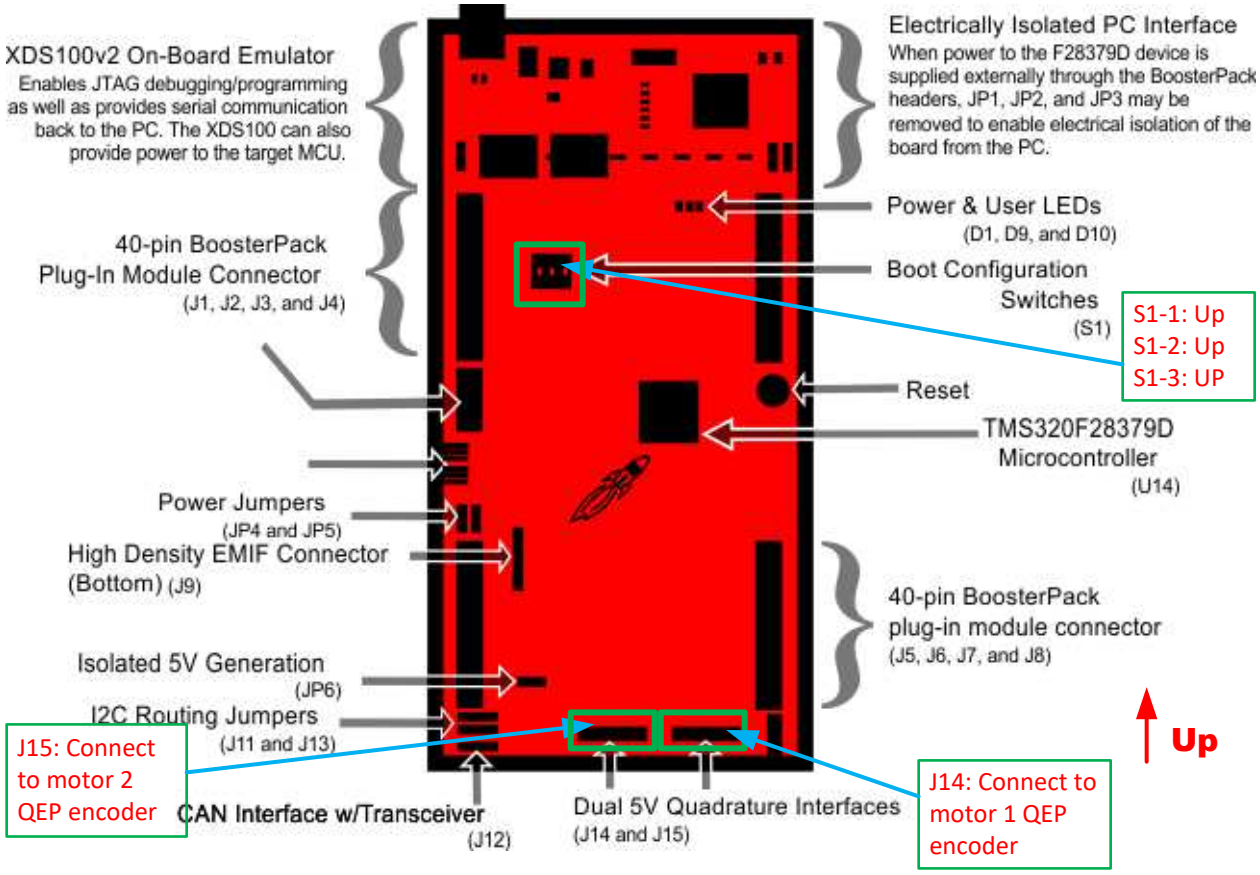


Figure 4. Layout of LAUNCHXL-F28379D and Switches Setting

Figure 5 shows the layout of LAUNCHXL-F280049C. For further details, see the *C2000™ Piccolo™ F28004x Series LaunchPad™Development Kit*.

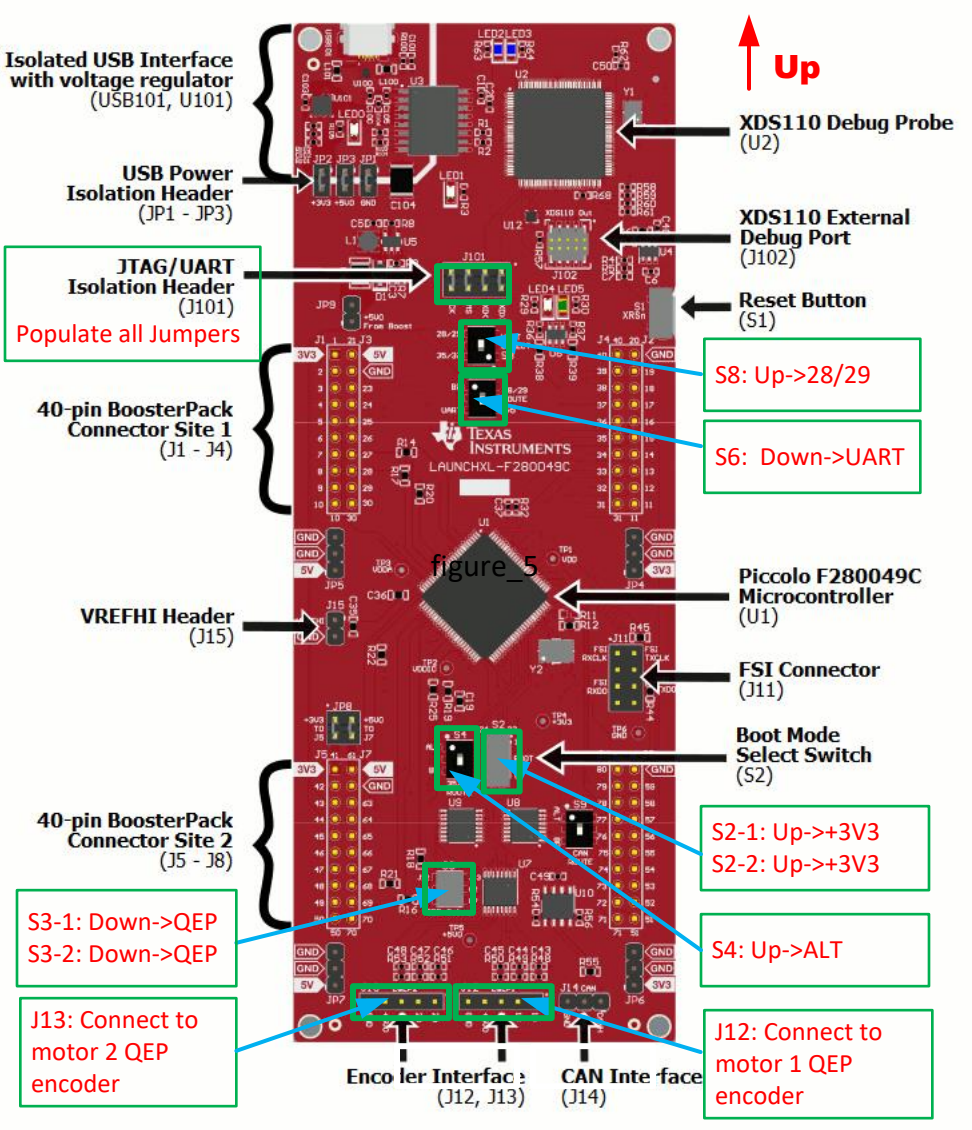


Figure 5. Layout of LAUNCHXL-F280049C and Switches Setting

6.1.1.1 DACs

Both F28379D and F280049C LaunchPads have a couple of DACs available on jumper pins J3-30 and J7-70. To use these DACs that needs to remove the R20 resistor on the 3PhGaNInv board or disconnect theJ3-30 and J7-70 to Inverter BOOSTXL-3PhGanInv.

6.1.1.2 QEPs

Both F28379D and F280049C LaunchPads have a couple of QEPs available on pins J14 and J15 (F28379D LaunchPad), J12 and J13 (F280049C LaunchPad). The connections between the LaunchPad and motor encoder are listed in Table 3.

Table 3. Encoder Wires Connections for Reference Kit

J14/J15 (F28379D), J12/J13 (F280049C)		Encoder Wires of Motor	
1	QEPA	A	Blue
2	QEPB	B	Orange
3	QEPI	Index	Brown
4	+5V	+5VDC	Red
5	GND	GND	Black

6.1.2 Inverter BoosterPack - GaN + INA240

Figure 6 shows the layout and pin out diagram of BOOSTXL-3PhGaNInv. For more details, see the *BOOSTXL-3PhGaNInv Evaluation Module User's Guide*.

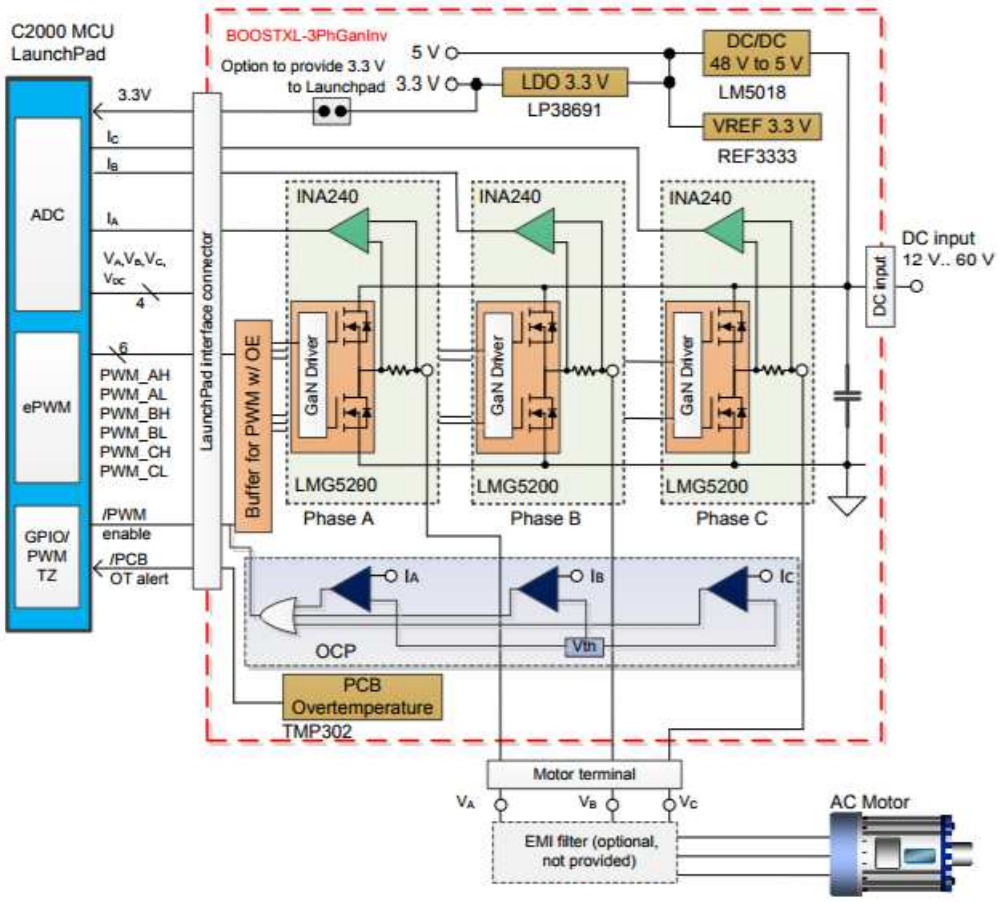


Figure 6. BOOSTXL-3PhGaNInv Functional Block Diagram

Figure 7 shows a dual BoosterPack assembly with LAUNCHXL-F28379D. The motor wires connections are as listed in Table 4.

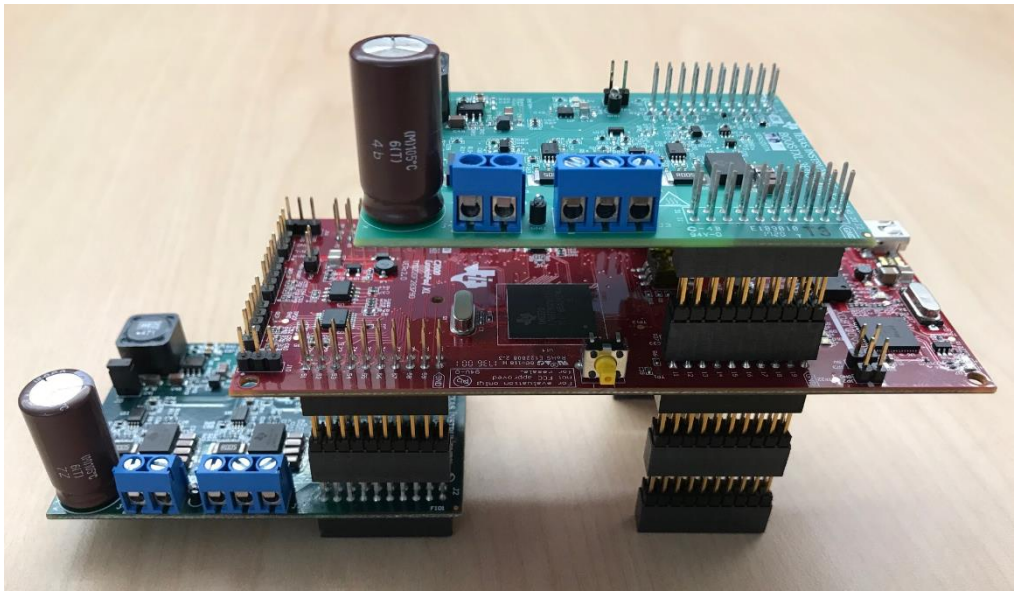


Figure 7. Dual Motor Control Assembly With LAUNCHXL-F28379D and BOOSTXL-3PhGaNInv

Table 4. Motor Phase Connections for Reference Kit

Inverter 3PhGanInv, J3 Connector		M-2310P-LNK-04 Motor	
Pin	Name	Pin	Color
3	VA	Phase R	Black
2	VB	Phase S	Red
1	VC	Phase T	White

6.1.3 Two Motor Dyno

The two motor dyno setups help to perform load test on the drive motor by mechanically coupling it to the other motor that acts as a generator. The kit comes with a coupler, mounting screws and key. Assemble the motor-dyno set as shown in Figure 8.

Figure 8. Two Motor Dyno Set

6.1.4 System Hardware Connections

There are various jumpers present on the LaunchPad. For more information, see the *LAUNCHXL-F28379D Overview User's Guide* and the *C2000™ Piccolo™ F28004x Series LaunchPad™Development Kit* separately. Before mounting the BoosterPacks, ensure that jumpers in the LaunchPad are set correctly as shown in Figure 4 and Figure 5.

The motor that comes with 2MTR-DYNO kit is a PMSM motor with both QEP and HALL sensors available on its headers J4 and J10, respectively. The control scheme is based on QEP feedback; therefore, its QEP header J4 is fed into the LaunchPad. Do not use the HALL sensor header J10.

The BoosterPacks suggested for this evaluation will mount directly on to the LaunchPad LAUNCHXL-F28379D or LAUNCHXL-F280049C. This connects the analog/digital IOs of the BoosterPack to the appropriate IOs of the CPU. Make sure to match the orientation of inverter BoosterPacks as shown in Figure 7 before mounting. Mount one inverter BoosterPack on LaunchPad connectors J1-J4, let us call it inverter INV1. Likewise, mount the other inverter on launchpad connectors J5-J8, and call it inverter INV2.

Until instructed, leave the INV output headers and QEP headers open. When instructed to connect motor 1, connect motor 1 terminal A, B and C to INV1 connector terminal Va, Vb and Vc and motor's QEP header to QEP-A on LaunchPad. Likewise, when instructed, connect motor 2 to INV2 and its QEP header to QEP-B on LaunchPad.

6.1.5 Powering Up the Setup

The following are important points to keep in mind while powering the setup:

- The max voltage of BoostXL-3PhGanInv is limited to 48 V.
- The current limit on power supply can be set at 2A. Depending on need, the current limit can be increased up to 5A.
- The +3.3 V power supply of controller on LaunchPad can be provided by USB or one of two BoosterPacks. You can only choose one source to avoid circulating currents between the +3.3 V power supplies of the two INVs and USB.
  - Using the +3.3 V power supply from LaunchPad.
    - Remove jumper J5 from both INV1 and INV2 BoosterPacks.
    - Make sure that jumpers JP1~JP5 on the LaunchPad are populated if using LAUNCHXL-F28379D.
    - Or, jumpers JP1-JP3, and JP8 on the LaunchPad are populated if using LAUNCHXL-F28009C.
  - Using the +3.3 V power supply from one of the two BoosterPacks.
    - Make sure that jumpers JP1~JP5 on the LaunchPad are removed if using LAUNCHXL-F28379D.
    - Or, jumpers JP1-JP3, and JP8 are removed, and JP9 is populated on the LaunchPad if using LAUNCHXL-F28009C.
    - Populate J5 on one BoosterPack. Only one J5 is populated on INV1 or INV2 at the same time to avoid circulating currents between the 3.3 V power supplies of the two INVs.

6.2 Software

The software is developed using FCL algorithm code and SFRA library which are released in C2000Ware MotorControl SDK. FCL is used to improve the current loop bandwidth and SFRA is used to do frequency response analysis of any control loops. As mentioned earlier, in this release, the FCL algorithm is customized and executed out of CPU and CLA in parallel to control two motors.

The project for F28379D can be found at:
"*ti\c2000\C2000Ware_MotorControl_SDK_<version>\solutions\boostxl_3phganinv\f2837x\ccs\sensored_foc* ".

The project for F280049C can be found at:
"*\ti\c2000\C2000Ware_MotorControl_SDK_<version>\solutions\boostxl_3phganinv\f28004x\ccs\sensored_foc*".

The FCL algorithm source code can be found at:
"*\ti\c2000\C2000Ware_MotorControl_SDK_<version>\libraries\fcl* ".

The SFRA software library can be found at:
"*\ti\c2000\C2000Ware_MotorControl_SDK_<version>\libraries\sfra* ".

The software is built such that two different motors can be controlled independently.

6.2.1 Incremental Build

The system is incrementally built up in order for the final system can be confidently operated. Six phases of the incremental system build are designed to verify the major modules in the system. In each build level, a certain operation of the system, could be hardware or software, is verified and integrated incrementally. In the final build level, all operations are integrated to make a complete system. Software modules are written as either C macros or C callable functions.

Table 5 and Table 6 summarize the core functions integrated and tested at each build level in the incremental build approach.

Table 5. Functions Verified in Each Incremental System Build

Build Level	Functional Integration
Level 1	Basic PWM generation
Level 2	Open loop control of motor and calibration of feedbacks
Level 3	CURRENT MODE - Closing current loop using FCL library
Level 4	SPEED MODE - Closing speed loop using inner FCL verified in LEVEL 3
Level 5	POSITION MODE - Closing position loop using inner speed loop verified in LEVEL 4
Level 6	SFRA ANALYSIS - Performing SFRA on current loop running motor in speed mode (LEVEL 4)

Table 6. Functional Modules Used in Each Incremental System Build

Software Module	Level 1	Level 2	Level 3	Level 4	Level 5	Level 6
PWM Generation	√√	√	√	√	√	√
QEP Interface in CLA		√√	√	√	√	√
FOC functions			√√	√	√	√
FCL			√√	√√	√	√
Position controller					√√	
SFRA functions						√√
Note: the symbol √ means this module is using and the symbol √√ means this module is testing in this phase.						

6.2.2 Software Setup for Dual-Axis Servo Drive Projects

Installing Code Composer Studio and MotoControl SDK

1. Go to http://www.ti.com/ccstudio to download the latest version of Code Composer Studio and run the installer.
2. Go to http://www.ti.com/tool/C2000WARE-MOTORCONTROL-SDK to download and run the MotorControl SDK installer. Allow the installer to download and update any automatically checked software for C2000.

Setting up Code Composer Studio for Project Evaluation

1. Open Code Composer Studio. Note that this document assumes version 9.1.0 or later .
2. Once Code Composer Studio opens, the workspace launcher may appear as Figure 9 that would ask to select a workspace location.
   a. Click the “Browse…” button as Figure.
   b. Create the path below by making new folders as necessary, like "*C:\ti\mcsdk_projects\dual_axis_drive*".
   c. Uncheck the box that says “Use this as the default and do not ask again”, and then click "Launch".

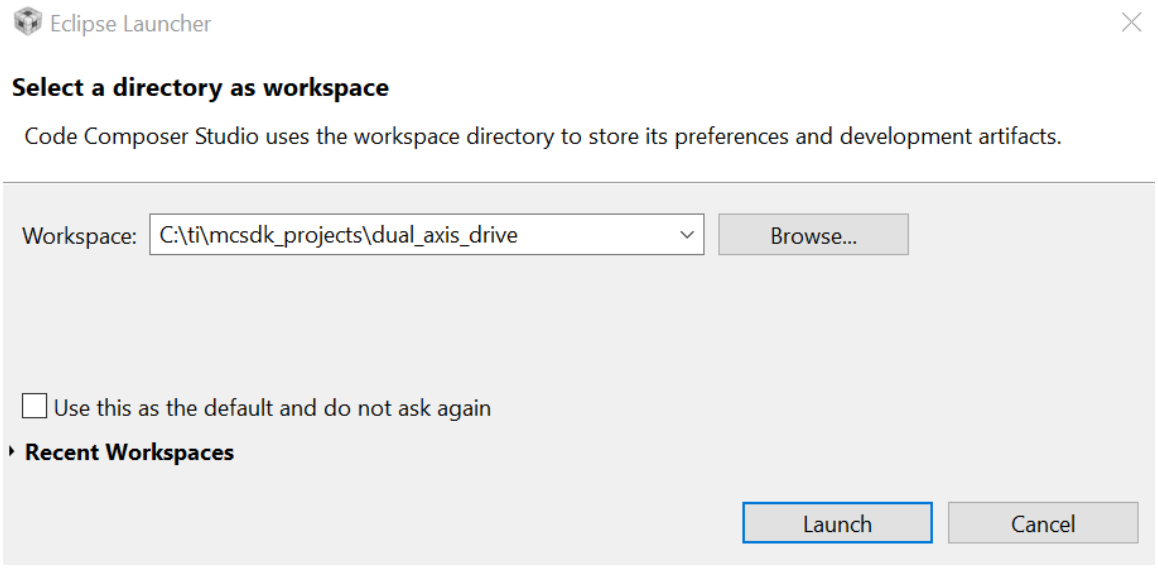


Figure 9. CCS Workspace Launcher

3. This will open a "Getting Started" tab with links to various tasks from creating a new project, importing an existing project to watching a Tutorial on CCS.
4. Add the motor control projects into the current workspace by clicking “Project->Import CCS Project”.
   a. Select the evaluation project by browsing as shown in Figure 10 to: "*\ti\c2000\C2000Ware_MotorControl_SDK_<version>\solutions\boostxl_3phganinv\f2837x\ccs\sensored_foc*".
   b. If there are multiple projects in this directory, then click and choose the projects to import. Click Finish. This copies all of the selected projects into the workspace. In Figure 10, there is only one project. Select it and click Finish.

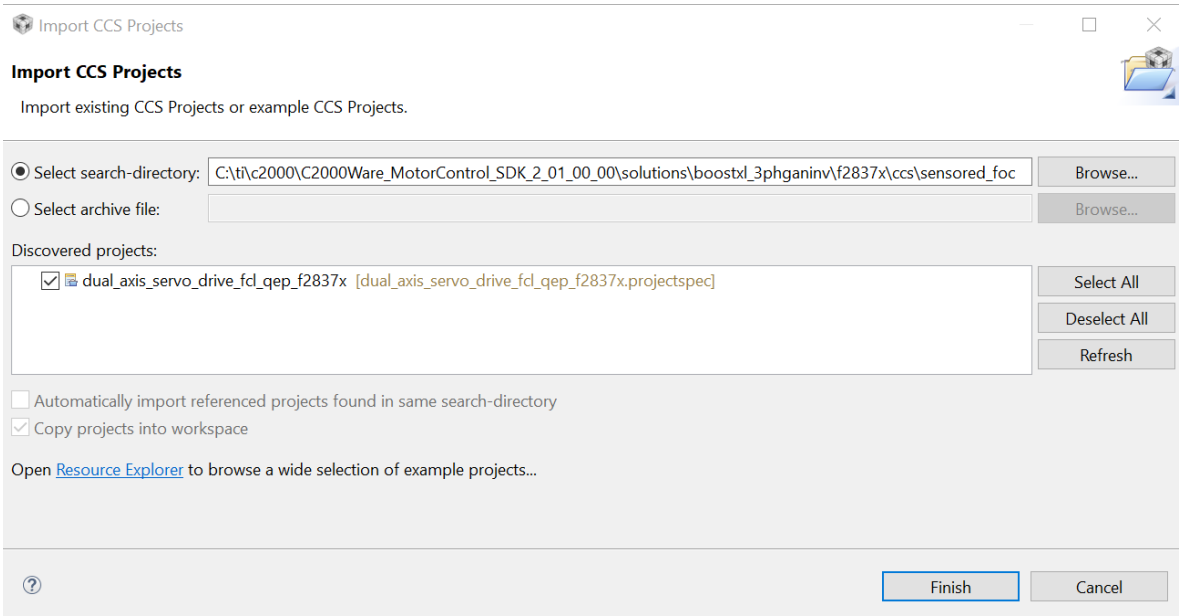


Figure 10. Adding Dual-Axis Drive Project to Workspace

Setting up the Target Configuration

1. Configure Code Composer Studio to know which MCU it will be connecting to. This is done by setting up the "Target Configuration". All of these are already set up and configured in "*TMS320F28379D.ccxml*" provided as part of the files in project. You can skip to step 5, if needed. However, for general information regarding setting up this configuration file, steps 1, 2 and 3 can be used.
2. A new configuration file can be set by clicking "File → New- → Target Configuration File" on the menu bar. This will open the Target Configuration window. In this window, give a name to the new configuration file depending on the target device. If "Use shared location" checkbox is checked, then this configuration file can be stored in a common location by CCS for use by other projects as well. Then, click Finish.
3. This should open up a new tab as shown in Figure 11. Select and enter the options as shown:
   a. Connection – Texas Instruments XDS100v2 USB Debug Probe.
   b. Device – the C2000 MCU on the control card, TMS320F28379D.
   c. Click Save and close.

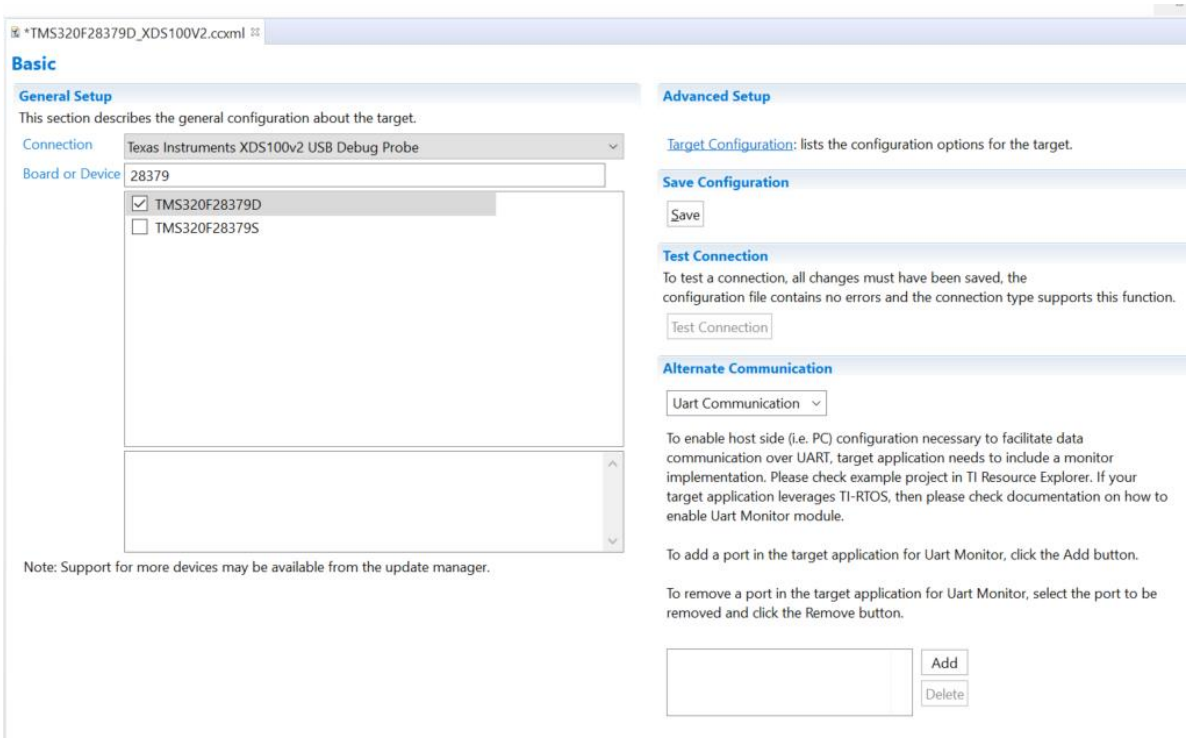


Figure 11. New Target Configuration

4. To use this configuration file, click "*View->Target Configurations*" on the menu bar. In the "User Defined" section, find the file that was created in step 1, 2 and 3. Right-click on this file and select "Set as Default".
5. To use the configuration file supplied with the project, click "*View->Target Configurations*", then expand "dual_axis_servo_drive_fcl_qep_f2837x" and right-click on the file "TMS320F28379D.ccxml" and "Set as Default". This tab also allows you to reuse existing target configurations and link them to specific projects.

Configuring a Project

1. The project can be configured to create code and run in either flash or RAM. You may select either of the two, however, for lab experiments use the RAM configuration most of the time and move to the FLASH configuration for production. As shown in Figure 12, right-click on an individual project and select "Build Configurations->Set Active->F2837x_RAM" configuration.

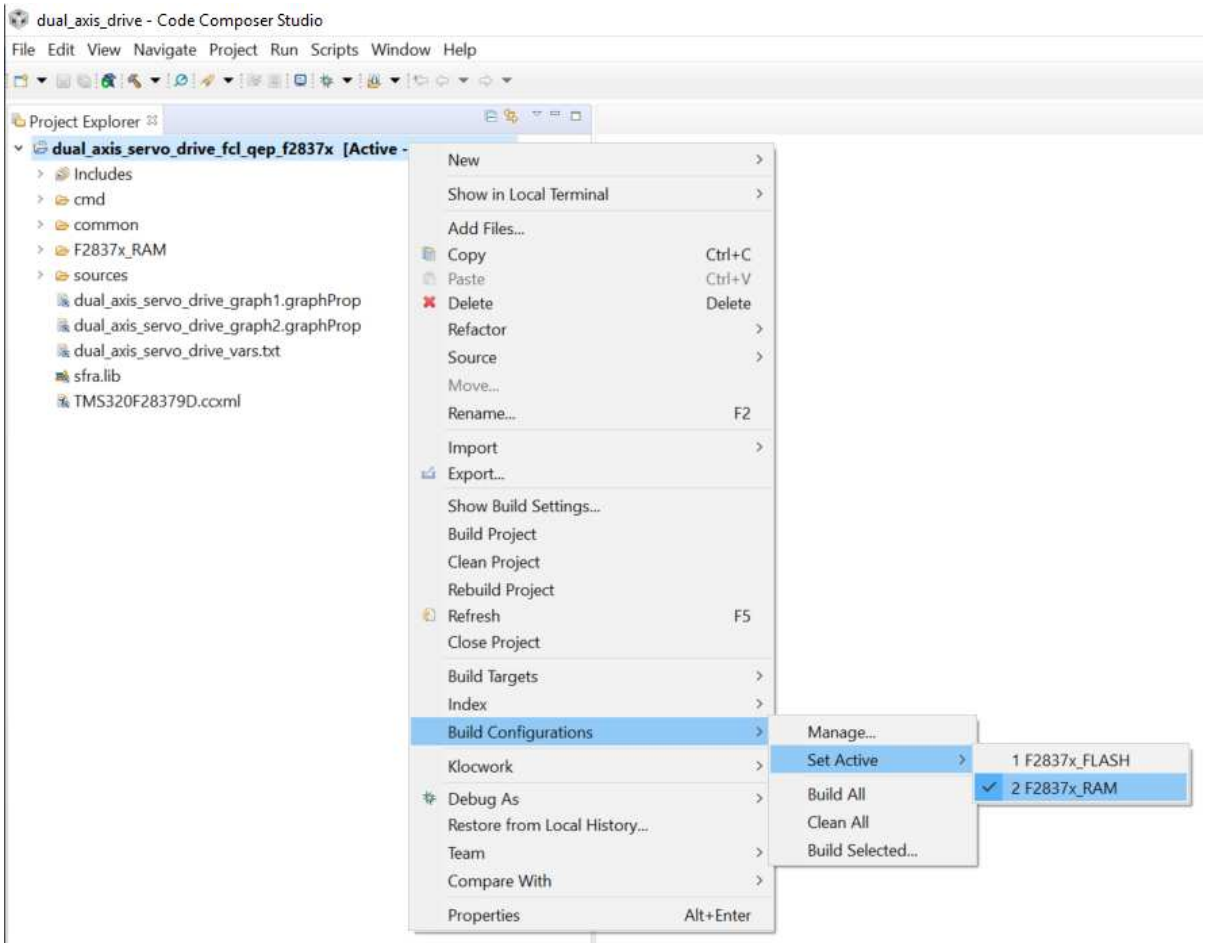


Figure 12. Selecting the F2837x_RAM Configuration

Build and Load the Project

1. The example project is provided with incremental builds where different components / macro blocks of the system are pieced together one by one to form the entire system. This helps in step by step debug and understanding of the system. From the CCS Edit Perspective, open the file "*dual_axis_servo_drive_settings.h*" and make sure that BUILDLEVEL is set to FCL_LEVEL1.
2. Open the "*dual_axis_servo_drive.c*" file and go to the function motor1ControlISR(). Locate the following piece of code in incremental build FCL_LEVEL1 and confirm that the datalog buffers are pointing to the right variables. These datalog buffers are large arrays that contain value-triggered data that can then be displayed to a graph. Note that in other incremental builds different variables may be put into this buffer to be graphed.
3. Now Right Click on the Project Name and click on “Rebuild Project” and watch the Console window. Any errors in the project will be displayed, which needs to be fixed. There may be some warning messages about certain functions or variables not being used. Such warning messages may be ignored, as they may be used in another build level.

Connecting the Hardware to Computer

1. Mount BoosterPack BOOSTXL-3PhGaNInv on LaunchPad headers J1-J4. DO NOT connect motor right now. Connect the LaunchPad to computer through an USB cable, this will light some LEDs on the emulator section of LaunchPad, indicating that the emulator is on. Power the BoosterPack with appropriate input dc voltage, 24V. This will glow various LEDs on both BoosterPack and LaunchPad.
2. Continuing from step 3 of "**Build and Load the Project**", on successful completion of the build, click the “Debug” button, located in the top-left side of the screen.
3. The IDE will now connect to the target, load the output file into the device and change to the Debug perspective.
4. Click “*Tools → Debugger Options → Program / Memory Load Options*”. You can enable the debugger to reset the processor each time it reloads program by checking “Reset the target on program load or restart” and click “Remember My Settings” to make this setting permanent.
5. Now click on the “Enable silicon real-time mode” button which also auto selects “Enable polite real-time mode” button . This allows you to edit and view variables in real-time. Do not reset the CPU without disabling these real time options!
6. A message box may appear. If so, select "YES" to enable debug events. This will set bit 1 (DGBM bit) of status register 1 (ST1) to a “0”. The DGBM is the debug enable mask bit. When the DGBM bit is set to “0”, memory and register values can be passed to the host processor for updating the debugger windows.

Configuring Expressions Window

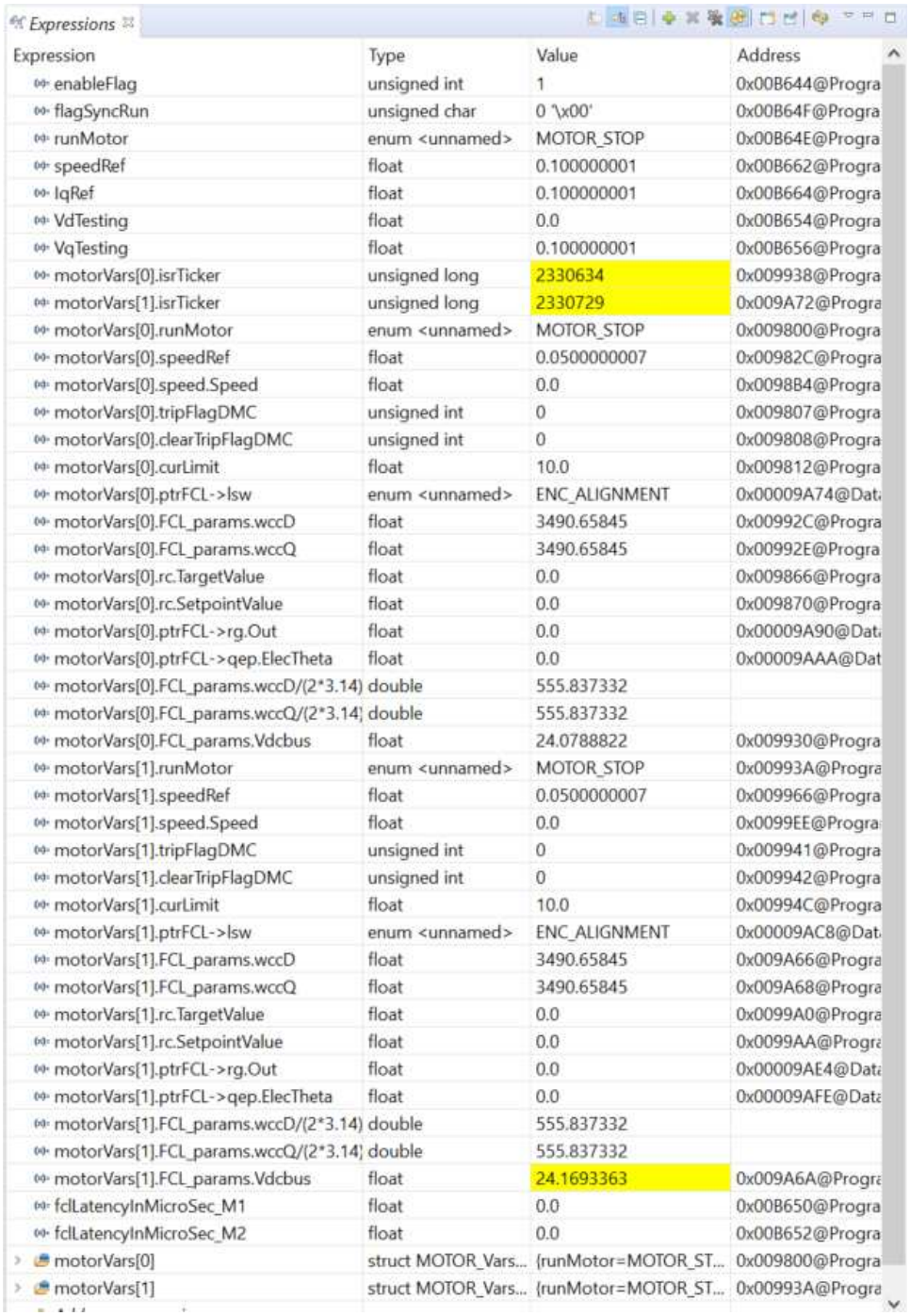
1. Click "*View- → Expressions*" on the menu bar to open an Expressions window to view the variables being used in the project. Add variables to the expressions window as shown below. It uses the number format associated with variables during declaration. You can select a desired number format for the variable by right clicking on it and choosing. Figure 13 shows a typical expressions window.

Expressions

Expression	Type	Value	Address
enableFlag	unsigned int	0	0x00B644@Program
flagSyncRun	unsigned char	0 '\x00'	0x00B64F@Program
runMotor	enum <unnamed>	MOTOR_STOP	0x00B64E@Program
speedRef	float	0.100000001	0x00B662@Program
IqRef	float	0.100000001	0x00B664@Program
VdTesting	float	0.0	0x00B654@Program
VqTesting	float	0.100000001	0x00B656@Program
motorVars[0]	struct MOTOR_Vars...	{runMotor=MOTOR_ST...	0x009800@Program
motorVars[1]	struct MOTOR_Vars...	{runMotor=MOTOR_ST...	0x00993A@Program

Figure 13. Configuring the Expressions Window

2. Alternately, a group of variables can be imported into the Expressions window, by right clicking within Expressions Window and clicking Import, and browse to the .txt file containing these variables. Here, browse to the directory of the project at "\ti\c2000\C2000Ware_MotorControl_SDK_<version>\solutions\common\sensored_foc\debug\" and pick "dual_axis_servo_drive_vars.txt" and click OK to import the variables shown in Figure 14.



Expressions

Expression	Type	Value	Address
enableFlag	unsigned int	1	0x00B644@Progra
flagSyncRun	unsigned char	0 '\x00'	0x00B64F@Progra
runMotor	enum <unnamed>	MOTOR_STOP	0x00B64E@Progra
speedRef	float	0.100000001	0x00B662@Progra
IqRef	float	0.100000001	0x00B664@Progra
VdTesting	float	0.0	0x00B654@Progra
VqTesting	float	0.100000001	0x00B656@Progra
motorVars[0].isrTicker	unsigned long	2330634	0x009938@Progra
motorVars[1].isrTicker	unsigned long	2330729	0x009A72@Progra
motorVars[0].runMotor	enum <unnamed>	MOTOR_STOP	0x009800@Progra
motorVars[0].speedRef	float	0.0500000007	0x00982C@Progra
motorVars[0].speed.Speed	float	0.0	0x0098B4@Progra
motorVars[0].tripFlagDMC	unsigned int	0	0x009807@Progra
motorVars[0].clearTripFlagDMC	unsigned int	0	0x009808@Progra
motorVars[0].curLimit	float	10.0	0x009812@Progra
motorVars[0].ptrFCL->lsw	enum <unnamed>	ENC_ALIGNMENT	0x00009A74@Dat
motorVars[0].FCL_params.wccD	float	3490.65845	0x00992C@Progra
motorVars[0].FCL_params.wccQ	float	3490.65845	0x00992E@Progra
motorVars[0].rc.TargetValue	float	0.0	0x009866@Progra
motorVars[0].rc.SetpointValue	float	0.0	0x009870@Progra
motorVars[0].ptrFCL->rg.Out	float	0.0	0x00009A90@Dat
motorVars[0].ptrFCL->qep.ElecTheta	float	0.0	0x00009AAA@Dat
motorVars[0].FCL_params.wccD/(2*3.14)	double	555.837332	
motorVars[0].FCL_params.wccQ/(2*3.14)	double	555.837332	
motorVars[0].FCL_params.Vdcbus	float	24.0788822	0x009930@Progra
motorVars[1].runMotor	enum <unnamed>	MOTOR_STOP	0x00993A@Progra
motorVars[1].speedRef	float	0.0500000007	0x009966@Progra
motorVars[1].speed.Speed	float	0.0	0x0099EE@Progra
motorVars[1].tripFlagDMC	unsigned int	0	0x009941@Progra
motorVars[1].clearTripFlagDMC	unsigned int	0	0x009942@Progra
motorVars[1].curLimit	float	10.0	0x00994C@Progra
motorVars[1].ptrFCL->lsw	enum <unnamed>	ENC_ALIGNMENT	0x00009AC8@Dat
motorVars[1].FCL_params.wccD	float	3490.65845	0x009A66@Progra
motorVars[1].FCL_params.wccQ	float	3490.65845	0x009A68@Progra
motorVars[1].rc.TargetValue	float	0.0	0x0099A0@Progra
motorVars[1].rc.SetpointValue	float	0.0	0x0099AA@Progra
motorVars[1].ptrFCL->rg.Out	float	0.0	0x00009AE4@Data
motorVars[1].ptrFCL->qep.ElecTheta	float	0.0	0x00009AFE@Data
motorVars[1].FCL_params.wccD/(2*3.14)	double	555.837332	
motorVars[1].FCL_params.wccQ/(2*3.14)	double	555.837332	
motorVars[1].FCL_params.Vdcbus	float	24.1693363	0x009A6A@Progra
fclLatencyInMicroSec_M1	float	0.0	0x00B650@Progra
fclLatencyInMicroSec_M2	float	0.0	0x00B652@Progra
motorVars[0]	struct MOTOR_Vars...	{runMotor=MOTOR_ST...	0x009800@Progra
motorVars[1]	struct MOTOR_Vars...	{runMotor=MOTOR_ST...	0x00993A@Progra

Figure 14. Variables Import for Project

3. The structure variables 'motorVars[0]' and 'motorVars[1]' have references to all peripherals and variables that are related to controlling dual motor. By expanding this variable, you can see them all and edit as needed.
4. Click on the Continuous Refresh button in the expressions window. This enables the window to run with real-time mode. By clicking the down arrow in this expressions window, you may select “Customize Continuous Refresh Interval” and edit the refresh rate of the expressions window. Note that choosing too fast an interval may affect performance.

Setting up Graphs

1. The datalog buffers point to different system variables depending on the build level. They provide a means to visually inspect the variables and judge system performance. Open and setup time graph windows to plot the data log buffers as shown below. Alternatively, the graph configurations files can be imported in the project folder by clicking '*Tools → Graph → DualTime*" on the menu bar and select import and browse to the following location at "*\ti\c2000\C2000Ware_MotorControl_SDK_<version>\solutions\common\sensored_foc\debug*" and select "*dual_axis_servo_drive_graph1.graphProp*", the Graph Properties window should now look like the Figure 15. Click OK, this should add the Graphs to your debug perspective. Click on Continuous Refresh button on the top left corner of the graph tab. If there is no real time graph in the window, click the Reset Graph button, and then click Continuous Refresh button again.

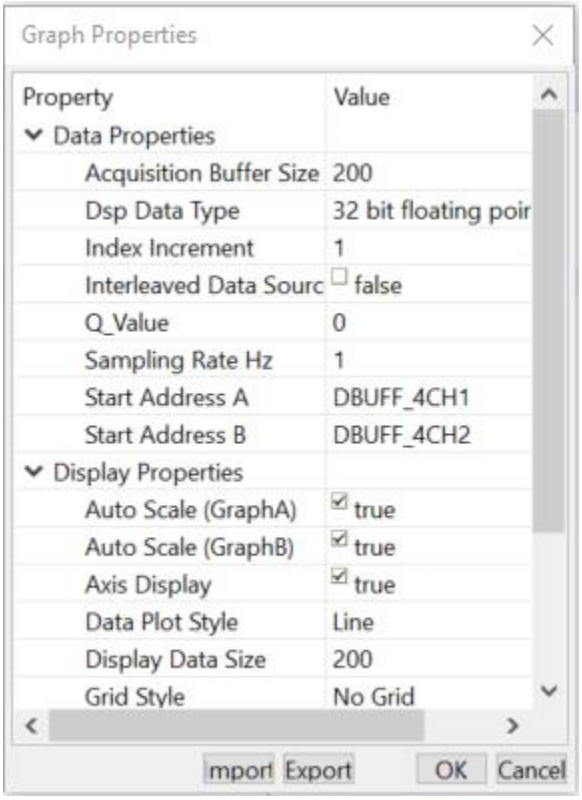


Figure 15. Graph Window Settings

NOTE:

- If a second graph window is used, you could import dual_axis_servo_drive_graph2.graphProp, the start Addresses for this should be DBUFF_4CH3 and DBUFF_4CH4.
- The default 'dlog.prescaler' is set to 5 which will allow the dlog function to only log one out of every five samples.
- The default 'dlog.trig_value' should be set to the right value to generate trigger for the plot as in oscilloscopes.

Run the Code

1. Run the code by clicking Run Button in the Debug Tab
2. In the Expressions window, set the variable ‘enableFlag’ to 1.
3. The project should now run, and the values in the graphs and expressions window should continuously update. Figure 16 and Figure 17 are some screen captures of typical CCS perspectives while using this project. You may want to resize the windows according to your preference. At this time, details of variables and graph are not discussed as they will be discussed in later sections
4. Once complete, turn off Real Time mode, then reset the processor (Run->Reset->CPU Reset) and then terminate the debug session by clicking Terminate in the Debug Tab. This halts the program and disconnects Code Composer from the MCU.

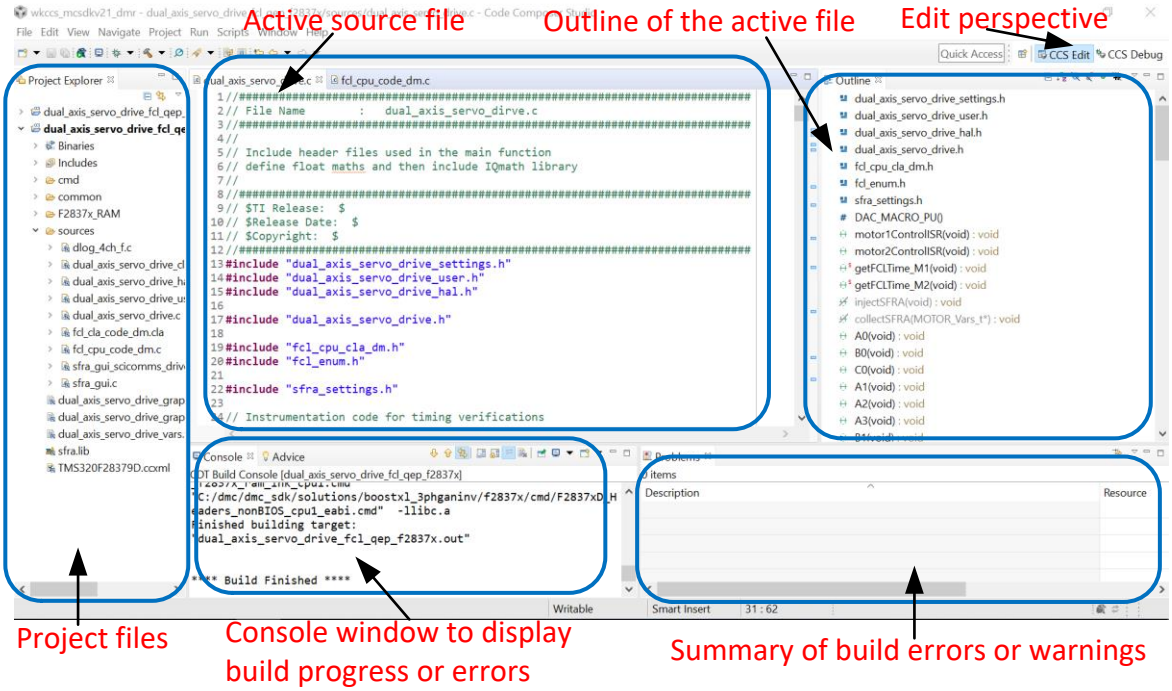


Figure 16. CCS IDE Showing Edit Perspective

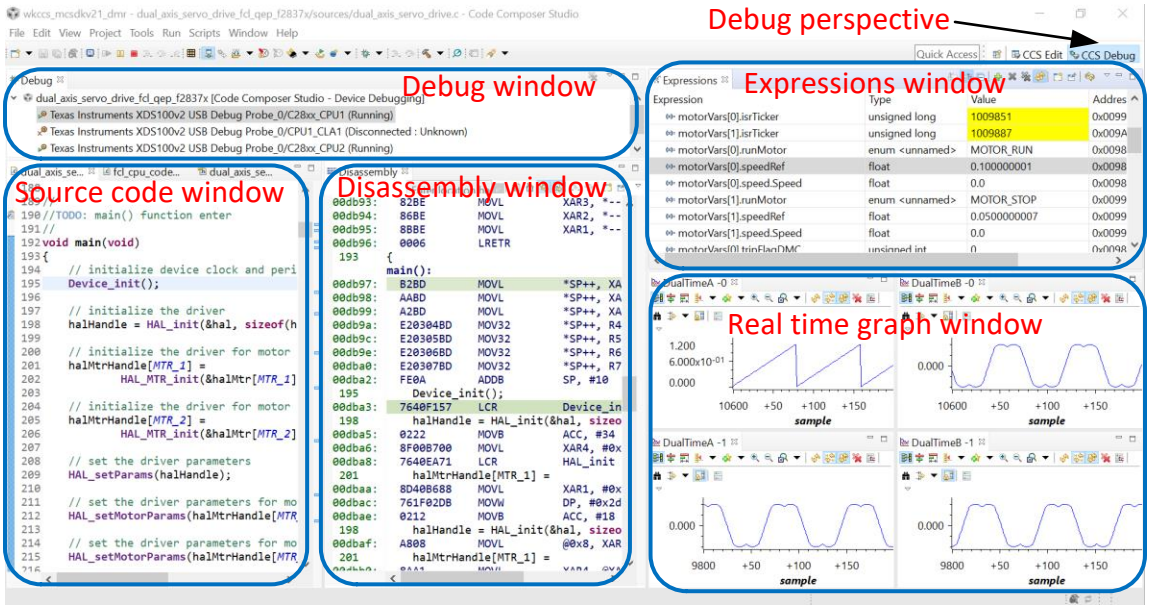


Figure 17. CCS IDE Showing Debug Perspective

Step 10. Next Operations

1. It is not necessary to terminate the debug session each time you change or run the code again. Instead the following procedure can be followed.
   a. Disable real time options, terminate the project, reset CPU (Run->Reset->CPU Reset) , rebuild and reload the project if changed the code.
   b. Disable real time options, terminate the project, reset CPU (Run->Reset->CPU Reset) , (Run->Restart), and enable realtime options if without changing the code.
   c. Terminate the project if the target device or the configuration is changed (Ram to Flash or Flash to Ram) prior to shutting down CCS.
2. The header file "dual_axis_servo_drive_settings.h" and "dual_axis_servo_drive_user.h" in the CCS Edit Perspective has macro definitions for motor control. You can change these parameters as needed after thinking through the impact of such change.
3. You can proceed to experiment various build levels in detail.

7 System Software Integration and Testing

This section deals with various incremental build levels starting from first level up to the final level where the system is fully integrated. After full integration, SFRA GUI is called into initiate frequency response analysis in the selected loop and the Bode plot is displayed by the GUI. Various trials can be performed at this point tweaking various parameters for performance tuning.

7.1 Incremental Build Level 1

The block diagram of the system built in BUILD LEVEL 1 is shown in Figure 18. During this step, keep the motor disconnected.

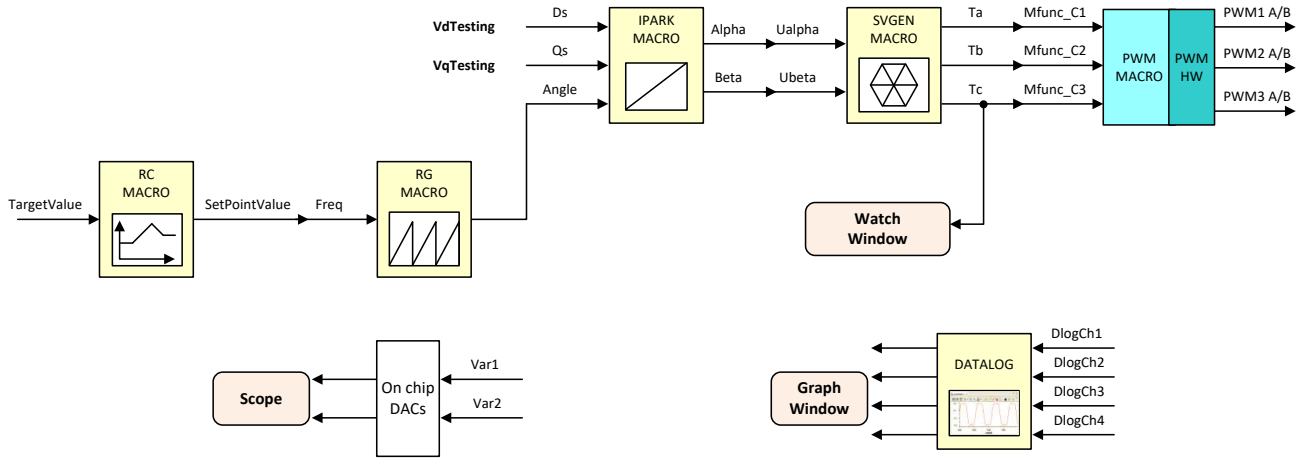


Figure 18. Level 1 Block Diagram

Assuming the load and build steps described in the Section 6.2.2 completed successfully. This section describes the steps for a minimum system check-out, which confirms operation of system interrupt, the peripheral and target independent inverse park transformation, space vector generator modules, and the peripheral dependent PWM initialization and update modules.

1. Open "*dual_axis_servo_drive_settings.h*" from the project directory. Select the level 1 incremental build option by setting the BUILDLEVEL to FCL_LEVEL1 (#define BUILDLEVEL FCL_LEVEL1).
2. Right click on the project name and click Rebuild Project.
3. When the build is complete, click on debug button, reset CPU, restart, enable real time mode, and run.
4. Add variables to the expressions window by right clicking within the Expressions Window and importing the file "*dual_axis_servo_drive_vars.txt*" from the debug directory and the expressions window will look as shown in Figure 14 in Section 6.2.2.
5. Set '*enableFlag*' to 1 in the expressions window. The variables named '*motorVars[0].isrTicker*' and '*motorVars[1].isrTicker*' are incrementally increased as shown in Expressions window to confirm the interrupts are working properly. In the software, the key variables within the structure of 'motorVars[0]' and 'motorVars[1]' to be adjusted are summarized below:
   a. motorVars[0].speedRef: for changing the rotor speed in per-unit.
   b. VdTesting: for changing the d-qxis voltage in per-unit.
   c. VqTesting: for changing the q-axis voltage in per-unit.

NOTE: The tests suggested below for motor 1 by setting 'motorVars[0]' that can be repeated for motor 2 by setting 'motorVars[1]' also to verify the hardware and software integrity in subsequent build levels.

7.1.1 SVGEN Test

The 'speedRef' value is fed into the ramp control module to ramp up the speed command. The output of the ramp module is fed into a ramp generator to generate the angle for sine wave generation. This angle as well as the variables VdTesting and VqTesting feeds into inverse park transformation block which then feeds into space vector modulation modules to generate three phase PWMs.

The PWM outputs from C2000 controller can be probed on scope a shown in Figure 19. There is a 90° shift between the PWM output of motor 1 and motor 2.

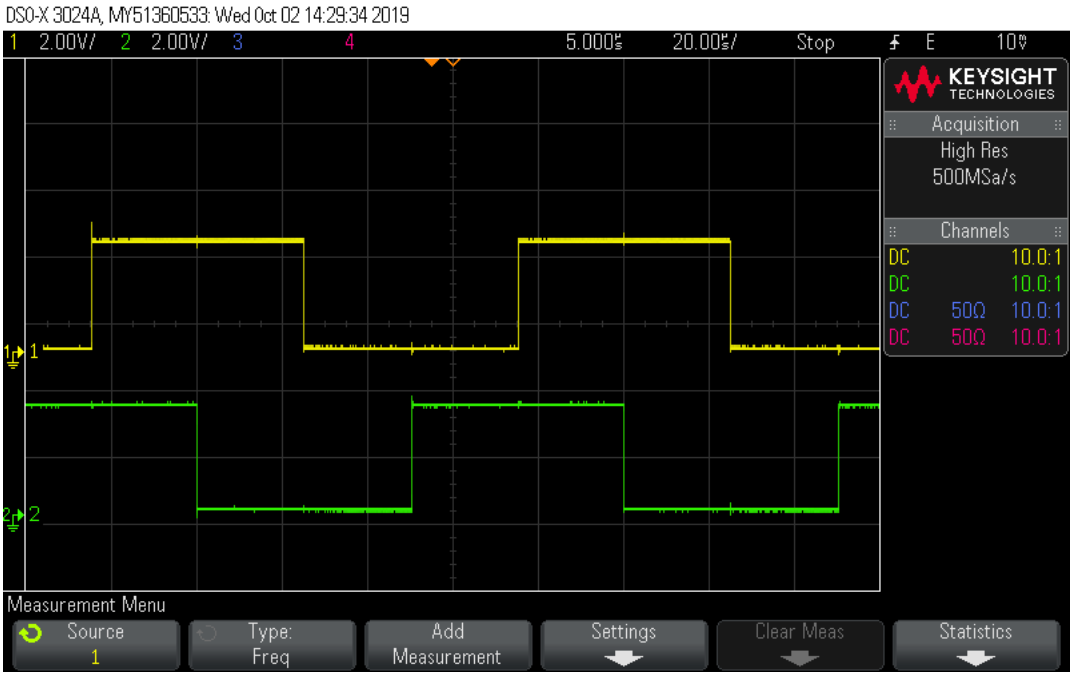


Figure 19. PWM_UH of Motor 1 and Motor 2 on Scope Plots

The outputs from space vector generation module can be viewed using the graph tool from the debug environment as "**Setup Graphs"** operation step in Section 6.2.2.

Figure 20 shows the voltage vector angle, and the pulse width values for the phases A, B, and C and are denoted as Ta, Tb, and Tc, where Ta, Tb, and Tc waveform are 120° apart from each other. Specifically, Tb lags Ta by 120° and Tc leads Ta by 120°.These are generated based on the values of 'motorVars[0].speedRef','VdTesting' and 'VqTesting'. These values can be changed to see the impact on these waveform. Check the PWM test points on the board to observe PWM pulses and ensure that the PWM module is running properly.

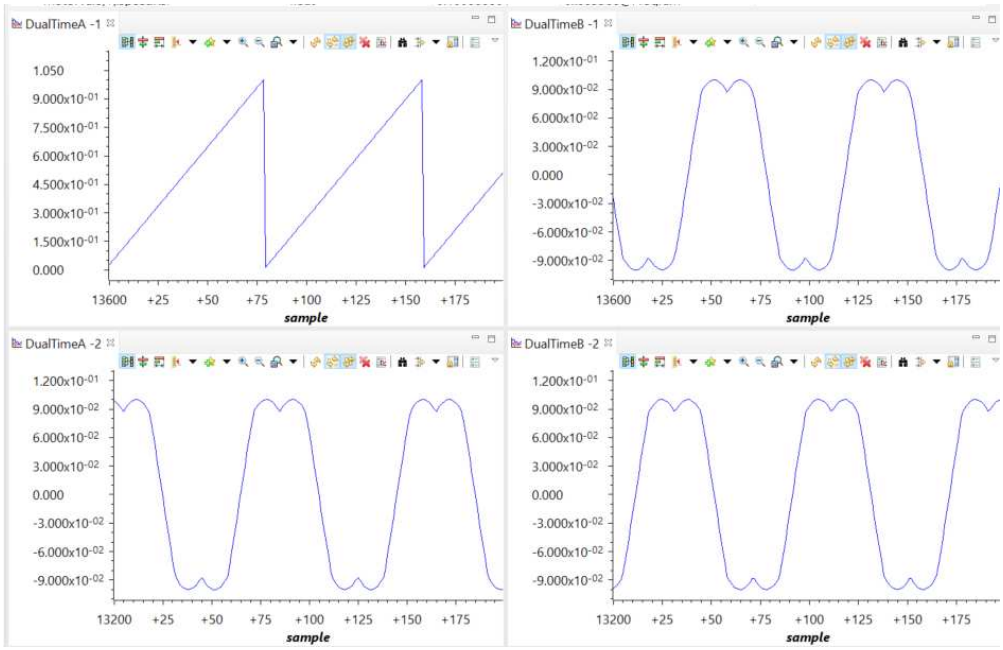


Figure 20. Voltage Vector Angle and SVGEN Ta, Tb, and Tc Using Graph Tool

NOTE: The operation suggested above for motor 1 by setting 'motorVars[0]' that can be repeated for motor 2 by setting 'motorVars[1]' also to verify the related modules. To use the graph tool for motor 2, change the datalog pointer to the space vector generator module of motor 2 as the following example code in motor1ControlISR() in " dual_axis_servo_drive.c".

```
// ---------------------------------------------------------------------------
// Connect inputs of the DATALOG module
// ---------------------------------------------------------------------------
    dlogCh1 = motorVars[1].ptrFCL->rg.Out;
    dlogCh2 = motorVars[1].svgen.Ta;
    dlogCh3 = motorVars[1].svgen.Tb;
    dlogCh4 = motorVars[1].svgen.Tc;
```

7.1.2 Testing SVGEN With DACs

To monitor internal signal values in real time, on-chip DACs are used. DACs are part of the analog module DACs A and B are available for this purpose. This is shown in Figure 21.

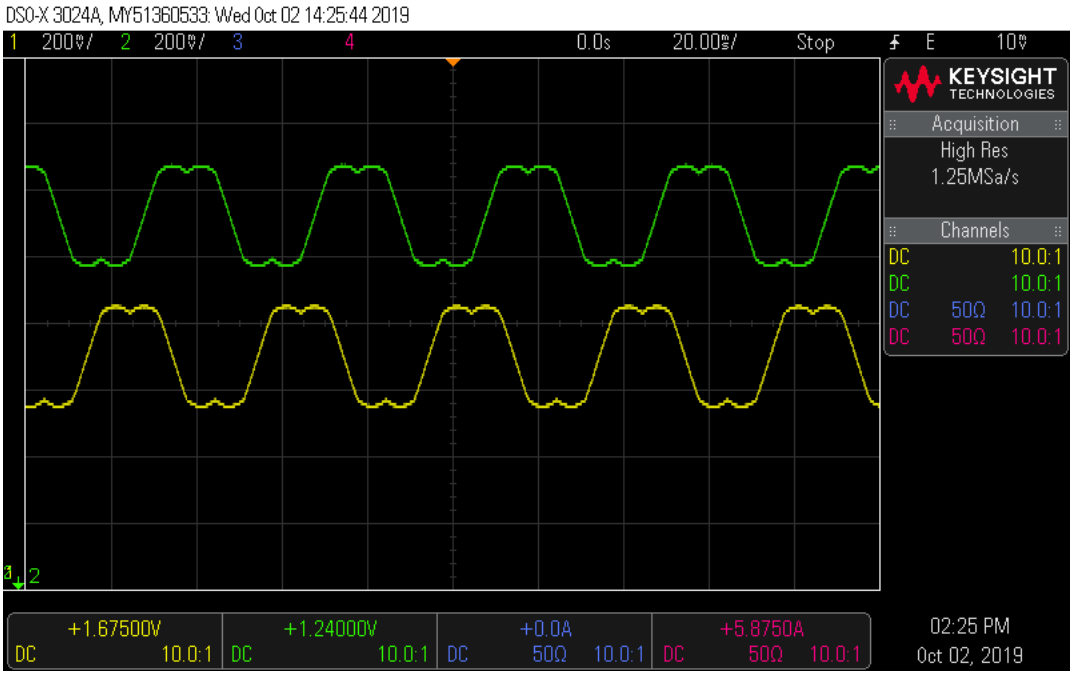


Figure 21. DAC Outputs Showing Ta, Tb Waveform

The operation suggested above for motor 1 that can be repeated for motor 2 also to verify the related modules. To use DACs for motor 2, change the linked variables to DACs for motor 2 as the following example code in motor1ControlISR() in " dual_axis_servo_drive.c".

```
//-----------------------------------------------------------------------------
// Variable display on DACs
//-----------------------------------------------------------------------------
    DAC_setShadowValue(hal.dacHandle[0], DAC_MACRO_PU(motorVars[1].svgen.Ta));
    DAC_setShadowValue(hal.dacHandle[1], DAC_MACRO_PU(motorVars[1].svgen.Tb));
```

NOTE: Remove the R20 on both BOOSTXL-3PhGaNInv boards, or disconnect J3-30 and J7-70 pins to both BOOSTXL-3PhGaNInv boards.

7.1.3 Inverter Functionality Verification

After verifying the space vector generation and PWM modules, the 3-phase inverter hardware can be tested by looking at inverter outputs U, V, and W on a scope. This can be compared against the PWM pulses fed into the inverter. It is advisable to gradually increase the DC bus voltage or change 'VdTesting' and 'VqTesting' values during this test. Check inverter outputs U, V, and W using an oscilloscope with respect to the inverter GND, while taking care of scope isolation requirements. This ensures that the inverter is working properly.

CAUTION

After verifying this, take the controller out of real time mode (disable), reset the processor. Note that after each test, this step needs to be repeated for safety purposes, otherwise an improper shutdown might halt the PWMs at certain states where the inverter can draw currents high enough to damage itself. Hence caution needs to be taken while doing these experiments.

7.2 Incremental Build Level 2

The control block diagram of the system built in BUILDLEVEL 2 for each motor is shown in Figure 22. Assuming build 1 is completed successfully, this section verifies the over current protection limits of the inverter and QEP interface running out of CLA. In this build, the motor is run in open loop.

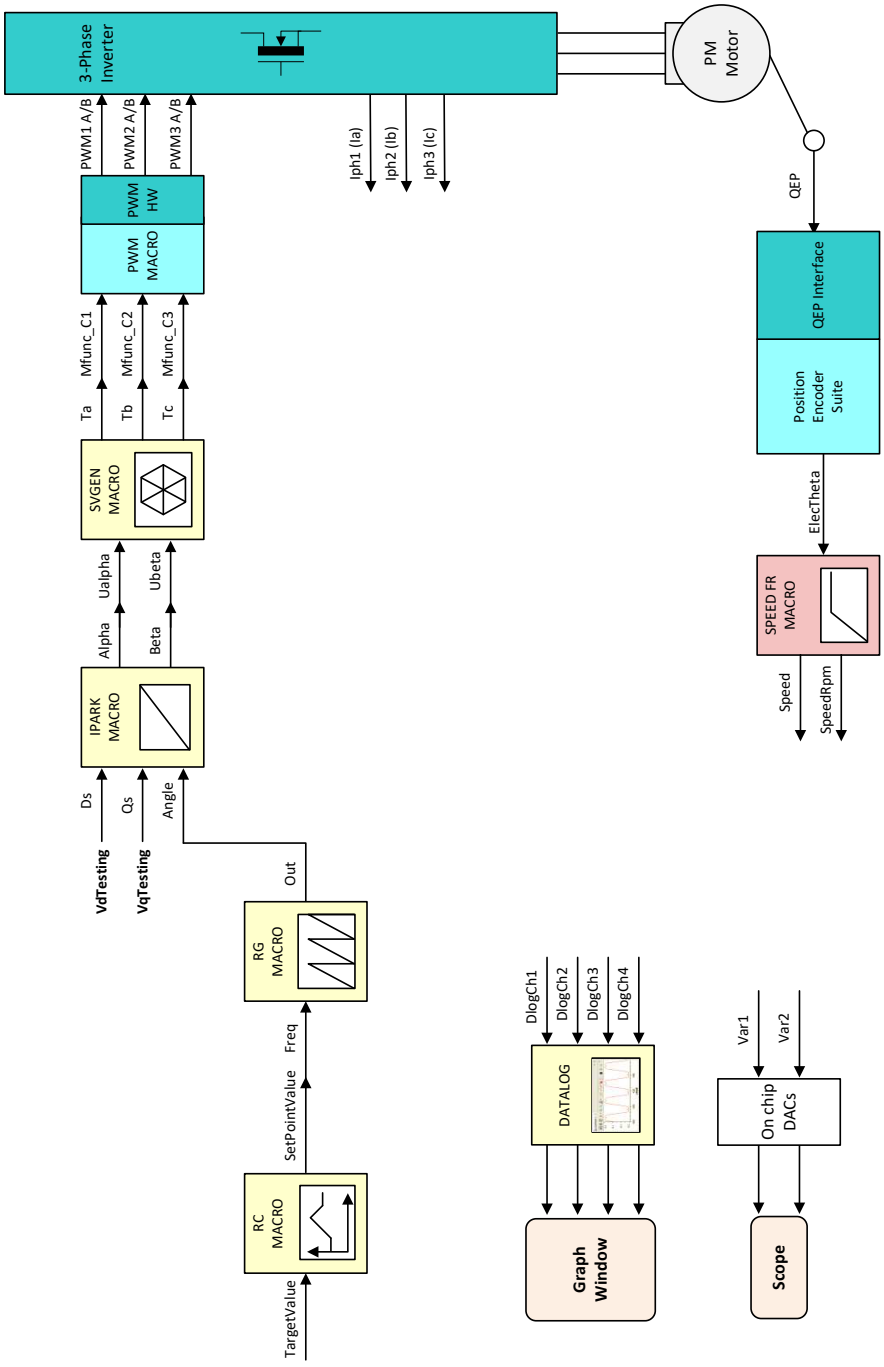


Figure 22. Level 2 Block Diagram

7.2.1 Connecting motor to INVs

Testing both motors at the same time with a coupled shaft, as shown in Figure 8, leads to chaotic behavior. If the assembly is already made, then it is better to test only one motor at a given time. Turn off DC bus voltage before connecting or disconnecting motor 1 or 2 to INV1 or INV2. To test motor 1, connect motor 1 power terminals to INV1 while keeping motor 2 terminals disconnected and safely insulated from each other. This is to avoid any short circuit between motor 2 phases whenever the shaft spins. Once motor 1 / INV1 test is complete, disconnect motor 1 from INV1 and keep its terminals safely insulated from each other. Then connect motor 2 terminals to INV2 for motor 2/ INV2 tests.

If the motor shafts are disengaged, then both motors can be connected to INV1 and INV2 and tested simultaneously. This operation is required in subsequent build levels.

7.2.2 Testing the Motors and INVs

The motor and INV can be tested by following the steps given below, as the PWM signals are already successfully proven through level 1 incremental build. Connect motor 1 to INV1 and / or motor 2 to INV2 as discussed earlier.

1. Open "*dual_axis_servo_drive_settings.h*" and select level 2 incremental build option by setting the BUILDLEVEL to LEVEL2 (#define BUILDLEVEL FCL_LEVEL2).
2. Select POSITION_ENCODER to QEP_POS_ENCODER. (The same setting for subsequent build levels).
3. Right-click on the project name and click "Rebuild Project".
4. When the build is complete, click on debug button, reset CPU, restart, enable real time mode, and run.
5. Set '*enableFlag*' to 1 in the expressions window. The variables named '*motorVars[0].isrTicker*' and '*motorVars[1].isrTicker*' are incrementally increased as shown in Expressions window to confirm the interrupts are working properly. Now set the variable named 'motorVars[0].runMotor' to MOTOR_RUN, the motor 1 starts spinning after a few seconds if enough voltage is applied to the DC-Bus. In the software, the key variables to be adjusted are as follows:
   a. motorVars[0].speedRef: for changing the rotor speed in per-unit
   b. VdTesting: for changing the d-axis voltage in per-unit
   c. VqTesting: for changing the q-axis voltage in per-unit

During the open loop tests, the variables 'VdTesting', 'VdTesting', 'motorVars[0].speedRef' and DC bus voltage must be adjusted carefully so that the motor runs smoothly without stalling or vibrating.

NOTE: Set 'motorVars[0].clearTripFlagDMC' or 'motorVars[1].clearTripFlagDMC' to 1 to clear the fault flag if the variable, 'motorVars[0].tripFlagDMC' or 'motorVars[1].tripFlagDMC' equals to 1, otherwise, the motorVars[0].runMotor or motorVars[1].runMotor cannot be set to MOTOR_RUN.

7.2.3 Setting Over-current Limit in the Software

Over-current monitoring is provided using on-chip comparator subsystem (CMPSS) module. The module has a programmable comparator and a programmable digital filter, the comparator generates the protection signal. The reference to the comparator is user programmable for both positive and negative currents limits. The digital filter module qualifies the comparator output signal, verifying its integrity by periodically sampling and validating the signal for a certain count time within a certain count window, where the periodicity, count, and count window are user programmable.

In the Expressions window, you can see the 'motorVars[0].curLimit' variable that sets the permitted current maximum through inline current shunt sensor.

'motorVars[0].tripFlagDMC' is a flag variable that represents the over-current trip status of the inverter. If this flag is set, then you can adjust the above settings and retry running the inverter by setting the flag 'motorVars[0].clearTripFlagDMC' to 1. This clears 'motorVars[0].tripFlagDMC', and clears the status in related CMPSS registers, and restarts the PWMs for the inverter.

The default current limit setting is to shut down the inverter if the phase current magnitude is greater than 6A. You can fine tune any of these settings to suit their needs. Once satisfactory values are identified, write them down, modify the code with these new values, and rebuild and reload for further tests.

7.2.4 Setting Current Regulator Limits

The outputs of the current regulators control the voltages applied on the d-axis and q-axis of the motor. The vector sum of the d and q outputs must be less than 1.0, which refers to the maximum duty cycle for PWM generation algorithm. In this particular application, the maximum allowed duty cycle is lesser than 1.0 due to the impact of ADC conversion time and PWM computation time. Higher computational speeds allow higher duty cycle operation and better use of the DC bus voltage.

The current regulator output is represented by the variable 'motorVars[0].pi_id.out' and 'motorVars[0].ptrFCL->pi_iq.out'. The regulator limits are set by 'motorVars[0].pi_id.Umax/min', and 'motorVars[0].ptrFCL->pi_iq.Umax/min'.

Bring the system to a safe stop by reducing the bus voltage to zero, taking the controller out of real-time mode, and resetting.

7.2.5 Position Encoder Feedback

During all the above tests, the QEP interface was continuously estimating position information. When the motor is commanded to run, it is taken through an initial alignment stage where the electrical angle and the QEP angle count are set to zero, before the rotor spins continuously. Reference position (motorVars[0].ptrFCL → rg.Out) and encoder feedback angle (motorVars[0].ptrFCL->qep.ElecTheta) signals, when plotted using DACs on J3-30 and J7-70 pins, should look as shown in Figure 23

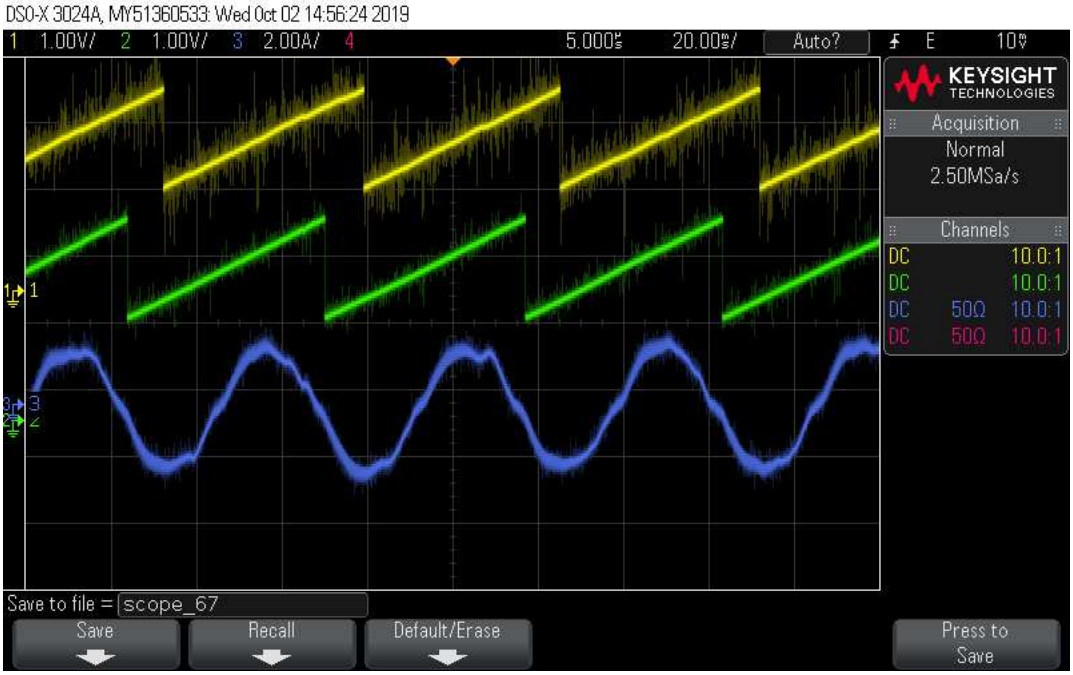
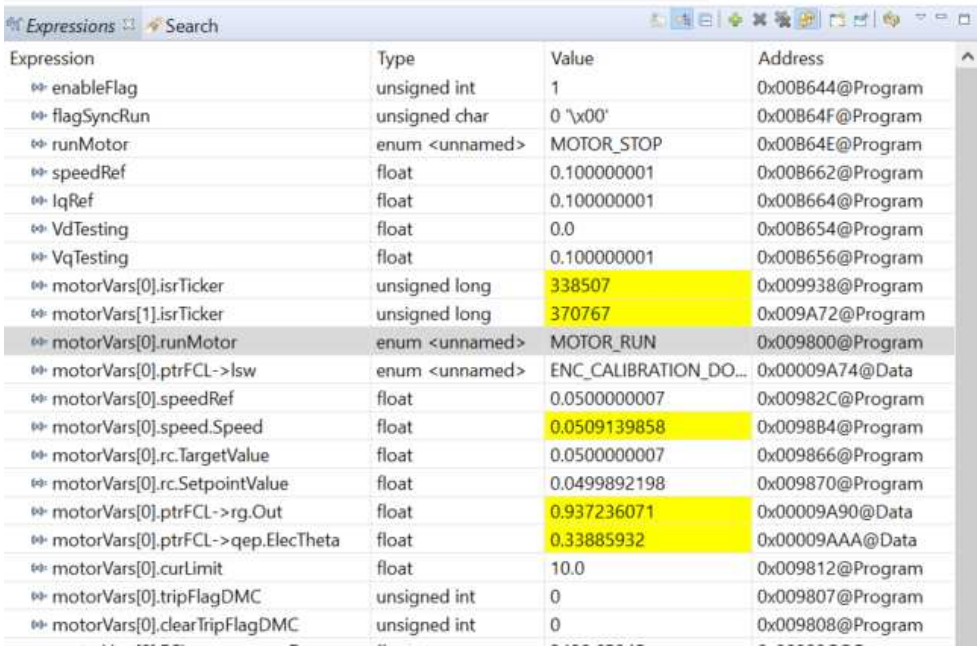


Figure 23. DAC Outputs on Scope Showing Reference Angle and Rotor Position

The waveform of channel 1 represents the reference position, while channel 2 represents the feedback position from QEP encoder. The ripple in feedback position estimate is indicative of the fact that the motor runs with some minor speed oscillation. Because of open loop control, the rotor position and reference position may not align. However, it is important to make sure that the sense of change of estimated angle should be same as that of the reference; otherwise, it indicates that the motor has a reverse sense of rotation. This can be fixed by swapping any two wires connecting the motor.

To ensure that the function runSpeedFR() works, change the 'motorVars[0].speedRef' variable in the Expressions window as shown in Figure 24, and check whether the estimated speed variable, 'motorVars[0].speed.Speed', follows the commanded speed. Because the motor is a PM motor, where there is no slip, the running speed follows the commanded speed regardless of the control being open loop.



Expression	Type	Value	Address
enableFlag	unsigned int	1	0x008644@Program
flagSyncRun	unsigned char	0 '\x00'	0x00864F@Program
runMotor	enum <unnamed>	MOTOR_STOP	0x00864E@Program
speedRef	float	0.100000001	0x008662@Program
IqRef	float	0.100000001	0x008664@Program
VdTesting	float	0.0	0x008654@Program
VqTesting	float	0.100000001	0x008656@Program
motorVars[0].isrTicker	unsigned long	338507	0x009938@Program
motorVars[1].isrTicker	unsigned long	370767	0x009A72@Program
motorVars[0].runMotor	enum <unnamed>	MOTOR_RUN	0x009800@Program
motorVars[0].ptrFCL->lsw	enum <unnamed>	ENC_CALIBRATION_DO...	0x00009A74@Data
motorVars[0].speedRef	float	0.0500000007	0x00982C@Program
motorVars[0].speed.Speed	float	0.0509139858	0x0098B4@Program
motorVars[0].rc.TargetValue	float	0.0500000007	0x009866@Program
motorVars[0].rc.SetpointValue	float	0.0499892198	0x009870@Program
motorVars[0].ptrFCL->rg.Out	float	0.937236071	0x00009A90@Data
motorVars[0].ptrFCL->qep.ElecTheta	float	0.33885932	0x00009AAA@Data
motorVars[0].curLimit	float	10.0	0x009812@Program
motorVars[0].tripFlagDMC	unsigned int	0	0x009807@Program
motorVars[0].clearTripFlagDMC	unsigned int	0	0x009808@Program

Figure 24. Reference and Feedback Speed Expressions Window

When the tests are complete, set ‘motorVars[0].runMotor’ to MOTOR_STOP to stop the motor, bring the system to a safe stop by reducing the bus voltage, taking the controller out of real-time mode, and resetting it. Now, the motor stops.

The same set of tests can be done on motor 2 by working with structure variable 'motorVars[1]'. Once done, take the controller out of real time mode and reset.

7.3 Incremental Build Level 3

Assuming the previous section is completed successfully, this section verifies the dq-axis current regulation performed by the FCL. One of the two current controllers can be chosen: PI or complex. The loop bandwidth can be set in the debug window. The implementation block diagram is given in Figure 25. The two motors shafts must be kept disconnected for more clarity.

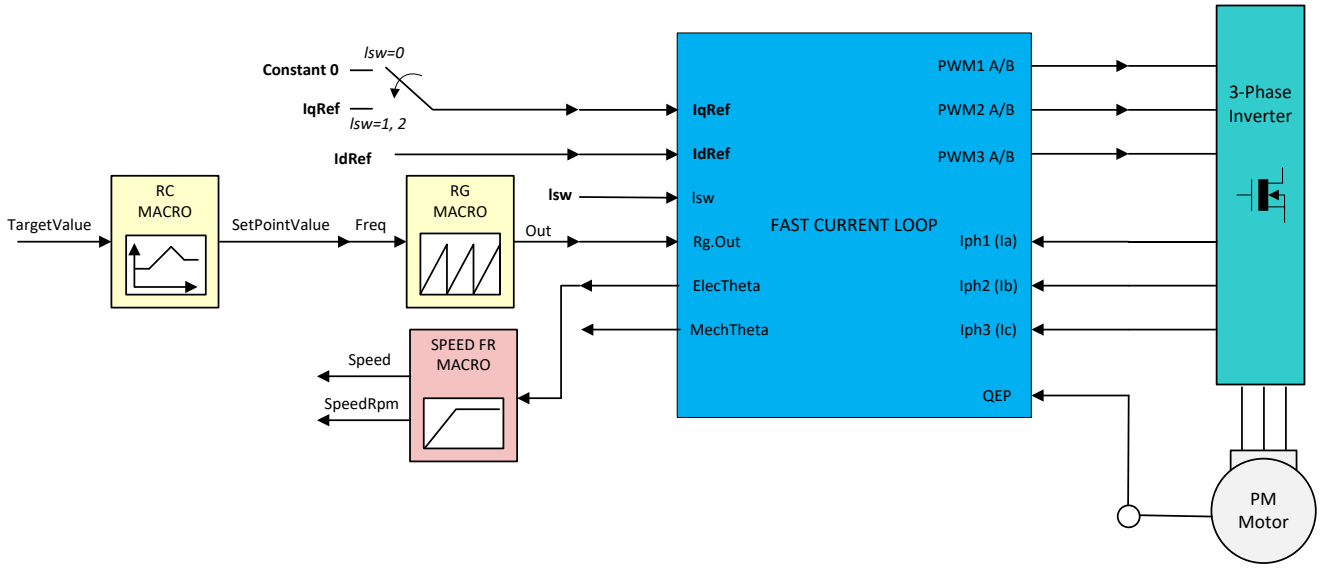


Figure 25. Level 3 Block Diagram Showing Inner Control Loop - FCL

WARNING

In this build, control is done based on the actual rotor position and the motor can run at higher speeds if the commanded 'IqRef' is higher and if there is no load on the motor. Therefore, it is advised to either add some mechanical load on the motor before the test or to apply lower values of 'IqRef'.

At start up, the motors are taken through QEP calibration phase where each motor takes turns to calibrate its QEP's angular offset with respect to its stator angle zero. To start with, motor goes through an alignment and then spins slowly based on an enforced angle waiting on index pulse for calibration. After the index pulse is received, it goes to float mode.

After calibration is done, when any of the motor is commanded to run, it runs in full self-control mode based on its own angular position. This calibration step happens for this build level and beyond. Since the calibration routine calibrates both motors, connect both motors but the shafts need not be connected together necessarily yet. If the shafts are already coupled, only one motor can be tested at a given time, otherwise both motors can be tested simultaneously.

1. Open "dual_axis_servo_drive_settings.h" and select level 3 incremental build option by setting the BUILDLEVEL to FCL_LEVEL3 (#define BUILDLEVEL FCL_LEVEL3). The current loop regulator can be selected to be the PI controller or the complex controller by setting FCL_CNTLR to PI_CNTLR or CMPLX_CNTLR. The current and position feedbacks can be sampled once or twice per PWM period depending on the sampling method. The sampling is synchronized to carrier max in single sampling method and to carrier max and carrier zero in double sampling method. This sample method selection is done in the example by selecting SAMPLING_METHOD to SINGLE_SAMPLING or SAMPLING_METHOD to DOUBLE_SAMPLING.

   NOTE: The maximum modulation index changes from 0.98 in SINGLE_SAMPLING method to 0.96 in DOUBLE_SAMPLING method. If the PWM_FREQUENCY is changed from 10 KHz, the maximum modulation index also changes.

2. Right-click on the project name, then click Rebuild Project.
3. When the build is complete, click the Debug button, reset the CPU, restart, enable real-time mode, and run. In the software, within the '*motorVars[0]*' structure, the key variables to add, adjust, or monitor are summarized as follows:
   a. motorVars[0].runMotor : flag to MOTOR_RUN or MOTOR_STOP the motor.
   b. motorVars[0].maxModIndex: maximum modulation index.
   c. motorVars[0].IdRef_run : changes the d-axis voltage in per-unit.
   d. motorVars[0].IqRef : changes the q-axis voltage in per-unit.
   e. motorVars[0].FCL_params.WccD : preferred bandwidth of d-axis current loop.
   f. motorVars[0].FCL_params.WccQ : preferred bandwidth of q-axis current loop.
   g. motorVars[0].fclLatencyInMicroSec: shows latency between ADC and QEP sampling, and PWM in µs.
   h. motorVars[0].fclClrCnt: flag to clear the variable motorVars[0].fclLatencyInMicroSec and let it refresh.
4. Set '*enableFlag*' to '1' in the expressions window. The variables named '*motorVars[0].isrTicker*' and '"*motorVars[1].isrTicker*' are incrementally increased as shown in Expressions window to confirm the interrupts are working properly.
5. Verify if the 'motorVars[0].maxModIndex' value is either 0.96 in double-sampling method or 0.98 in single-sampling method.
6. Set 'motorVars[0].speedRef' to 0.3 pu (or another suitable value if the base speed is different), 'motorVars[0].IdRef_run' to zero, and 'motorVars[0].IqRef' to 0.05 pu (or another suitable value). 'motorVars[0].speedRef' helps only until the QEP index pulse is received. Thereafter, the motor is controlled based on its rotor position. The soft-switch variable (motorVars[0].ptrFCL->lsw) is auto promoted in a sequence inside the FCL. In the code, 'motorVars[0].ptrFCL->lsw' manages the loop setting as follows:
   a. lsw = ENC_ALIGNMENT --> lock the rotor of the motor
   b. lsw = ENC_WAIT_FOR_INDEX --> motor in running mode, waiting for first instance of QEP Index pulse
   c. lsw = ENC_CALIBRATION_DONE --> motor in running mode, first Index pulse of encoder occurred
7. Gradually increase voltage at DC power supply to, for example, 20% of the rated voltage.
8. Set 'motorVars[0].runMotor' flag to MOTOR_RUN to run the motor.
9. Check 'motorVars[0].pi_id.fbk' in the watch windows with continuous refresh feature and see if it can track 'motorVars[0].IdRef'.
10. Check 'motorVars[0].ptrFCL->pi_iq.fbk' in the watch windows with continuous refresh feature and see if it can track 'motorVars[0].IqRef'.
11. To confirm these two current regulator modules, try different values of 'motorVars[0].pi_id.ref' and 'motorVars[0].ptrFCL->pi_iq.ref' by changing 'motorVars[0].IdRef_run' and 'motorVars[0].IqRef' respectively.

12. Try different bandwidths for the current loop by tweaking the values of 'motorVars[0].FCL_params.wccD' and 'motorVars[0].FCL_params.wccQ'. The default setting for the bandwidth is 1/18 of the sampling frequency.
13. If the motor shaft can be held tight, then the 'motorVars[0].IqRef' value can be changed back and forth from 0.5 to–0.5, to study the effect of loop bandwidth.
14. Set ‘motorVars[0].runMotor’ to MOTOR_STOP to stop the motor.
15. Bring the system to a safe stop by reducing the bus voltage, taking the controller out of real-time mode, and resetting. Now the motor stops.

    The same set of tests can be done on motor 2 by working with structure variable 'motorVars[1]'.

7.3.1 Observation One – Latency

While running the motor in this build level and subsequent build levels, observe the variable 'motorVars[0].fcl_LatencyInMicroSec' in the Expressions window. Figure 26 shows a snapshot of the Expressions window.

motorVars[0].FCL_params.wccD	float	3490.65845	0x00992C@Program
motorVars[0].FCL_params.wccQ	float	3490.65845	0x00992E@Program
motorVars[0].fclLatencyInMicroSec	float	1.75	0x009938@Program
motorVars[1].fclClrCntr	unsigned int	0	0x009A78@Program
motorVars[0].FCL_params.wccD/(2*3.14)	double	555.837332	
motorVars[0].FCL_params.wccQ/(2*3.14)	double	555.837332	

Figure 26. Expressions Window Snapshot For Latency of Motor 1

This variable indicates the amount of time elapsed between the feedback sampling and PWM updating. The elapsed time, or latency, is computed based on the count of the EPWM timer right after the PWM update. The value shown here is more than the actual update time by a few clock cycles. Immediately after setting the 'motorVars[0].runMotor' to MOTOR_RUN and the motor begins to run, the latency time shows up as nearly 1.25µS due to initial setup in the code. This amount of latency occurs at a time when the duty cycle is moderate and is therefore acceptable. After this period, you can refresh the latency time by setting 'motorVars[0].fclClrCntr' to 1. Regardless of SAMPLING_METHOD, latency remains the same for a given FCL_CNTLR. (see the following note).

NOTE:

- These times can be reduced further by around 0.1µs range using code inline and other optimization techniques.
- The sampling window for ADC is kept wide enough to ensure a cleaner signal acquisition. Depending on board layout and circuits feeding in to ADC channels, it maybe possible to reduce this time window by nearly 60%.

Do the same test on motor 2 by working with structure variable motorVars[1],Figure 27 shows a snapshot of the Expressions window during the motor 1 and motor 2 run simultaneously.

motorVars[0].runMotor	enum <unnamed>	MOTOR_RUN	0x009800@Program
motorVars[0].ptrFCL->lsw	enum <unnamed>	ENC_CALIBRATION_DO...	0x00009A7C@Data
motorVars[1].runMotor	enum <unnamed>	MOTOR_RUN	0x00993E@Program
motorVars[1].ptrFCL->lsw	enum <unnamed>	ENC_CALIBRATION_DO...	0x00009AD0@Data
motorVars[0].fclLatencyInMicroSec	float	1.75	0x009938@Program
motorVars[1].fclLatencyInMicroSec	float	1.74000001	0x009A76@Program

Figure 27. Expressions Window Snapshot For Latency of Motor 1 and Motor 2

7.4 Incremental Build Level 4

Assuming the previous section is completed successfully, this section verifies the speed PI module and speed loop. The implementation block diagram is given in Figure 28. The motor shafts must be kept disconnected to run these motors at different speed settings simultaneously or only one motor can be tested at a given time. When the motor is commanded to run, it is subjected to an initial alignment stage where the electrical angle and the QEP angle count are set to zero. After ensuring a stable alignment, the motor starts running.

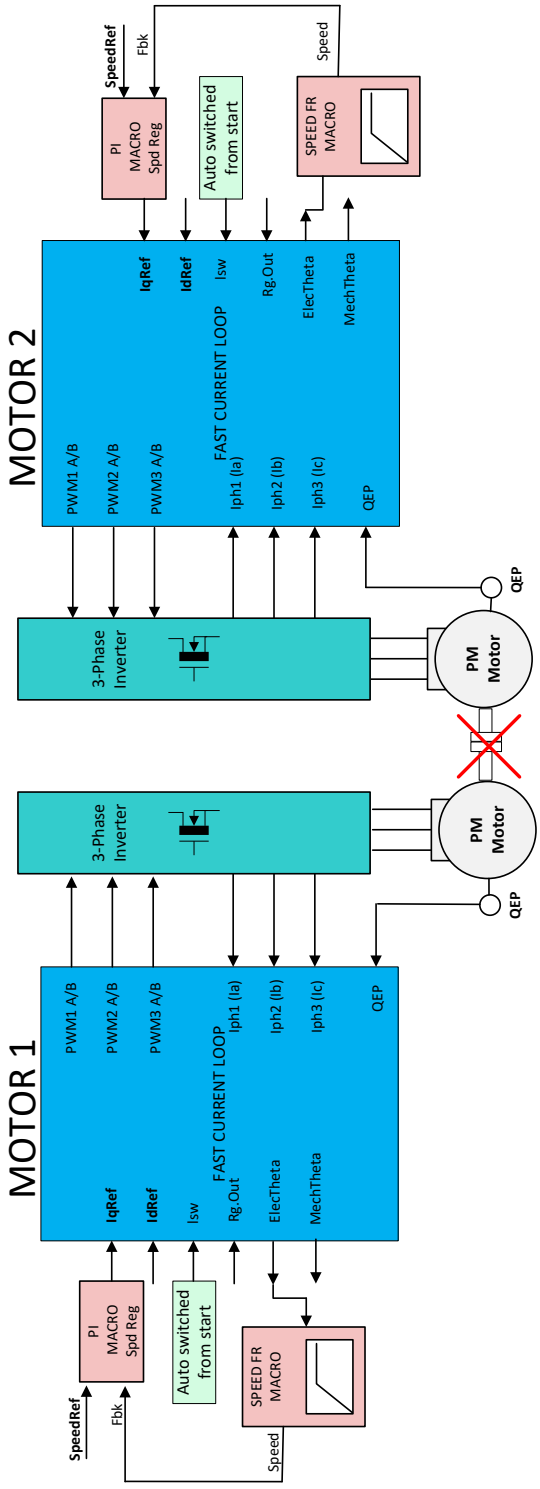


Figure 28. Level 4 Block Diagram Showing Speed Loop for Dual Motor With Inner FCL

1. Open "dual_axis_servo_drive_settings.h" and select level 4 incremental build option by setting the BUILDLEVEL to FCL_LEVEL4 (#define BUILDLEVEL FCL_LEVEL4). The current loop regulator can be selected to be the PI controller or the complex controller by setting FCL_CNTLR to PI_CNTLR or CMPLX_CNTLR.
2. Right-click on the project name, and then click Rebuild Project.
3. When the build is complete, click the Debug button, reset the CPU, restart, enable real-time mode, and run. In the software, within the 'motorVars[0]' structure, the key variables to add, adjust, or monitor are summarized as follows:
   a. motorVars[0].runMotor : flag to MOTOR_RUN or MOTOR_STOP
   b. motorVars[0].speedRef: for changing the rotor speed in per-unit.
4. Set 'enableFlag' to 1 in the expressions window. The variables named 'motorVars[0].isrTicker' and 'motorVars[1].isrTicker' are incrementally increased as shown in Expressions window to confirm the interrupts are working properly.
5. Set 'motorVars[0].speedRef' to 0.3 pu (or another suitable value if the base speed is different).
6. Add 'motorVars[0].pid_spd' variable to the Expressions window.
7. Gradually increase voltage at DC power supply to get an appropriate DC-bus voltage.
8. Add the soft-switch variable 'motorVars[0].ptrFCL->lsw' to the watch window to start the motor. The variable is auto promoted in a sequence inside the FCL. In the code, 'motorVars[0].ptrFCL->lsw' manages the loop setting as follows:
   a. lsw = ENC_ALIGNMENT --> lock the rotor of the motor.
   b. lsw = ENC_WAIT_FOR_INDEX --> motor in running mode, waiting for first instance of QEP Index pulse.
   c. lsw = ENC_CALIBRATION_DONE --> motor in running mode, first Index pulse of encoder occurred.
9. Set 'motorVars[0].runMotor' flag to MOTOR_RUN to run the motor, now the motor runs with this reference speed (0.3 pu). Compare the 'motorVars[0].speed.Speed' with 'motorVars[0].speedRef' in the watch windows with the continuous refresh feature to see whether or not it is nearly the same.
10. To confirm this speed PID module, try different values of 'speedRef' (positive or negative). The P, I, and D gains may be tweaked to get a satisfactory response.
11. At a very low speed range, the performance of the speed response relies heavily on the good rotor position angle provided by the QEP encoder.
12. Set ‘motorVars[0].runMotor’ to MOTOR_STOP to stop the motor.
13. Bring the system to a safe stop by reducing the bus voltage, taking the controller out of real-time mode, and resetting.

The same set of tests can be done on motor 2 by working with structure variable 'motorVars[1]'.

Figure 29 shows flux and torque currents in the synchronous reference frame under a step load and 0.6 pu speed. The waveform of channel 1 represents the feedback Q-axis current (torque current), channel 2 represents the feedback D-axis current (flux current).

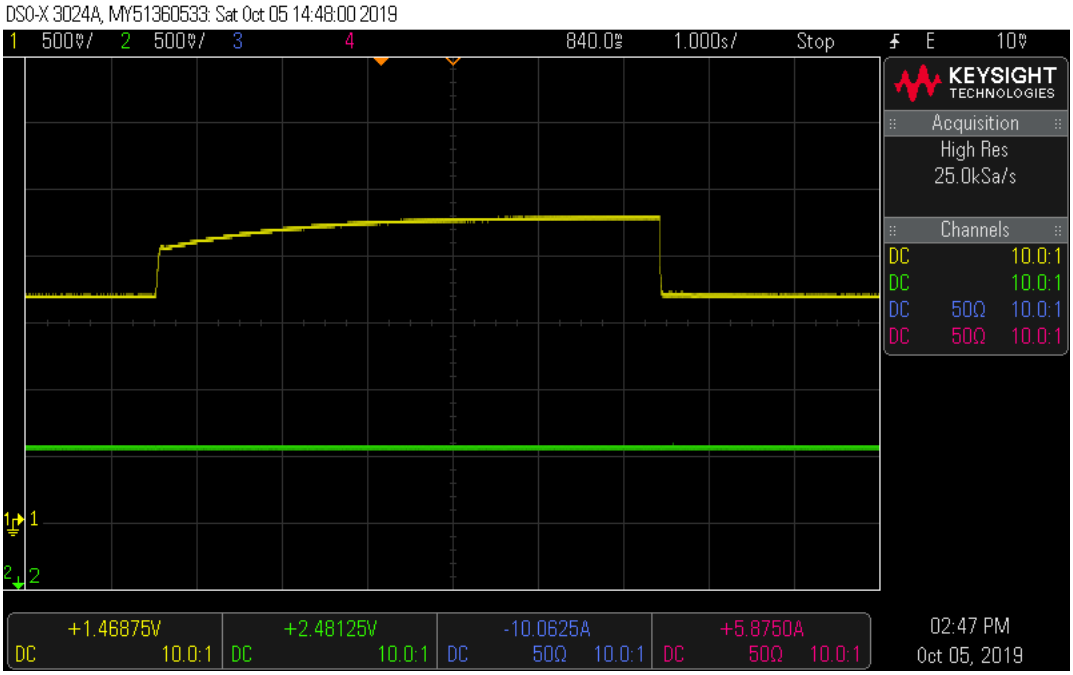


Figure 29. Flux and Torque Current Under Step-Load and 0.6-pu Speed

7.4.1 Observation

In the default set up, the current loop bandwidth is set up as 1/18 of the SAMPLING_FREQUENCY for both CMPLX_CNTLR and PI_CNTLR. As the bandwidth is increased, control becomes stiff and the motor operation becomes noisier as the controller reacts to tiny perturbations in the feedback trying to correct them, see the note below. The gain cross over frequency (or open loop bandwidth) can be taken up to 1/6 of the SAMPLING_FREQUENCY and still get good transient response over the entire speed range including higher speeds. If the motor rotation direction is reversed occasionally due to any malfunction, try restarting it by setting motorVars[0].runMotor to MOTOR_STOP and then MOTOR_RUN again. It may need some fine tuning in transitioning from lsw = ENC_WAIT_FOR_INDEX to lsw = ENC_CALIBRATION_DONE. This can be used as an exercise to fix it.

NOTE: The fast current loop is a high bandwidth controller. When the designed bandwidth is high, the loop gains can also be high. This pretty much ties the loop performance to the quality of current feedback. If the SNR of current feedback signal into the digital domain is poor, then the loop can be very audibly noisy as the controller tries to minimize the error. If the noise is bothersome, you may be required to reduce the bandwidth to avoid the audible noise.

7.4.2 Dual Motor Run With Speed Loop

In the software, motor 1 and motor 2 can be controlled as above steps separately. Or, both motors can be controlled simultaneously. The key variables to add, adjust, or monitor are summarized as follow to control dual motor.

- flagSyncRun: flag to 0 that control dual motor separately, flag to 1 that control dual motor simultaneously.
- runMotor : flag to MOTOR_RUN or MOTOR_STOP for setting 'motorVars[0].runMotor' and 'motorVars[1].runMotor' simultaneously.
- speedRef: for changing the motorVars[0].speedRef and motorVars[0].speedRef in per-unit with the same setting value.

1. Set 'enableFlag' to 1 in the expressions window.
2. Set 'flagSyncRun' to 1 to enable controlling dual motor simultaneously.
3. Set 'speedRef' to 0.1pu (or another suitable value if the base speed is different). The variables, 'motorVars[0].speedRef' and 'motorVars[0].speedRef' are changed to the value equals to 'speedRef'.
4. Set 'runMotor' flag to MOTOR_RUN to run the dual motor, now both motors run with this reference speed (0.1 pu).
5. Set 'runMotor' to MOTOR_STOP to stop the dual motor.
6. Bring the system to a safe stop by reducing the bus voltage, taking the controller out of real-time mode, and resetting.

7.5 Incremental Build Level 5

Assuming the previous build levels are verified successfully, this section verifies the position PI module and position loop with a QEP. When the motor is commanded to run, it is subjected to an initial alignment stage where the electrical angle and the QEP angle count are set to zero. After ensuring a stable alignment, the motor starts to run.

The implementation block diagram is given in Figure 30. The motor shafts must be kept disconnected to run these motors at different position settings simultaneously or only one motor can be tested at a given time.

1. Open "dual_axis_servo_drive_settings.h" and select level 5 incremental build option by setting the BUILDLEVEL to FCL_LEVEL5 (#define BUILDLEVEL FCL_LEVEL5). The current loop regulator can be selected to be the PI controller or the complex controller by setting FCL_CNTLR to PI_CNTLR or CMPLX_CNTLR.
2. Right-click on the project name, and then click Rebuild Project.
3. When the build is complete, click the Debug button, reset the CPU, restart, enable real-time mode, and run.

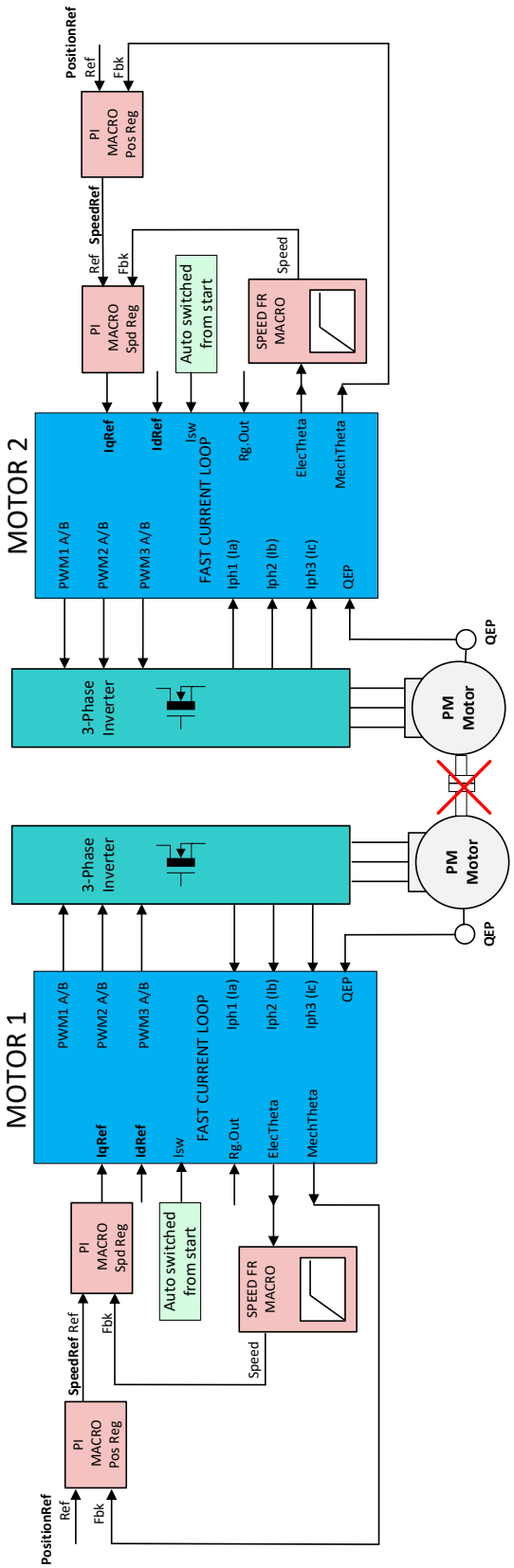


Figure 30. Level 5 Block Diagram Showing Position Loop for Dual Motor With Inner FCL

4. The software runs the motor through predefined motion profiles and position settings as set by the refPosGen() module. This module basically cycles the position reference through a set of values as defined in an array 'posArray[]'. These values represent the number of the rotations and turns with respect to the initial alignment position. Once a certain position value as defined in the array is reached, it pauses for a while before slewing toward the next position in the array. Therefore, these array values can be referred to as parking positions. During transition from one parking position to the next, the rate of transition (or speed) is set by 'motorVars[0].posSlewRate'. The number of positions in 'posArray[]' through which it passes before restarting from the first value is decided by 'ptrMax'. Hence, add the key variables 'posArray', 'ptrMax', and 'motorVars[0].posSlewRate' to the Expressions window as follows:
   a. motorVars[0].runMotor : flag to MOTOR_RUN or MOTOR_STOP
   b. motorVars[0].ptrFCL->lsw: the soft-switch flag that is auto promoted in a sequence inside the FCL.
   c. motorVars[0].posSlewRate: the rate of transition from one parking position to the next position.
   d. motorVars[0].pi_pos: the position PI controller structure variable.
   e. posArray: the position reference for dual motor.
   f. ptrMax: the maximum position sets.
5. Set “enableFlag” to 1 in the expressions window. The variables named 'motorVars[0].isrTicker' and 'motorVars[1].isrTicker' are incrementally increased as shown in Expressions window to confirm the interrupts are working properly.
6. Gradually increase voltage at DC power supply to get an appropriate DC-bus voltage.
7. Set 'motorVars[0].runMotor' flag to MOTOR_RUN to run the motor, now the motor must be turning to follow the commanded position (see the following note if the motor does not turn properly).
8. The parking positions in 'posArray[]' can be changed to different values to determine if the motor turns as many rotations as set.
9. The number of parking positions 'ptrMax' can also be changed to set a rotation pattern.
10. The position slew rate can be changed using 'motorVars[0].posSlewRate'. This rate represents the angle (in pu) per sampling instant.
11. The proportional and integral gains of the speed and position PI controllers may be returned to get satisfactory responses. TI advises to first tune the speed loop and then the position loop.
12. Set 'motorVars[0].runMotor' to MOTOR_STOP to stop the motor.
13. Bring the system to a safe stop by reducing the bus voltage, taking the controller out of real-time mode, and resetting.

The same set of tests can be done on motor 2 by working with structure variable 'motorVars[1]'.

Figure 31 shows the position reference, and position feedback are plotted in the scope plot using DACs. They are aligned with negligible lag, which may be attributed to software. If the Kp and Ki gains of the position loop controller are not chosen properly, this may lead to oscillations in the feedback or a lagged response.

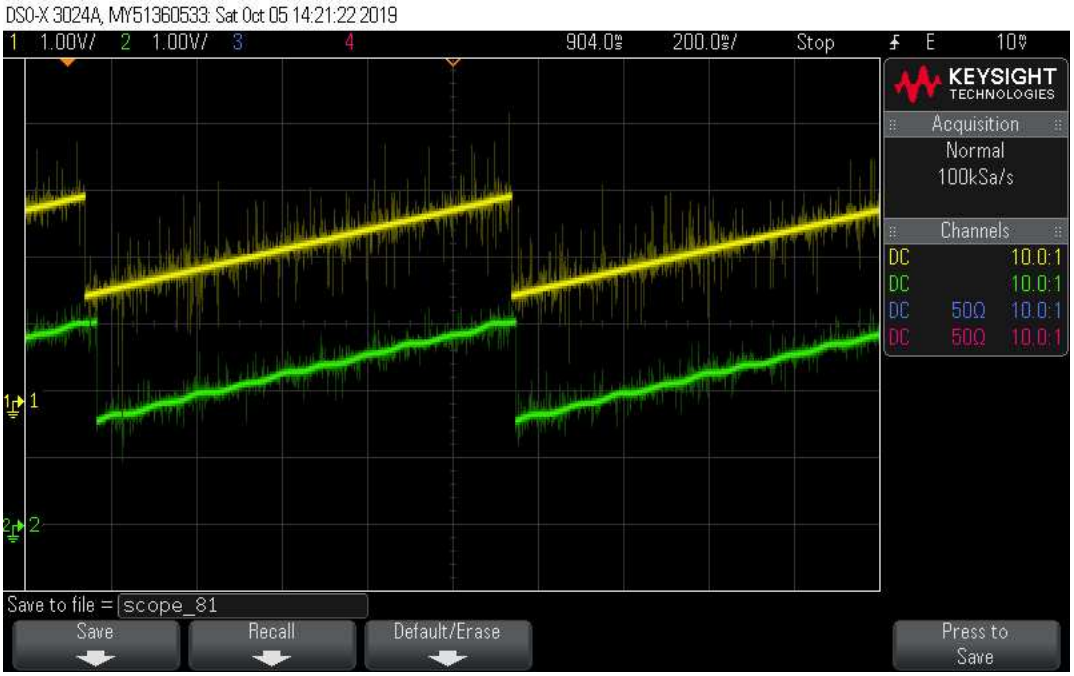


Figure 31. DACs in Scope Plot of Reference Position to Servo and Feedback Position

NOTE:

- If the motor response is erratic, then the sense of turn of the motor shaft and the encoder may be opposite. Swap any two phase connections to the motor and repeat the test.
- The position control implemented here is based on an initial aligned electrical position (=0). If the motor has multiple pole pairs, then this alignment can leave the shaft in different mechanical positions depending on the prestart mechanical position of the rotor. If the mechanical position repeat ability or consistency is needed, then the QEP index pulse must be used to set a reference point. This may be taken as an exercise .

7.5.1 Dual Motor Run with Position Loop

In the software, motor 1 and motor 2 can be controlled as above steps separately. Or, both motors can be controlled simultaneously. The key variables to add, adjust, or monitor are summarized as follow to control dual motor.

- flagSyncRun: flag to 0 that control dual motor separately, flag to 1 that control dual motor simultaneously.
- runMotor : flag to MOTOR_RUN or MOTOR_STOP for setting 'motorVars[0].runMotor' and 'motorVars[1].runMotor' simultaneously.

1. Set 'enableFlag' to 1 in the expressions window.
2. Set 'flagSyncRun' to 1 to enable controlling dual motor simultaneously.
3. Set 'runMotor' flag to 'MOTOR_RUN' to run the dual motor, now both motors run with this reference speed (0.1 pu).
4. Set 'runMotor' to 'MOTOR_STOP' to stop the dual motor.
5. Bring the system to a safe stop by reducing the bus voltage, taking the controller out of real-time mode, and resetting.

7.6 Incremental Build Level 6

Assuming the previous build levels are successfully completed, this build level attempts to study the frequency response analysis of the FCL using C2000's Software Frequency Response Analyzer (SFRA) tool, available as a library in the C2000ware MotorControl SDK.

7.6.1 Integrating SFRA Library

The SFRA tool runs only on C2000 MCU platform to study the frequency response analysis of any control loop that it controls. It consists of an embedded firmware part that runs on the MCU and a graphical user interface part (GUI) that runs on the development computer.

C2000™ Software Frequency Response Analyzer (SFRA) Library and Compensation Designer in SDK Framework describes the SFRA tool and guides you into integrating it into the C2000 platform. This can be found at: \ti\c2000\C2000Ware_MotorControl_SDK_<version>\libraries\sfra\Doc.

The embedded firmware is available as a library in the MotorControl SDK at: \ti\c2000\C2000Ware_MotorControl_SDK_<version>\libraries\sfra

The SFRA GUIs are available as executable applications in the MotorControl SDK at: \ti\c2000\C2000Ware_MotorControl_SDK_<version>\libraries\sfra\gui

Some example projects to understand SFRA are available at: \ti\c2000\C2000Ware_MotorControl_SDK_<version>\libraries\sfra\examples

In the ISR code, there are two functions as follows that inject noise for SFRA and then collect the feedback data from the loop.

- injectSFRA()
- collectSFRA()

The roles of these functions are self-explanatory from their names. They should be used in the code to collect the data in right sequence.

NOTE:

- The disturbances due to analog signal path and quantization will impact the loop performance and hinder high bandwidth selections that can be verified using SFRA results. Therefore it is important to provide a current feedback with a higher SNR.
- When evaluating current loops, if it is possible to hold the motor speed constant, it will help to minimize the impact of speed jitter related errors in the SFRA results. This is particularly useful when studying the Iq loop. If the voltage decoupling of current loop is good, then this requirement may not matter.

This tool provides the ability to study the D-axis or Q-axis current loops or the speed loop. The motor can be run at different speed / load conditions and at different bandwidths and the performance can be evaluated at each of these conditions. It can be seen that the controller can provide the designed bandwidth under all these conditions with a certain tolerance.

The implementation block diagram is given in Figure 32. The SFRA tool injects noise signal into the system at various frequencies and analyzes the system response and provides a Bode Plot of the actual physical system as seen during the test.

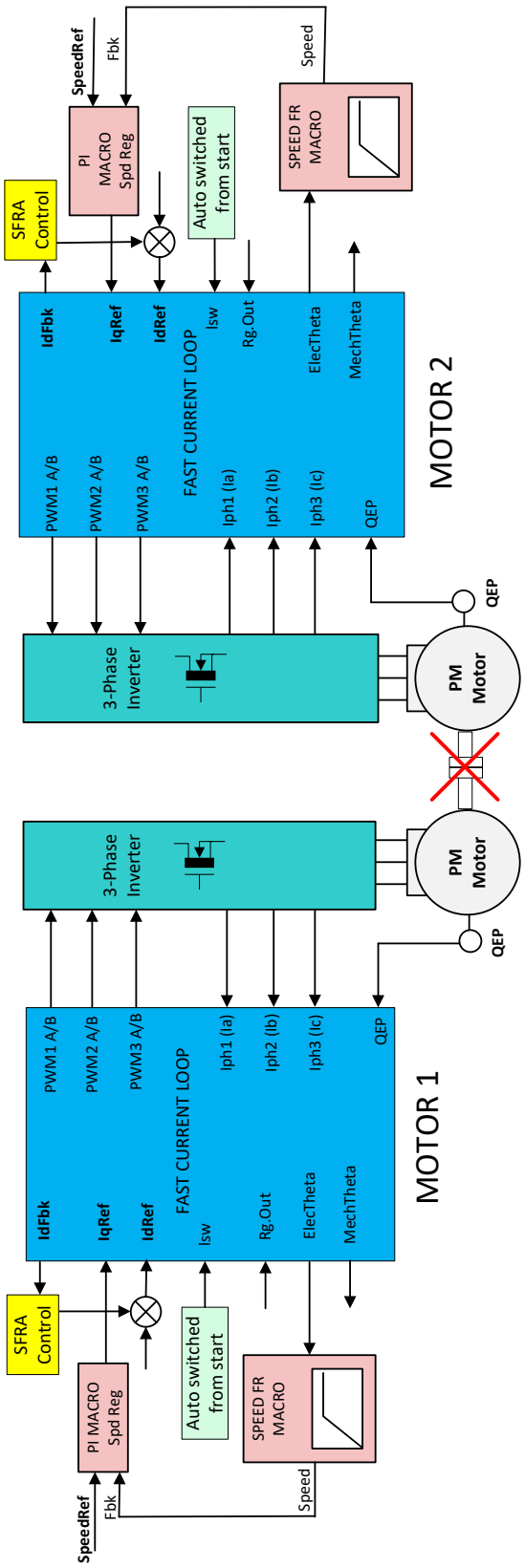


Figure 32. Level 6 Block Diagram With Inner FCL and SFRA

7.6.2 Initial Setup Before Starting SFRA

The setting up involves co-ordination between the debug environment and the SFRA GUI. Until getting familiar with connecting the SFRA GUI to the target platform, it is a good idea to turn off the power supply input to the inverter board.

1. Open 'dual_axis_servo_drive_settings.h' and select level 6 incremental build option by setting the BUILDLEVEL to FCL_LEVEL6 (#define BUILDLEVEL FCL_LEVEL6) . Also, in this file, watch out for the definitions:
   a. SFRA_FREQ_START
   b. SFRA_FREQ_LENGTH
   c. FREQ_STEP_MULTIPLY

   These definitions inform the GUI about the starting value of noise frequency, number of different noise frequencies to sweep and the ratio between successive sweep frequencies, respectively. More information is available in the *C2000™ Software Frequency Response Analyzer (SFRA) Library and Compensation Designer User's Guide* associated with SFRA. In the context of this evaluation project, it is important to know and appreciate these parameters to tweak them for further repeat tests.

   The default setting of the code is that SFRA will be performed on motor1. To do SFRA on motor 2, call the SFRA functions with the motor 2 handle (or pointer) by setting the SFRA_MOTOR to MOTOR_2 (#define SFRA_MOTOR MOTOR_2) in "dual_axis_servo_drive_settings.h".

   In this motor control project, there are three different loops such as the speed loop, D axis current loop and Q axis current loop. Any of these loops could be analyzed for frequency response. Technically, this could be performed on position loop as well, but is not included in this project scope.
2. Right click on the project name and click Rebuild Project.
3. Once the build is complete click on debug button, reset CPU, restart, enable real time mode and run.
4. Add the following variable in the Expressions window:
   a. sfraTestLoop : for selecting the control loop on which to evaluate SFRA, letting you choose between the following settings.
      i. SFRA_TEST_D_AXIS - D axis current loop
      ii. SFRA_TEST_Q_AXIS - Q axis current loop
      iii. SFRA_TEST_SPEEDLOOP - speed loop
5. Set 'enableFlag' to 1 in the watch window. The variable named 'motorVars[0].isrTicker' and 'motorVars[1].isrTicker' will be incrementally increased as seen in watch windows to confirm the interrupt working properly.
6. The SCI initialization needed to communicate with the GUIs should be complete by now.
7. Further steps with the debug window will follow after setting up the GUI to connect to target platform.

7.6.3 SFRA GUIs

There are two GUIs available to perform the frequency response analysis: one (SFRA_GUI) to plot open loop and plant Bode diagram, and another (SFRA_GUI_MC) to plot open loop and closed loop Bode diagram. They can be invoked and connected to the target platform to study the control loops. The GUI executables are available in the location as mentioned in Section 7.6.1.

1. Double click on the choice of GUI executable and the GUI screen will appear as shown in Figure 33 for SFRA_GUI or in Figure 34 for SFRA_GUI_MC. They look almost identical, the difference is in the pull down menu under 'FRA Settings' starting with the label 'Open Loop'.
   a. In the SFRA_GUI, this pull down menu helps to select between Open Loop Model and Plant Model.
   b. In the SFRA_GUI_MC, this pull down menu helps to select between Open Loop Model and Closed Loop Model.

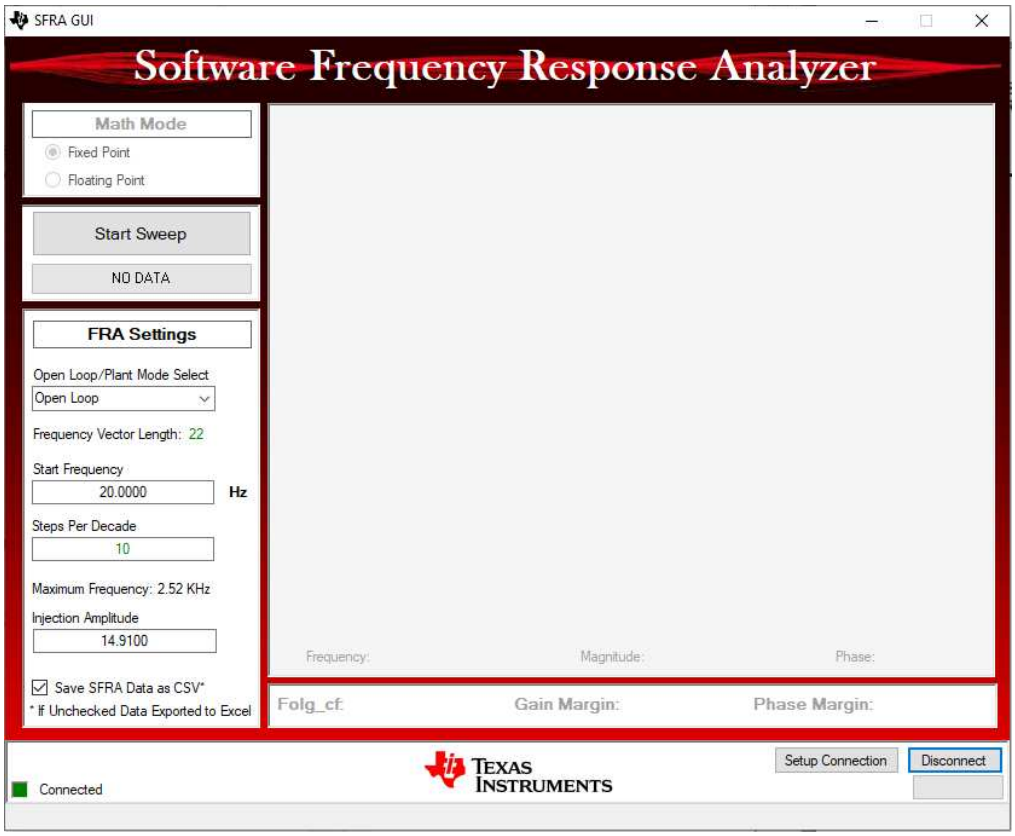


Figure 33. SFRA GUI

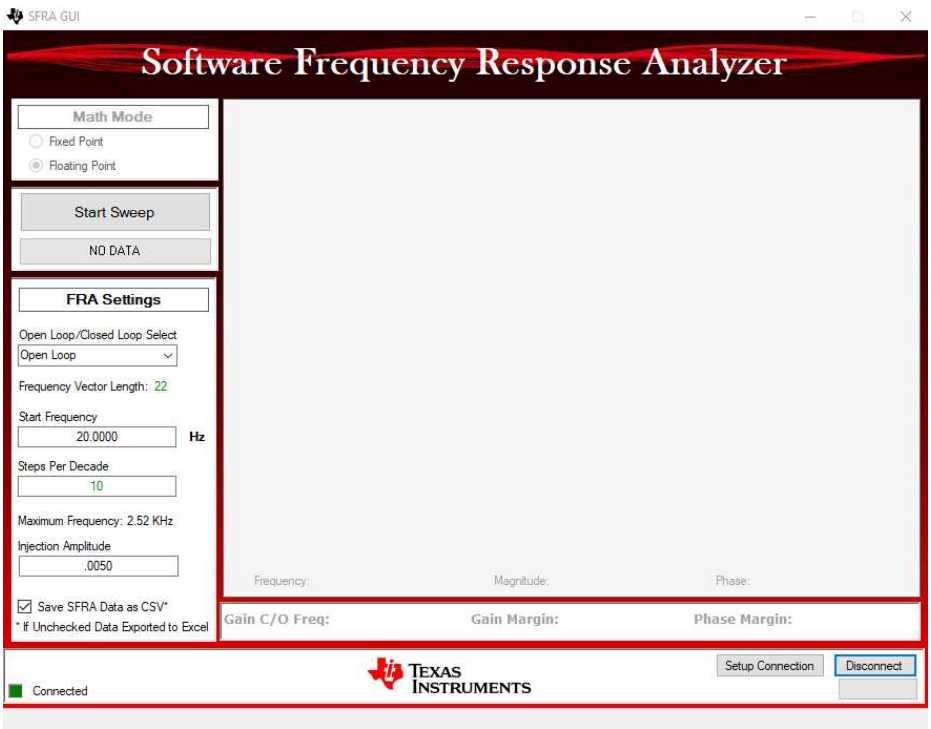


Figure 34. SFRA GUI MC

This demo uses the GUI 'SFRA_GUI_MC'. However, it is encouraged to experiment with the SFRA_GUI as well to study the plant. With the SFRA_GUI, you can plot the same graph as in SFRA_GUI_MC by passing the argument 'SFRA_GUI_PLOT_GH_CL' in the function configureSFRA() as shown in the code snippet below:

```
configureSFRA(SFRA_GUI_PLOT_GH_H, M1_SAMPLING_FREQ);
```

But the inferences from the plots are not according to that in SFRA_GUI_MC. Therefore, it is advised to configure SFRA for 'SFRA_GUI_PLOT_GH_H' so that you can see open loop, closed loop and plant model plots using these two GUIs, by using one at a time.

7.6.4 Setting Up the GUIs to Connect to Target Platform

Both GUIs have identical procedures to connect to the target platform. The GUI lets you select appropriate settings based on the target platform and development computer.

The following is a list of things to do on the GUI before starting the analysis:

1. Math Mode: Depending on the target C2000 development platform, either the fixed point or floating point option is chosen. For F2837x or later C2000 MCUs, select the ‘Floating Point’ option .
2. Since the USB port on the LaunchPad is already connected to the computer for JTAG purposes, no additional connection is required. However, for a standalone operation, an USB connector needs to be connected to the target board. In the XDS100 emulator present on the LaunchPad, in addition to a JTAG link, an SCI port link is also provided and the GUI uses this link to connect to the SCI port of the target platform. While the debug environment of CCS is using JTAG, the GUI can also use SCI at the same time.
3. Click on the Setup button at the bottom right corner. This will pop open a Setup Connection window as shown in Figure 35.

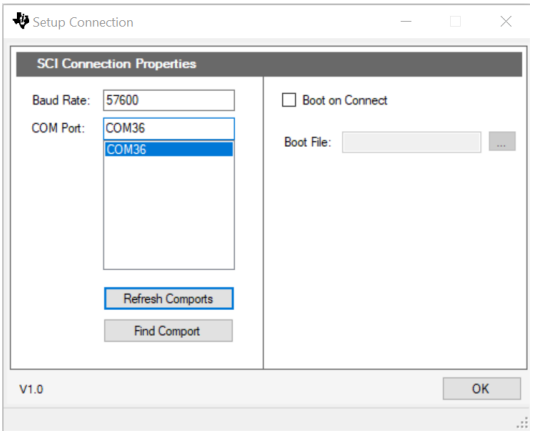


Figure 35. GUI Setup Diagram

4. Click ‘Refresh Comports’ button to get the Comport number show up in the window.
5. Select the Comport representing the connection to the target C2000 board.
6. Uncheck ‘Boot on Connect’ .
7. Click OK button.
8. This should establish the connection to the LaunchPad and the GUI will appear as shown in Figure 33 indicating the connection status at the bottom left corner.
9. The frequency sweep related settings are shown in ‘FRA Settings’ Panel. These values are already pre-filled from the C2000 device and they can be left as is.

10. As mentioned earlier, the visual difference between the two GUIs is in the pull down menu under 'FRA Settings' starting with Open Loop.
    a. In the SFRA_GUI, this pull down menu helps to select between Open Loop Model and Plant Model.
    b. In the SFRA_GUI_MC, this pull down menu helps to select between Open Loop Model and Closed Loop Model.
    c. This menu becomes relevant after a complete noise injection sweep of the system at various frequencies. Then, you can pick and view the plot of choice using this menu.
    d. Bandwidth reporting is different as mentioned earlier. Gain cross over frequency is reported in the open loop plot of the SFRA_GUI_MC instead of bandwidth as in SFRA_GUI.
11. This completes the initial setup of GUI environment.

7.6.5 Running the SFRA GUIs

If the power supply to the inverter board is turned off before, restore it back now. From the debug environment, the steps to be followed are as shown below:

1. Verify that sfraTestLoop is set to SFRA_TEST_D_AXIS so as to test Id loop.
2. Set 'motorVars[0].FCL_params.wccD' to the desired value, within limits, (when test is performed for Q axis, adjust this parameter for Q axis - motorVars[0].FCL_params.wccQ)
3. Set motorVars[0].speedRef = 0.05 (in pu, 1 pu = 250Hz) and then set motorVars[0].runMotor = MOTOR_RUN to run the motor. Now motor shaft should start spinning and settle at the commanded speed.
4. The state machine variable (motorVars[0].ptrFCL->lsw) is auto promoted in a sequence, its states are as follows:
    a. lsw = ENC_ALIGNMENT --> lock the rotor of the motor.
    b. lsw = ENC_WAIT_FOR_INDEX --> motor in run mode and waiting for the first instance of QEP index pulse.
    c. lsw = ENC_CALIBRATION_DONE --> motor in run mode - QEP index pulse occurred.
5. Now, the GUI can be called into perform a frequency sweep of the D axis current loop by clicking on the "Start Sweep" button in the GUI. The sweep progress will be indicated by a green bar in the location marked as "NO DATA".
6. When the frequency sweep is fully done, it will compute the Bode plot and display the results as shown in Figure 36 and Figure 37.

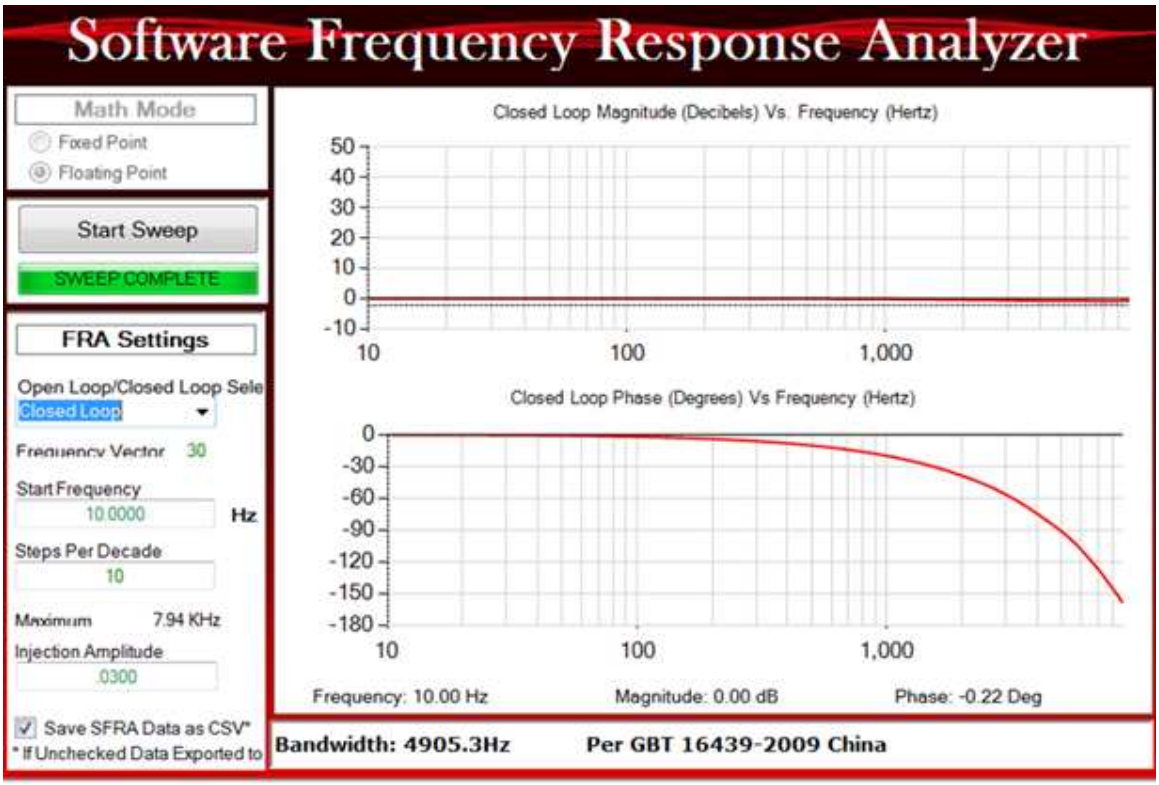


Figure 36. SFRA Open Loop Bode Plots of the Current Loop Showing Magnitude and Phase Angle

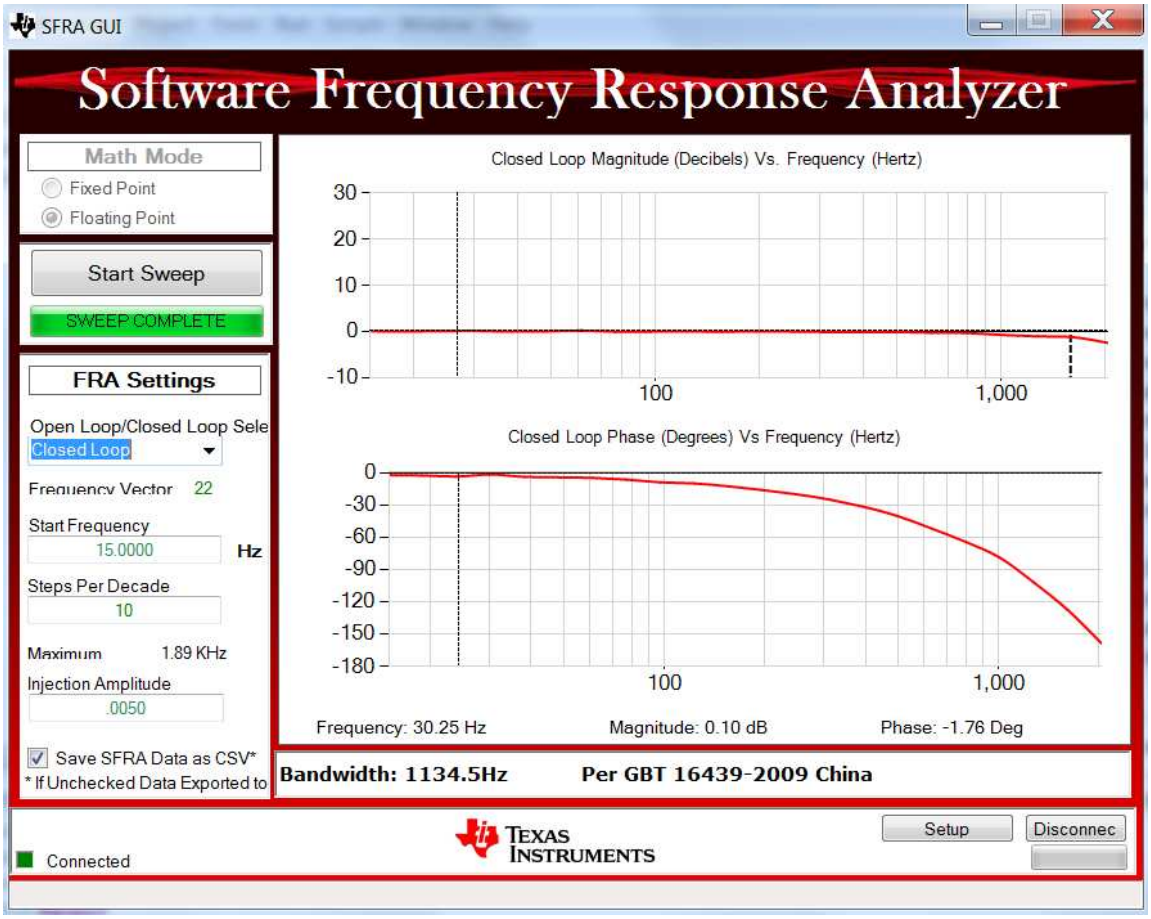


Figure 37. SFRA Closed Loop Bode Plots of the Current Loop Showing Magnitude and Phase Angle

7. The GUI also computes and displays the loop bandwidth, gain margin and phase margin.
8. Repeat the test, if desired, by changing the variable 'motorVars[0].FCL_params.wccD', and at different speed and load conditions.
9. To disconnect the GUI, click the 'Disconnect' button on the GUI.
10. To stop the motor, set 'motorVars[0].runMotor' to 'MOTOR_STOP'.
11. After the motor stops, take the controller out of real-time mode and reset.

The same set of tests can be done on motor 2 by working with structure variable 'motorVars[1]', and by changing the SFRA_MOTOR to MOTOR_2 (#define SFRA_MOTOR MOTOR_2) in "dual_axis_servo_drive_settings.h".

7.6.6 Influence of Current Feedback SNR

The fast current loop is a high bandwidth enabler. When the designed bandwidth is high, the loop gains can also be high. This ties the loop performance to the quality of current feedback. If the SNR of current feedback signal into the digital domain is poor, then the loop can be very audibly noisy as the controller tries to minimize the error. If the noise is bothersome, you may be required to reduce the bandwidth to avoid the audible noise. Therefore, for a higher bandwidth and higher performance, the feedbacks should be of high SNR to get the frequency responses a shown in Figure 38 and Figure 39.

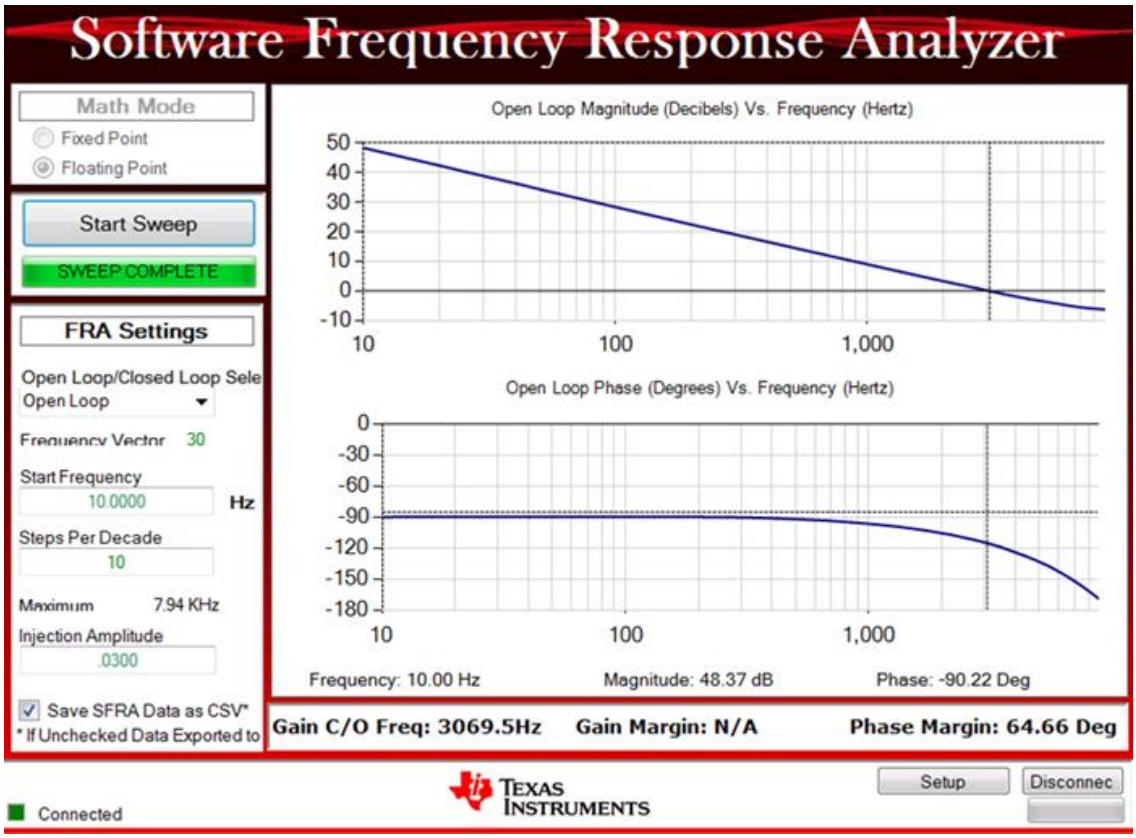


Figure 38. SFRA Open Loop Bode Plots of the Current Loop - Current Feedback With High SNR

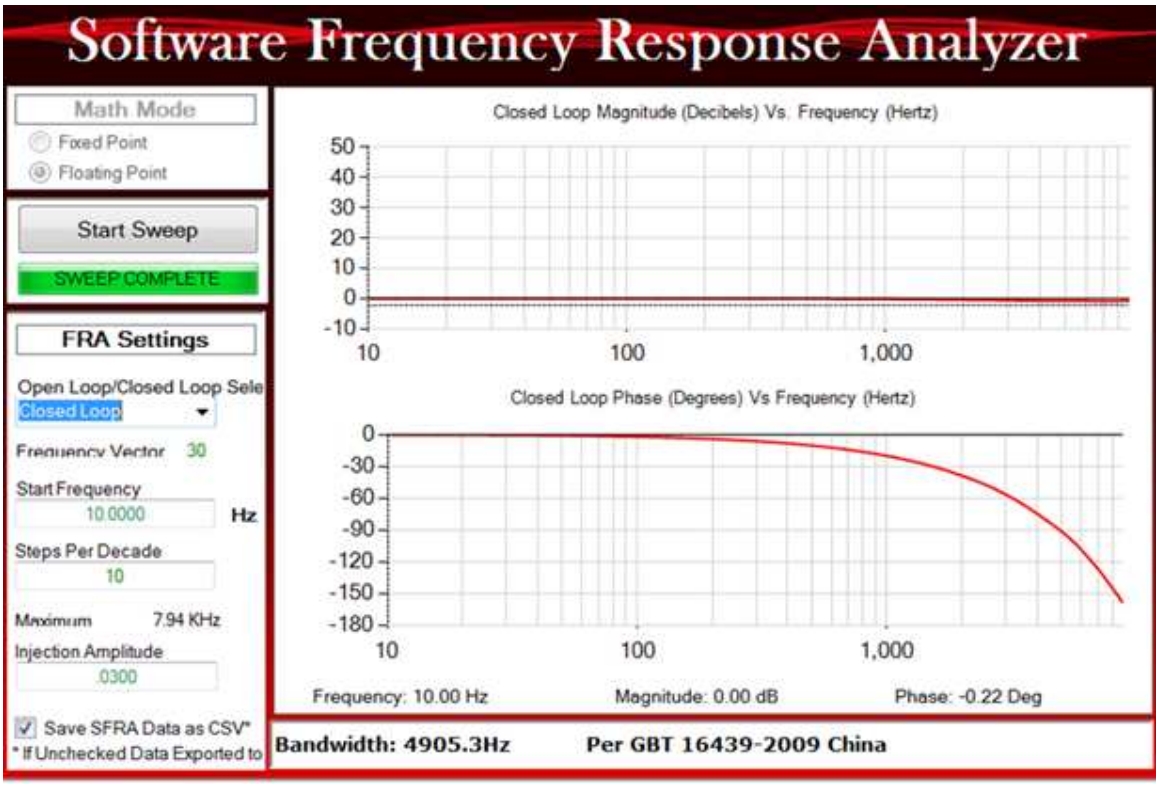


Figure 39. SFRA Closed Loop Bode Plots of the Current Loop - Current Feedback With High SNR

NOTE: With the hardware platform LaunchPad and BoosterPack, there is scope for improving the SNR of the current signal feeding into the ADCs of the MCU. Therefore, higher bandwidth tests can be more noisier (chattering in nature) on this platform.

7.6.7 Inferences

- Bandwidth determination from closed loop plot.
  - The controller implemented for the open loop and closed loop plots shown in Figure 38 and Figure 39 is a dead beat controller where the output catches up to the input in just one sample cycle without any overshoots or requiring multiple cycles. From the closed loop plot, it is clear that the closed loop gain is always 0dB (unity gain) at all frequencies and, therefore, magnitude-based bandwidth determination is not practical. Hence, the phase plot is chosen as reference and the frequency at which the phase lag goes beyond 90° is taken as bandwidth per the NEMA ICS 16 (speed loop). In this test case, the PWM frequency is chosen as 10 KHz and the sampling frequency is 20 KHz and the current loop bandwidth obtained from the closed loop plot is about 5000Hz per these guidelines.
- Phase margin determination from open loop plot.
  - From the open loop plots, the phase margin obtained is about 65°. Such a high margin should give a very robust performance across the frequency ranges within the bandwidth obtained.

Maximum modulation index determination from PWM update time.
From Section 7.3.1, the time lapse between feedback sampling instantiation to PWM update is about 1.75 µs. In this system where the PWM frequency is 10 KHz, the maximum modulation index is limited by the sampling method as follows:

- Double sampling - just above 96% (F2837x), or 93% (F28004x)
- Single sampling - just about 98% (F2837x), or 96% (F28004x)

This is quite comparable to FPGA based systems where the entire algorithm is implemented in hardware.

- Voltage decoupling in current loop
  - The SFRA test can be performed at zero speed (by rigidly locking the shaft if needed) to get one plot as reference. The gain crossover frequency and phase margin at zero speed may be noted down. Then at different speeds and load conditions, this test can be repeated to verify if there is any change in bandwidth or phase margin. Any variation in the plot at different speed is indicative of the quality of decoupling in current loops.

7.6.8 Phase Margin vs Gain Crossover Frequency

By varying the control bandwidth and repeating these tests and noting down the resulting gain cross over frequency and phase margin, a set of plots are obtained for Id loop as shown in Figure 40. Two sets of tests are performed: one based on classical current control method and the other based on FCL. Both these tests were performed using different current regulators. They all gave converging results.

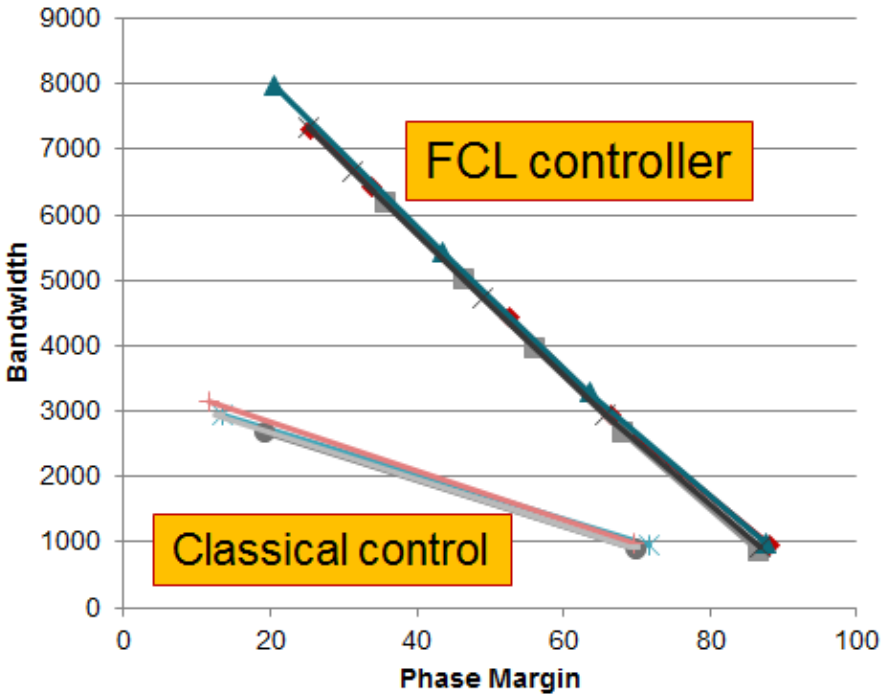


Figure 40. Plot of Gain Cross over Frequency vs Phase Margin as Experimentally Obtained

8 Summary

This evaluation platform helps to control two different motors with FCL technology, and with or without SFRA. The FCL shows a substantial improvement in control bandwidth and phase margin. The SFRA tool shows the impact of FCL on control bandwidth and phase margin, and evaluates the current and speed control loop performance.

The presence of fast ADC, control law architecture (CLA) and trigonometric math unit (TMU) helped to reduce the latency between feedback sampling and PWM update, in turn, resulted in higher control bandwidth and increase in maximum modulation index. Higher modulation index helps to improve the DC bus utilization by the drive and to increase the control speed range of the motor.

Depending on the control speed range of motors in target applications, it is possible to control dual motors in multi-axes configurations using FCL with a single F2837x or F28004x series controller, this makes it suitable for high end servo control applications.

9 References

- Texas Instruments: *Fast Current Loop Driverlib Library*
- Texas Instruments: *LAUNCHXL-F28379D Overview User's Guide*
- Texas Instruments: *C2000™ Piccolo™ F28004x Series LaunchPad™Development Kit*
- Texas Instruments: *BOOSTXL-3PhGaNInv Evaluation Module User's Guide*
- Texas Instruments: *C2000™ Software Frequency Response Analyzer (SFRA) Library and Compensation Designer User's Guide*
- Texas Instruments: *Performance Analysis of Fast Current Loop (FCL) in Servo Drives Using SFRA on C2000™ Platform*
- Texas Instruments: *Dual Motor Control Using FCL and Performance Analysis Using SFRA on TMS320F28379D LaunchPad*
- Texas Instruments: *C2000™ Software Frequency Response Analyzer (SFRA) Library and Compensation Designer in SDK Framework*

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