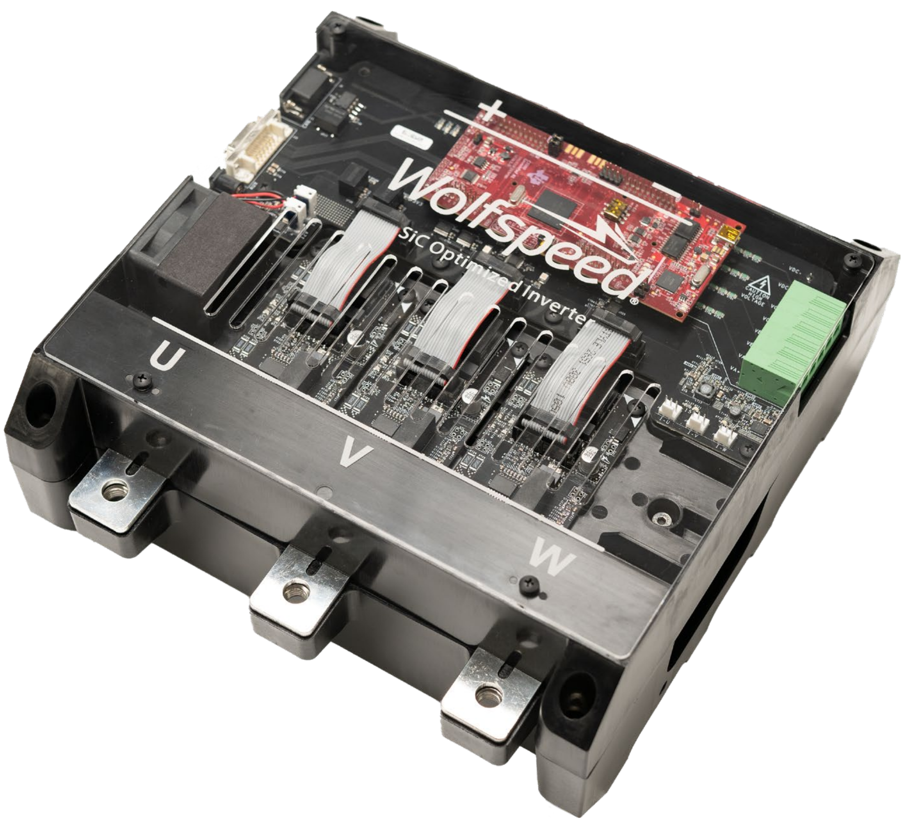
**USER GUIDE** PRD-06975

# XM3 Three Phase Inverter Reference Design User Guide



# XM3 Three Phase Inverter Reference Design User Guide

This user guide covers Wolfspeed's **CRD300DA12E-XM3**, **CRD250DA12E-XM3**, and **CRD200DA12E-XM3** three-phase inverter reference designs featuring the XM3, 1200 V, Silicon Carbide (SiC) half-bridge power module in Wolfspeed's next generation package and optimized CGD12HBXMP gate drivers with built-in protections. The XM3 module features Wolfspeed® C3M™ SiC MOSFETs, in a low inductance (6.7 nH), high power density power module package capable of 175°C maximum junction temperature operation. The XM3 three-phase inverter also features an optimized laminated bussing which reduces total power loop inductance and a high-performance liquid cold plate to maximize power dissipation. System controller and sensors are included to allow designers to quickly evaluate the XM3 module's performance in applications such as motor drives or converters.

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*This document is prepared as a user guide to install and operate Wolfspeed® evaluation hardware.*

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**DEATH ▲ SERIOUS INJURY ▲ ELECTROCUTION ▲ ELECTRICAL SHOCK ▲ ELECTRICAL BURNS ▲ SEVERE HEAT BURNS**

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警告

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请勿在通电情况下接触板子，在操作板子前应使大容量电容器的电荷完全释放。接通电源后，该评估板上通常会存在危险的高电压，板子上一些组件的温度可能超过 50 摄氏度。此外，移除电源后，上述情况可能会短时持续，直至大容量电容器电量完全释放。

操作板子时应确保遵守正确的安全规程，否则可能会出现下列危险：

死亡 ▲ 严重伤害 ▲ 触电 ▲ 电击 ▲ 电灼伤 ▲ 严重的热烧伤

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警告

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**CAUTION**

**IT IS NOT NECESSARY FOR YOU TO TOUCH THE BOARD WHILE IT IS ENERGIZED. WHEN DEVICES ARE BEING ATTACHED FOR TESTING, THE BOARD MUST BE DISCONNECTED FROM THE ELECTRICAL SOURCE AND ALL BULK CAPACITORS MUST BE FULLY DISCHARGED.**

**SOME COMPONENTS ON THE BOARD REACH TEMPERATURES ABOVE 50$^{o}$ CELSIUS. THESE CONDITIONS WILL CONTINUE AFTER THE ELECTRICAL SOURCE IS DISCONNECTED UNTIL THE BULK CAPACITORS ARE FULLY DISCHARGED. DO NOT TOUCH THE BOARD WHEN IT IS ENERGIZED AND ALLOW THE BULK CAPACITORS TO COMPLETELY DISCHARGE PRIOR TO HANDLING THE BOARD.**

**PLEASE ENSURE THAT APPROPRIATE SAFETY PROCEDURES ARE FOLLOWED WHEN OPERATING THIS BOARD AS SERIOUS INJURY, INCLUDING DEATH BY ELECTROCUTION OR SERIOUS INJURY BY ELECTRICAL SHOCK OR ELECTRICAL BURNS, CAN OCCUR IF YOU DO NOT FOLLOW PROPER SAFETY PRECAUTIONS.**

警告

通电时不必接触板子。连接器件进行测试时，必须切断板子电源，且大容量电容器必须释放完所有电荷。

板子上一些组件的温度可能超过 50 摄氏度。移除电源后，上述情况可能会短暂持续，直至大容量电容器完全释放电荷。通电时禁止触摸板子，应在大容量电容器完全释放电荷后，再操作电路板。

请确保在操作电路板时已经遵守了正确的安全规程，否则可能会造成严重伤害，包括触电死亡、电击伤害、或电灼伤。，大容量电容器已释放了所有电量。只有在切断板子电源，且大容量电容器完全放电后，才可更换待测试器件。

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通電している時にボードに接触する必要がありません。設備をつないで試験する時、必ずボードの電源を切ってください。また、大容量のコンデンサーで電力を完全に釈放してください。

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# 1. Introduction

This guide covers Wolfspeed's **CRD300DA12E-XM3**, **CRD250DA12E-XM3**, and **CRD200DA12E-XM3** three-phase inverter reference designs featuring the XM3, 1200 V, Silicon Carbide (SiC) half-bridge power module in Wolfspeed's next generation package and optimized CGD12HBXMP gate drivers with built-in protections. The XM3 module features Wolfspeed® C3M™ SiC MOSFETs, in a low-inductance (6.7 nH), high power density power module package capable of 175°C maximum junction temperature operation. The XM3 three-phase inverter also features an optimized laminated bussing which reduces total power loop inductance and a high-performance liquid cold plate to maximize power dissipation. System controller and sensors are included to allow designers to quickly evaluate the XM3 module's performance in applications such as motor drives or converters.

## 1.1 Features

- XM3 module enables high system power density
- Low inductance bussing and dc-link capacitors
- Integrated protections in gate drivers
- Closed-loop current sensors for improved feedback
- High-performance liquid cooled cold plate
- Included sensors and control hardware

## 1.2 Applications

- Motor and traction drives
- Grid-tied distributed generation
- High-efficiency converters

# 2. System overview

To take advantage of the low-inductance power module, the remaining power components of the inverter's DC side must be designed to minimize stray inductance. Lower power loop inductance results in lower peak overshoot voltages seen by the switches as well as reduction in ringing and oscillation. A complete low-inductance structure therefore enables faster turn-on and turn-off times and thereby lowers switching losses.

The design philosophy for the inverter directly follows the design philosophy utilized in the module: maximize performance through high-ampacity, low-inductance designs while minimizing cost and complexity. To achieve this, 5 key parameters were considered. First, due to the high current density achieved through SiC devices and compact module size, a high-performance thermal stack up must be implemented to maximize heat transfer. Second, the stray inductance introduced by the busbar structure should be minimized using low inductance, overlapping planar structures. Third, to close the high-frequency switching loop effectively, low-inductance and high ripple rating capacitors must be utilized. Fourth, optimal device control with high-speed protections and high-noise immunity must be utilized in the gate driver to effectively switch the devices and provide maximum survivability under fault conditions. Fifth and finally, the entire structure's cost should be minimized and the entire stack up should be engineered to minimize complexity for assembly and manufacturing. The inverter measures 279 mm by 291 mm by 115 mm for a total volume of 9.3 L and a power density of up to 32.25 kW/L more than 2x comparable Silicon (Si) based inverters. Compared to Wolfspeed's previous 250 kW, 1.2 kV 3-phase inverter, this design offers approximately 65% reduction in volume and approximately 340% increase in power density.

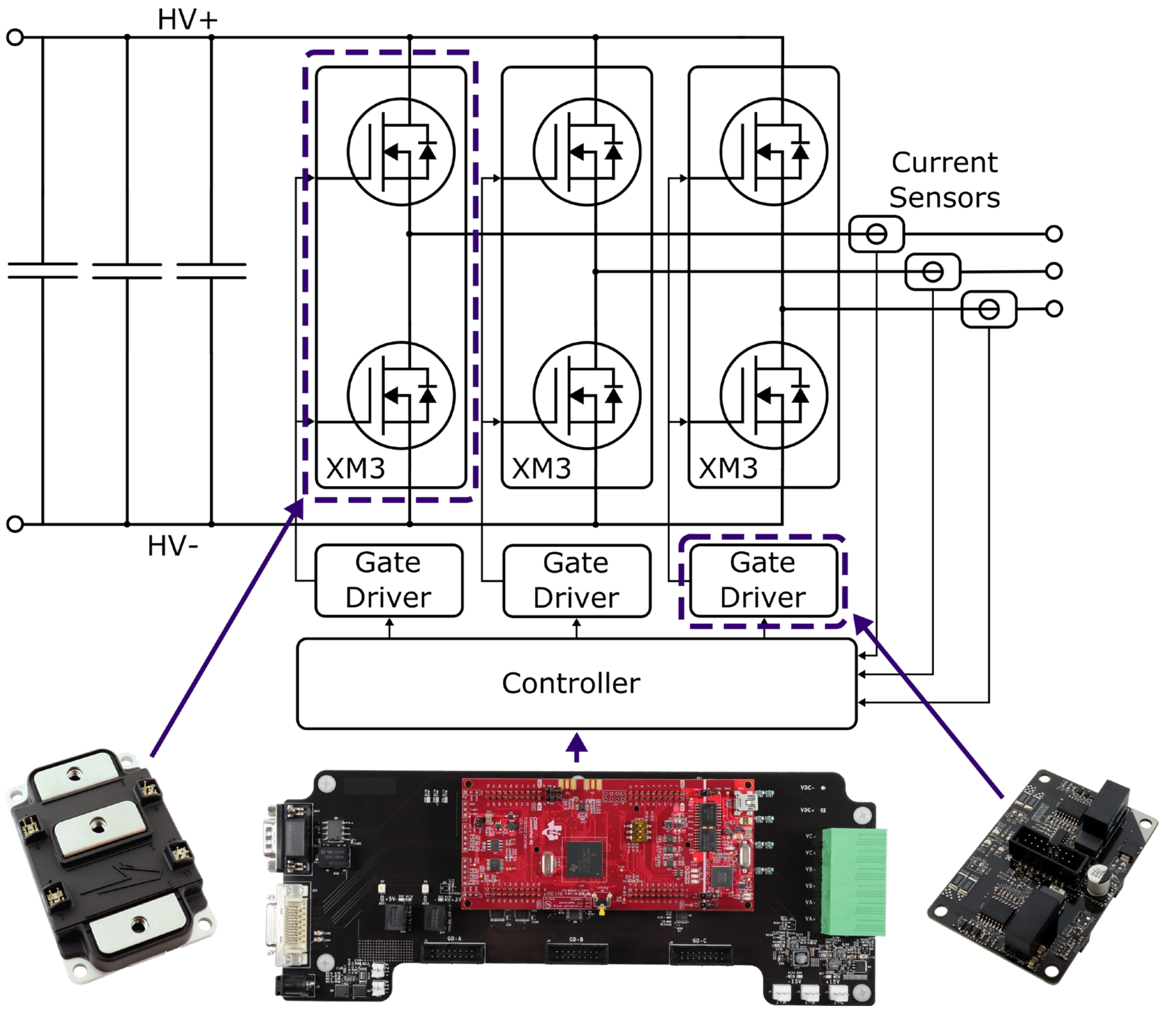



*Figure 1. System Block Diagram*

## 2.1 XM3 Module

Wolfspeed's XM3 module is designed to simplify SiC power modules by creating an all new package that is both high-performance and easy to use. Wolfspeed has developed a high-performance next generation module that is easy to use and has been optimized in a manner that is intended to achieve the maximum performance out of all sizes of commercially available 650–1700 V Wolfspeed C3M™ SiC MOSFETs. It offers the capability to carry high currents (300 to >600 A) in a small footprint (53 x 80 mm) with a terminal arrangement that allows for straight-forward bussing and interconnection. A low-inductance, evenly matched layout results in high quality switching events, minimizing oscillations both internal and external to the module. The module has a stray inductance of only 6.7 nH. When coupled with the low-inductance bussing and capacitors in this reference design, a total loop inductance of 12 nH is obtained, which is lower than the internal stray inductance of many standard power module packages. The XM3 platform offers 40% of the volume and 45% of the footprint of a package that is typically used in the industry (as illustrated in Figure 2 below) and therefore offers a more compact power module for high power density systems. Table 1 lists which variant of the XM3 module is included with each three-phase inverter reference design.

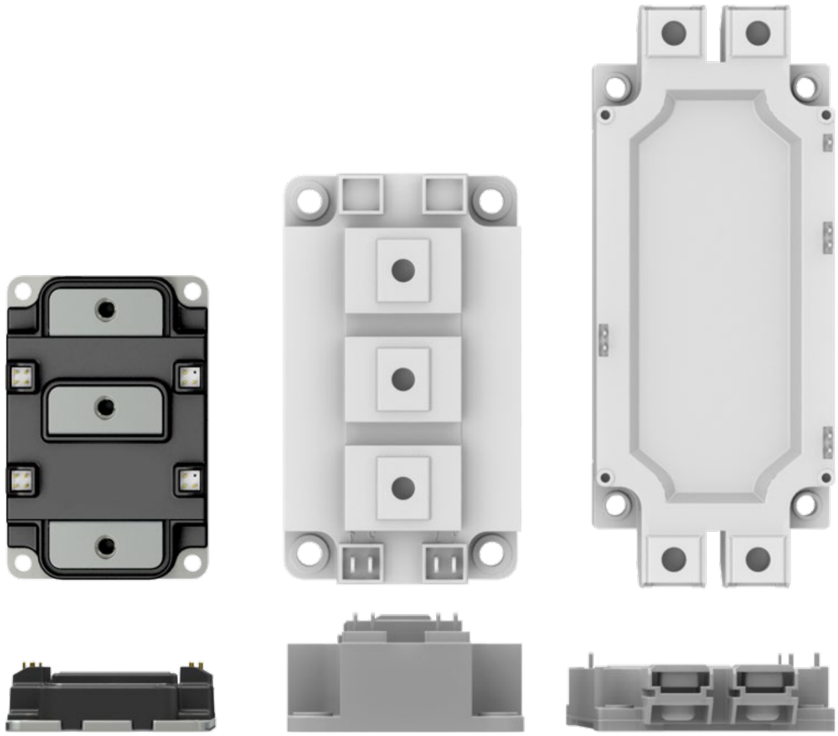


*Figure 2. Size Size Comparison Between XM3 (Left), 62 mm (Center), and EconoDUAL® (Right)*

*Table 1. XM3 Module Part Number Reference*

| Reference Design | Module Part Number |
|---|---|
| CRD300DA12E-XM3 | CAB450M12XM3 |
| CRD250DA12E-XM3 | CAB425M12XM3 |
| CRD200DA12E-XM3 | CAB400M12XM3 |

### 2.1.1 Module Power Terminals

The current loops in the XM3 power module have been designed such that they are wide, low profile, and evenly distributed between the devices so that they each have equivalent impedances across a switch position. The power terminals are vertically offset as shown in Figure 3 such that the bus bars between the DC link capacitors and the module can be laminated all the way up to the module without requiring bends, coining, standoffs, or complex isolation. A representative 3-phase inverter bussing is illustrated in Figure 4. Ultimately this achieves a low inductance throughout the entire power loop from the DC link capacitors to the SiC devices. An XM3 module without devices was connected to a Keysight E4990A Impedance Analyzer to extract the parasitic inductance of the package. The power loop inductance from V+ to V- is 6.7 nH measured at 10 MHz.

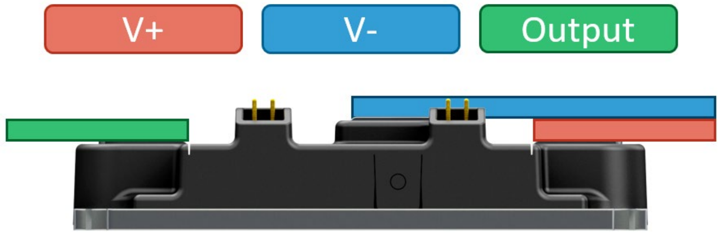



*Figure 3. Side view of XM3 module showing non-planar power leads.*

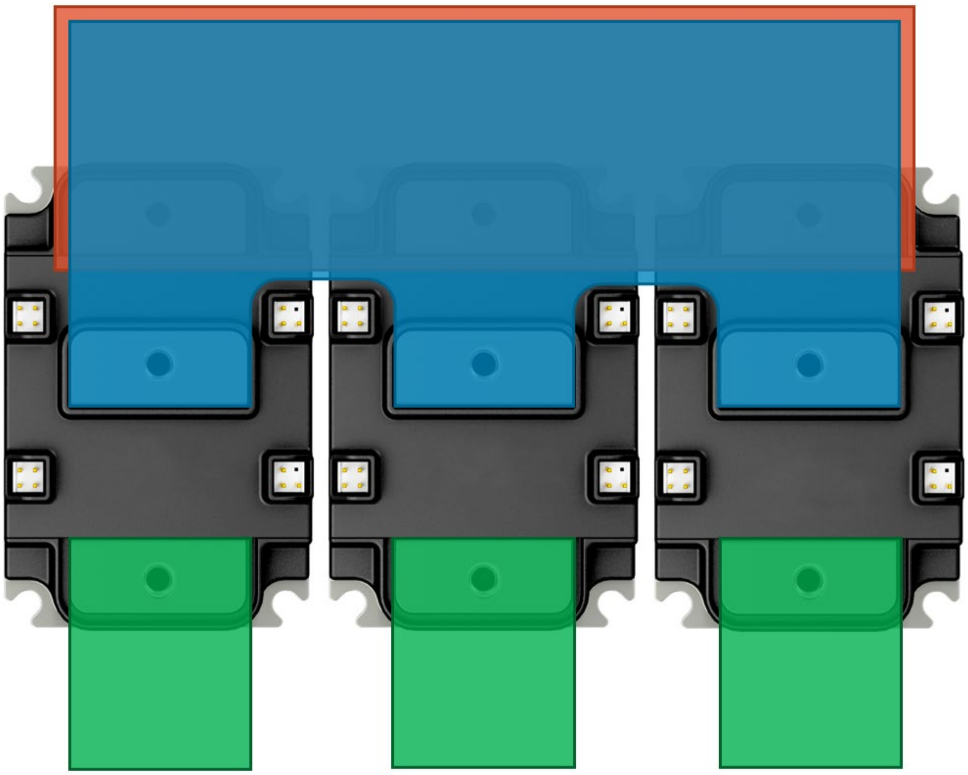


*Figure 4. Illustration Showing 3-phase Bussing Layout*

### 2.1.2 Module signal terminals

The signal pins on the XM3 module consist of four sets of male header pins grouped by function located on the left and right edge of the module as shown in Figure 5. Along the left side are the gate pins for both the high side and low side switch positions and their associated source-kelvin pins. In the upper right position is the Desat/Overcurrent pins which are internally connected to the V+ power terminal to provide a connection point for high side gate driver protection circuitry to measure $V_{DS}$. In the lower right position are the pins for the internal negative temperature coefficient (NTC) temperature sensor. The NTC is located on an electrically isolated substrate pad near the lower switch power devices and may need additional galvanic isolation according to application requirements. With Wolfspeed's CGD12HBXMP gate driver the NTC measurement signal is isolated up to 5.7 kV. The signal connectors on the right side both have one pin not populated so that the gate driver may be keyed to prevent improper installation.

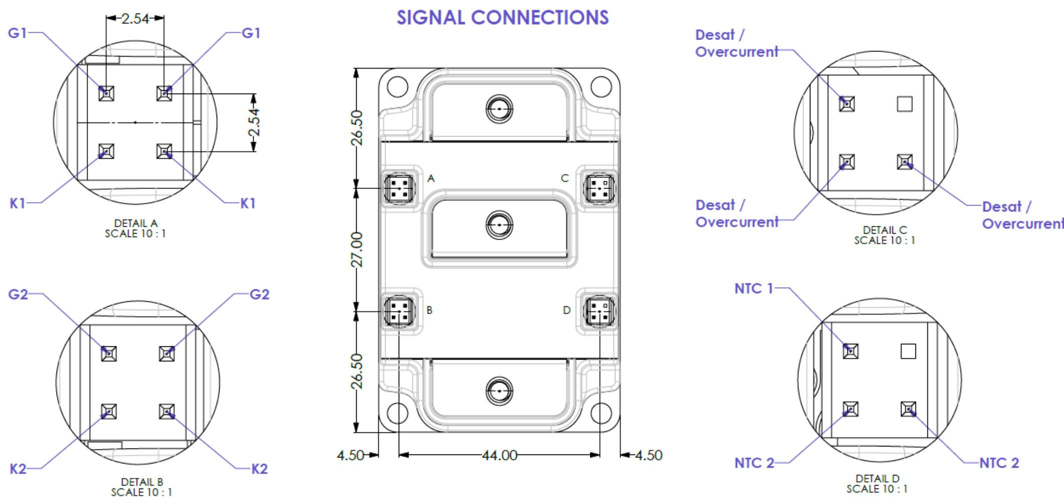



*Figure 5. XM3 Module Signal Terminal Pinout*

### 2.1.3 XM3 Switching Loss

The XM3 utilizes internal gate resistors with a short gate signal loop and wide, overlapping, low inductance paths so that the paralleled devices remain stable during high switching speeds. The modules can be safely used with zero external gate resistors when a low-inductance bus structure and low-inductance capacitors are utilized. This will assist the designer when sizing external gate resistors to ensure they do not trigger any unwanted characteristics and maintain reverse bias safe operating area (RBSOA). Additional external gate resistance can be utilized if desired.

## 2.2 Controller Board

This inverter reference design includes sensors, interfaces, power supplies, and a controller necessary for a complete motor-drive or inverter system. Three current sensors are included at the output terminals and differential, high-voltage measurements are provided for the DC bus and three external connections. Isolated gate drivers are connected via ribbon cable to the controller printed circuit board (PCB) which provides power, differential signals, and control signals. External high voltage sense connections are made on a separate side of the enclosure from the low voltage external connections for input / output (I/O) and power. An external, protected +12 V DC power jack powers the low voltage circuitry including gate drivers, controller, and current sensors. The DC power jack utilizes a 5.5 mm outer diameter barrel jack with center positive and the power adaptor is recommended to be rated to 5 A to allow for overhead when using maximum gate driver switching frequency. A powerful floating-point digital signal processor (DSP) is used to run the control-loop for the inverter as well as handle I/O.


*Figure 6. Left Side View Showing Controller Interfaces Connectors*

*Table 2. J10 Controller Auxiliary Connector Pinout*

| Pin Number | Name | Type | Description |
|---|---|---|---|
| **1** | CANBL | I/O | Non-isolated CAN port B Low |
| **2** | CANBH | I/O | Non-isolated CAN port B High |
| **3** | GND | - | Controller Ground |
| **4** | GND | - | Controller Ground |
| **5** | GND | - | Controller Ground |
| **6** | IEXT-m | I | External Current Sensor Signal |
| **7** | -15V | PWR | External Current Sensor Power -15V |
| **8** | +15V | PWR | External Current Sensor Power +15V |
| **9** | GND | - | Controller Ground |
| **10** | +3V3 | PWR | +3.3V Power Supply Output |
| **11** | GND | - | Controller Ground |
| **12** | +5V | PWR | +5V Power Supply Output |
| **13** | GND | PWR | Controller Ground |
| **14** | QEA_A | I | Quadrature Encoder Port A Input A |
| **15** | GND | - | Controller Ground |
| **16** | QEA_B | I | Quadrature Encoder Port A Input B |

| | | | |
|---|---|---|---|
| **17** | GND | - | Controller Ground |
| **18** | QEA_I | I | Quadrature Encoder Port A Input I |
| **19** | GND | - | Controller Ground |
| **20** | +5V | PWR | +5V Power Supply Output |
| **21** | GND | - | Controller Ground |
| **22** | QEB_A | I | Quadrature Encoder Port B Input A |
| **23** | GND | - | Controller Ground |
| **24** | QEB_B | I | Quadrature Encoder Port B Input B |
| **25** | GND | - | Controller Ground |
| **26** | QEB_I | I | Quadrature Encoder Port B Input I |

Table 3. J11 Barrel Jack Pinout

| Pin Number | Name | Type | Description |
|---|---|---|---|
| **Center** | +12V | PWR | +12V Input Power |
| **Sleeve** | Ground | - | Controller Ground |

### 2.2.1 Current Sensors

The phase current sensors are LEM® LF 510-S, 500 A, closed-loop current transducers. This part has an insulation voltage rating of 1500 V between primary and secondary circuits. The current output signal is preferred for better immunity against electrical noise injected into the wiring between the sensor and the controller. Closed-loop transducers have higher accuracy and lower temperature drift compared to open-loop transducers. The output busbar for each phase passes through the aperture of one of the current sensors, and the output signal is fed back to the controller. The current signal is filtered and scaled and then sensed as a voltage signal by the analog-to-digital converter (ADC). The ±800 A peak primary current corresponds to a 0-3 V signal centered at 1.5 V at the ADC input. The controller features a DC/DC converter to provide the bipolar ±15 V power required for the sensors. Provisions for a fourth current sensor are available on the controller board for an external sensor to measure an additional current.

### 2.2.2 Voltage Sensors

Three external high-voltage measurements are supported by the controller. Differential connections are provided for each input through a 6 pin Phoenix Contact® 1719231 connector, J7. A narrow tool such as a small screwdriver can be inserted into the upper square opening and pushed in to open the spring-loaded contact to allow the wire end to be inserted into the lower circular opening. The plus and minus inputs, -P and -M respectively, are stepped down to a low voltage by a voltage divider on the controller with an insulation voltage rating of 1800 V. This low voltage signal is filtered and sensed by the ADC. A ±1200 V input is scaled down to 0-3 V centered at 1.5 V for a 0 V input. The voltage sense measurements are brought in as high-voltage signals without pre-scaling for better noise immunity. Any noise injected onto the high voltage signal will create negligible noise on the final signal compared to transmitting the signal pre-scaled to a low voltage 0-5 V signal.

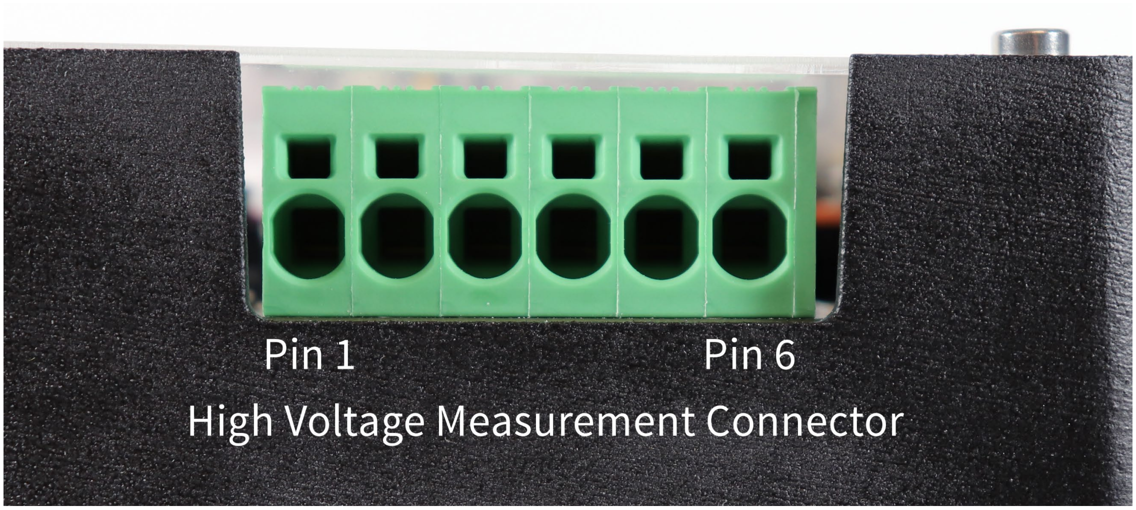



*Figure 7. High Voltage Measurement Input Connector*

*Table 4. External High-Voltage Measurement Connector Pinout*

| Pin Number | Name | Type | Description |
|---|---|---|---|
| **1** | VA-P | I | Positive High-Voltage Measurement Input Phase A |
| **2** | VA-M | I | Negative High-Voltage Measurement Input Phase A |
| **3** | VB-P | I | Positive High-Voltage Measurement Input Phase B |
| **4** | VB-M | I | Negative High-Voltage Measurement Input Phase B |
| **5** | VC-P | I | Positive High-Voltage Measurement Input Phase C |
| **6** | VC-M | I | Negative High-Voltage Measurement Input Phase C |

### 2.2.3 DC Bus Voltage Sense Connection

A voltage sense connection for the DC bus voltage is provided by a board-to-board connector between the discharge PCB and the connector on the bottom side of the controller. This allows the controller application to monitor the DC bus voltage. The full bus voltage is present at connector J8 on the controller and is stepped down through a voltage divider and filtered before reaching the ADC input. A 0-1200 V DC bus voltage signal is scaled to a 0-3 V ADC voltage.

### 2.2.4 Temperature Sensing

The NTC temperature sensor built into the power module is sensed and fed back to the controller via an isolated digital signal. This signal is a 50% duty cycle square wave with varying frequency. The temperature sensor is positioned as close as possible to the power devices while remaining electrically isolated from them and therefore provides an approximate baseplate temperature. The temperature reported by the NTC differs largely from the junction temperature of the SiC MOSFETs and should not be used as an accurate junction temperature measurement. There are two ways to measure the NTC feedback signal for the three XM3 modules with the controller. The first method is using the enhanced capture (eCAP) peripheral to digitally measure the frequency of the signal coming directly from the differential receivers. The relationship of the NTC signal frequency to the NTC temperature is given in Figure 8 and Table 5. For the second method, the frequency signal is filtered and converted into an analog signal which can be measured by ADC on the controller. The analog voltage measures 0.38 V when the frequency is 4.6 kHz and 2.5 V when the frequency is 30.1 kHz.

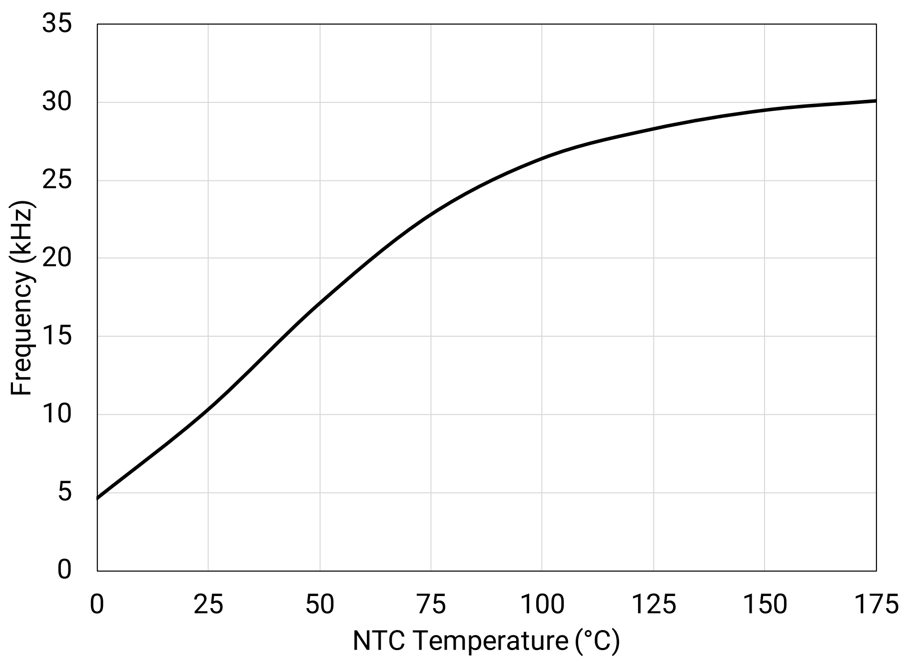



*Figure 8. NTC Temperature vs. Signal Frequency*

*Table 5. NTC Temperature, Resistance, and Frequency Correlation*

| NTC Temperature (°C) | NTC Resistance (Ω) | Frequency Output (kHz) |
|---|---|---|
| **0** | 13491 | 4.6 |
| **25** | 4700 | 10.3 |
| **50** | 1928 | 17.1 |
| **75** | 898 | 22.8 |
| **100** | 464 | 26.4 |
| **125** | 260 | 28.3 |
| **150** | 156 | 29.5 |
| **175** | 99 | 30.1 |

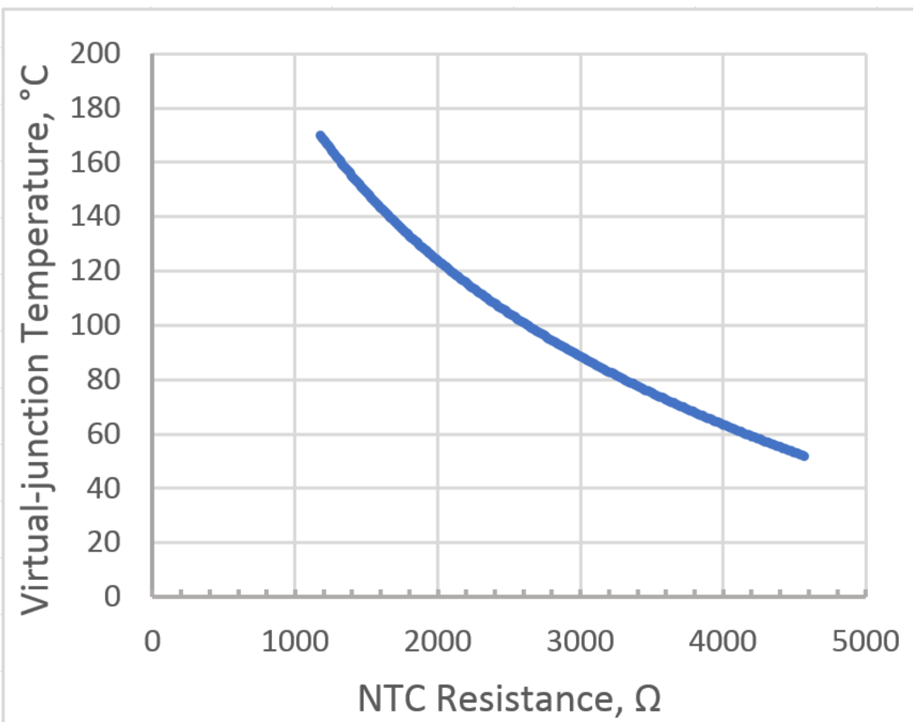



*Figure 9. CAB450M12XM3 Virtual-junction temperature (TVJ) versus NTC resistance with 25°C coolant.*

The mapping between the NTC of the CAB450M12XM3 module and the virtual junction temperature is shown in Figure 9. Equation ( 1 ) gives the virtual-junction temperature, TVJ, in Celsius for a given measured NTC resistance in Ohms.

$$T_{VJ} = -87.12\ln(NTC) + 786.14 \quad (1)$$

One additional temperature sensor is installed on the controller PCB to provide a measurement of the ambient temperature inside the reference design case. This temperature sensor consists of a 10 kΩ NTC surface mount thermistor and a 10 kΩ fixed resistor forming a voltage divider. As the temperature increases so will the voltage at the midpoint of the voltage divider. This voltage is low-pass filtered to remove any high-frequency noise from the slowly changing temperature. The conversion between this voltage signal, $V_T$, and the temperature of the thermistor (in Kelvin) can be done with the following Equation ( 2 ).

$$T = \left( \frac{\ln\left(\frac{3.3}{V_T} - 1\right)}{3900} + \frac{1}{298.15} \right)^{-1} \quad (2)$$

### 2.2.5 CAN

One of the controller's two Controller Area Network (CAN) ports is isolated and brought out via a DE-9 male connector with industry standard pinout. The port also includes an isolated +5 V power supply with 165 mA available to external circuitry. The isolation voltage of the interface is rated to 1000 VDC. The interface can support CAN baud rates up to 1000 kbps.

*Table 6. J9 CAN Port Pinout*

| Pin Number | Name | Type | Description |
|---|---|---|---|
| **1** | NC | - | NO CONNECT |
| **2** | CANA-L | I/O | Isolated CAN port A Low |
| **3** | GND-1 | - | Isolated Ground |
| **4** | NC | - | NO CONNECT |
| **5** | GND-1 | - | Isolated Ground |
| **6** | NC | - | NO CONNECT |
| **7** | CANA-H | I/O | Isolated CAN port A High |
| **8** | NC | - | NO CONNECT |
| **9** | +5V-ISO | PWR | Isolated +5V Power Supply Output |

### 2.2.6 DSP

The DSP used in the reference design controller is a Texas Instruments® (TI) TMS320F28379 dual-core, 200 MHz, 32-bit processor with built-in peripherals targeted at real-time control applications. Some of the included peripherals that make the TMS320F28379D suited for motor drive and converter control applications are two CAN interfaces for communications, two 5 V quadrature encoder inputs for position feedback, 24 advanced PWM outputs, and 4 independent ADCs with 12-bit resolution and 24 external inputs. Dual floating-point cores allow for the separation of fast control-loop from slower application code onto separate parallel CPUs. Table 7 shows the mapping of DSP General Purpose Input Output (GPIO) pins to controller functions or peripherals. All analog feedback signals for voltage, current, and temperature go through a filtering and scaling stage before passing to the ADC inputs. Table 8 shows the mapping for the input number and ADC block to which each analog signal is connected.

*Table 7. TMS320F28379D GPIO Pin Function Map*

| GPIO# | Name | Function | Direction |
|---|---|---|---|
| **18** | CANA-RX | CANA | INPUT |
| **19** | CANBH | I/O | OUTPUT |
| **12** | CANB-TX | CANB | OUTPUT |
| **17** | CANB-RX | CANB | INPUT |
| **0** | AHS-PWM | EPWM | OUTPUT |
| **1** | ALS-PWM | EPWM | OUTPUT |
| **2** | BHS-PWM | EPWM | OUTPUT |
| **3** | BLS-PWM | EPWM | OUTPUT |
| **4** | CHS-PWM | EPWM | OUTPUT |
| **5** | CLS-PWM | EPWM | OUTPUT |
| **6** | A-FAULT | FAULT | INPUT |
| **7** | B-FAULT | FAULT | INPUT |
| **8** | C-FAULT | FAULT | INPUT |
| **15** | GLOBAL-FAULT | FAULT | INPUT |
| **14** | C-PSDIS-OUT | GD-CONTROL | OUTPUT |
| **25** | A-OCEN-OUT | GD-CONTROL | OUTPUT |
| **26** | B-OCEN-OUT | GD-CONTROL | OUTPUT |
| **27** | A-LEN-OUT | GD-CONTROL | OUTPUT |
| **63** | C-OCEN-OUT | GD-CONTROL | OUTPUT |
| **64** | B-LEN-OUT | GD-CONTROL | OUTPUT |
| **66** | B-PSDIS-OUT | GD-CONTROL | OUTPUT |
| **130** | C-LEN-OUT | GD-CONTROL | OUTPUT |
| **131** | A-PSDIS-OUT | GD-CONTROL | OUTPUT |
| **10** | CASE-LED | LED | OUTPUT |

| | | | |
|---|---|---|---|
| **31** | LP-LED-BLUE | LED | OUTPUT |
| **34** | LP-LED-RED | LED | OUTPUT |
| **41** | LED-G | LED | OUTPUT |
| **52** | LED-Y | LED | OUTPUT |
| **65** | LED-R | LED | OUTPUT |
| **124** | SHUTDOWN+15V | PS-Control | OUTPUT |
| **125** | SHUTDOWN-15V | PS-Control | OUTPUT |
| **20** | QEA_A | QEP1 | INPUT |
| **21** | QEA_B | QEP1 | INPUT |
| **99** | QEA_1 | QEP1 | INPUT |
| **54** | QEB_A | QEP2 | INPUT |
| **55** | QEB_B | QEP2 | INPUT |
| **57** | QEB_1 | QEP2 | INPUT |

*Table 8. TMS320F28379D ADC Pin Input Map*

| ADC# | INPUT# | NAME | Function |
|---|---|---|---|
| **A** | 0 | A-Current | Current |
| **A** | 1 | EXT-Current | Current |
| **A** | 2 | B-Current | Current |
| **A** | 3 | Vsense-B | Voltage |
| **A** | 4 | A-TEMP | Temperature |
| **A** | 5 | C-TEMP | Temperature |
| **A** | 15 | CASE-TEMP | Temperature |
| **B** | 2 | C-Current | Current |
| **B** | 3 | Vsense-C | Voltage |
| **C** | 2 | Vsense-A | Voltage |
| **C** | 3 | Vsense-DC | Voltage |
| **C** | 4 | B-TEMP | Temperature |

## 2.3 CGD12HBXMP Gate Driver

Wolfspeed's CGD12HBXMP footprint matching gate driver for the XM3 platform is used to drive each of the three power modules. The gate driver has been optimized for Wolfspeed's C3M devices to extract the maximum performance from the modules. +15 V / -4 V voltage rails are used for the output stage of the driver to match the recommended $V_{GS}$ rating for C3M devices. A Murata® MGJ2D121505SC DC-DC converter provides 2 W for each channel with an isolation voltage of 5.2 kV with only 2.9 pF of isolation capacitance. The maximum switching frequency of the inverter will be limited by the available isolated output power of the gate driver according to Equation ( 3 ),

$$f_{sw} = \frac{P_{GD}}{Q_G * \Delta V_{GS}} \quad (3)$$

where $Q_G$ is the total gate charge of the module in coulombs and $\Delta V_{GS}$ is the gate output voltage swing or the difference between $V_{GATE,HIGH}$ and $V_{GATE,LOW}$. For the CGD12HBXMP the $\Delta V_{GS}$ is 19 V and the maximum output power is 2 W. Therefore, for a CAB450M12XM3 module with 1300 nC of total gate charge, the maximum switching frequency will be approximately 80 kHz.

The ground reference of the high side gate driver is connected to the midpoint of the half-bridge module and will switch between the DC bus voltage and power ground every switching cycle with slew rates up to 100 kV/µs. This dv/dt is applied across the isolator's capacitance and will create a common-mode current to flow into the primary side of the gate driver and the controller connected to it. Low isolation capacitance and common mode chokes for both power supplies help limit the common-mode current and prevent primary side ground bounce.

Separate output resistors for turn-on and turn-off can be changed to tune the gate rise and fall times. The output resistors are size 2512, 2 W surface mount power resistors. A starting value of 5 Ω is recommended, which can be decreased while observing the peak $V_{DS}$ overshoot voltage during turn-off and the magnitude of the ringing on the $V_{DS}$ and $I_{DS}$ waveforms. A high output current gate driver integrated circuit (IC) is used to quickly charge and discharge the gate capacitance and enable use of low $R_{Gext}$ for reduce switching loss. The gate and source-kelvin trace are routed on adjacent layers with wide, overlapping paths to reduce gate-loop inductance.

### 2.3.1 Protection Features

Protection features of the gate drivers include tunable over-current detection with soft-shutdown, under-voltage lockout, and anti-overlap of PWM inputs. The over-current detection circuit forward biases a high-voltage blocking diode connected to the drain terminal during the on-time and latches a fault signal if the voltage exceeds a tunable threshold.

The anti-overlap protection of the gate driver will set both output channels low if both PWM input signals are high to prevent a controller error leading to a shoot-through event. The timing diagram in Figure 10 shows the anti-overlap feature operation on the right side. The gate driver does not feature built-in dead-time generation. Dead-time will need to be added by the controller. A dead-time value of 2 µs as a starting point is recommended, which may be decreased after measuring both high side and low side gates during operation with high-bandwidth isolated oscilloscope probes such as Tektronix's IsoVu® series of optically isolated voltage probes.

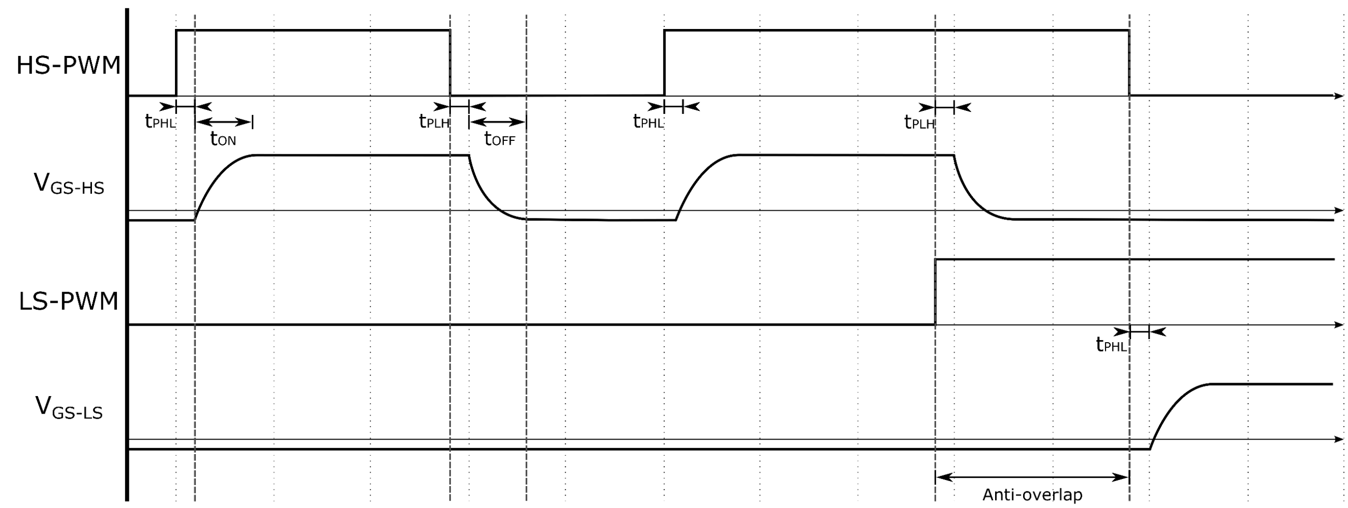



*Figure 10. Gate Timing Diagram*

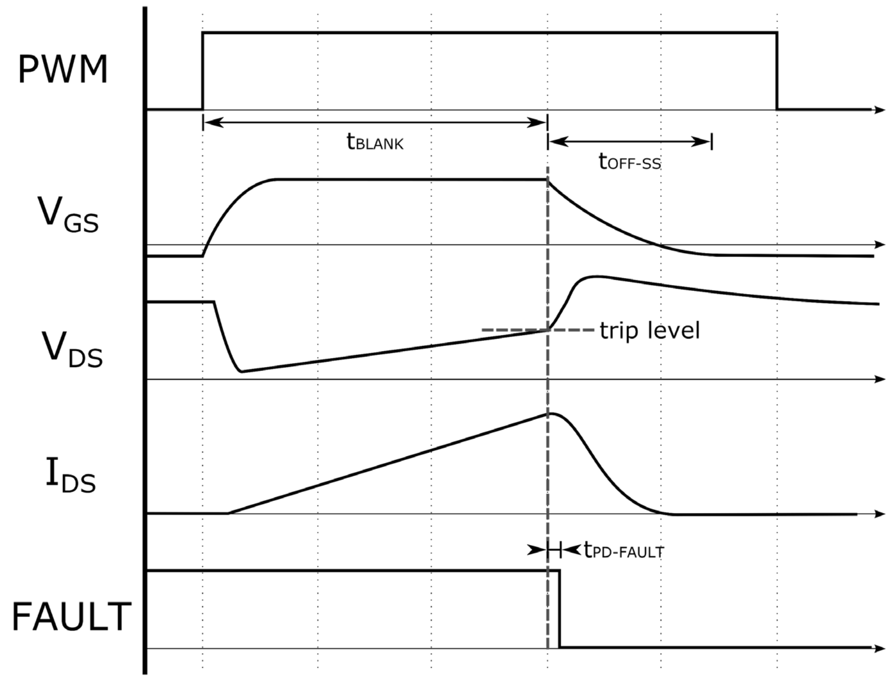



*Figure 11. Over-current Protection Timing Diagram*

### 2.3.2 Differential Signal Communication

Signal integrity is of the upmost importance when controlling power devices with a gate driver. A gate driver that is susceptible to the powerful interference generated by power devices can induce a shoot-through condition in the module. The extremely fast turn-on and turn-off times during the switching events in a SiC power system create immense electromagnetic interference (EMI) that can easily couple onto the gate control signals. For this reason, differential signaling was chosen to replace standard, single-ended connections between the gate driver and control board.

Differential signaling significantly reduces the impact of radiated noise from the switching events of a power module. A single-ended signal can easily be converted to a differential signal by transmitting both the original signal and its complement in two closely coupled wires. At the receiver, the two signals are compared in order to reconstruct the original signal. Figure 12 illustrates this principle with an example of induced noise forced onto the cable somewhere between the transmitter and receiver. The noise affects both the original signal and the complement by the same magnitude assuming the cables are consistently coupled. Thus, when the receiver compares the two signals, the difference is unaffected by the noise induced on the line and the intended original signal is created.

For each gate driver in the inverter the HS-PWM and LS-PWM inputs as well as the FAULT and RTD outputs are all RS-422 compatible differential signals. It is recommended to keep the single ended side of these signals as short as possible with a closely coupled ground plane under the traces. For this reason, the driver and receivers are located on the controller PCB as close as possible to the microcontroller pins.

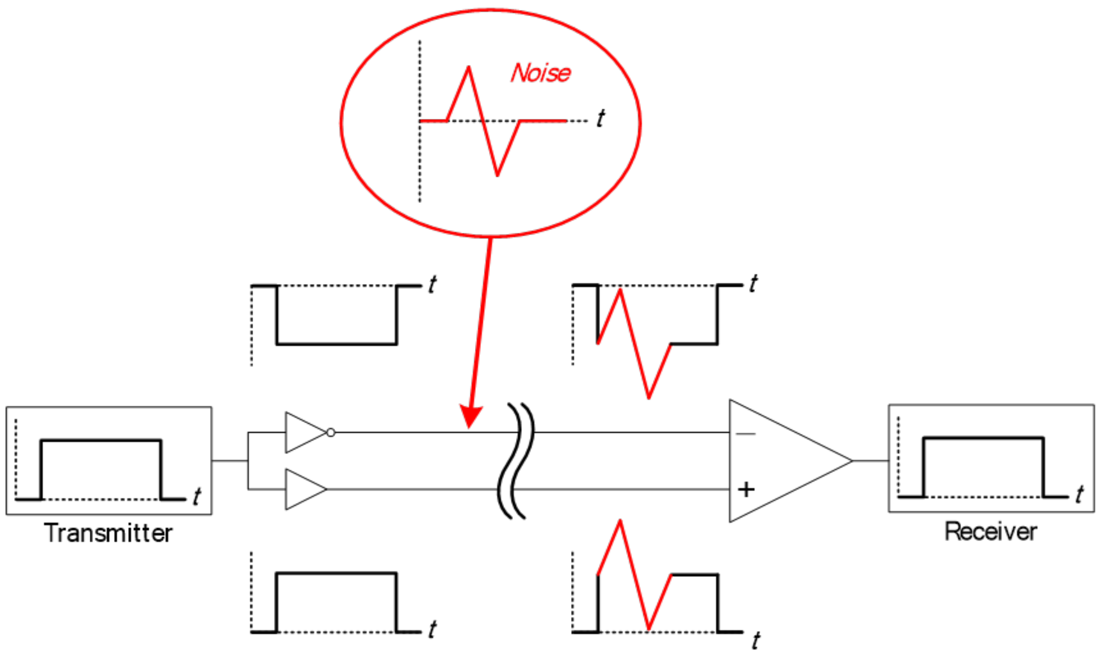



*Figure 12. EMI Noise Immunity of Differential Signals*

*Table 9. CGD12HBXMP Input Connector Pinout*

| Pin Number | Name | Type | Description |
|---|---|---|---|
| **1** | +12V | PWR | +12V Power Output |
| **2** | GND | - | Controller Ground |
| **3** | HS-PWM-P | O - Diff Pair | Positive Line of High Side PWM Signal Pair |
| **4** | HS-PWM-N | O - Diff Pair | Negative Line of High Side PWM Signal Pair |
| **5** | LS-PWM-P | O - Diff Pair | Positive Line of Low Side PWM Signal Pair |

| | | | |
|---|---|---|---|
| **6** | LS-PWM-N | O - Diff Pair | Negative Line of RS-422 Low Side PWM Signal Pair |
| **7** | FAULT-P | I - Diff Pair | Positive Line of Fault Condition Signal Pair |
| **8** | FAULT-N | I - Diff Pair | Negative Line of Fault Condition Signal Pair |
| **9** | RTD-P | I - Diff Pair | Positive Line of Temperature Dependent Resistor Output Signal Pair |
| **10** | RTD-N | I - Diff Pair | Negative Line of Temperature Dependent Resistor Output Signal Pair |
| **11** | PSDIS | O | Gate Driver Isolated Power Supply Disable Input |
| **12** | GND | - | Controller Ground |
| **13** | LEN | O | Gate Driver Logic Enable Input |
| **14** | GND | - | Controller Ground |
| **15** | RESET | O | Gate Driver Fault Detection Reset Input |
| **16** | GND | - | Controller Ground |

*PWM Signals:* High side and low side PWM are RS-422 compatible differential inputs. The termination impedance of the differential receiver is 120 Ω. Overlap protection is provided to prevent both the high side and low side gates from turning on simultaneously. The overlap protection should not be used as a dead time generator.

*FAULT Signal:* The fault signal is a RS-422 compatible differential output with a maximum drive strength of 20mA. A high signal (positive line > negative line) means there are no fault conditions for either gate driver channel. This signal will be low if an undervoltage-lockout (UVLO) or over-current fault is detected on either channel. See below for further description for what the individual faults indicate.

*UVLO Fault:* The UVLO circuit detects when the output rails of the isolated DC/DC converter fall below safe operating conditions for the gate driver. A UVLO fault indicates that the potential between the split output rails has fallen below the UVLO active level. The gate for the channel where the fault occurred will be pulled low through $R_G$ for the duration of the fault regardless of the PWM input signal. The fault will automatically clear once the potential has risen above the UVLO inactive level. There is hysteresis for this fault to ensure safe operating conditions. The UVLO faults for both channels are combined along with the over-current fault in the FAULT output signal.

*Over-Current Fault:* An over-current fault is an indication of an over-current event in the SiC power module. The over-current protection circuit measures the drain-source voltage, and the fault will indicate if this voltage has risen above a level corresponding to the safe current limit. When a fault has occurred the corresponding gate driver channel will be disabled, and the gate will be pulled down through a soft-shutdown resistor, $R_{SS.}$ The drain-source limit can be configured through on-board resistors. The over-current fault is latched upon detection and must be cleared by the user with a high pulse of at least 500 ns on the RESET signal.

*RTD Signal:* RTD output is a differential signal that measures the resistance of the temperature sensor integrated into XM3 modules. The signal is a frequency modulated signal that encodes the resistance of the temperature sensor. The approximate temperature of the module can be determined from this resistance. See Section 2.2.4 for further details.

*PSDIS Signal:* The PSDIS signal disables the output of the isolated DC/DC converters for the two channels. It is a single-ended input that must be pulled low to turn off the power supplies. With the power supplies disabled the gate will be held low with a pull-down resistor. This signal can be used for startup sequencing. LEN Signal: This is a single-ended input that enables the PWM inputs for both channels. When this signal is pulled down the differential receivers for both channels are disabled and the gates will both be pulled low through $R_G$. All protection circuitry and power supplies will continue to operate including FAULT and RTD outputs.

*Over-Voltage and Reverse Polarity Protection:* Power input on pin 1 of the gate driver connector features a power management IC to protect the gate driver from damage if a power source that exceeds the voltage rating of the gate driver is connected or if the current limit is exceeded. There is also a diode and MOSFET in-line with the power input to protect against connecting a power source with positive and negative polarity reversed.

## 2.4 Laminated busing and DC Bus Capacitors

The vertical offset of the module's power terminals allows the busbar design to remain simple and cost-effective while maintaining a low power loop inductance. A low-inductance busbar is utilized to interconnect the DC-link capacitors (located under the busbar) to the power modules. Again, the offset power module terminals enable the busbar assembly to have no bends or standoffs, which reduces cost and maximizes overlap. The capacitors are affixed as close as possible to minimize the total loop area. As can be seen in Figure 13, the busbars consist of one flat plate connecting V+ terminals of the modules and capacitors followed by an insulator and then a second flat plate connecting to the raised V- terminals of the modules and the capacitors with coining or spacer for the capacitor terminal. The structure is simple enough that it can be made with minimal fabrication which reduces the cost and lead-time.

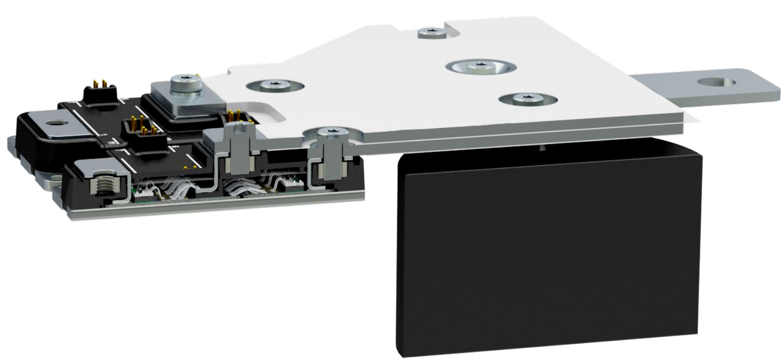


*Figure 13. Cross-section View of Laminated Busbar Structure Showing Power Loop*

Optimized orientation for the capacitors was determined by measuring the inductance of three prototypes of the bussing geometry fabricated as two-layer PCBs. Between each prototype the capacitor terminals were rotated vertically, horizontally, and diagonally at 45 degrees. The horizontal orientation offered the lowest relative inductance with capacitors installed and is the orientation used for the laminated bussing. The film capacitors serve two purposes: to close the high-frequency power loop and to provide local energy storage. To fulfil these roles the bus capacitors must be both low-inductance and have a high ripple current rating. The reference design features three Fischer & Tausche® CX100µ1100d51KF6 capacitors each rated to 100 A ripple current and 100 µF. A 1100 V voltage rating is sufficient for operating on a 900 V maximum DC bus with allowance for peak overshoots from aggressive switching rates. Each capacitor has an equivalent series inductance (ESL) of 10.5 nH. Having three of these capacitors reduces the total ESL for the capacitor bank to 3.5 nH which with a total measured inductance for the DC bussing and capacitors of 5.3 nH means the bussing by itself contributes 1.8 nH. The 5.3 nH inductance of the DC bus plus 6.7 nH power loop inductance for the XM3 module results in a combined power loop inductance of 12 nH which is lower than the stray inductance of many standard footprint modules alone.

### 2.4.1 Discharge PCB

Due to the large amount of energy storage possible in the DC bus capacitors, discharge resistors are required to bring the DC bus to a safe voltage in a reasonable amount of time. The Discharge PCB mounts to the V+ and V- terminals of one of the DC bus capacitors and has high-power surface mount resistors in addition to a board-to-board connector for the DC bus voltage sense measurement on the Controller. The resistors are sized to discharge the bus from a nominal voltage of 800 V to less than 50 V in under a minute. This requires the resistor network to dissipate a maximum of 9.4 W across 9 resistors and it has a working voltage rating of 1500 V.

**WARNING: The inverter should never be energized without the Discharge PCB connected as it is necessary to safely discharge the bulk capacitors.**

**CAUTION**

**IT IS NOT NECESSARY FOR YOU TO TOUCH THE BOARD WHILE IT IS ENERGIZED. WHEN DEVICES ARE BEING ATTACHED FOR TESTING, THE BOARD MUST BE DISCONNECTED FROM THE ELECTRICAL SOURCE AND ALL BULK CAPACITORS MUST BE FULLY DISCHARGED.**

**SOME COMPONENTS ON THE BOARD REACH TEMPERATURES ABOVE 50° CELSIUS. THESE CONDITIONS WILL CONTINUE AFTER THE ELECTRICAL SOURCE IS DISCONNECTED UNTIL THE BULK CAPACITORS ARE FULLY DISCHARGED. DO NOT TOUCH THE BOARD WHEN IT IS ENERGIZED AND ALLOW THE BULK CAPACITORS TO COMPLETELY DISCHARGE PRIOR TO HANDLING THE BOARD.**

**PLEASE ENSURE THAT APPROPRIATE SAFETY PROCEDURES ARE FOLLOWED WHEN OPERATING THIS BOARD AS SERIOUS INJURY, INCLUDING DEATH BY ELECTROCUTION OR SERIOUS INJURY BY ELECTRICAL SHOCK OR ELECTRICAL BURNS, CAN OCCUR IF YOU DO NOT FOLLOW PROPER SAFETY PRECAUTIONS.**

警告

通电时不必接触板子。连接器件进行测试时，必须切断板子电源，且大容量电容器必须释放完所有电荷。

板子上一些组件的温度可能超过 50 摄氏度。移除电源后，上述情况可能会短暂持续，直至大容量电容器完全释放电荷。通电时禁止触摸板子，应在大容量电容器完全释放电荷后，再操作电路板。

请确保在操作电路板时已经遵守了正确的安全规程，否则可能会造成严重伤害，包括触电死亡、电击伤害、或电灼伤。，大容量电容器已释放了所有电量。只有在切断板子电源，且大容量电容器完全放电后，才可更换待测试器件。

警告

通電している時にボードに接触する必要がありません。設備をつないで試験する時、必ずボードの電源を切ってください。また、大容量のコンデンサーで電力を完全に釈放してください。

ボードのモジュールの温度は 50 度以上になるかもしれません。電源を切った後、上記の状況がしばらく持続する可能性がありますので、大容量のコンデンサーで電力を完全に釈放するまで待ってください。通電している時にボードに接触するのは禁止です。大容量のコンデンサーで電力をまだ完全に釈放していない時、ボードを操作しないでください。

ボードを操作している時、正確な安全ルールを守っているのを確保してください。さもなければ、感電、電撃、厳しい火傷などの死傷が出る可能性があります。

## 2.5 Power Terminals

The power terminals for both the DC and AC side consist of portions of the bussing that extends out two sides of the case with mounting holes and captive M10 nuts. Users may connect to these terminals with cables with lugs or with bus bars. Tighten the bolts to the specified torque rating from the module datasheet available at www.wolfspeed.com.  All the bus terminal tabs are 3 mm thick and 29.5 mm wide. Exterior DC bus terminals have a vertical offset as a result of the laminated structure of the thick bus bar. This offset can be seen in Figure 3. The cables or busbar used for the power connections must be sized according to the current requirements for the application. Suggested cable size is a copper cross-sectional area of 107 mm2 (AWG 4/0).

## 2.6 Coolant

A liquid coolant system is necessary to operate the reference design with any load. The pump and heat exchanger or radiator must be sized appropriately to reject enough heat to maintain the desired cold plate temperature. Maximum output power is de-rated when operating with coolant temperatures above 25°C according to the chart in the CRD300DA12E-XM3, CRD250DA12E-XM3, or CRD200DA12E-XM3 reference design datasheet. The suggested coolant liquid is a 50/50 mixture of water-ethylene glycol (WEG). Coolant ports are G3/8, BSPP thread, with a 15 mm thread depth. An o-ring is required to seal the male fitting or pipe.

## 2.7 Ground Connection

Connect the grounding stud to an earth ground connection for safety. The grounding stud is connected internally to the cold plate and module baseplates.

**WARNING: The inverter should never be energized without the safety grounding stud connected to earth ground as this could damage the reference design and/or any connected equipment.**

# 3. Performance Data

## 3.1 Short Circuit Operation

Wolfspeed's CGD12HBXMP gate driver is designed to quickly detect and respond to short circuit events and safely limits the duration to less than 2 µs. The gate driver features soft-shutdown which will pull the module $V_{GS}$ voltage low when the over-current protection detects a fault condition. The soft-shutdown circuit is separate from the primary gate driver output stage and has its own external resistor, $R_{SS}$, which can be tuned to set the soft-shutdown turn-off time, $t_{SS}$, independently of the normal turn-on and turn-off times. The value of $R_{SS}$ is larger than RGEXT-OFF to reduce the VDS overshoot peak during turn-off of high drain current. The duration of a short circuit event is determined by the blanking time of the protection circuit and $R_{SS}$. During a short circuit fault, the drain voltage will saturate while the drain-sense voltage will stay clamped by protection diodes at its maximum and will charge the blanking time capacitor, $C_{BLANK}$, to the over-current trip voltage at the minimum $t_{BLANK}$. Even though the VDS exceeds the trip level the fault protection circuit will not engage until after the blanking time has expired. A short-circuit fault timing diagram is given in Figure 14.

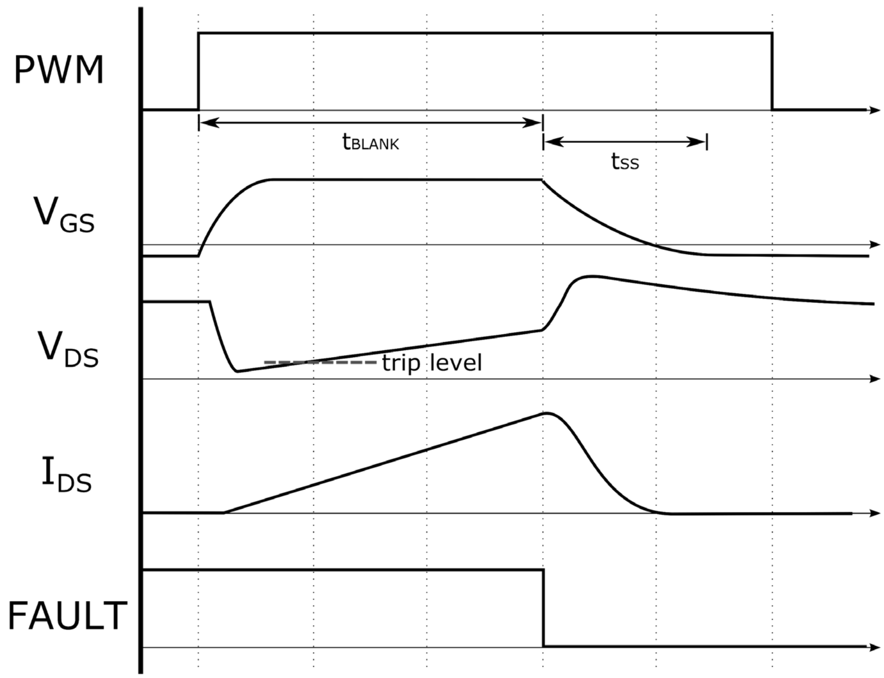



*Figure 14. Timing Diagram for Short Circuit Event*

An example waveform from a short circuit test with CAB450M12XM3 is shown in Figure 15 with a bus voltage of 800 V and an $R_{SS}$ value of 5 Ω. A copper shorting strip was installed directly across the module terminals thus creating a very low impedance short. This example shows an overshoot voltage of 985 V with a peak $I_{DS}$ current of 6.2 kA. It can be seen from this example that the $t_{BLANK}$ was set to approximately 1.5 µs.

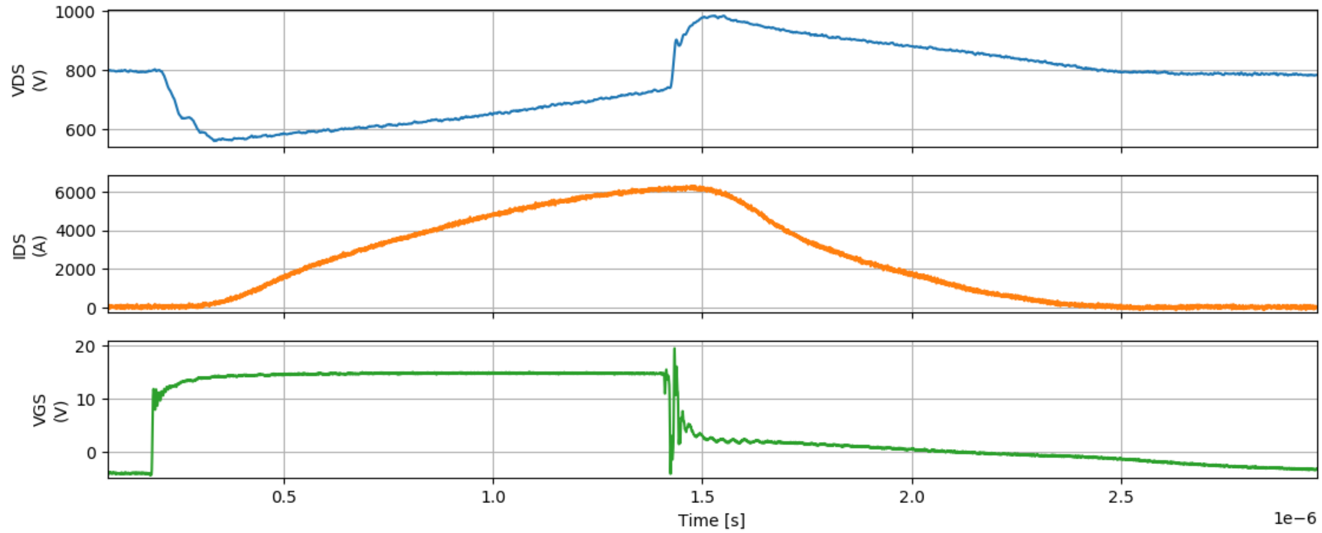



*Figure 15. Over-current waveform showing soft shutdown with RSS of 5Ω at 800 V.*

## 3.2 Power Testing Results

Full power testing of the inverter stack is demonstrated with a 3-phase recirculating power test bench. The three load inductors are connected between one of the output terminals of the inverter and the midpoint of a large capacitor bank. A DC power supply is used to charge the capacitor bank and to supply the losses of the system. Energy is transferred from one half of the capacitors to the other half through the inductor during each switching cycle. The direction of energy transfer reverses over one cycle of the fundamental frequency. The power factor is unity from the perspective of the inverter because the current and voltage is always in phase. The schematic for this test setup is shown in Figure 17. This test setup allows for full power testing to be performed without requiring a load and power supply capable of the full power rating as well. The load current and the upper switch position drain current are monitored along with the midpoint voltage and the upper switch's gate voltage. For the current measurements, PEM® CWT UM/3/B/1/80, 600 A wrap-around style Rogowski Coils are used around the output cable for each phase. These current probes have a 30 MHz bandwidth which is sufficient for measuring fundamental and switching frequencies but will not capture turn-on and turn-off dynamics as accurately as the current viewing resistor used in clamped inductive load testing. Tektronix® THDP0200, 200 MHz, High Voltage Differential Probes are connected between each phase to measure phase-to-phase waveforms. The bus voltage is set to 800 V and the modulation factor is increased until the load current reached 360 ARMS. In the results shown in Figure 16 the inverter was run at a fundamental frequency of 300 Hz and a switching frequency of 10 kHz with a load current of up to 360 ARMS. With half the DC bus applied to the inductor, the 3-phase inverter processed a total of 300 kW of power. The total inverter losses for this test was approximately 2.6 kW. The coolant loop for this test was held at a constant 25°C at the inlet port with a flowrate of 12 L/min.

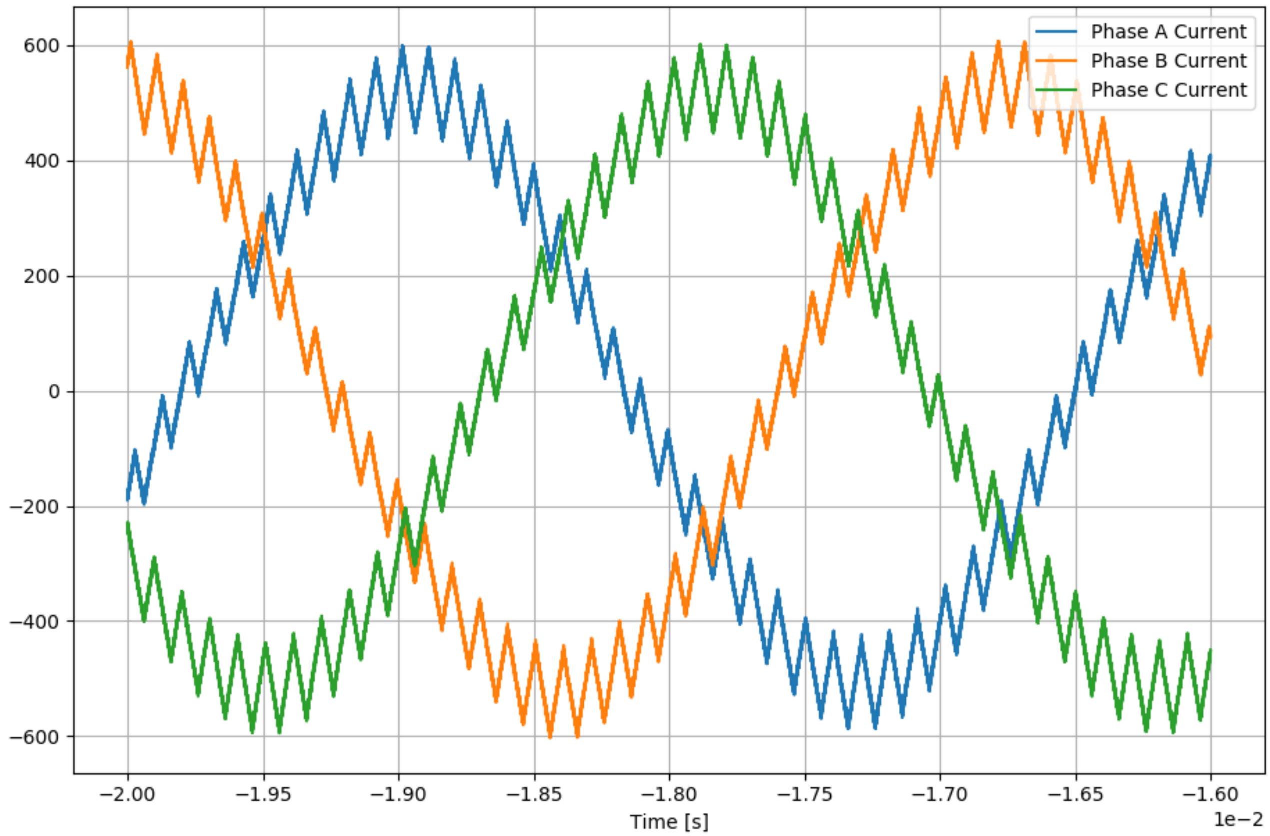



*Figure 16. 3-phase Output Current Waveforms at 360 ARMS and 800 V for CRD300DA12E-XM3*

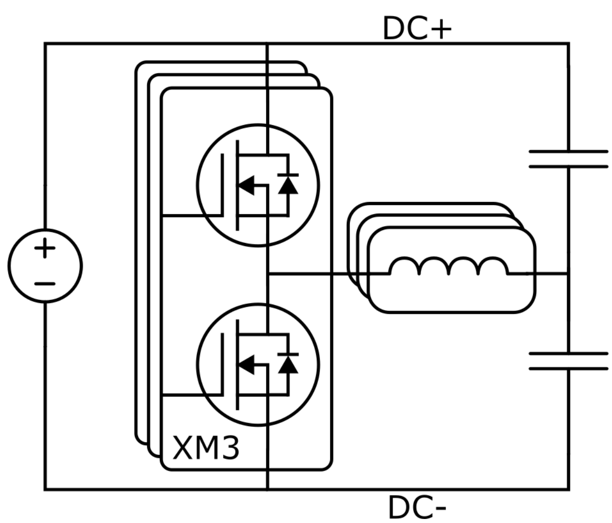



*Figure 17. 3-Phase Recirculating Power Test Schematic*

# 4. Application Example

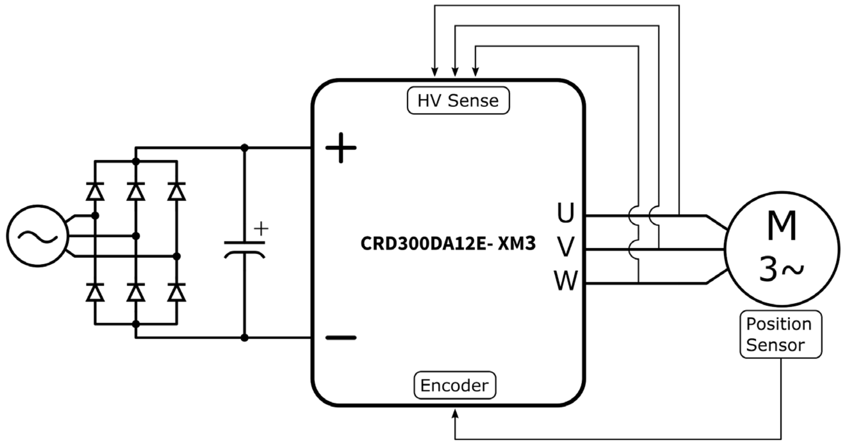



*Figure 18. Variable Frequency Motor Drive Application*

# 5. Software Overview

The XM3 3-Phase Inverter Reference Design is shipped pre-flashed with firmware providing basic open-loop 3-phase sine-PWM control of the inverter. This open-loop firmware can be controlled with the isolated CAN port on J9 to change parameter of the open-loop control. Switching frequency, modulation factor, dead-time, and fundamental output frequency can be controlled via CAN communication. The source code for the pre-flashed firmware is provided so that the user may use the firmware with Wolfspeed's XM3 3-phase Inverter Reference Design. Wolfspeed also provides host program for use with the provided firmware to control the parameters of the controller from a host computer with a graphical user interface (GUI) window. This program allows the user to test the reference design at their desired test conditions without needing to modify the controller firmware. The following sections will guide the user through the process of obtaining the required files, installing the additional software, and using Wolfspeed's XM3 Inverter CAN Interface software.

## 5.1 Important Notes Regarding Source Code, Firmware, and Software

Wolfspeed retains ownership of the source code, firmware, and software provided by Wolfspeed in connection with this reference design. This source code, firmware, and software is provided solely for use by the initial recipient and solely for the operation of the evaluation hardware described in this User Guide. This source code, firmware, and software provided by Wolfspeed is not provided by Wolfspeed to anyone other than the initial recipient and is not provided by Wolfspeed for any other purpose or use.

In addition, Sections 5 through 8 of this User Guide include guidance for downloading, installing, and/or using source code, firmware, and software, including software provided by various third-party providers. If the user follows this guidance, he or she may be or will be asked to (1) accept certain risks identified by anti-virus software, pop-up windows, or firewalls, (2) provide information and/or make certain representations or certifications to software licensors, and/or (3) accept the terms and conditions of various license agreements that govern the use of the software. A user should not proceed with this guidance unless and until he or she carefully reviews each identified risk, each request for information or a representation or certification, or each license agreement, in each case as it arises, and decides and agrees for himself or herself to accept that risk, provide that information, make that representation or certification, or comply with the terms and conditions of that license agreement, as applicable.

THE SOURCE CODE, FIRMWARE, AND SOFTWARE PROVIDED BY WOLFSPEED IN CONNECTION WITH THIS REFERENCE DESIGN, AS WELL AS ANY THIRD PARTY SOFTWARE THAT IS DESCRIBED IN THIS USER GUIDE AND DOWNLOADED BY THE USER, IS PROVIDED, DESCRIBED, AND/OR DOWNLOADED, AS APPLICABLE, "AS IS" AND "WHERE IS" AND WOLFSPEED EXPRESSLY DISCLAIMS ALL WARRANTIES OF ANY KIND REGARDING THIS SOURCE CODE, FIRMWARE, AND SOFTWARE, INCLUDING BUT NOT LIMITED TO ANY WARRANTY OF NON-INFRINGEMENT, MERCHANTABILITY, OR FITNESS FOR A PARTICULAR PURPOSE, WHETHER EXPRESS OR IMPLIED. WOLFSPEED MAKES NO REPRESENTATION THAT THE OPERATION OF THIS SOURCE CODE, FIRMWARE, OR SOFTWARE WILL BE UNINTERRUPTED OR ERROR-FREE. IN NO EVENT SHALL WOLFSPEED BE LIABLE FOR ANY DAMAGES OF ANY KIND ARISING FROM THE POSSESSION, USE, OPERATION, LICENSE, SUBLICENSE, SALE, TRANSFER, CONVEYANCE, OR DISPOSAL OF ANY OF THIS SOURCE CODE, FIRMWARE, OR SOFTWARE, INCLUDING BUT NOT LIMITED TO DIRECT, INDIRECT, INCIDENTAL, SPECIAL, COVER, RELIANCE, OR CONSEQUENTIAL DAMAGES, REGARDLESS OF THE THEORY OF LIABILITY.

The user hereby releases Wolfspeed, its affiliates, and their respective agents, officers, directors, and employees from and against any and all liability and waives any and all claims and actions it now has or which it may have in the future against any of them which, either directly or indirectly, are in any way connected with, arise out of, or result from the user's possession, use, operation, license, sublicense, sale, transfer, conveyance, or disposal of this source code, firmware, or software.

# 6. Wolfspeed Firmware Installation

## 6.1 Install Code Composer Studio

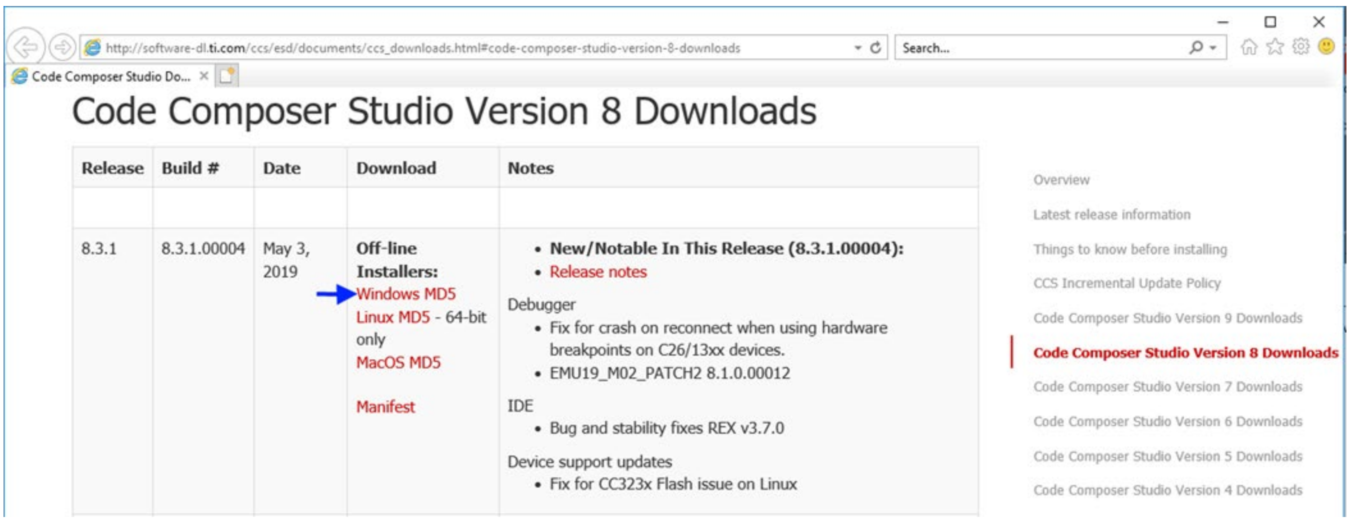
Wolfspeed's open-loop inverter firmware was developed and tested with Code Composer Studio (CCS), Version 8.3.1.00004, from Texas Instruments, Inc. (TI). It is recommended to use this version when working with Wolfspeed's source code. If used, it must be downloaded from TI's website.

### 6.1.1 Download Code Composer Studio

Open your web browser and go to the following link to download version 8.3.1.00004.

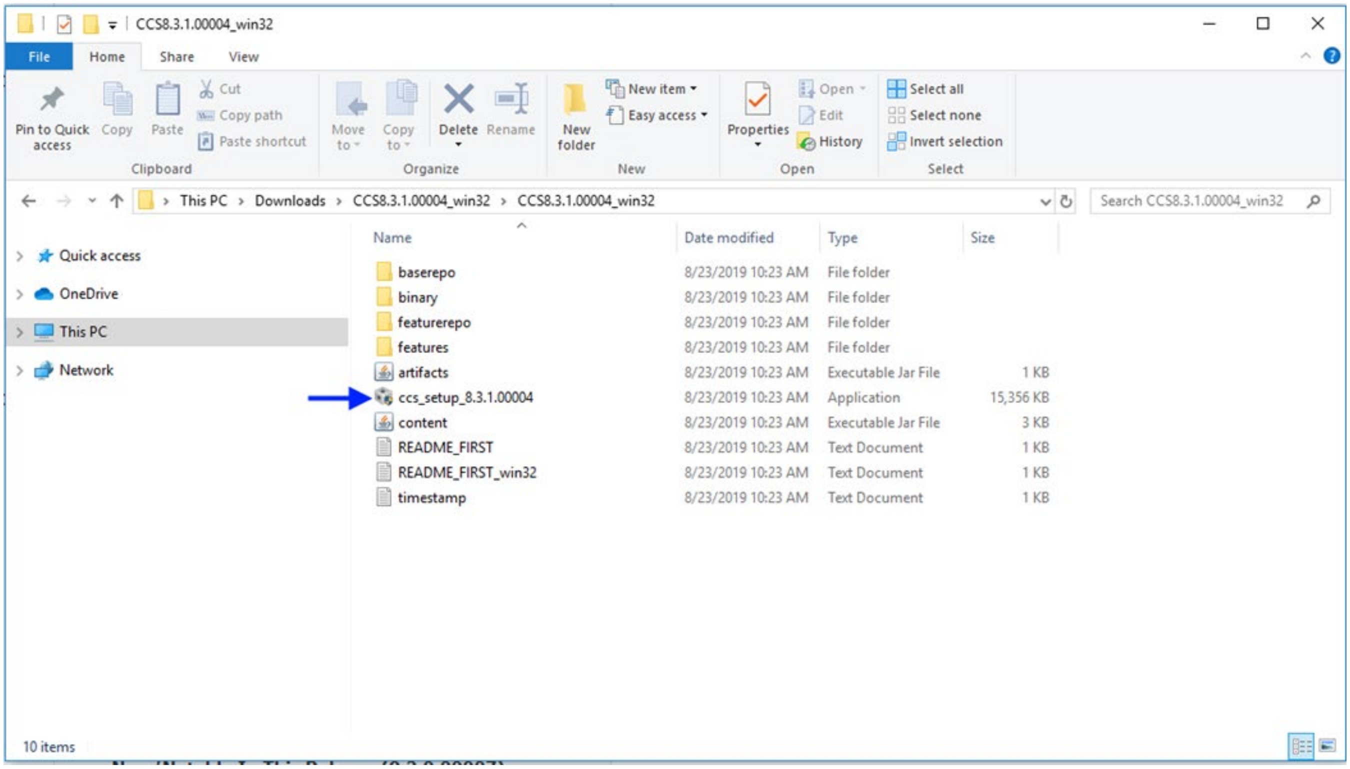
http://software-dl.ti.com/ccs/esd/documents/ccs_downloads.html#code-composer-studio-version-8-downloads

Click the download link for the Windows installer.

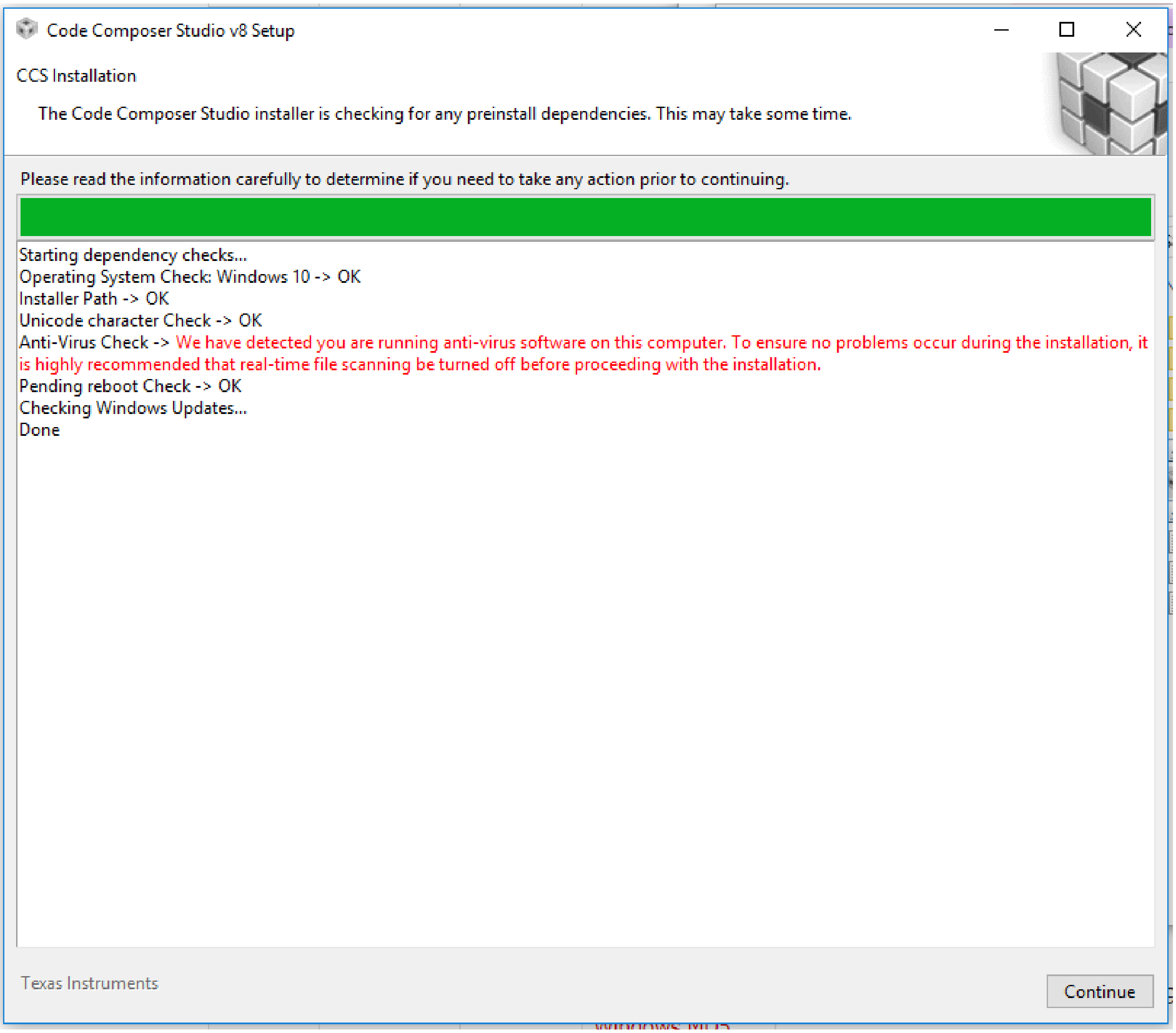


Browse in File Explorer to the location where the download was saved.

Unzip the file "CCS8.3.1.00004_win32.zip” and open the resulting folder. There will be another folder inside named “CCS8.3.1.00004_win32” which you should open.

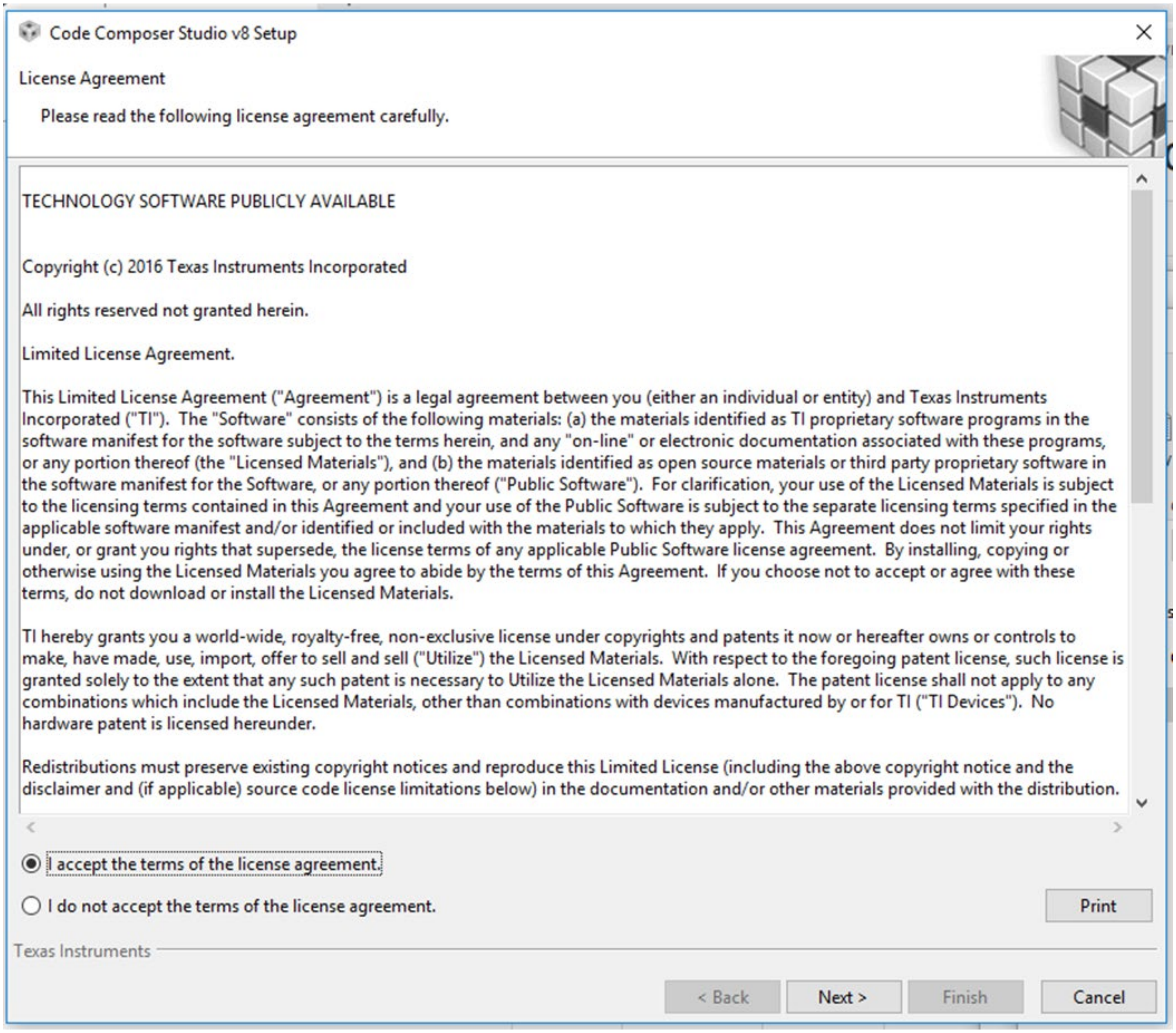


Run the application named “ccs_setup_8.3.1.00004.exe”

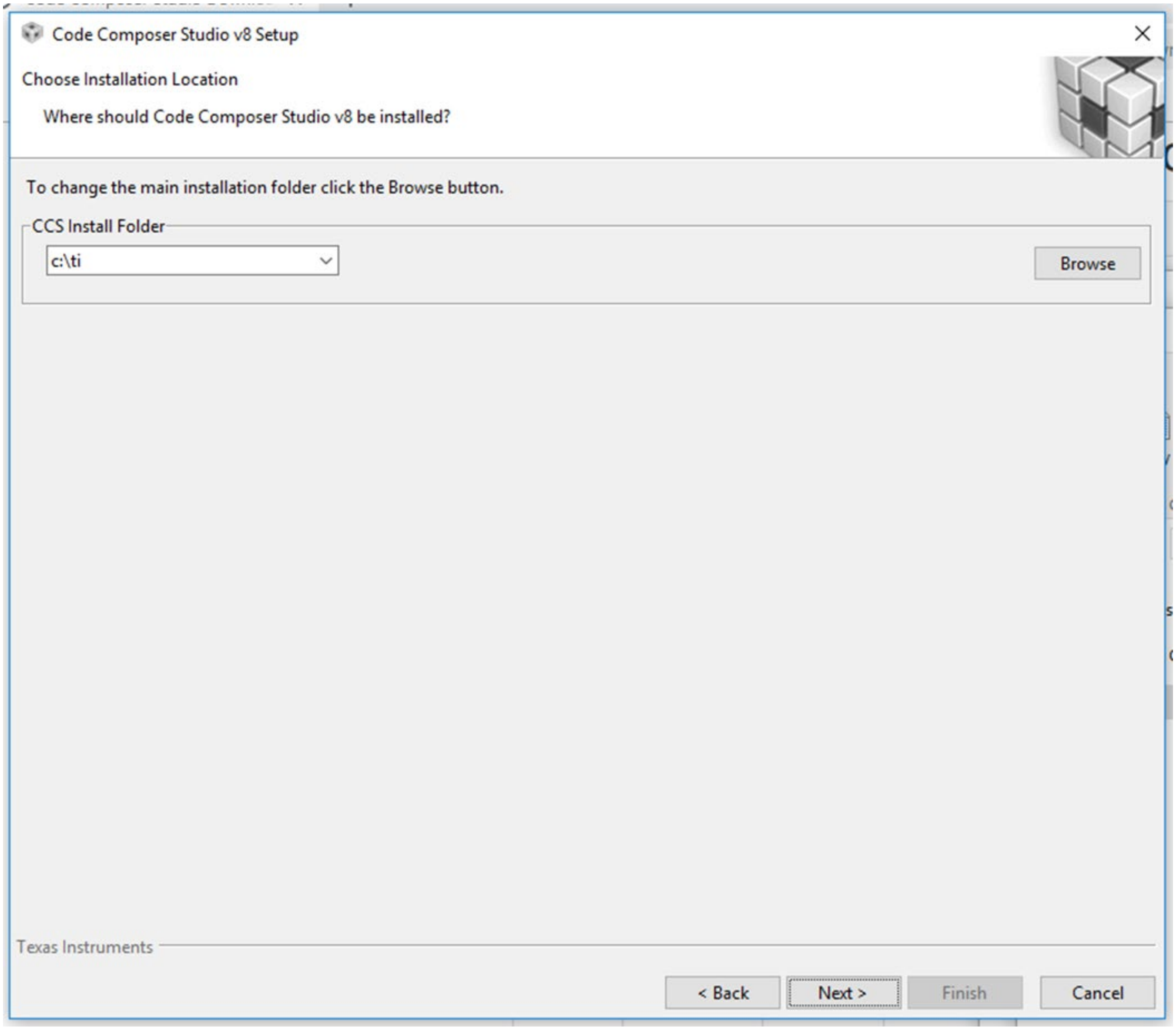



There may be a warning if you have anti-virus software installed, as illustrated above. After careful review and acceptance of the risk(s) identified by the warning, click Continue.

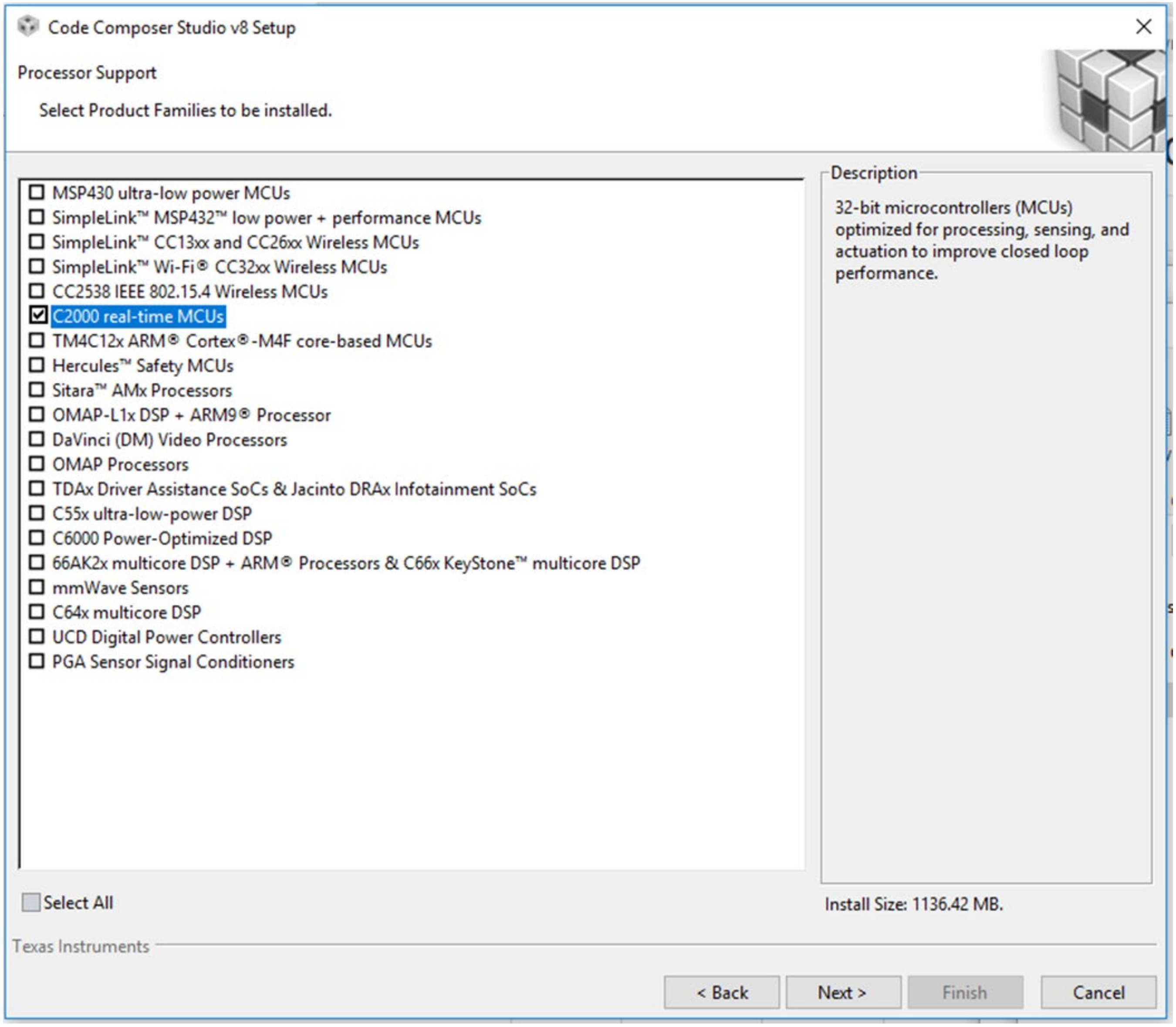
After careful review and acceptance of its terms, select that you accept the license agreement and click Next.



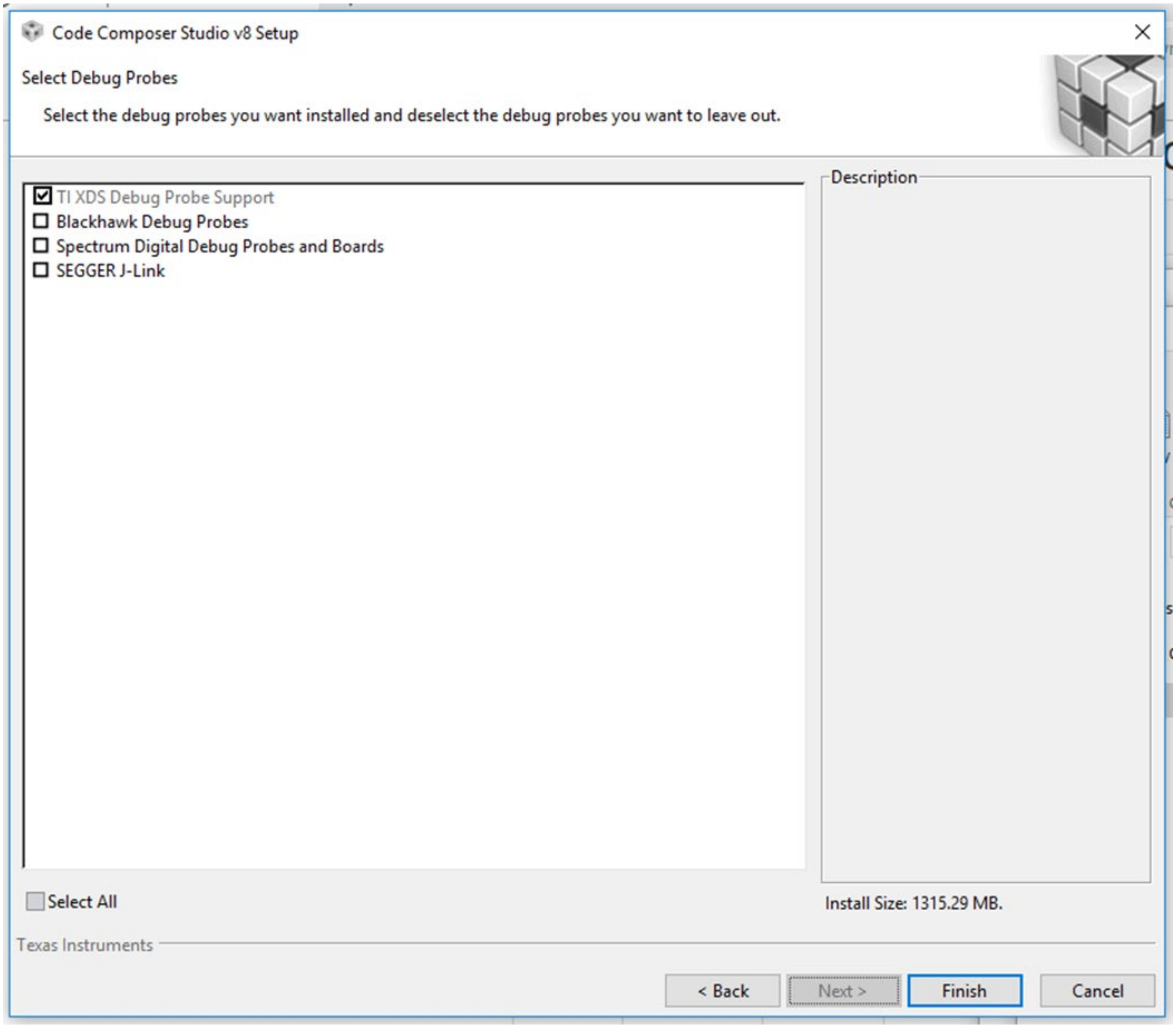
Select the installation directory to be “C:\ti”. This should be selected already as default.



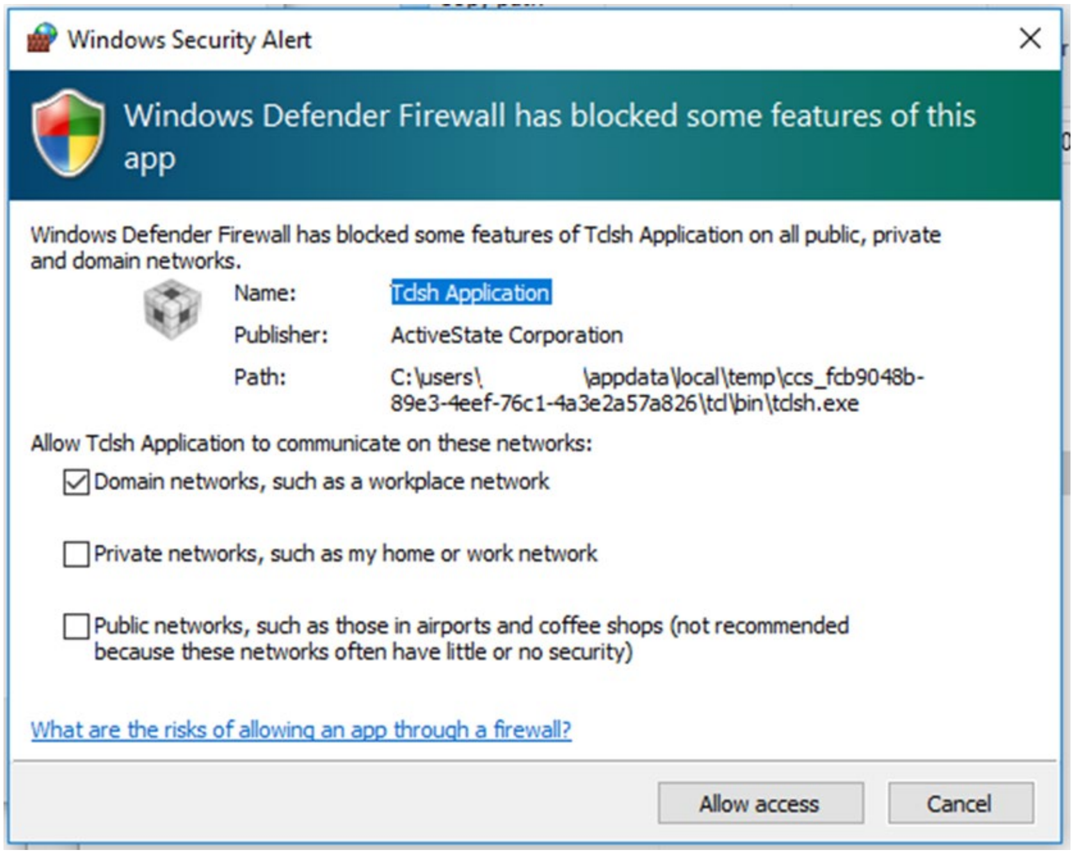
Select “C2000 real-time MCUs” on the following screen. Then click Next.



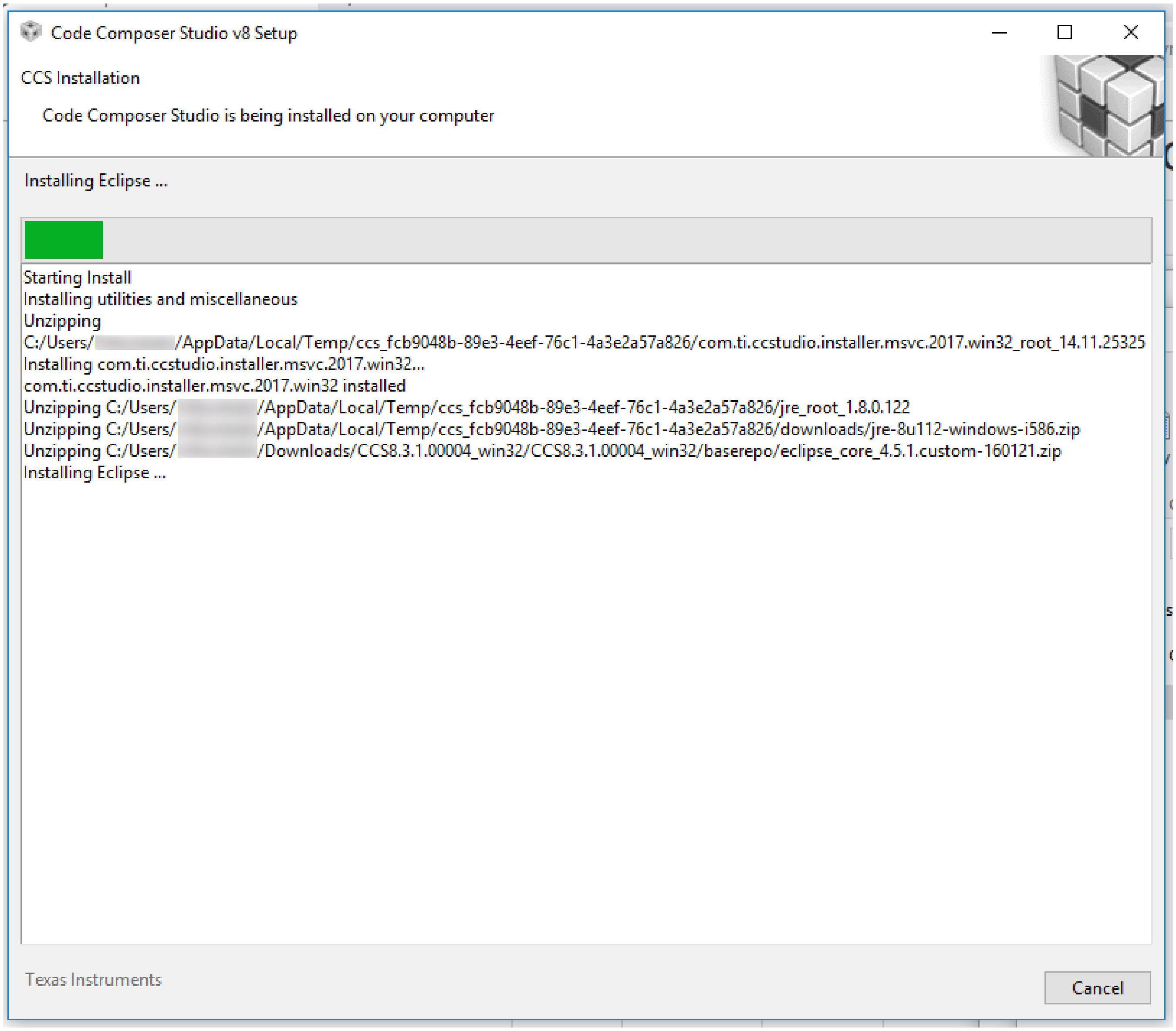
Leave the “TI XDS Debug Probe Support” selected and then click Finish.



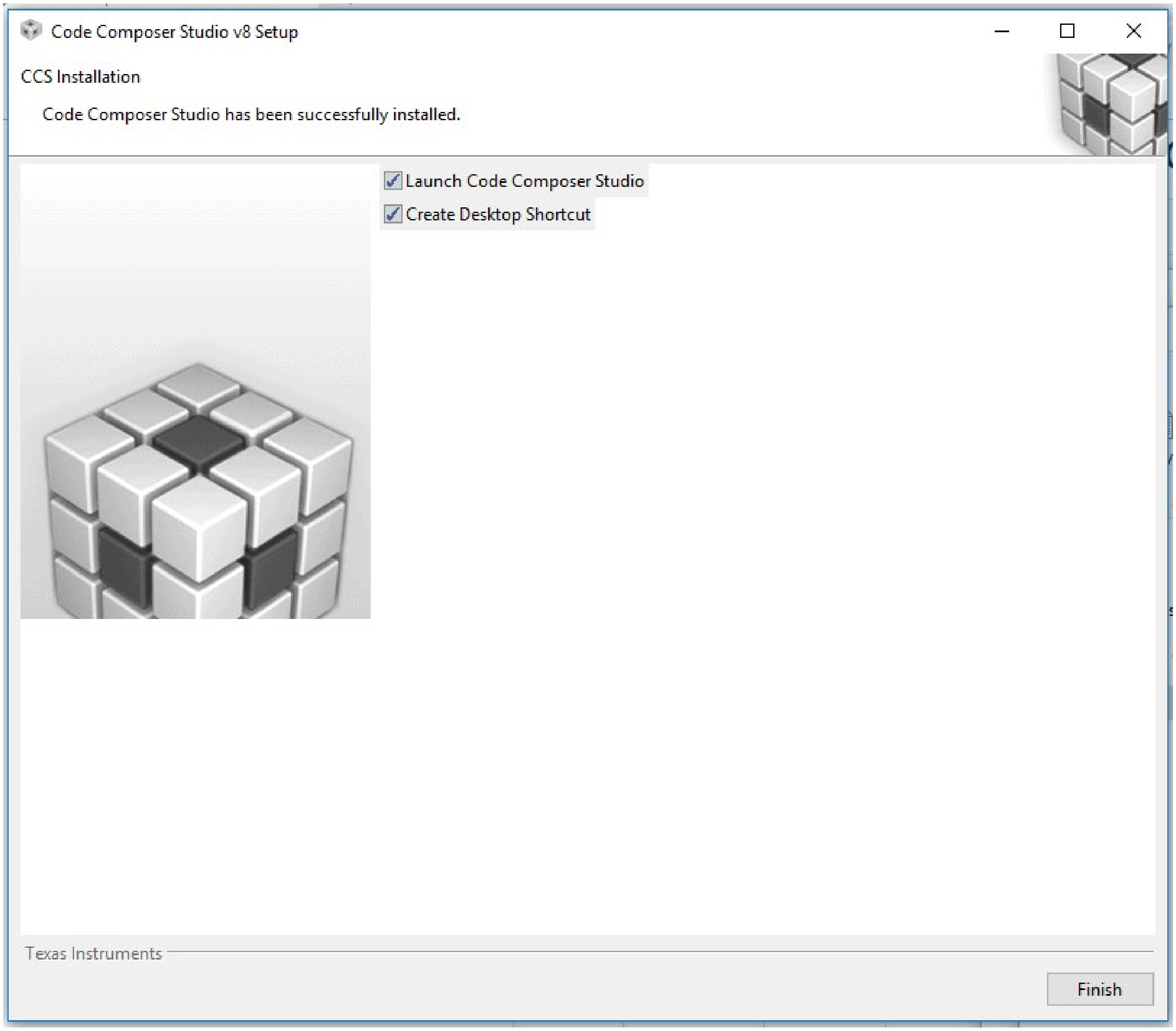
If you receive any pop-up window during the installation process and you wish to continue with the installation after reviewing the content of the window, select Allow access.



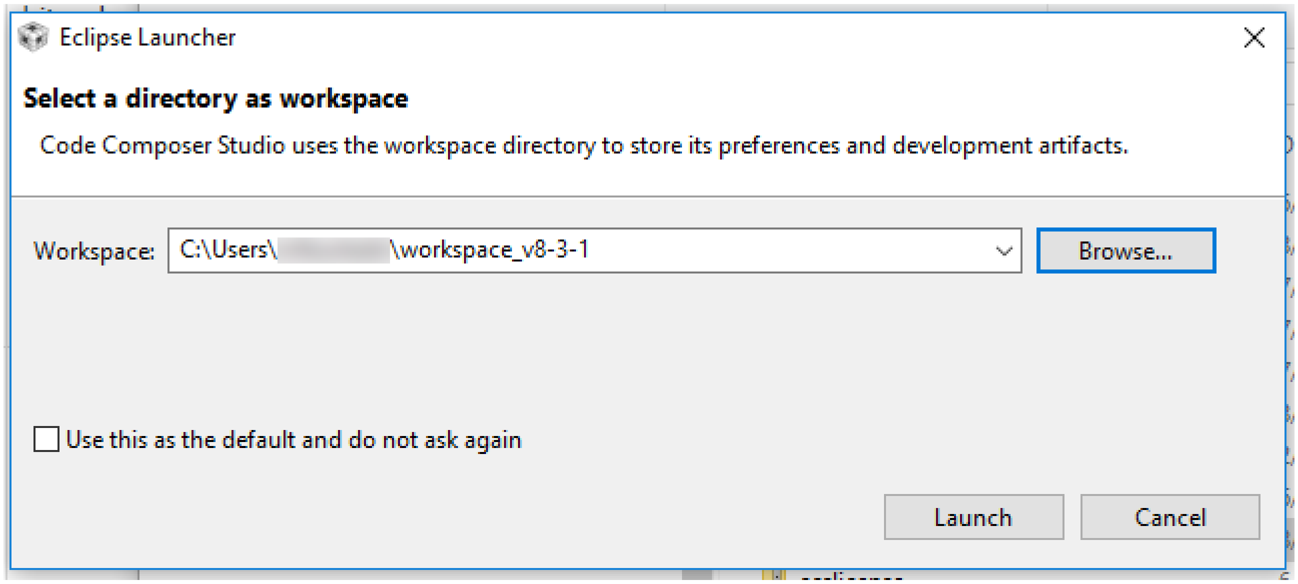
Code Composer Studio will begin installing



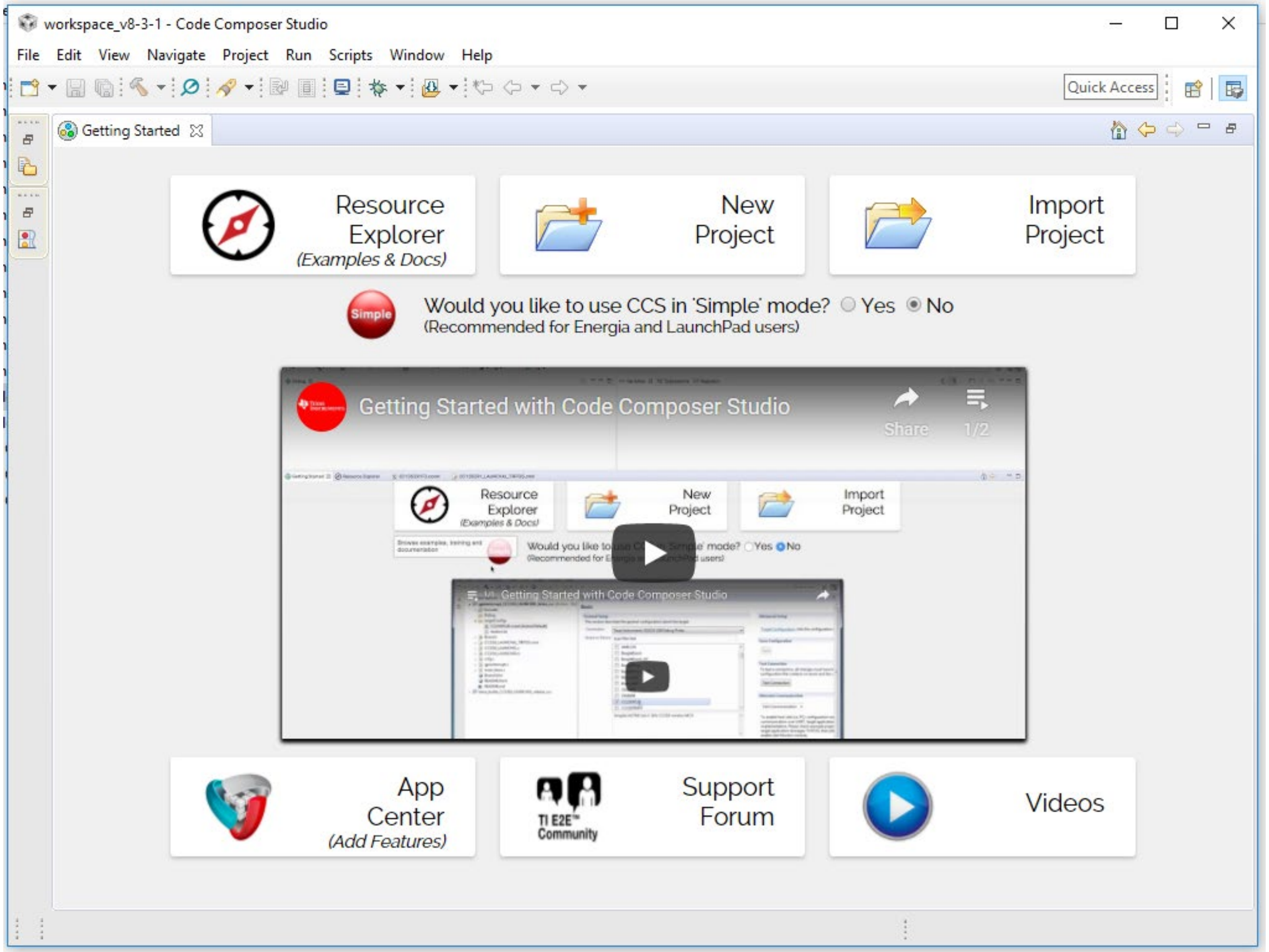
Select Finish and CCS will launch.



Select a folder for the workspace directory.



CCS should now start and will look like the below screen.



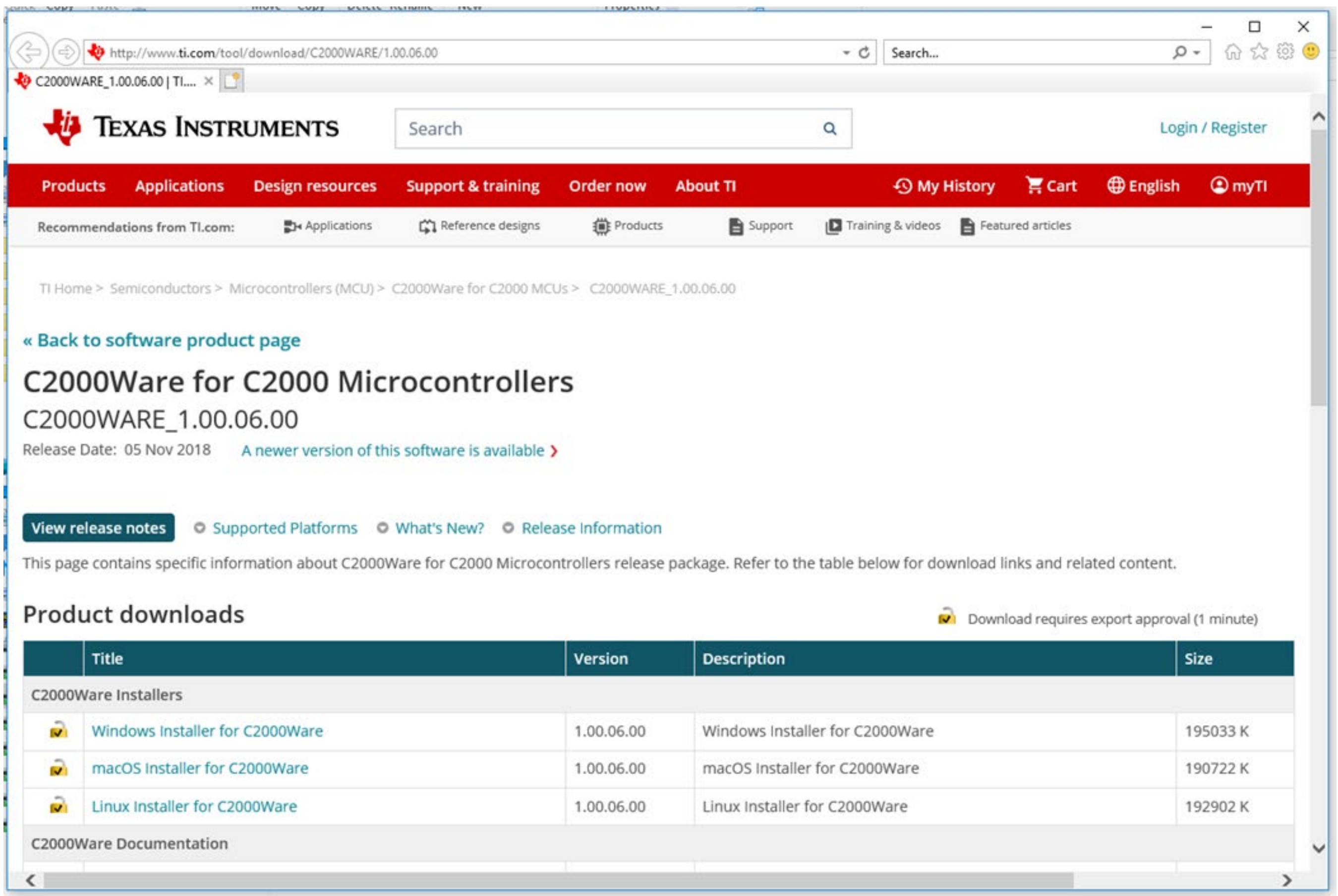
## 6.2 C2000Ware Installation

Wolfspeed's open-loop inverter firmware was developed and tested with TI's C2000Ware library version 1.00.06.00. It is recommended to use this version when working with Wolfspeed's source code. If used, it must be downloaded from TI's website.

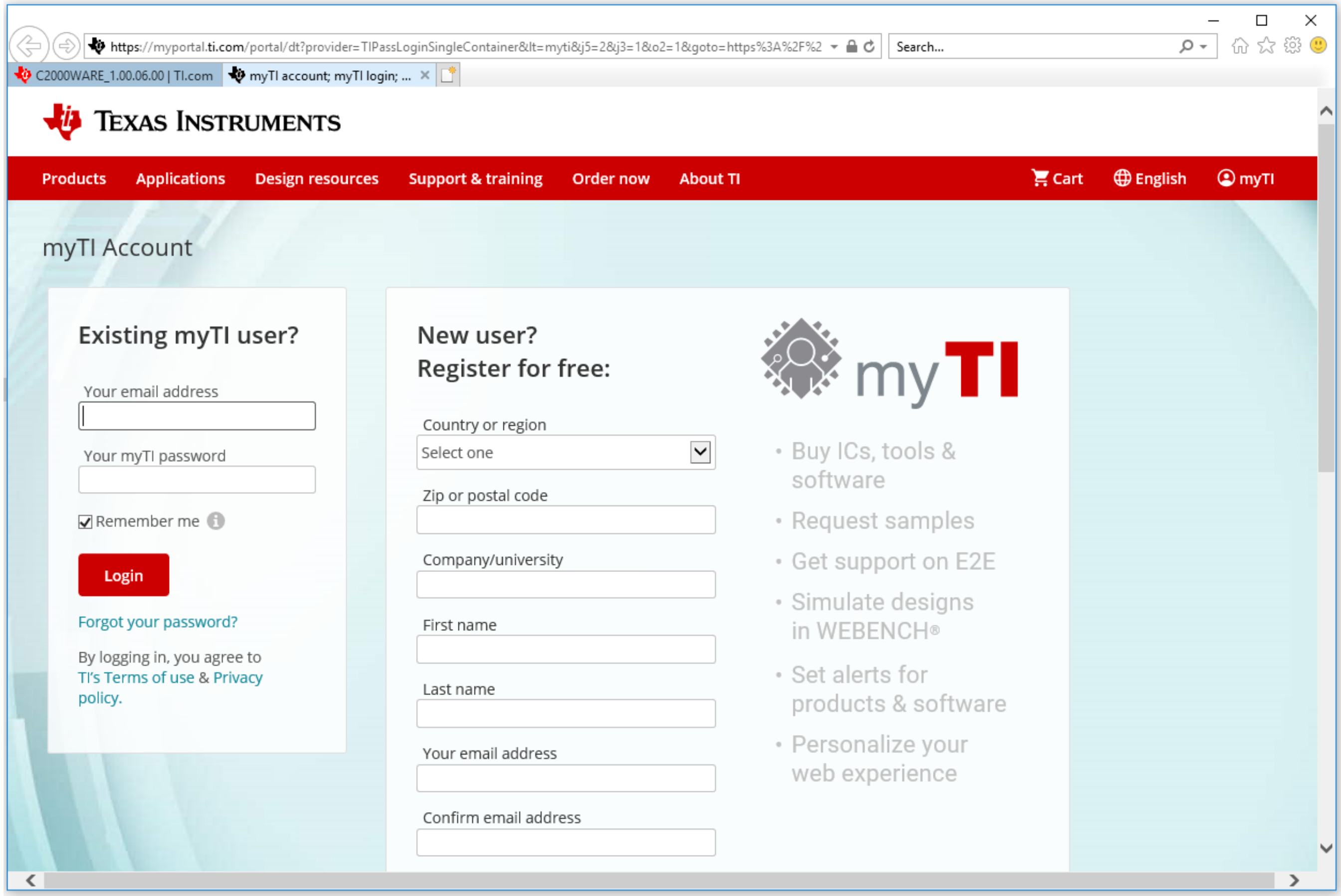
Open your web browser and go to the following link to download version 1.00.06.00.

http://www.ti.com/tool/download/C2000WARE/1.00.06.00

Click the download link for the Windows installer.




Next login or register with myTI to enable the download.



https://myportal.ti.com/portal/dt?provider=TIPassLoginSingleContainer&lt=myti&j5=2&j3=1&o2=1&goto=https%3A%2F%2
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Your email address
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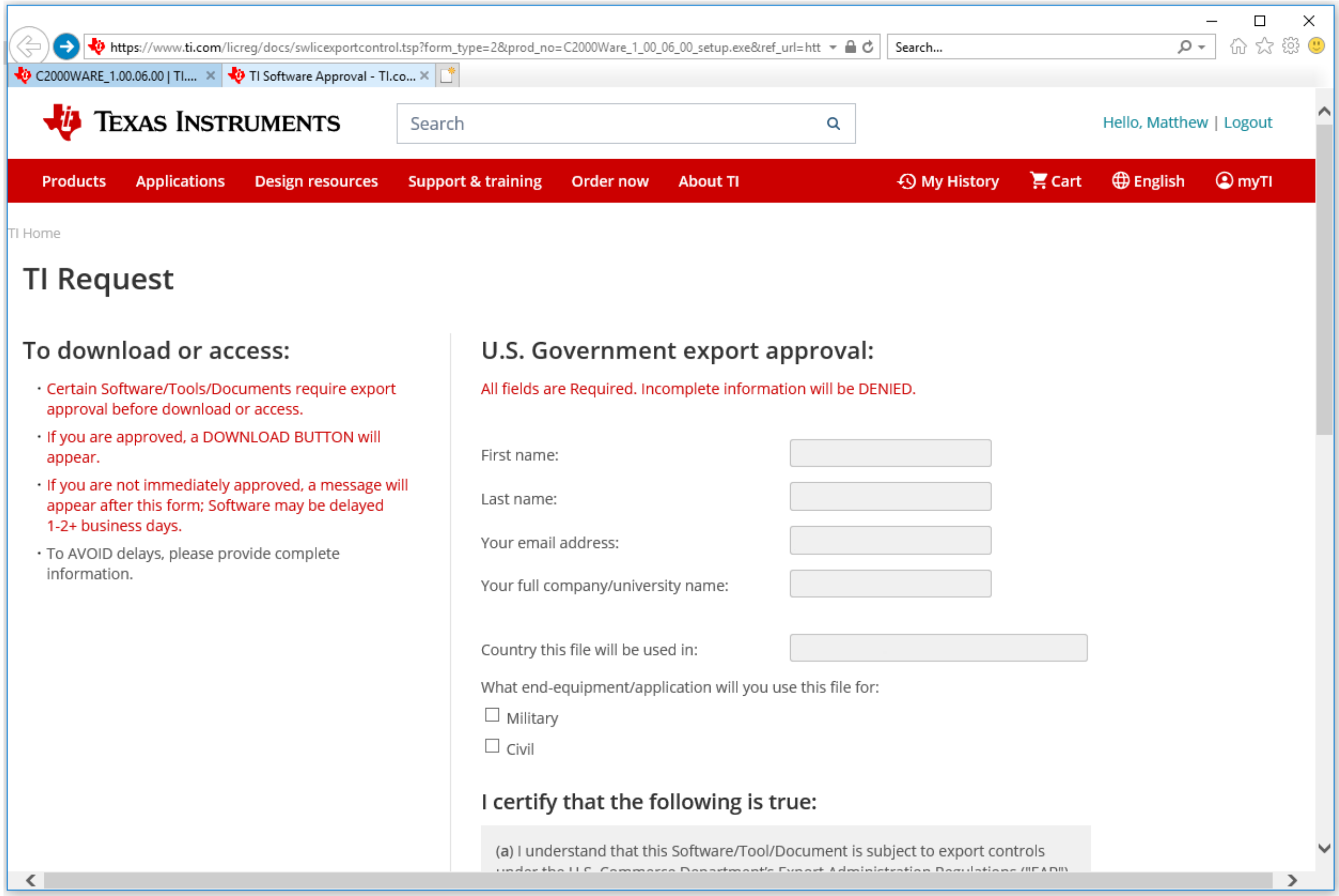
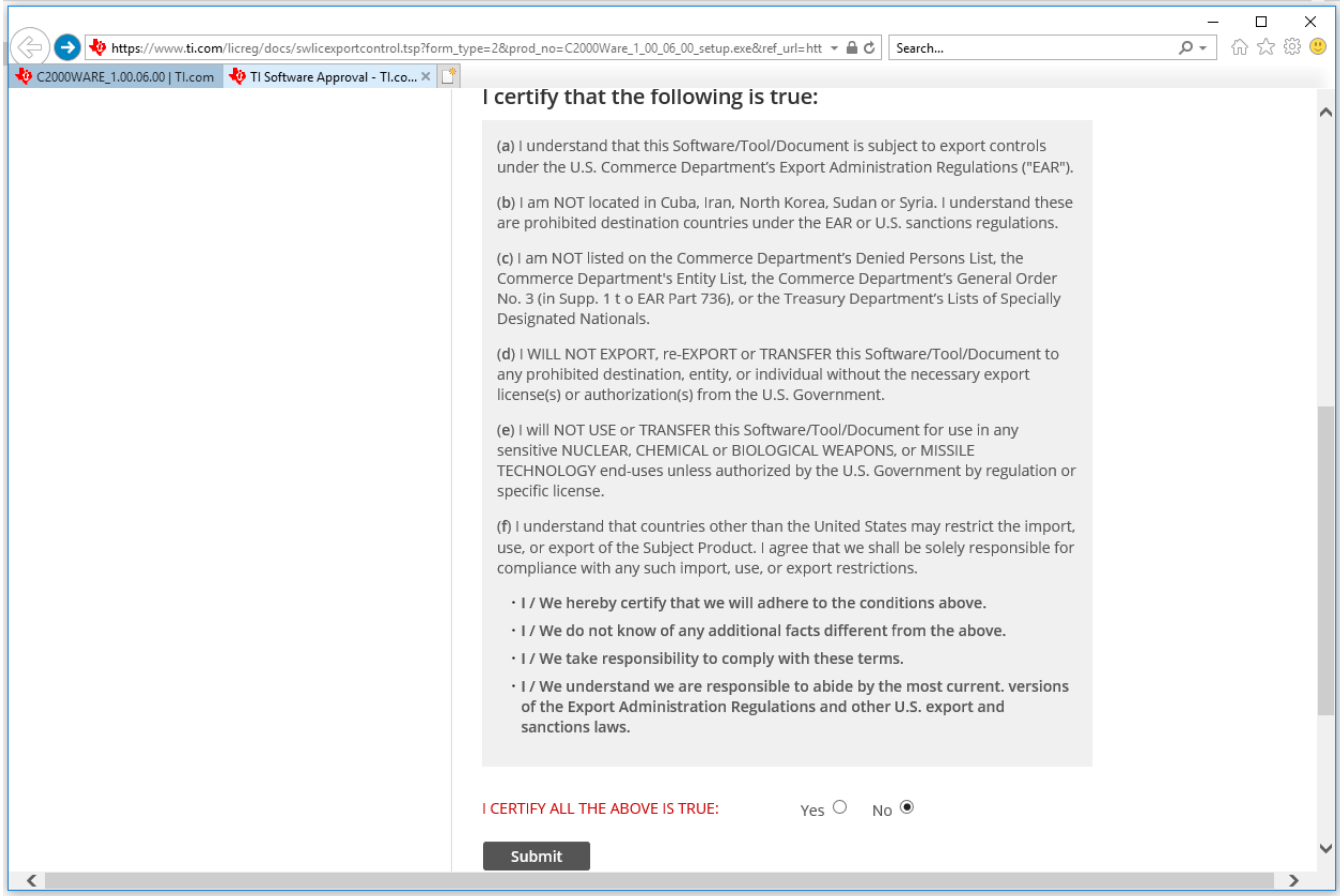
Remember me
Login
Forgot your password?
By logging in, you agree to TI's Terms of use & Privacy policy.
New user?
Register for free:
Country or region
Select one
Zip or postal code
Company/university
First name
Last name
Your email address
Confirm email address
my TI
Buy ICs, tools & software
Request samples
Get support on E2E
Simulate designs in WEBENCH®
Set alerts for products & software
Personalize your web experience

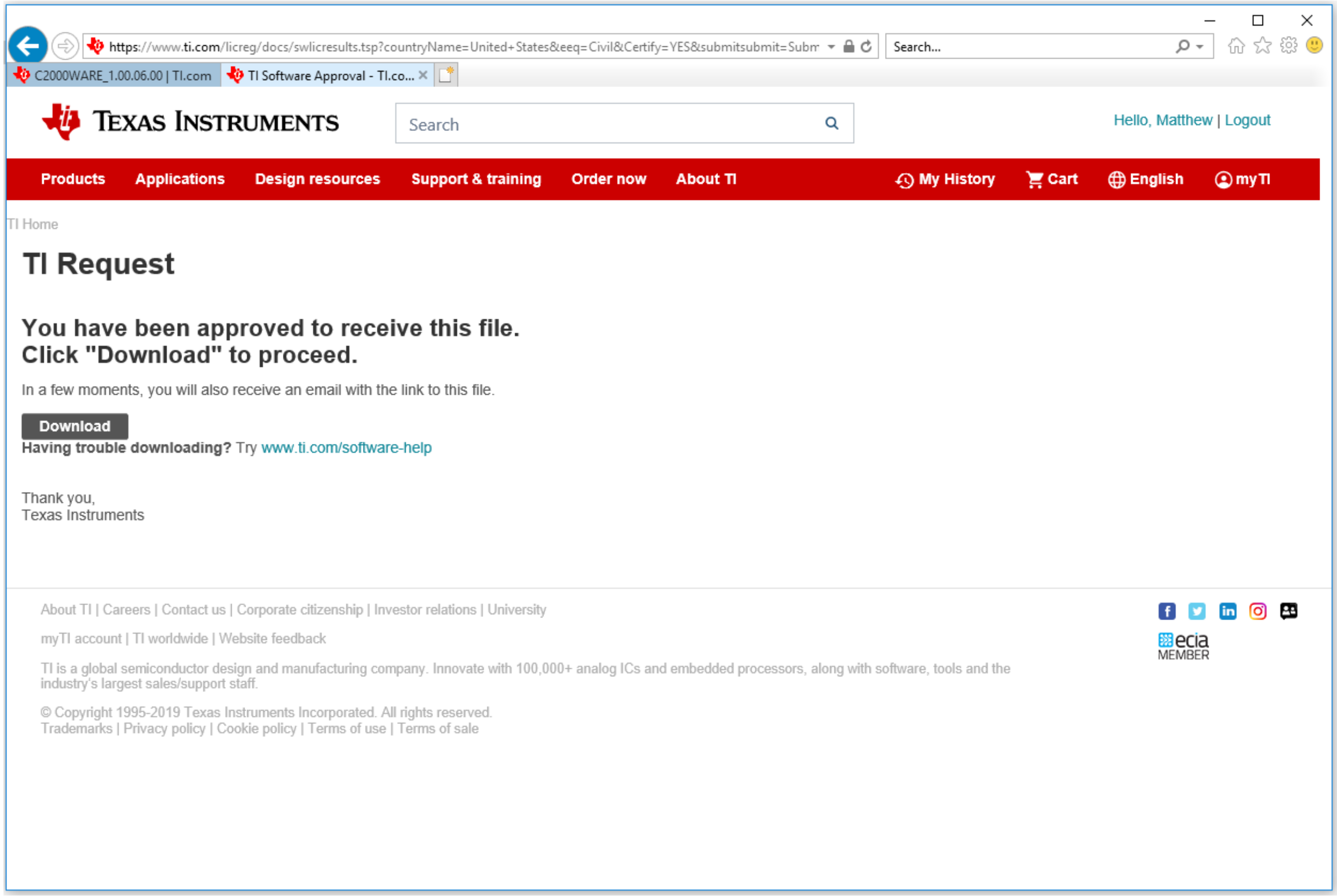
Carefully review the information that is required in connection with the download. If you are willing to provide this information to TI, please do so and then select the end application.



Carefully review the certifications that are required of you in connection with the download.  If you are willing to make these certifications and they are true and correct, please select Yes and click Submit.



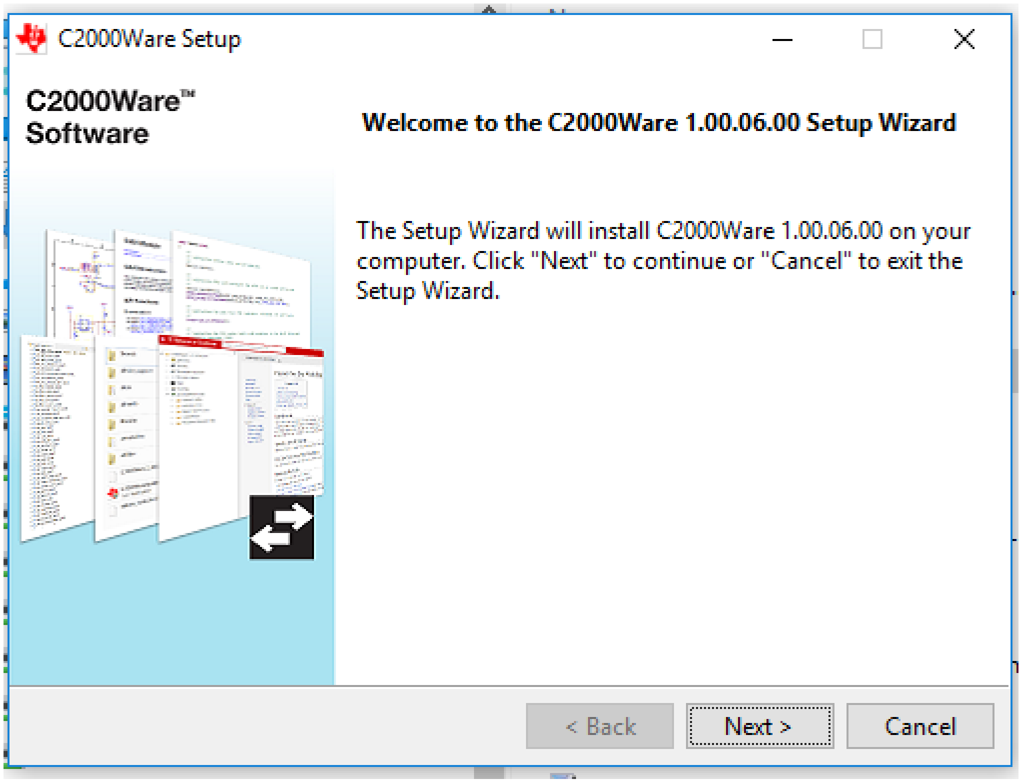
Click the download button to the file.



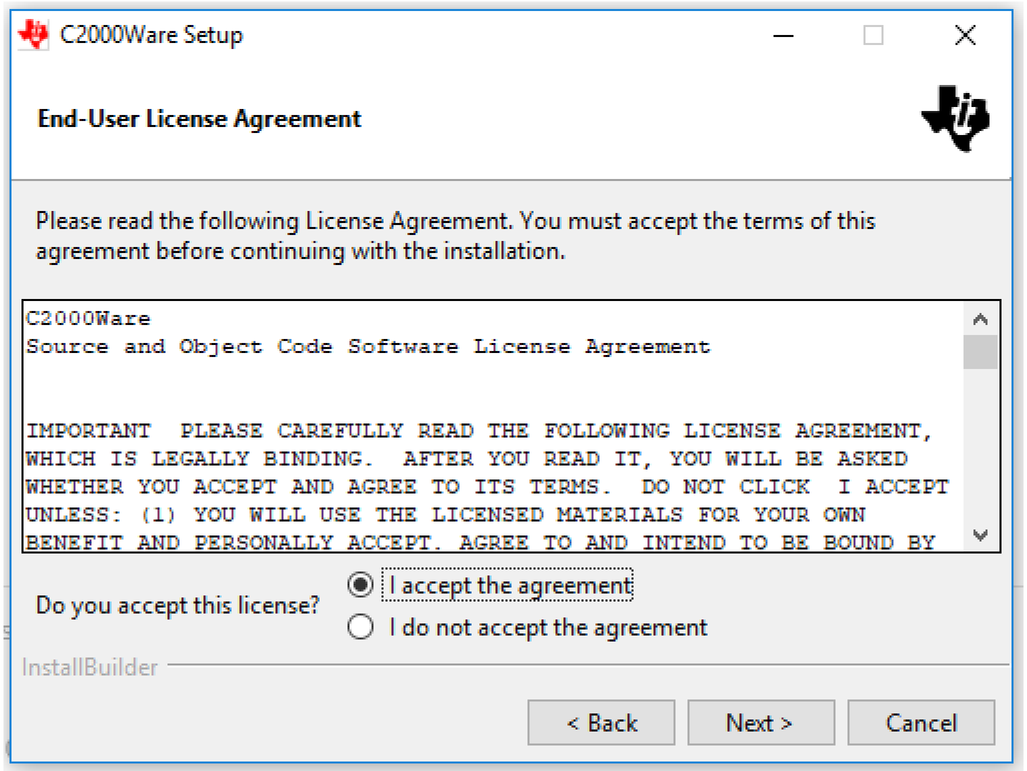

You should now have a "C2000Ware_1_00_06_00_setup.exe" file.

Run this file to begin the installation.

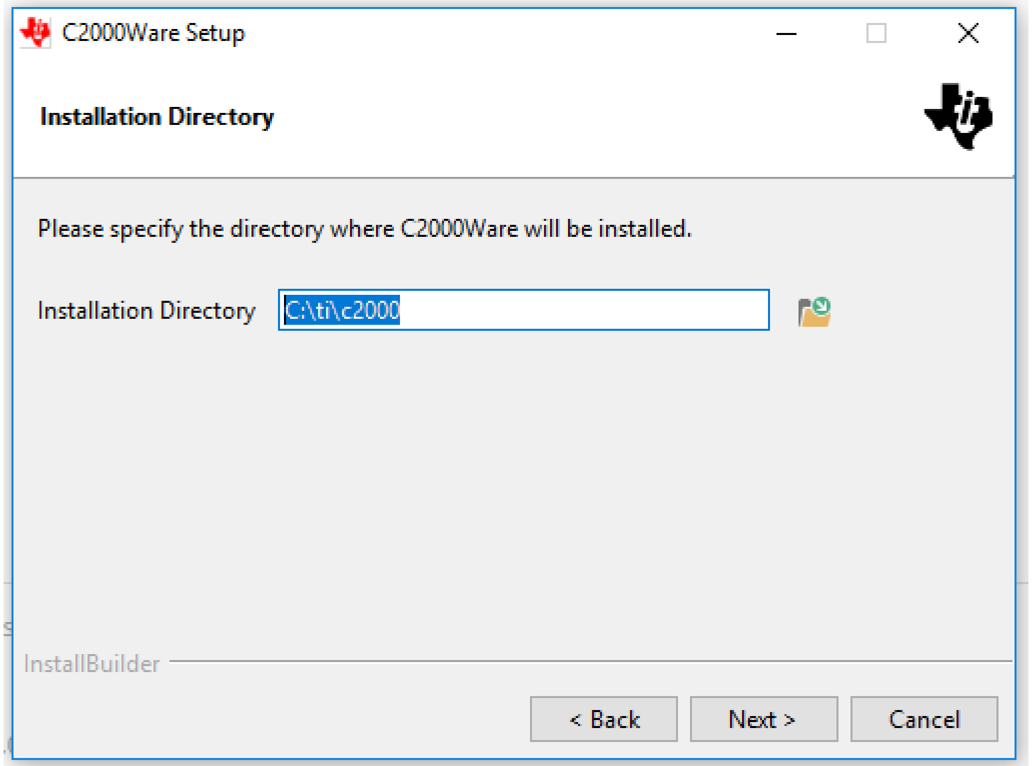
Click Next


C2000Ware Setup
C2000Ware™
Software
Welcome to the C2000Ware 1.00.06.00 Setup Wizard
The Setup Wizard will install C2000Ware 1.00.06.00 on your computer. Click "Next" to continue or "Cancel" to exit the Setup Wizard.
< Back
Next >
Cancel

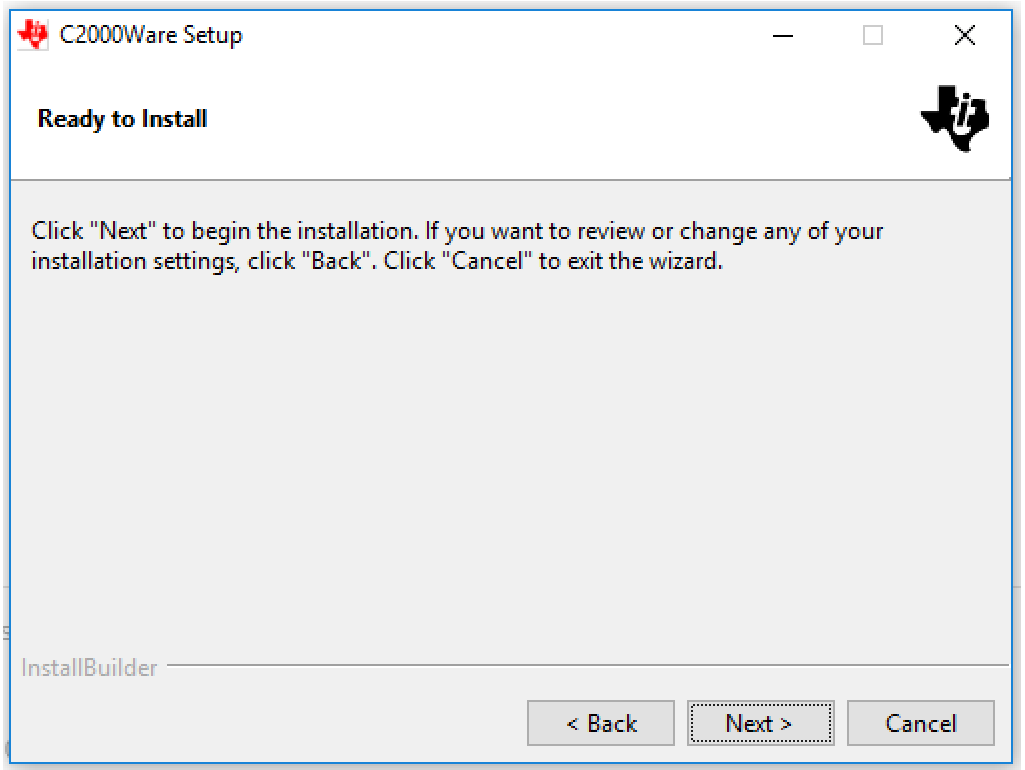
After careful review and acceptance of its terms, select that you accept the license agreement and click Next.



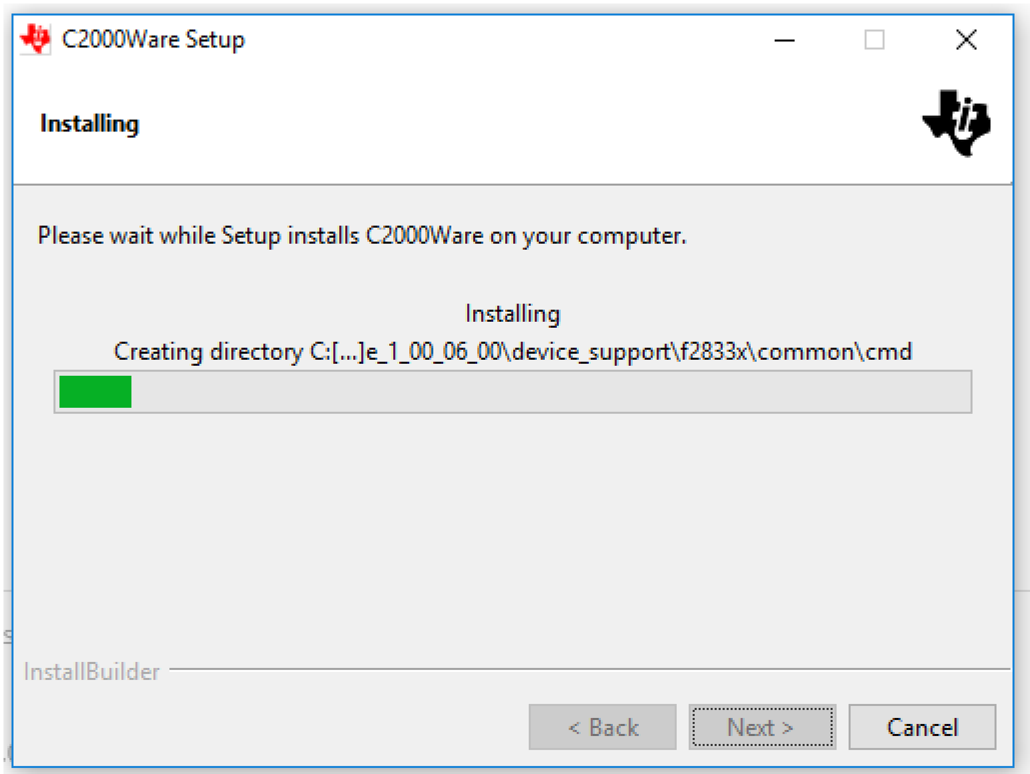
Select the directory to install the C2000Ware library to be “C:\ti\c2000”.



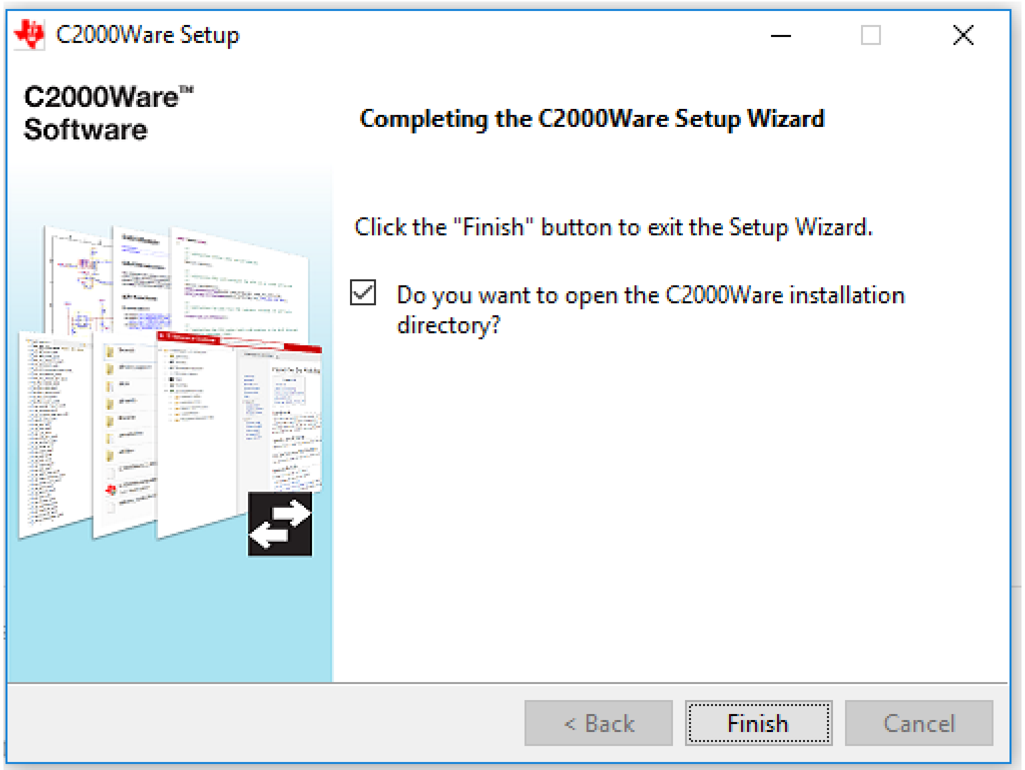
Click Next to start the install.



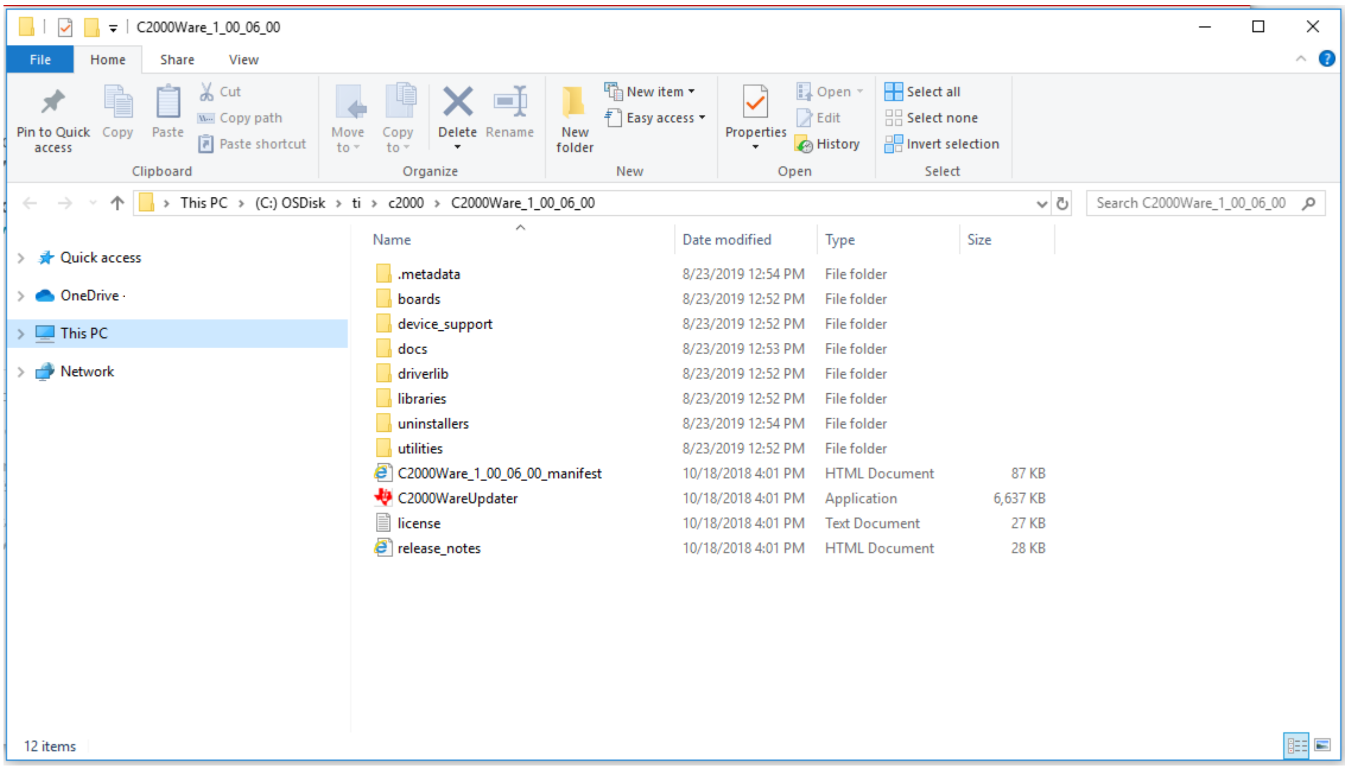
Wait for the installation to complete. If there is any pop-up  window during the installation process and you wish to continue with the installation after reviewing the content of the window, select allow to continue the installation.



The C2000Ware installation is now complete.

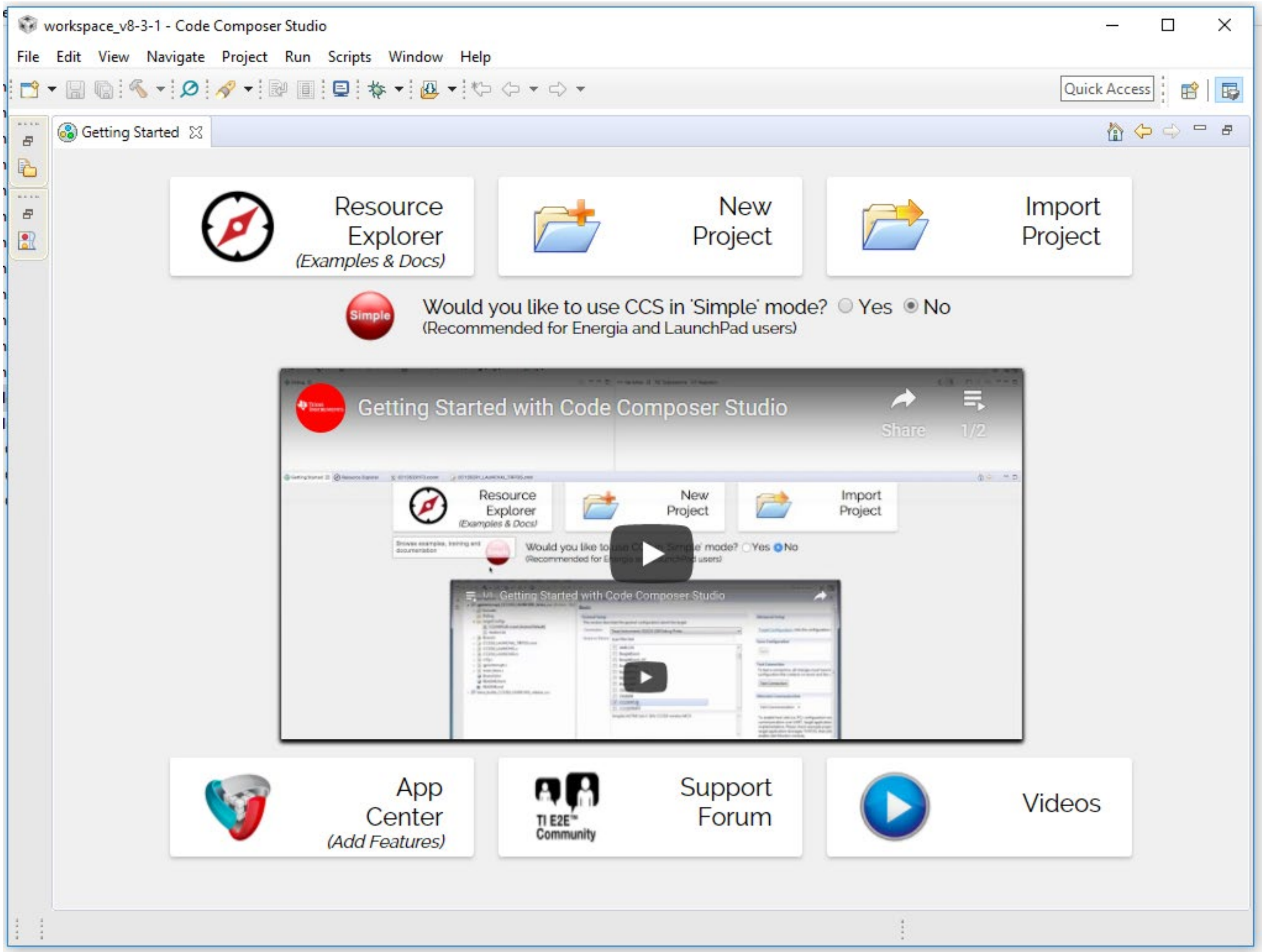


The installation directory should now reflect the following:

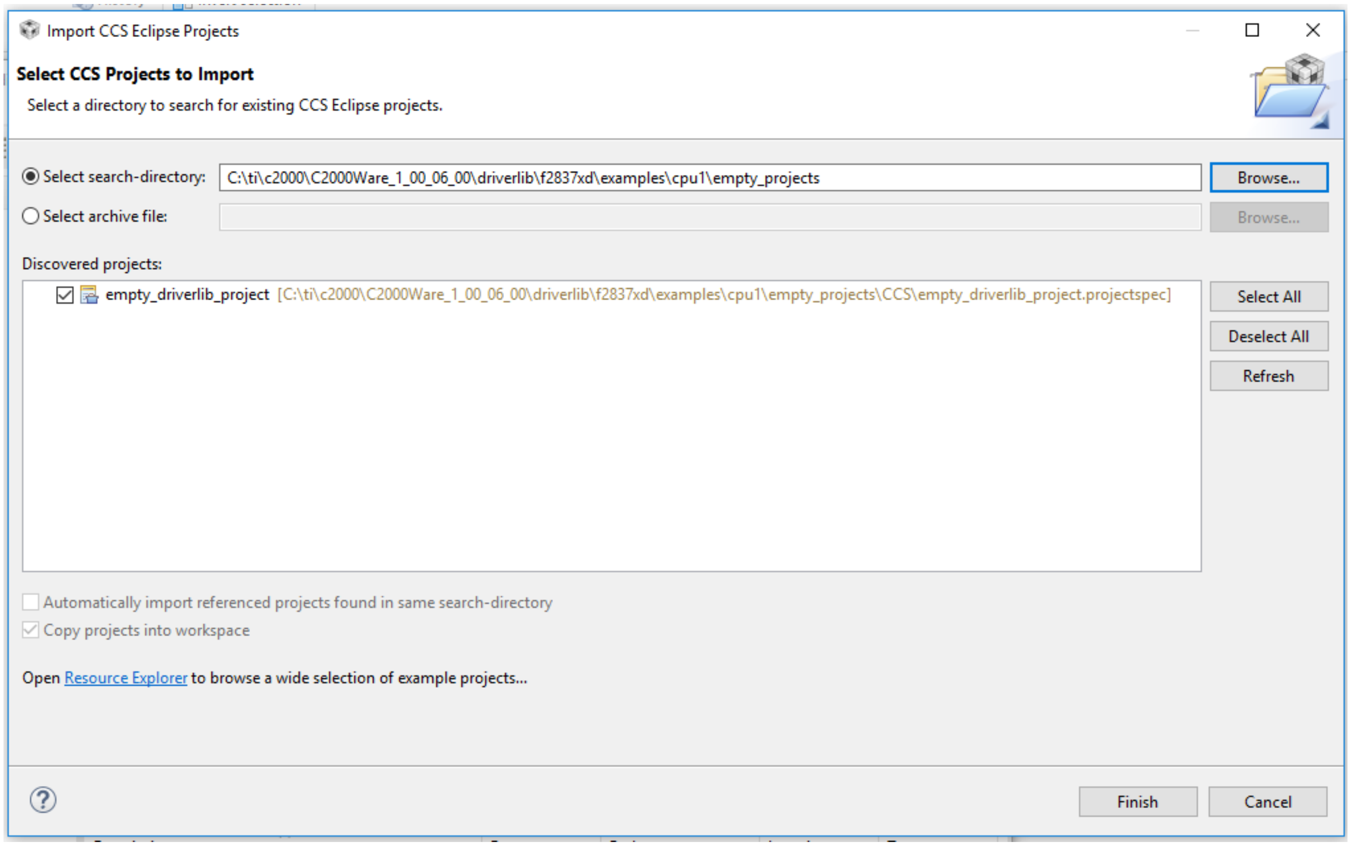


First a new empty project will be created into which the Wolfspeed example code and the C2000Ware library will be imported.

Restart CCS and navigate to the Project menu at the top and select Import CCS Projects.

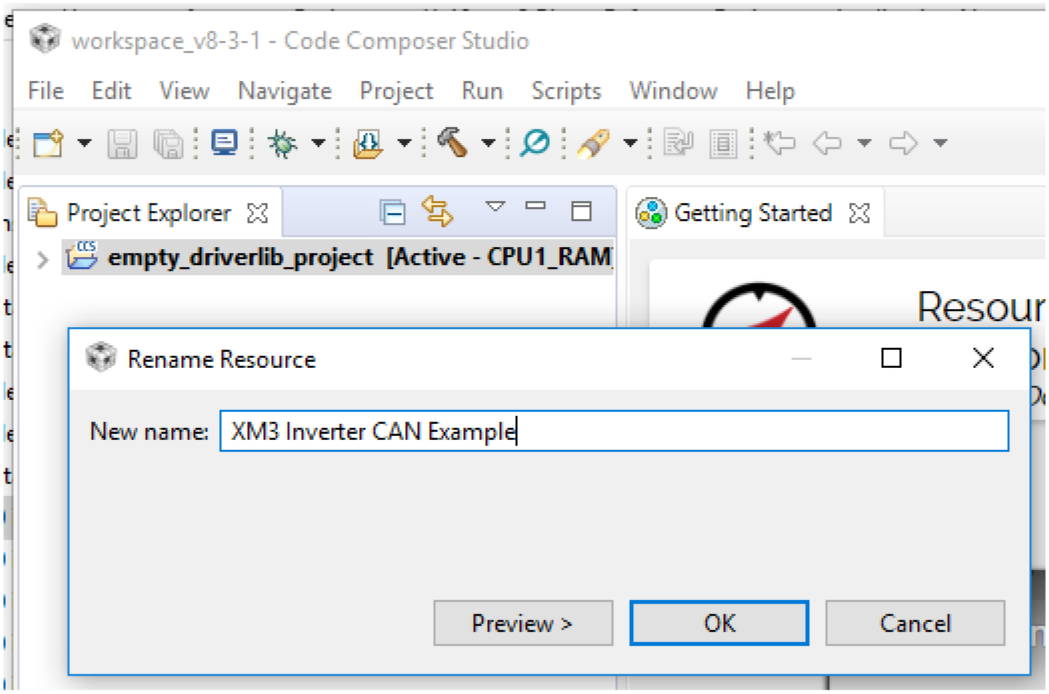


In the Import CCS Project dialog select browse and navigate the driverlib directory of the C2000Ware installation. This will be at "C:\ti\c2000\C2000Ware_1_00_06_00_Software\driverlib\f2837xd\examples\cpu1\empty_projects"

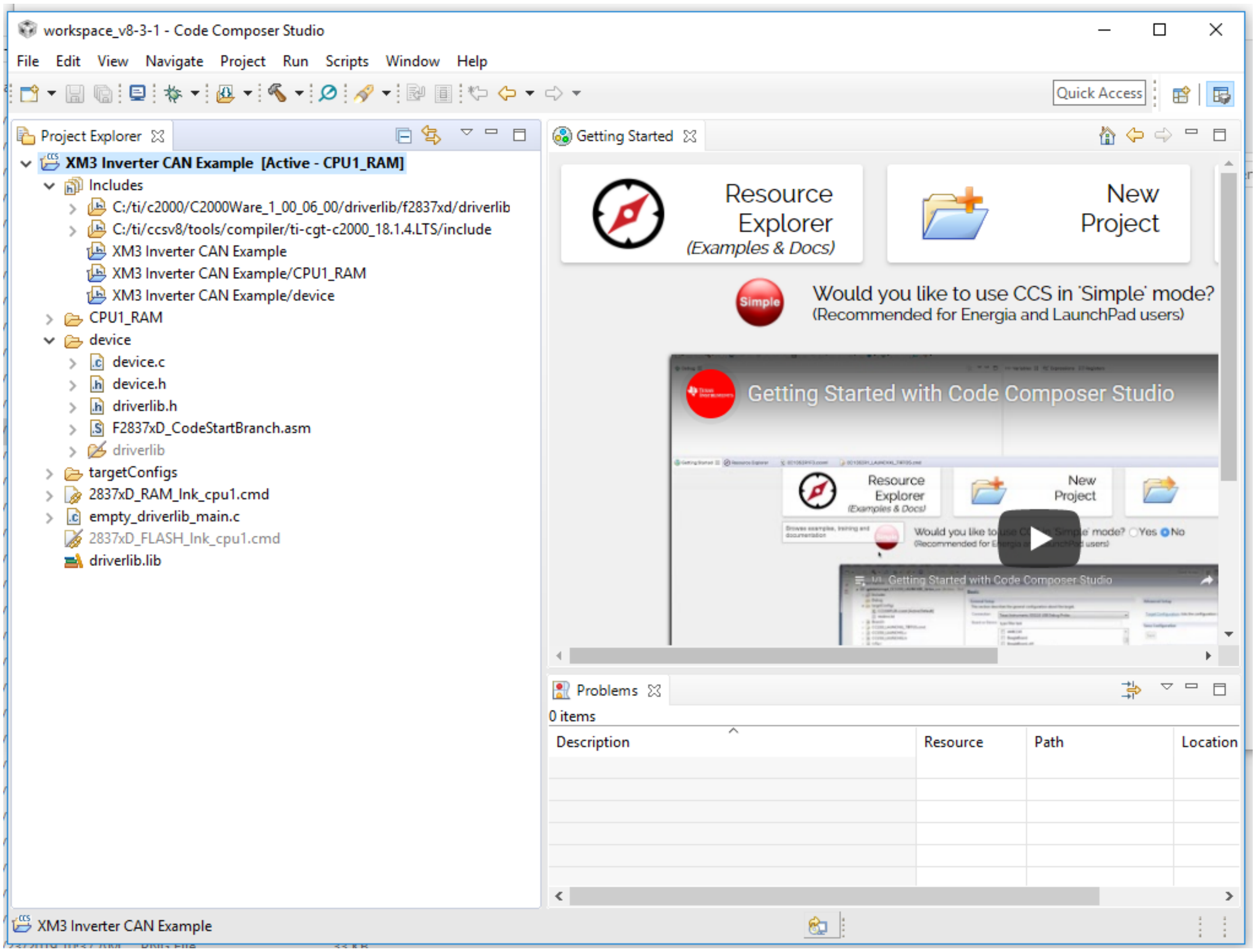



Click Finish

Right Click on the new project named "empty_driverlib_project" and select Rename and give it a new name, such as "XM3 Inverter CAN Example".

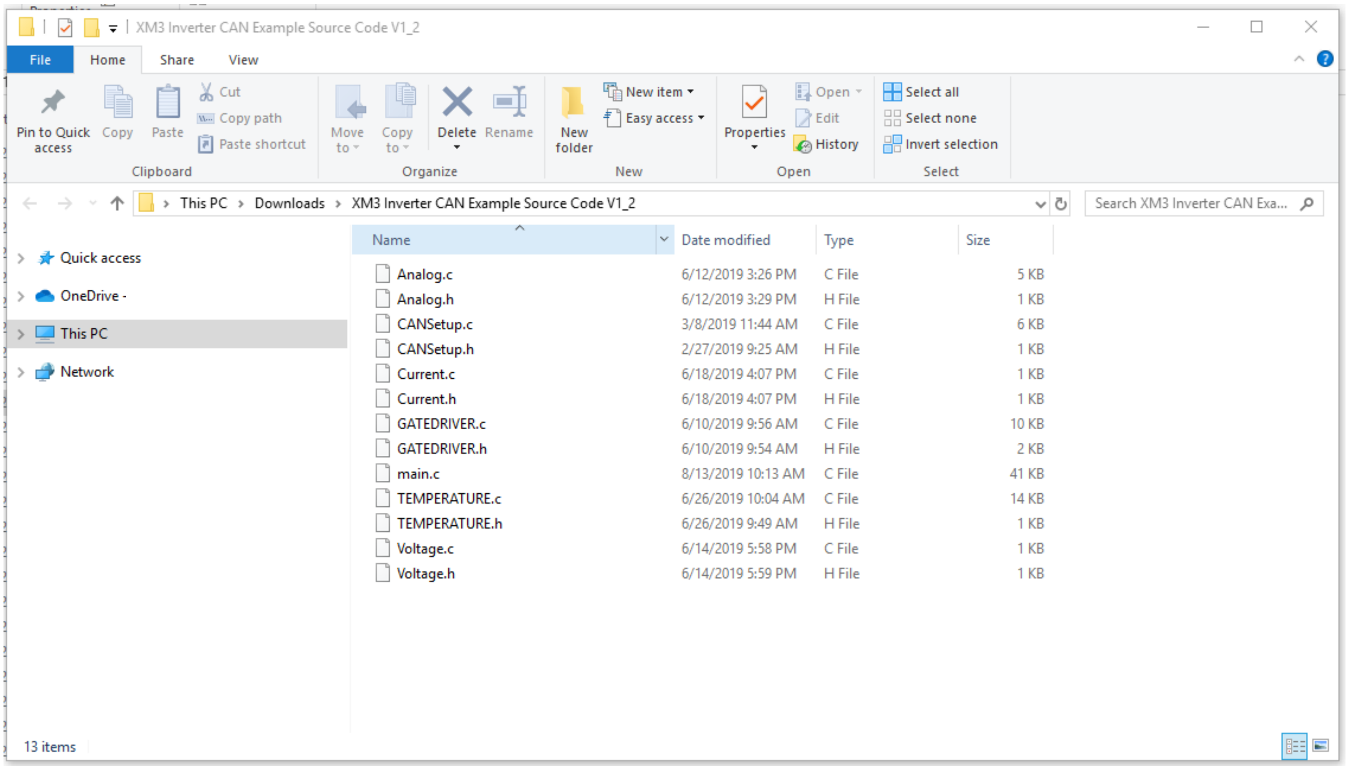


The new project should look like the below screen. There should be a "device" folder with driverlib.h and device.h. Under the Includes folder there should also be the driverlib directory.

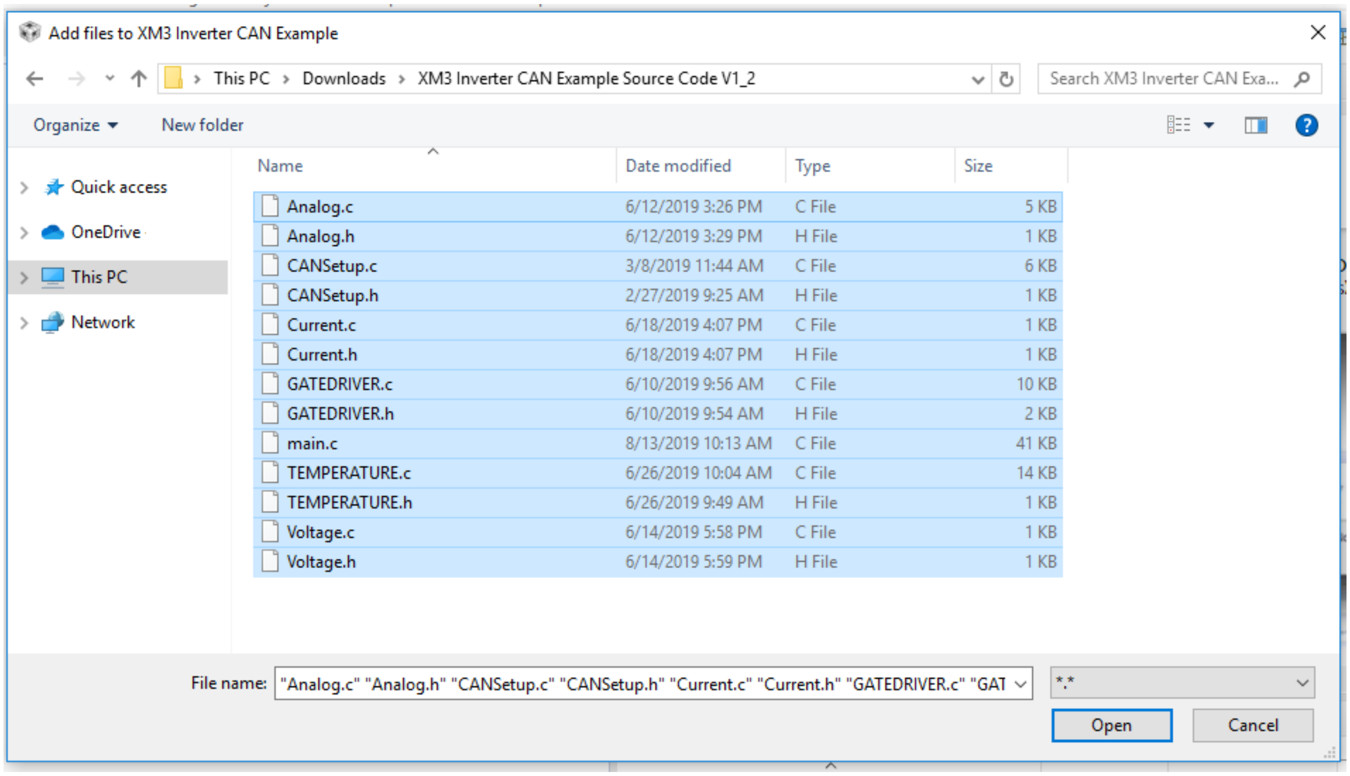


Next take the Wolfspeed source code file and unzip in a location such as downloads.

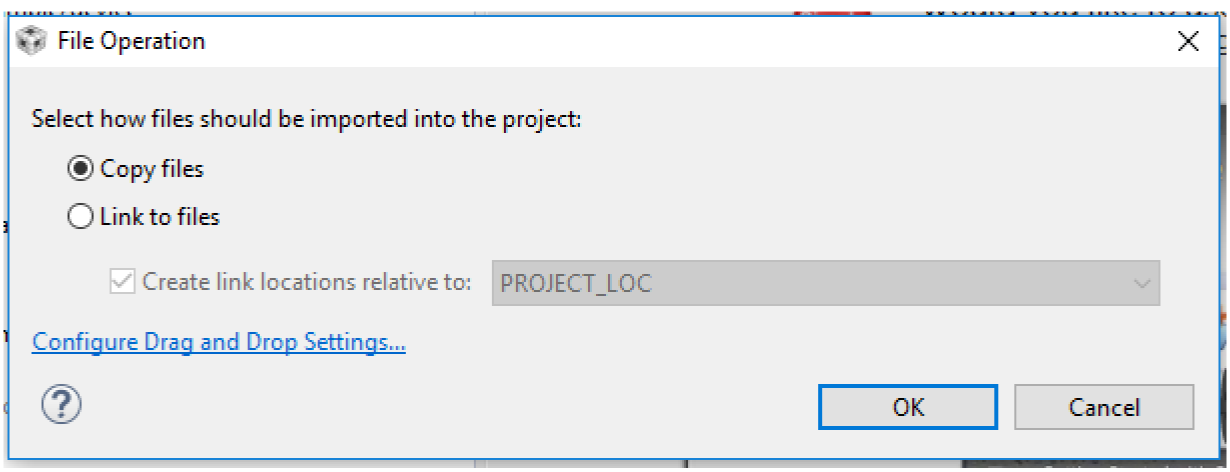
The unzipped directory should look like the below screen.



Next right-click on the project name and select Add Files. Navigate to the directory in which you unzipped the Wolfspeed source code and select all the code files.




Click Open



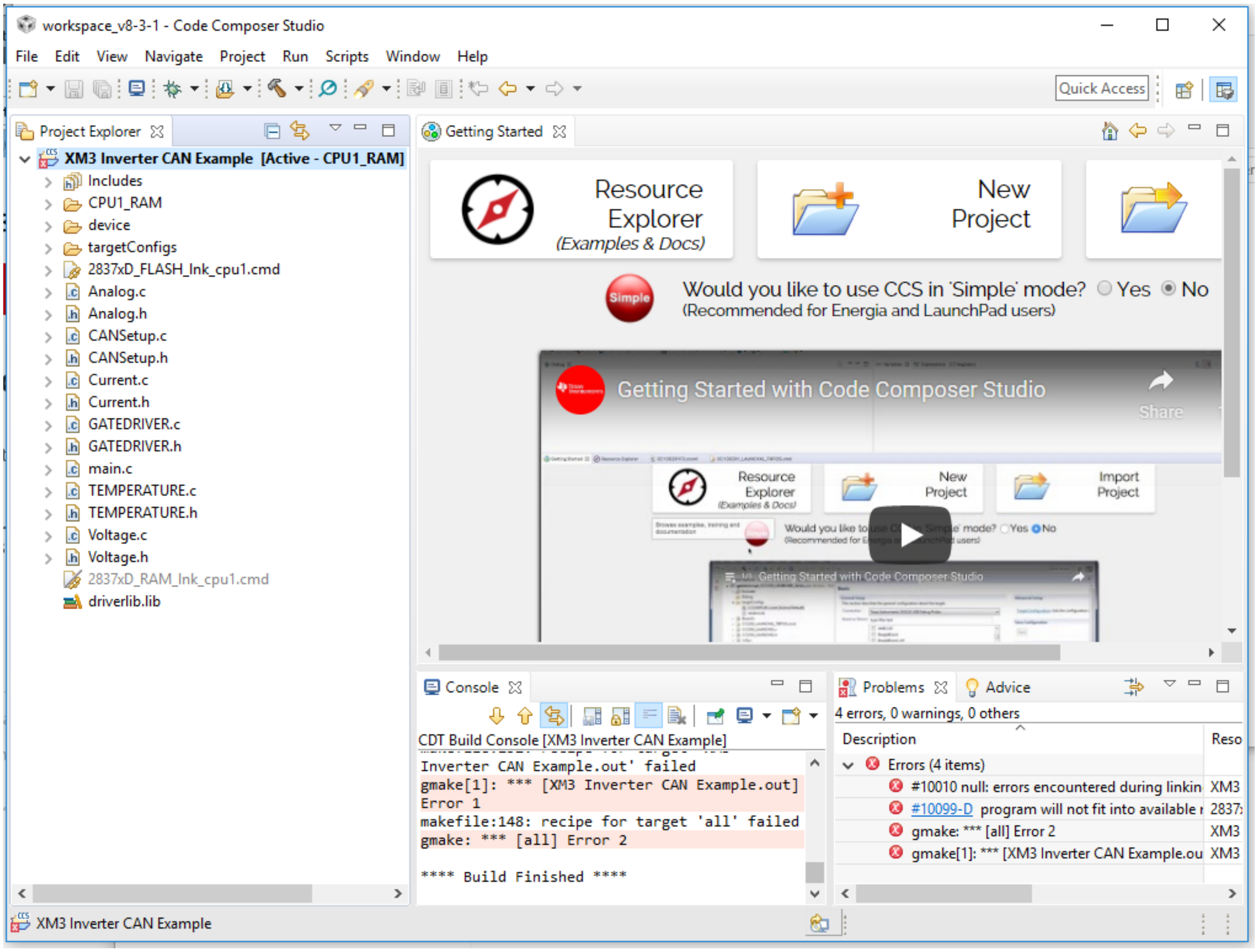

Select the Copy Files option to copy the files to your workspace directory project.

Next under the expanded project in CCS right click on the “empty_driverlib_main.c” and select Delete and then OK.

Then right-click on the “2837XD_RAM_lnk_cpu1.cmd” file and select the Exclude from Build option.

Then right-click on the “2837XD_FLASH_lnk_cpu1.cmd” file and unselect the Exclude from Build option.

The project should now look like the below screen.

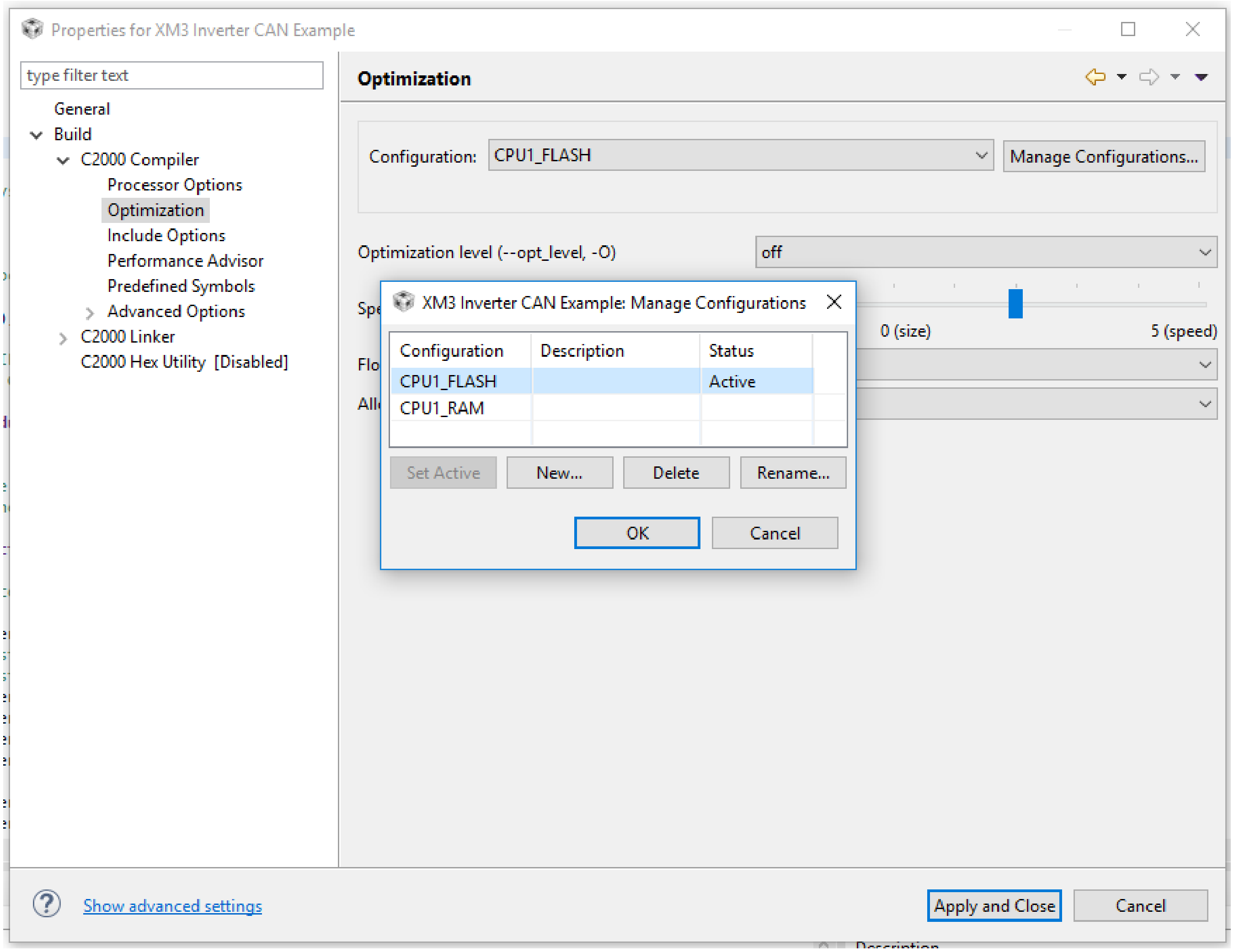


Right-click on the project and select Show Build Settings.

Click Manage Configurations.

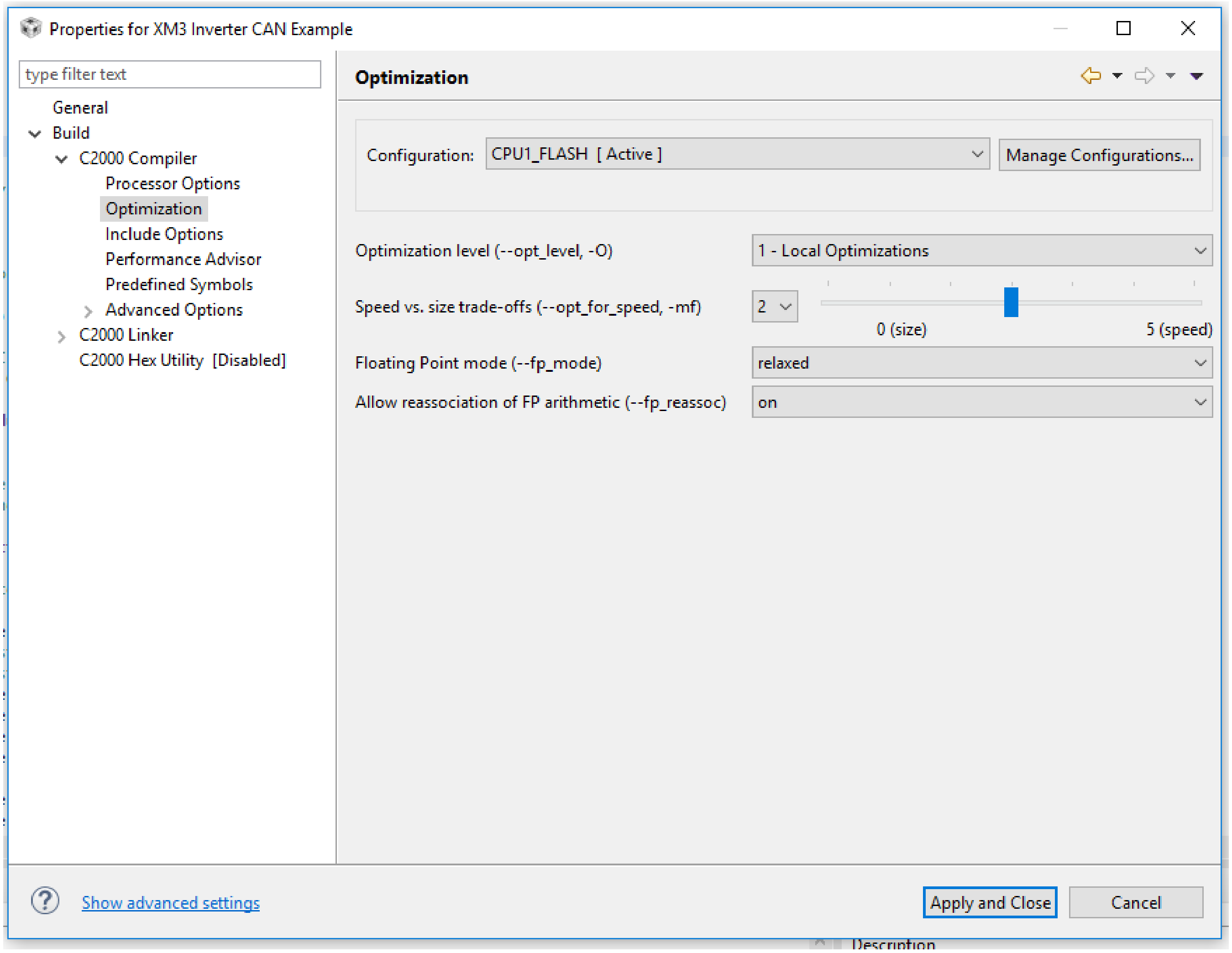
Select CPU1_FLASH and click Se Active.

The project files are too large to debug in ram on the DSP so this sets the debug session to write to flash memory.

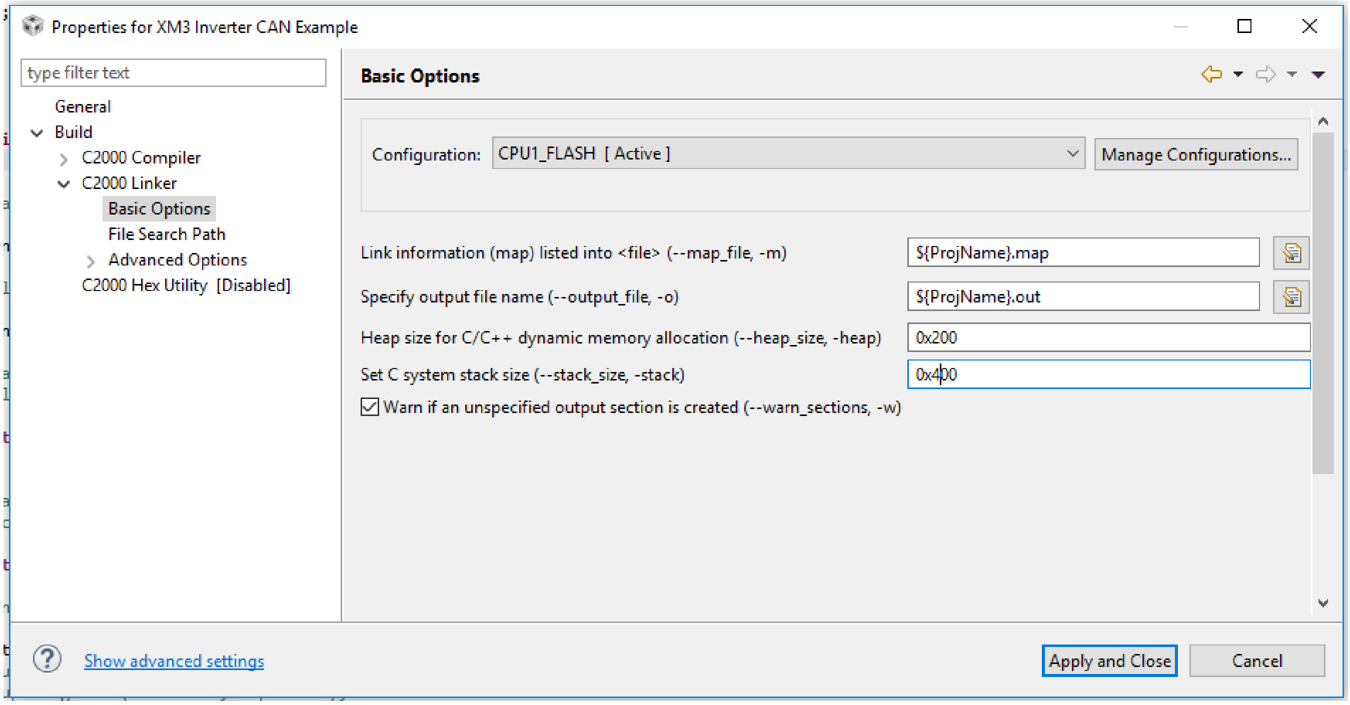


Next select the Optimization option on the left panel then make sure you have the CPU1_FLASH configuration selected in the Configuration drop down and it is marked as [ Active ]

Then set the Optimization level to "1 – Local Optimizations" and set the Floating Point mode to "relaxed".



Under C2000 Linker->Basic Options change the Heap size to "0x200" and change the C system stack size to "0x400". Click Apply and Close.



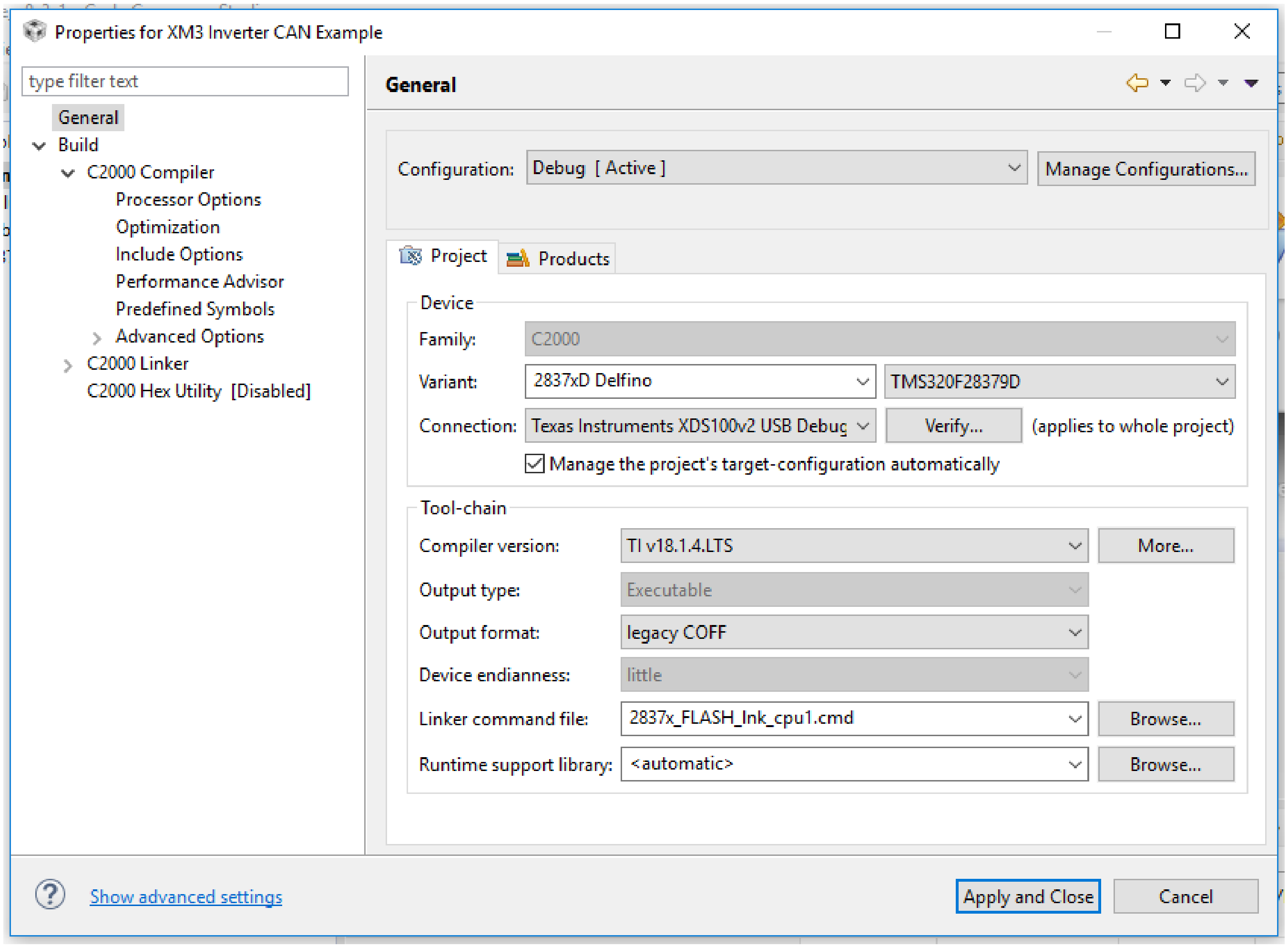
Under Build Settings -> General from the variant drop-down select “2837xD Delfino” and then TMS320F28379D in the next drop down.

Under Connection select “Texas Instruments XDS100v2 USB Debug Adapter” as this is the type built-in to the LaunchPad.

Plug in the miniUSB cable between the controller LaunchPad and the computer and the DC barrel jack power supply.

Now click Verify and CCS will test the connection with the DSP. It should say test successful at the bottom of the verification dialog.

Ensure the “Manage project’s target-configuration automatically” box is checked.



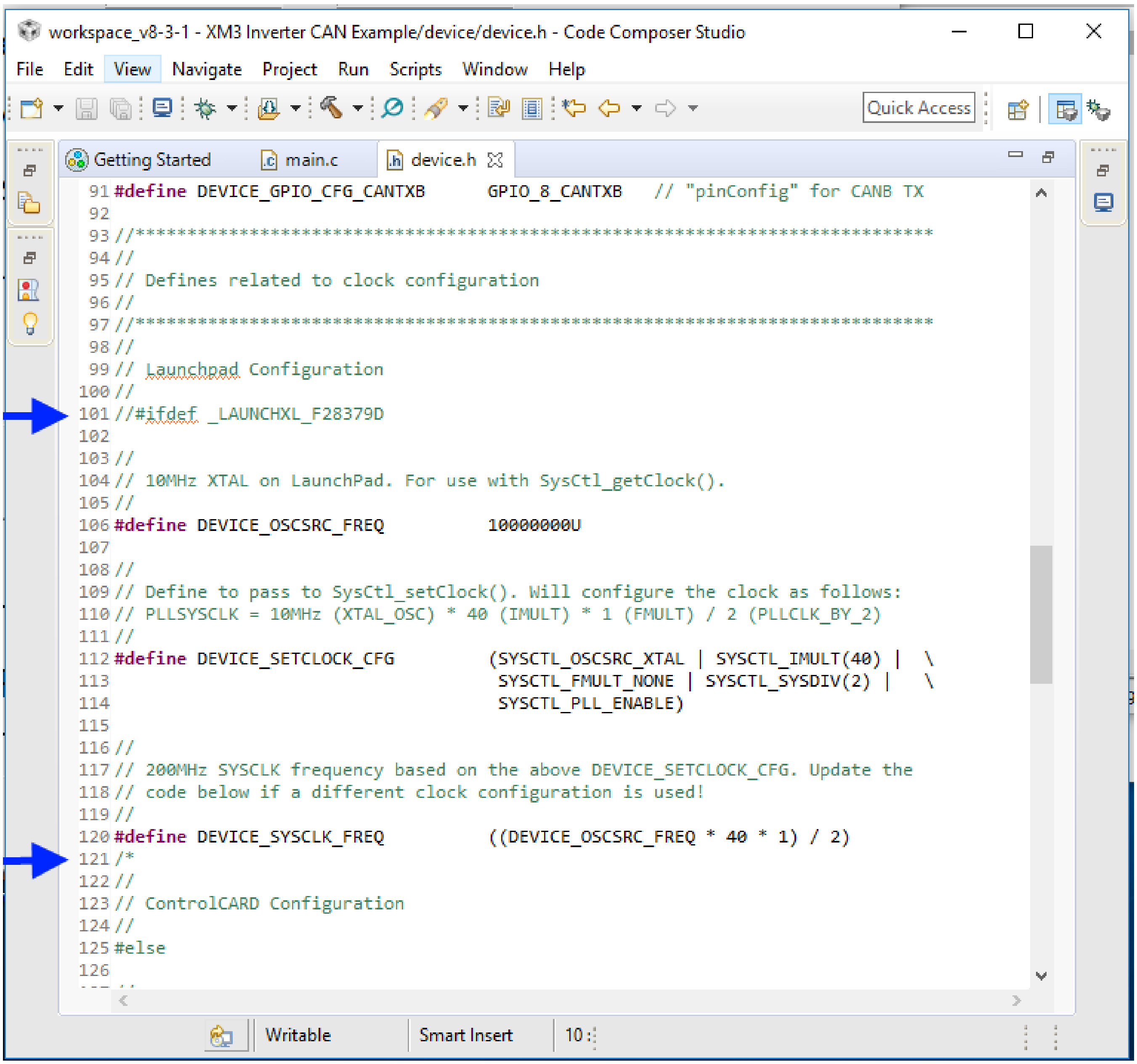
The default library assumes the DSP is on a control card which has a different crystal frequency than the one on the launchpad used on the controller. The device.h file must be modified to set the crystal frequency correctly so the clock speed will be right.

Open the “device.h” file under the “device” directory under the project.

Add two forward slashes ( // ) to the beginning of line 101 that starts with “ifdef _LAUNCHXL_F28379D”.

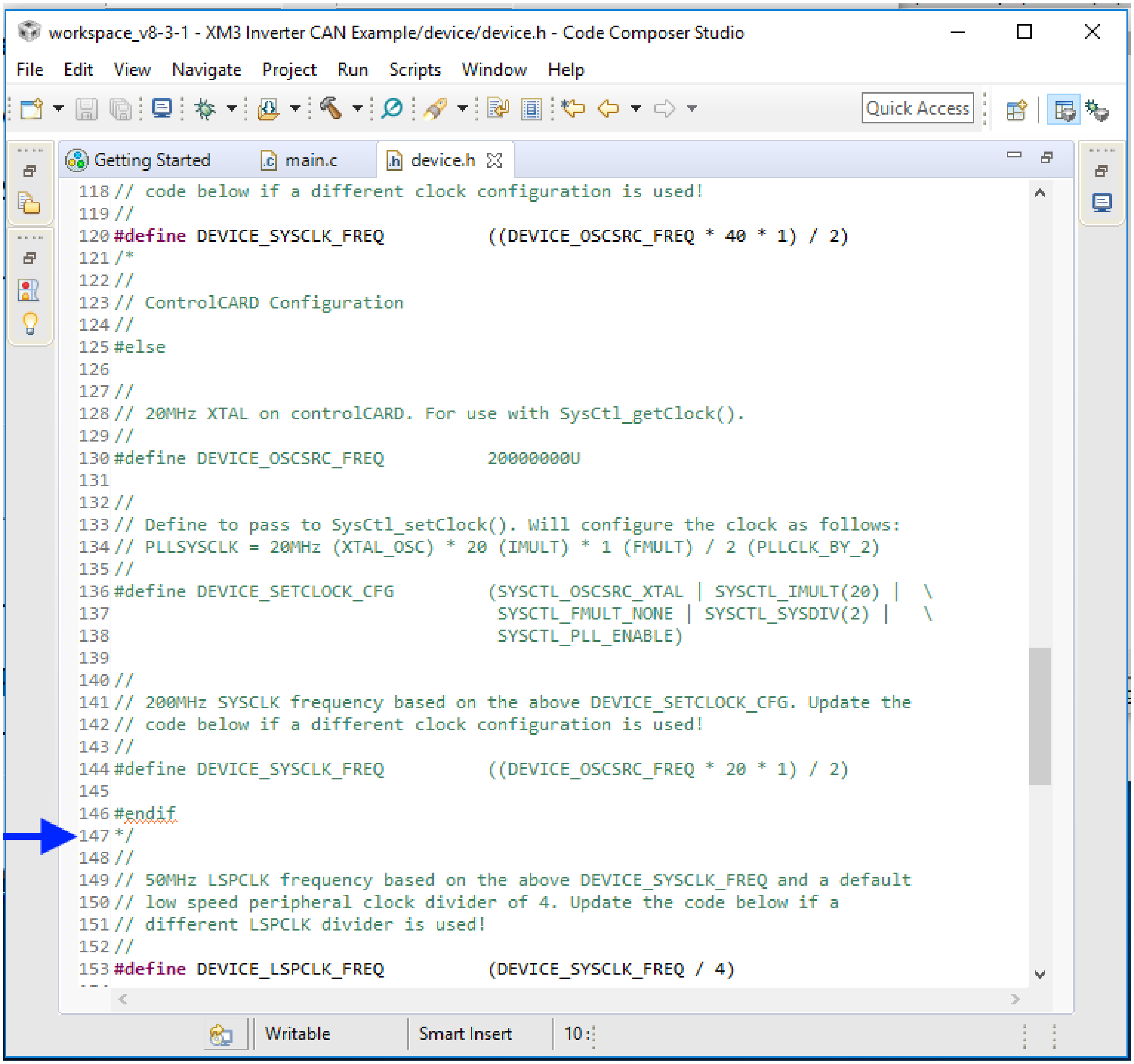
Add a forward slash and an asterisk ( /* ) to a new line before the comment for “Control Card Configuration”

The screen below shows what the code should look like after the modification noted by the two blue arrows.



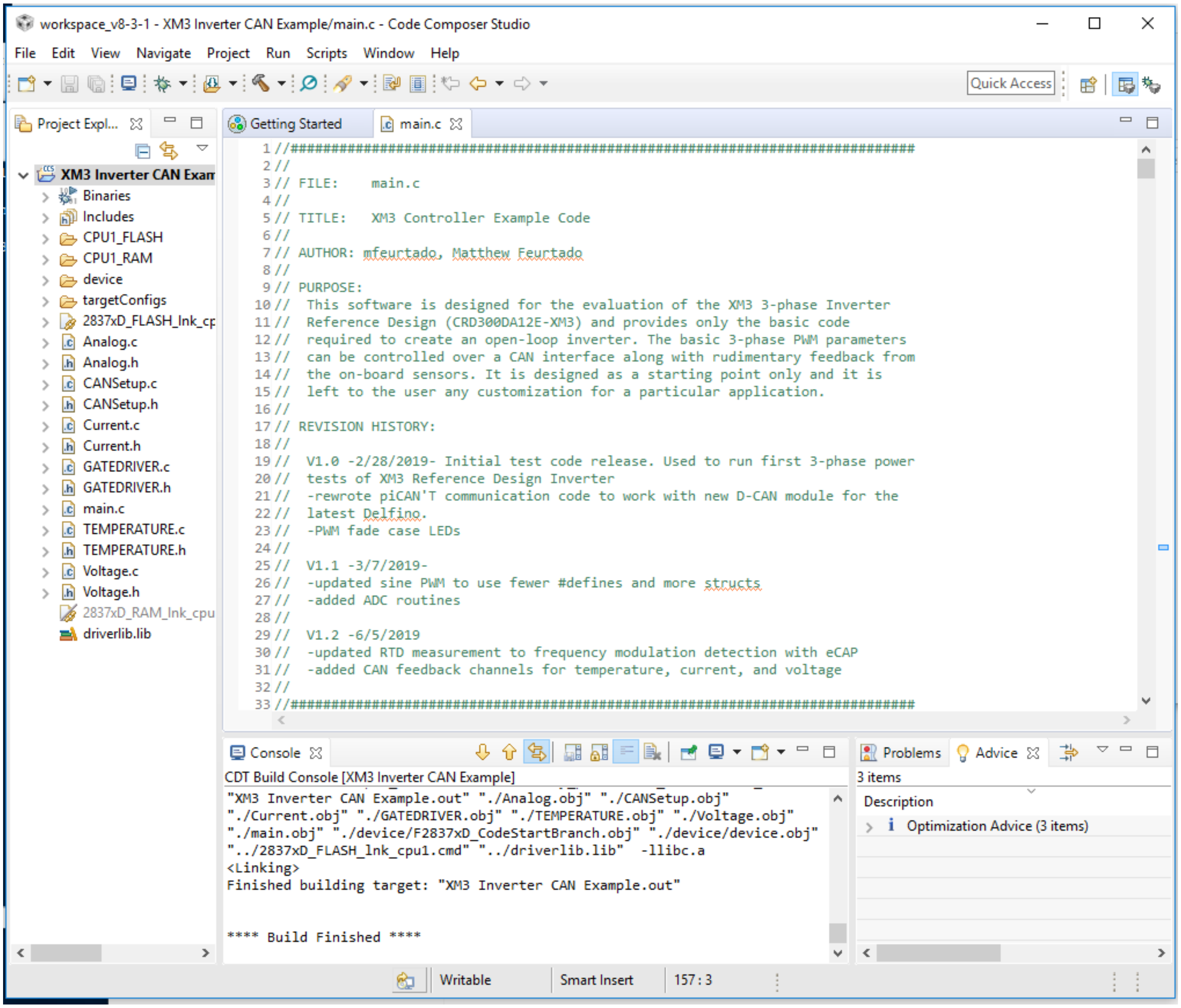
Scroll down further in the same “device.h” file and add an asterisk and a forward slash ( */ ) to the line immediately after “#endif”.

The screen below indicates the line to be added.



Click the hammer icon to rebuild the project.

The project should complete the build with no errors or warnings. Optimization or Performance Advice notices can be accepted because the project can still be uploaded to the controller and debugged.




The Wolfspeed Inverter CAN Example setup is now complete.

## 6.3 debugging The Example Project

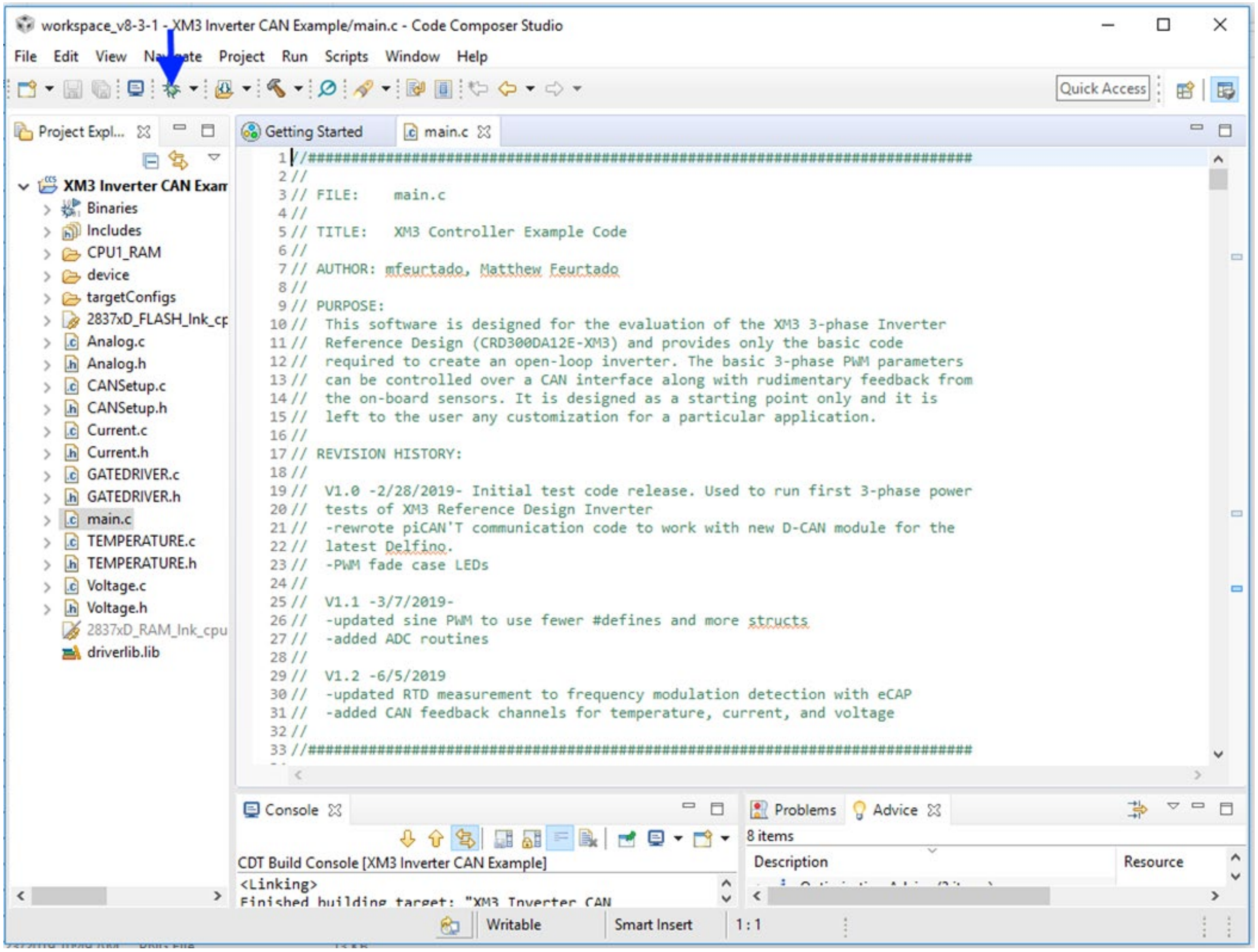
Make sure that the project is in bold with the word [Active] next to it.

On the LaunchPad, ensure jumpers JP1, JP2, JP3 are NOT installed.

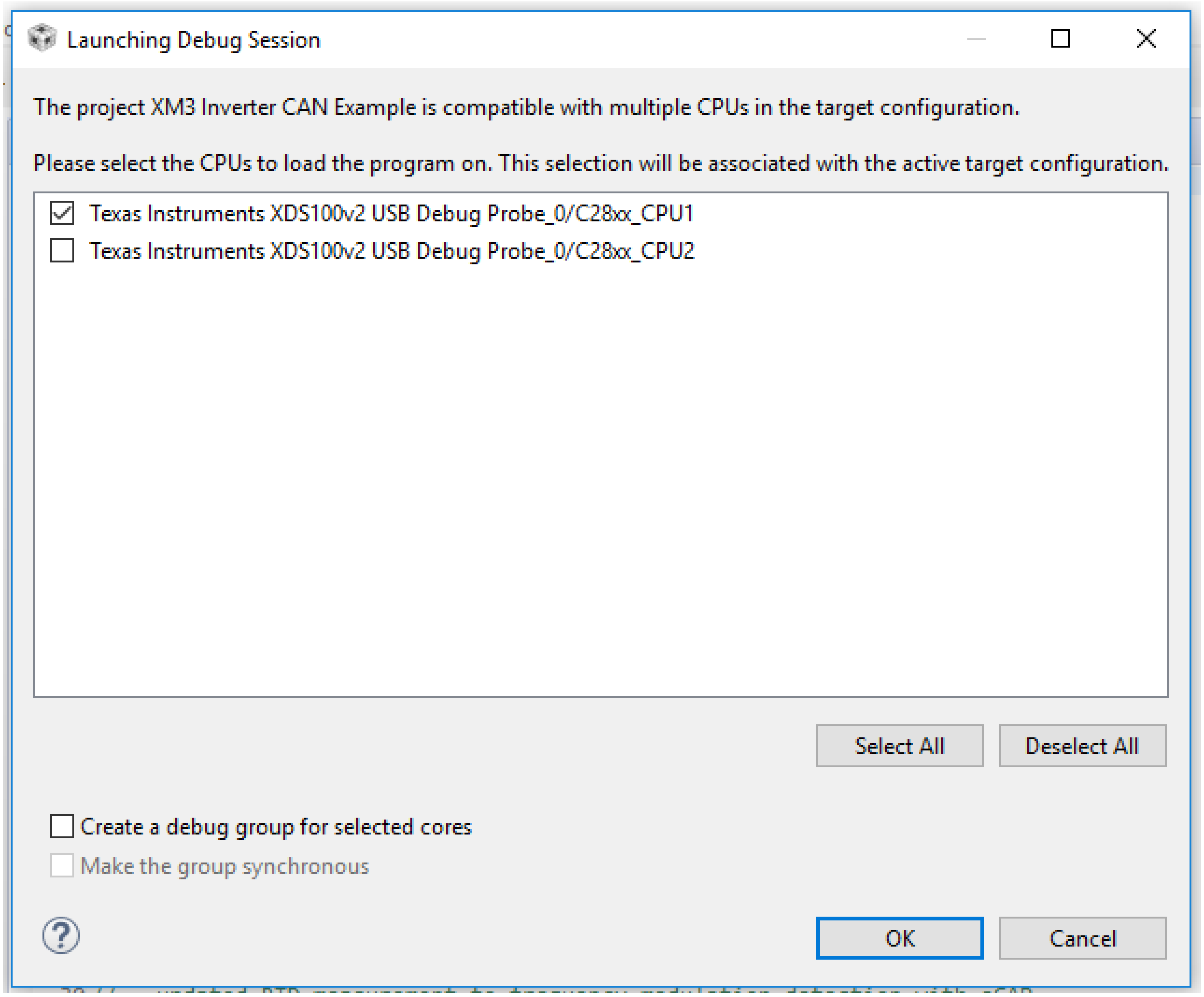
Plug in the mini-USB cable into the LaunchPad and the computer.

Plug in the +12 V DC barrel jack power supply. The DSP is now powered and connected to the debug computer.

Click on the bug shaped debug icon to start a debug session for this project.

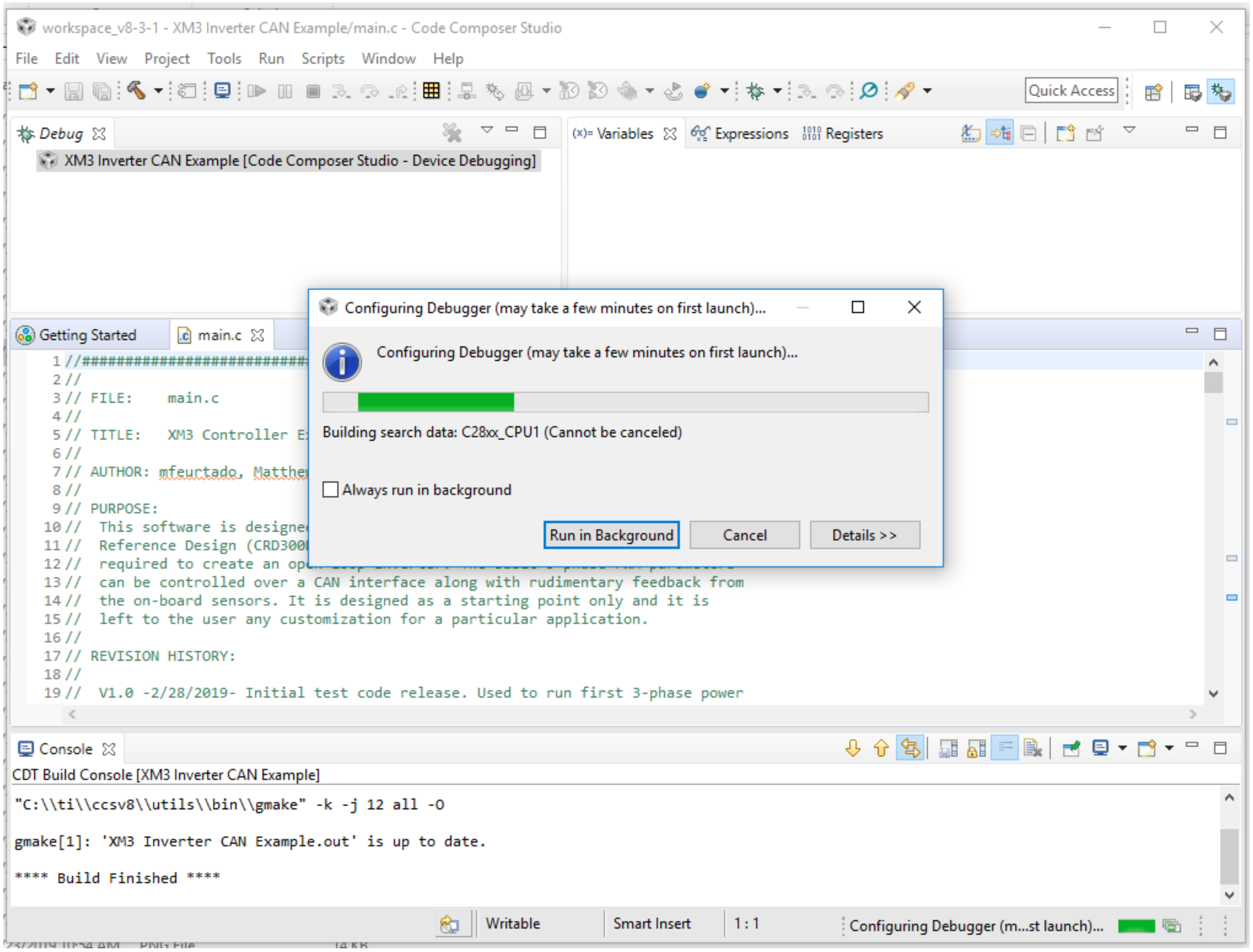


Select only the CPU1 for the debug session and click OK.

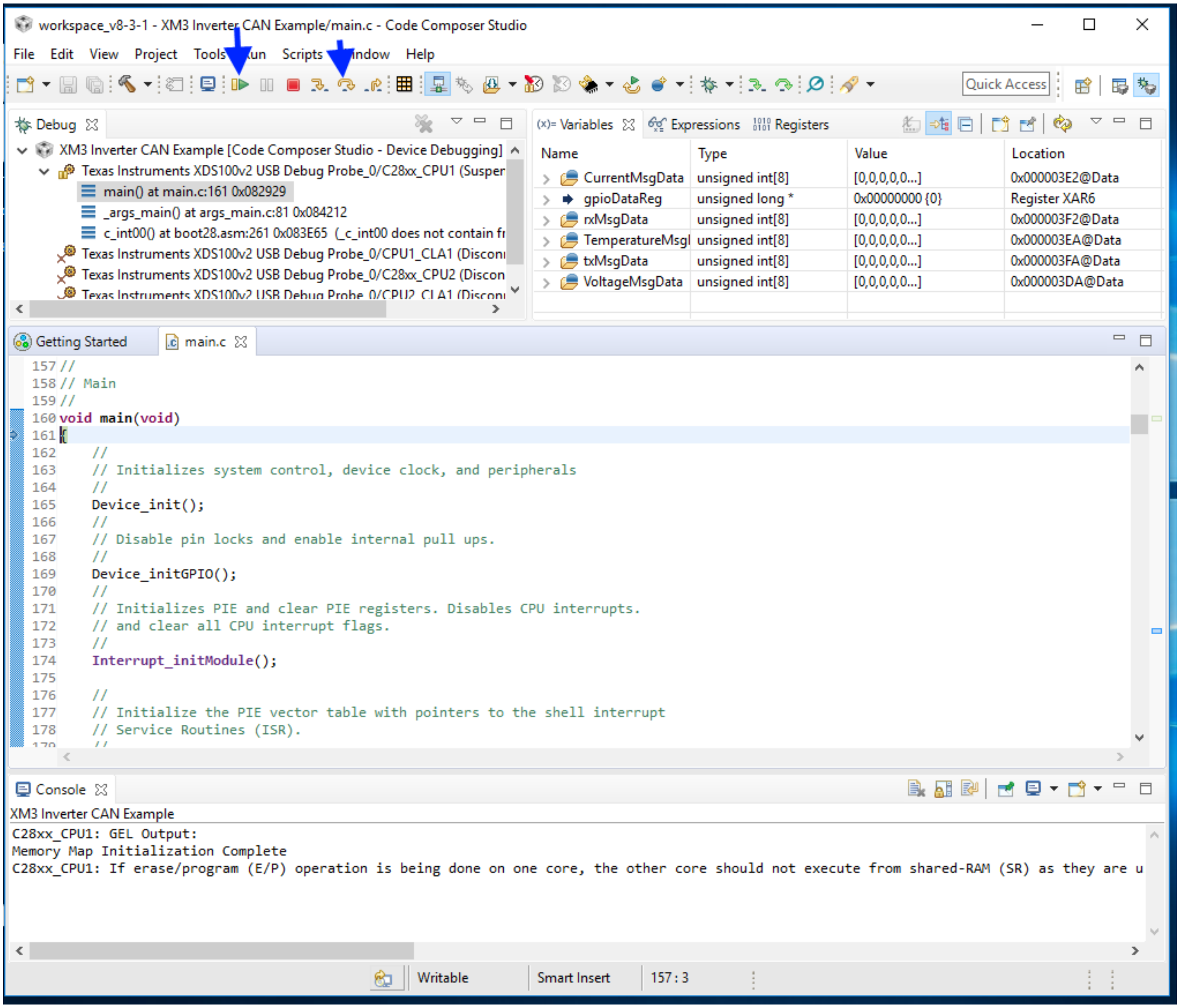


The environment will switch to the debug mode. The mode is selectable between edit and debug in the top right corner of CCS.

CCS will save the project and start building and uploading the code to flash memory.



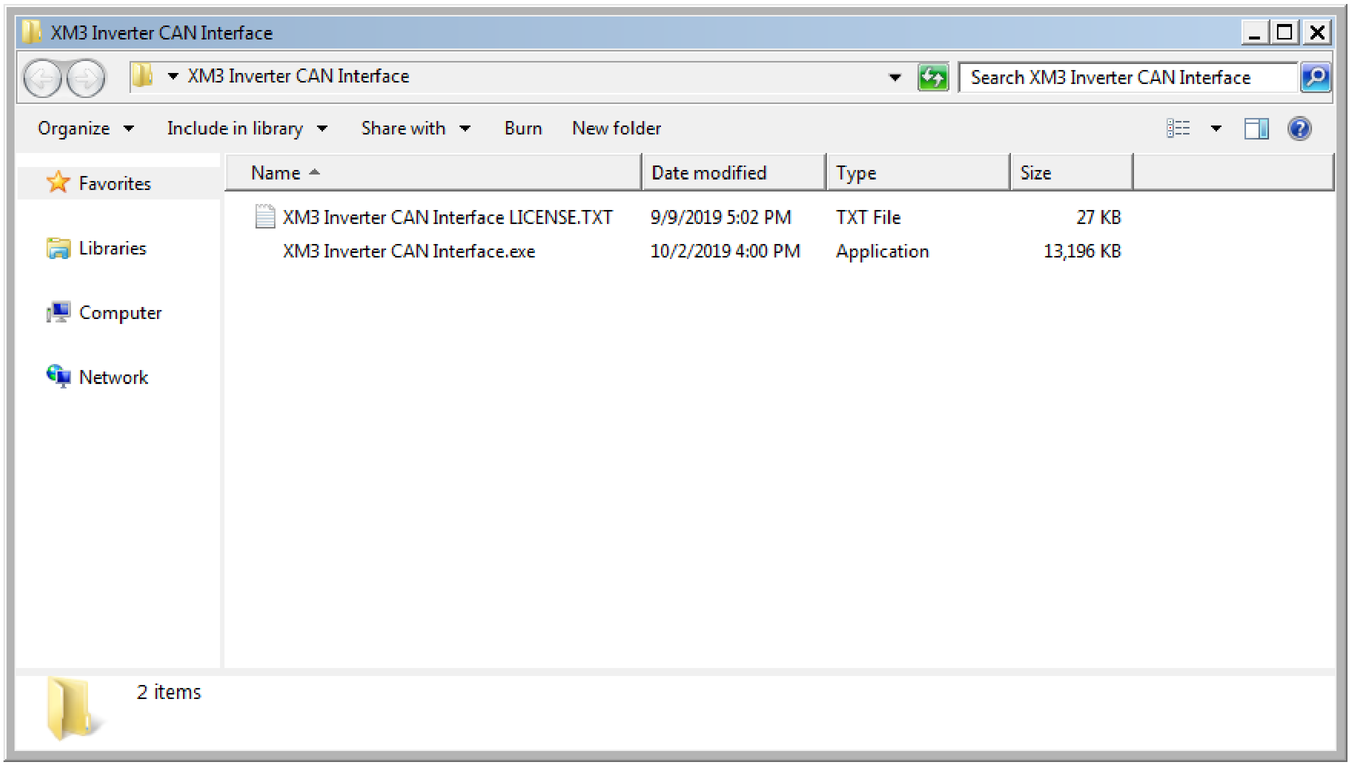
After the code has been loaded use the icons at the top of the screen to Run the code, Pause, and Step through the code.



# 7. Wolfspeed's XM3 Inverter CAN Interface Installation

## 7.1 Download the XM3 INverter CAN INterface

Download the Wolfspeed application "XM3 Inverter CAN Interface.zip" to a local directory on the host computer. Navigate to the download location and right-click on the zip file and select Extract All. Open the resulting directory and there should be a file named "XM3 Inverter CAN Interface.exe" which is the main program file that will be executed to run the program.




The XM3 Inverter CAN Interface software requires the controller DSP to be running the open-loop inverter firmware which comes pre-flashed with the reference design or can be built using the provided example source code shown in section **Error! Reference source not found.**. In addition to the host software, the host computer will require a hardware CAN adapter. Wolfspeed's host software supports the following CAN adapters:

- National Instruments (NI) USB-8473
- Korlan USB2CAN
- Kvaser Leaf Light V2
- CANable Pro

The following sections describe the installation procedure for the first two adapters listed above. Additional adapters supported by python-can can be used but have not been tested. For more information of supported adapter hardware see https://python-can.readthedocs.io/en/master/interfaces.html

## 7.2 Install National Instruments NI-CAN

Using the NI USB-8473 CAN adapter with Wolfspeed's XM3 Inverter CAN Interface requires the National Instruments NI-CAN software to provide the device driver for the USB-8473 hardware.

**REQUIREMENTS:**

- National Instruments USB-8473 high-speed CAN adapter
- National Instruments NI-CAN driver
- Microsoft Windows 10
- USB 2.0 port

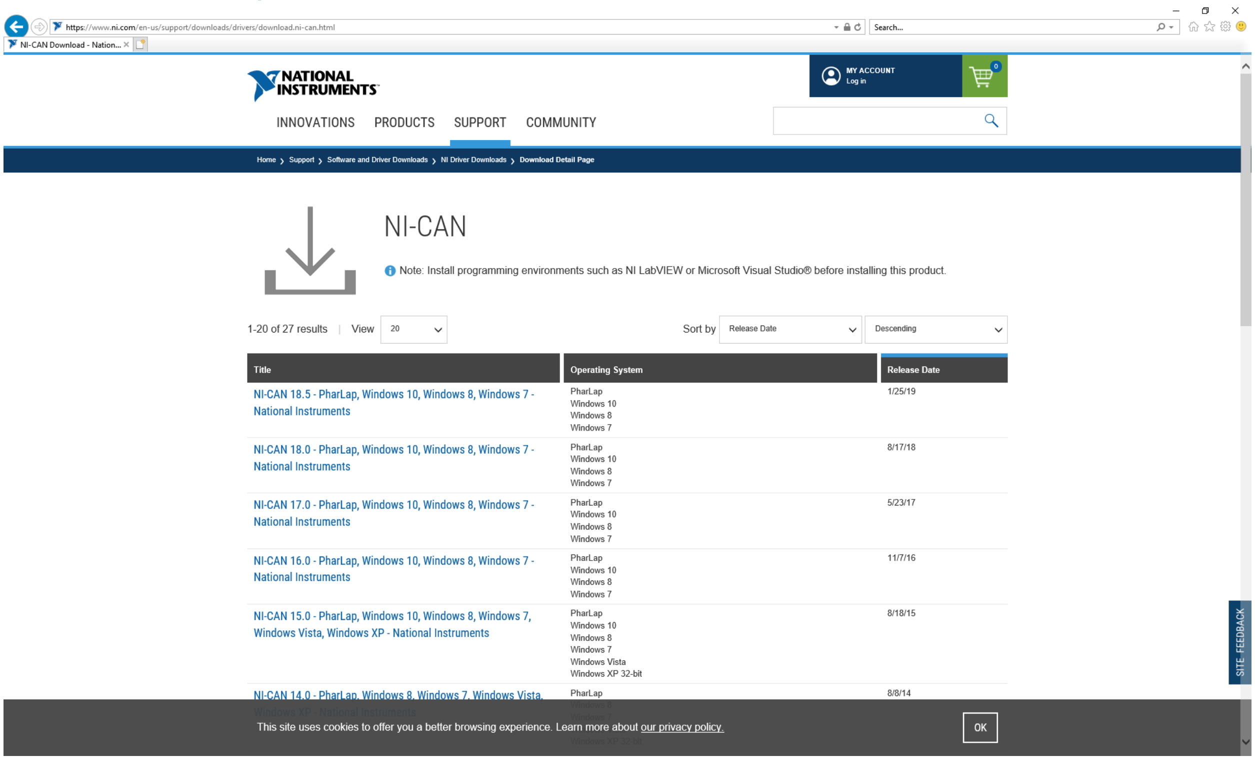
### 7.2.1 Download NI-CAN

Open a web browser and navigate to the download page for NI-CAN at the following link.

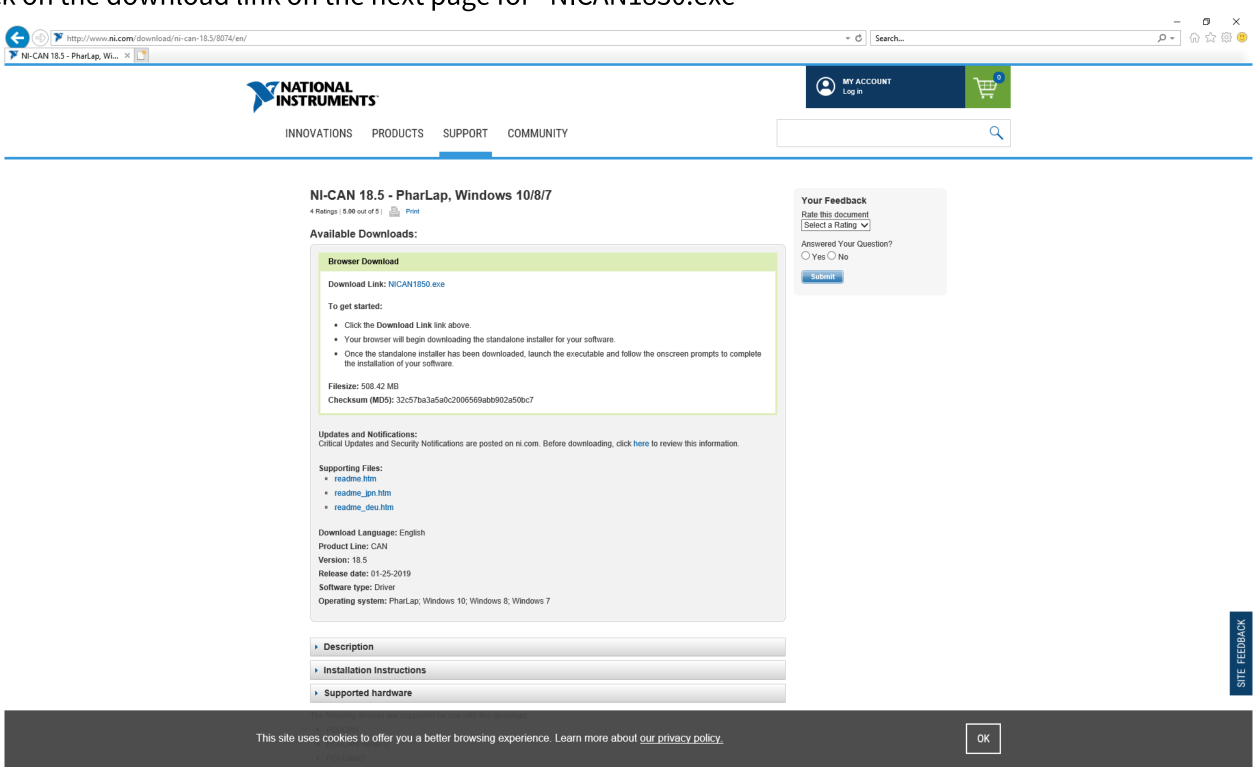
https://www.ni.com/en-us/support/downloads/drivers/download.ni-can.html

Click on the link to download NI-CAN version 18.5

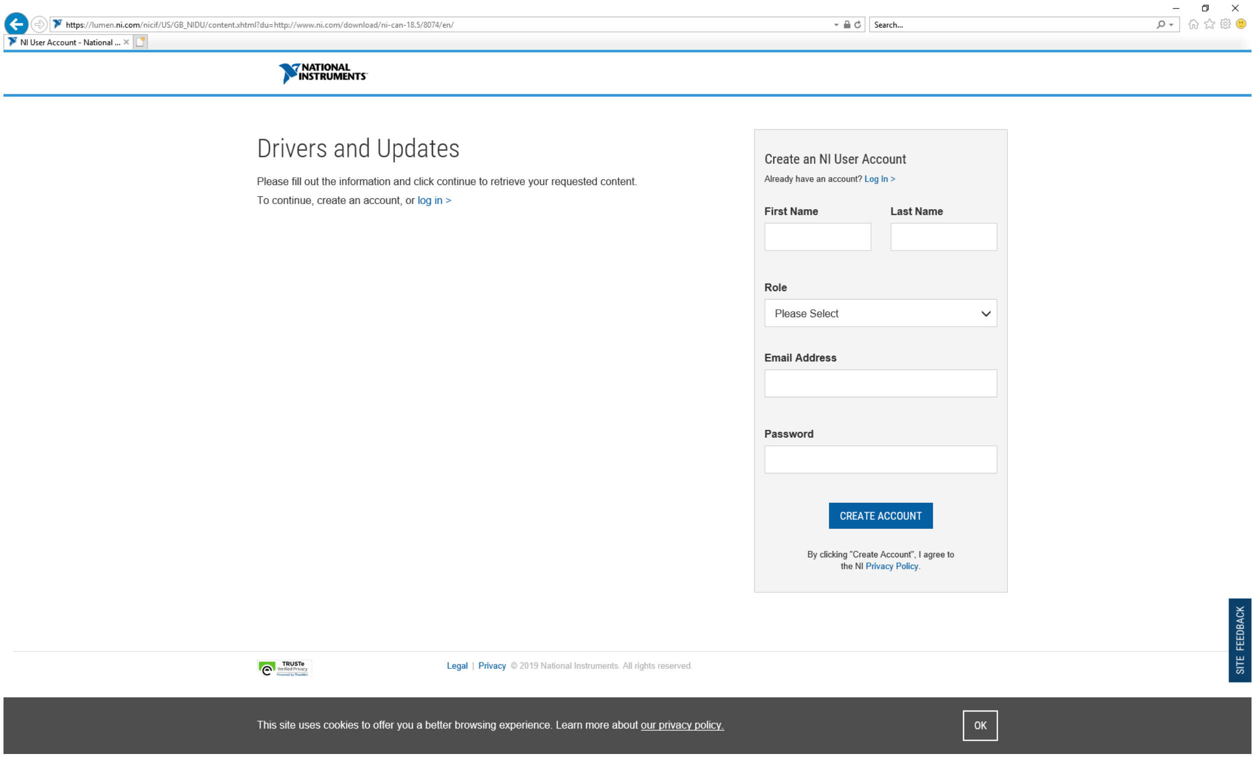
[NI-CAN 18.5 - PharLap, Windows 10, Windows 8, Windows 7 - National Instruments]



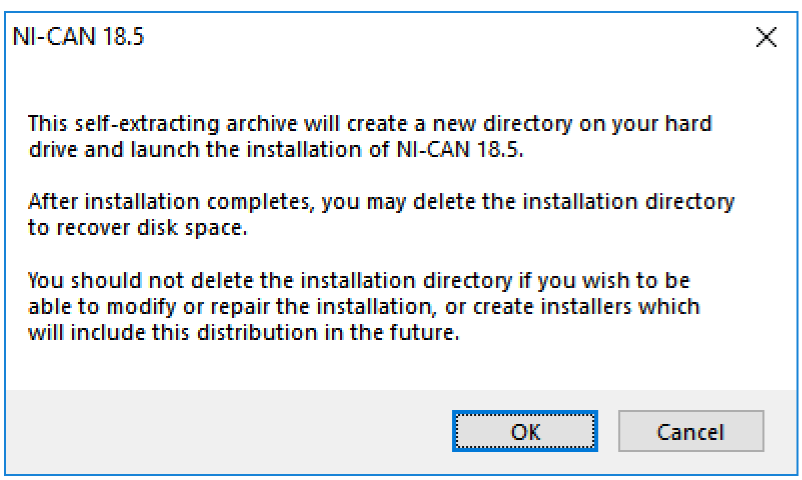

Click on the download link on the next page for “NICAN1850.exe”



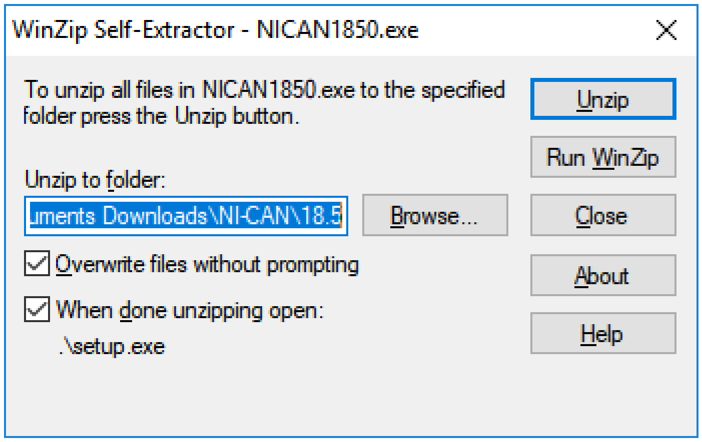
Log in to create a new user account to enable the download.



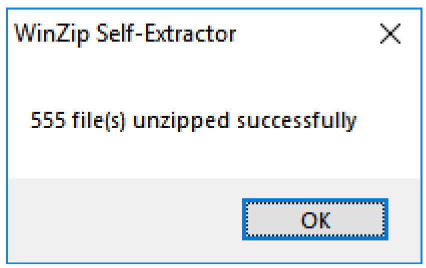

Run the newly downloaded "NICAN1850.exe" program. If you agree to the request to extract the installer, click OK.



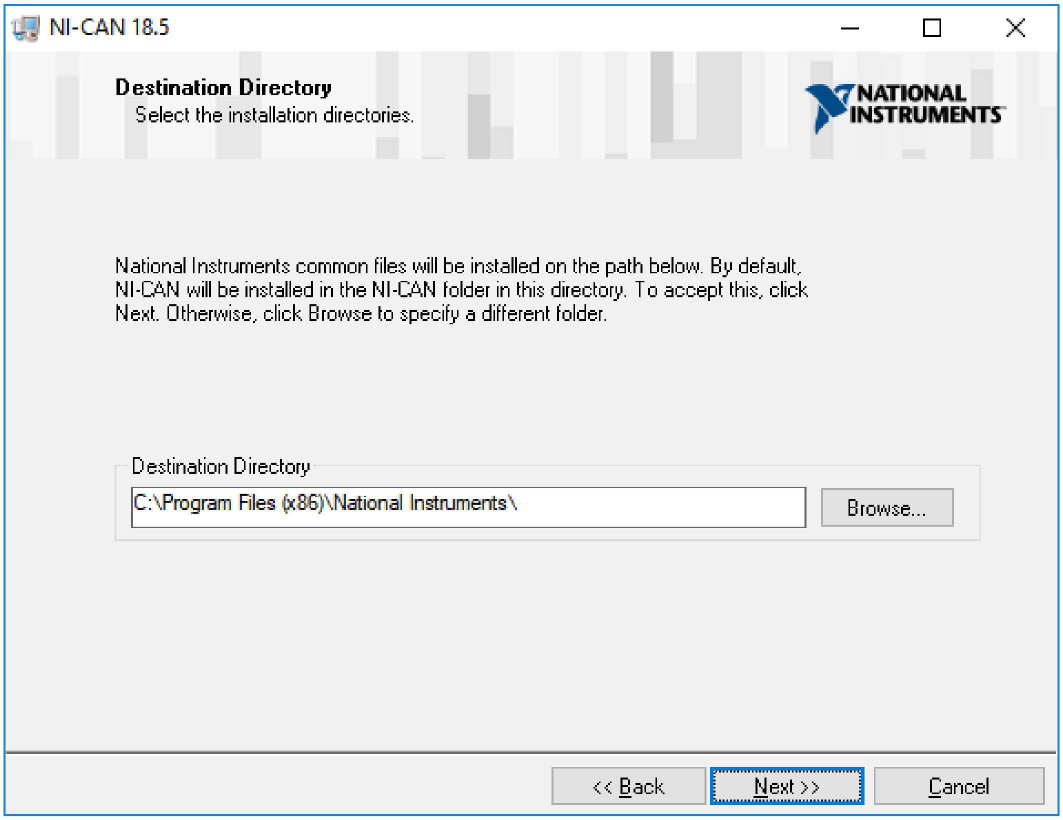
Choose a directory for the archive to extract into. This is not the installation directory so the downloads directory is ok. Click unzip.



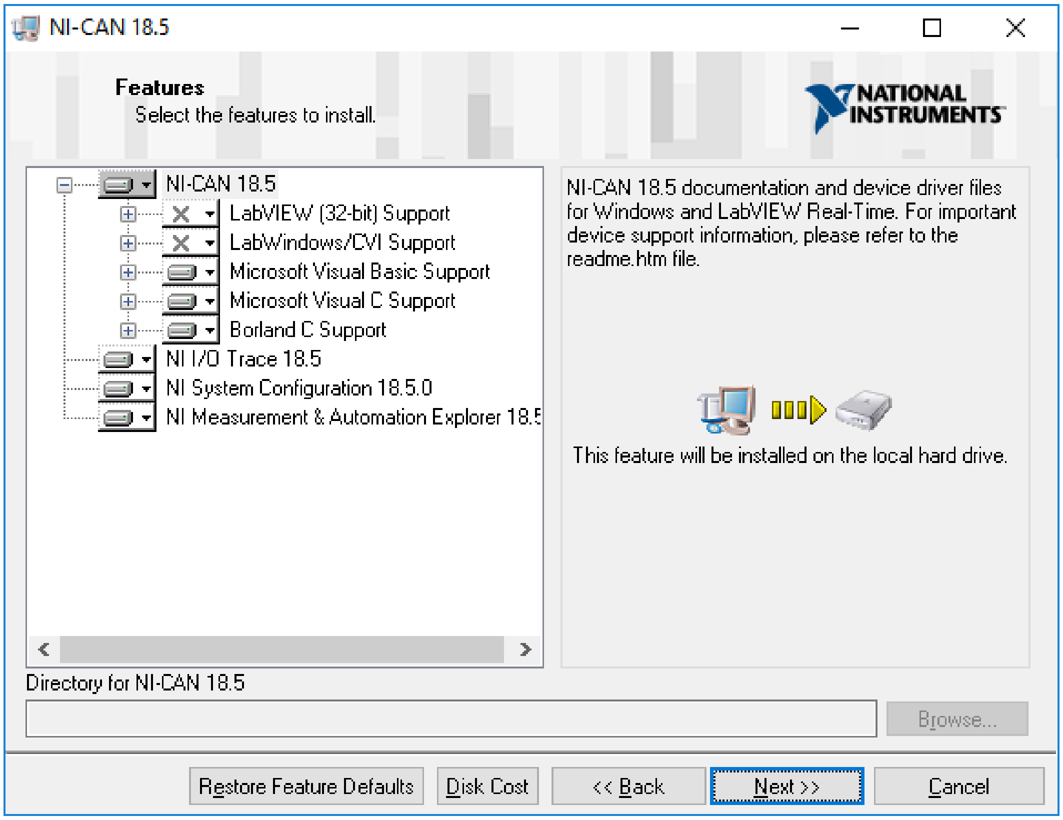

After it is finished extracting a success dialog will pop-up. Click OK.



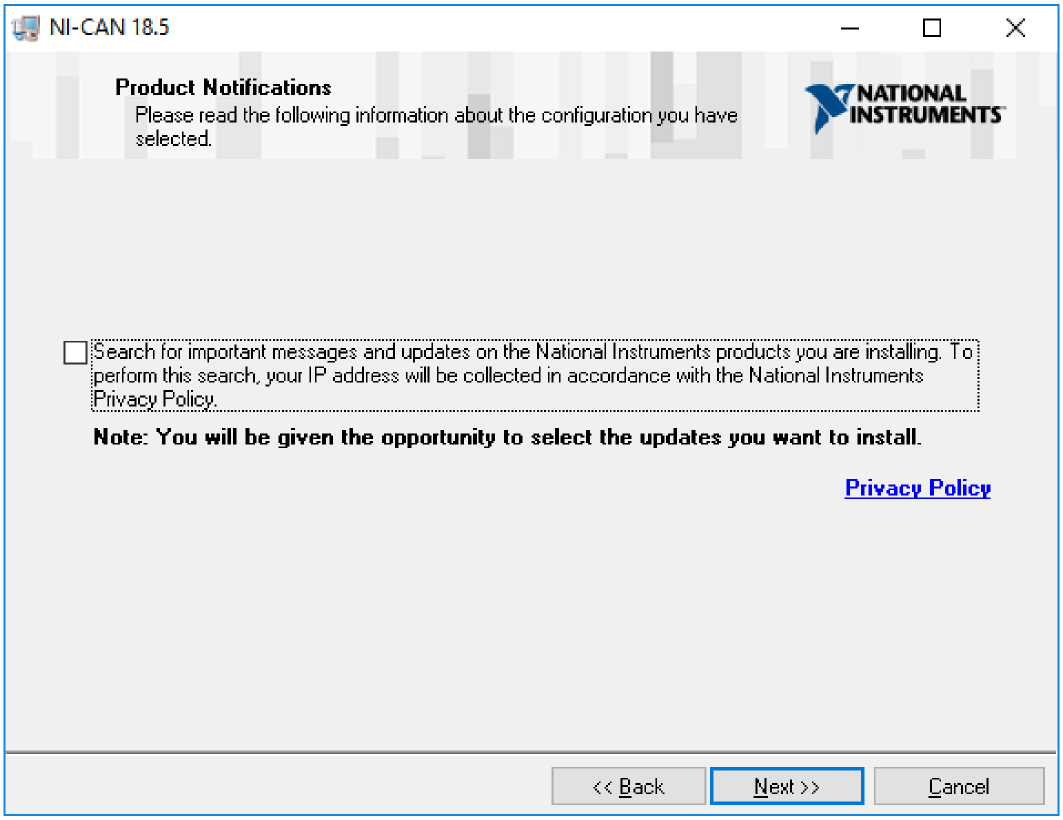
Next the installer for NI-CAN will run. Choose the “C:\Program Files (x86)\National Instruments\” directory if it is not already selected. Then click Next.



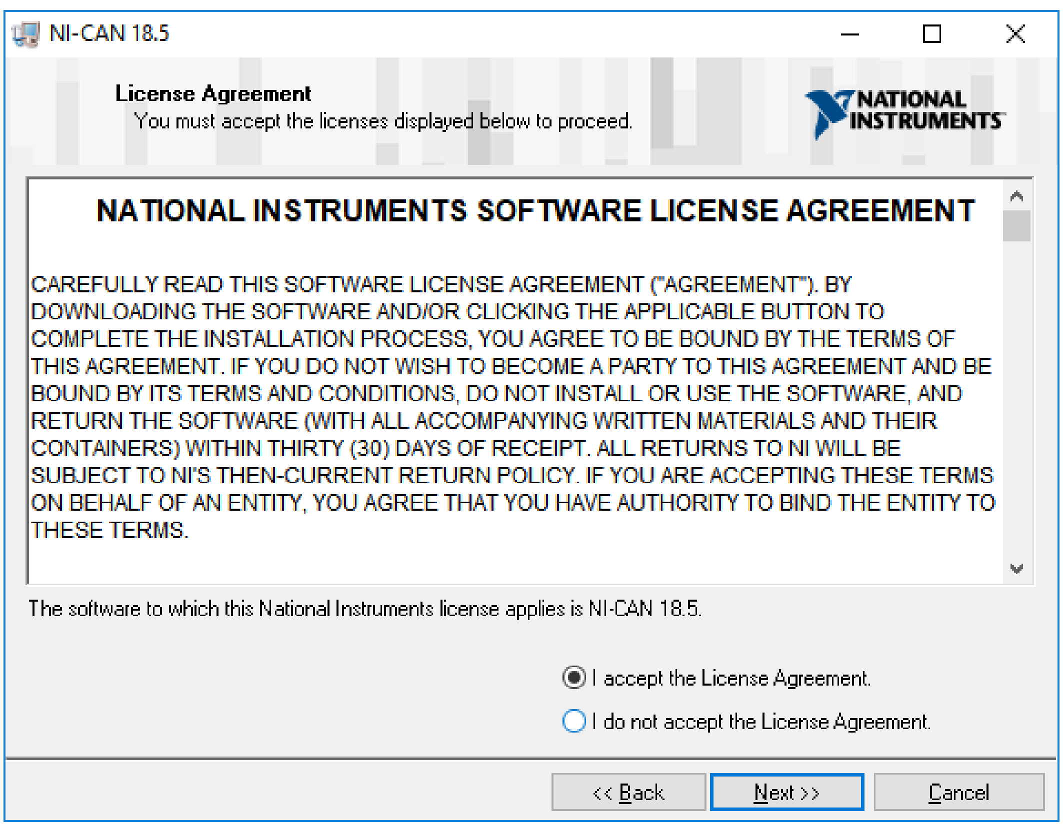

Leave the default options on the Features menu. Then click Next.



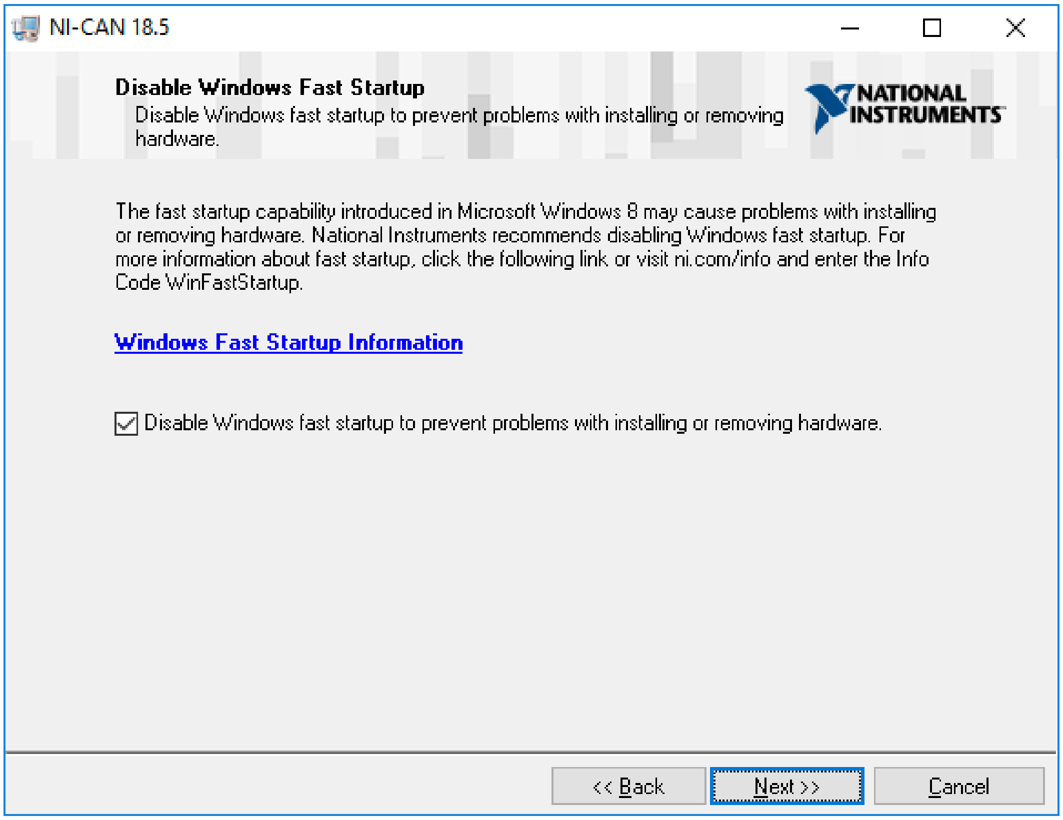

Decide whether you want product notifications and then click Next.



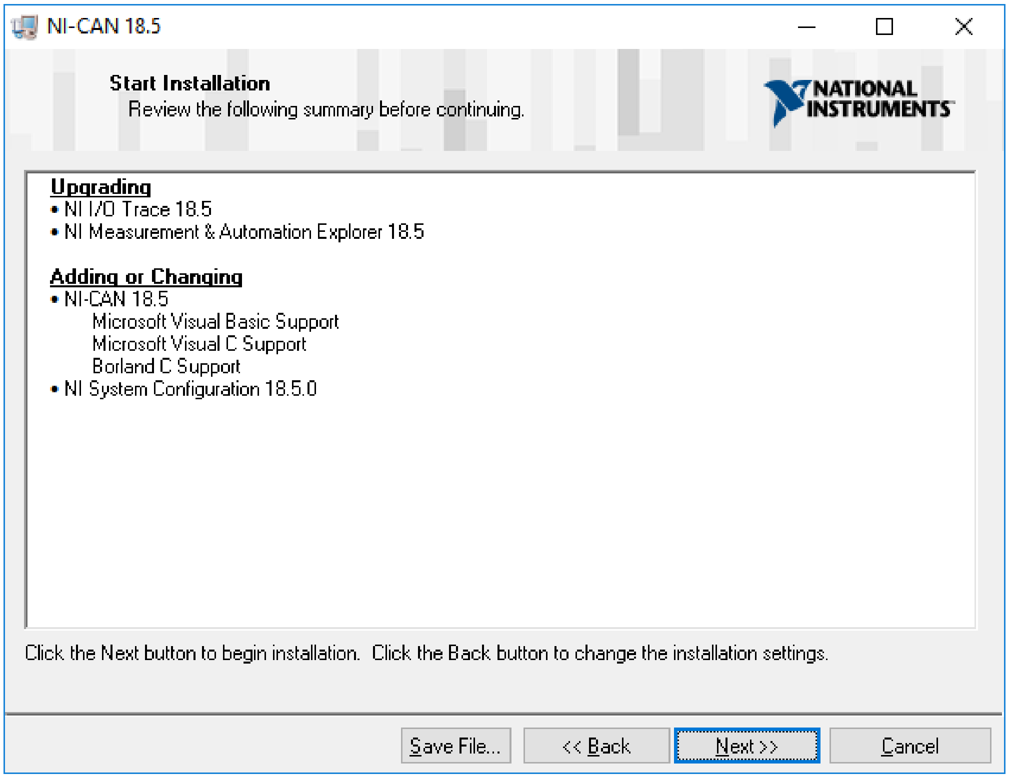

After careful review and acceptance of its terms, select that you accept the License Agreement and then click Next.



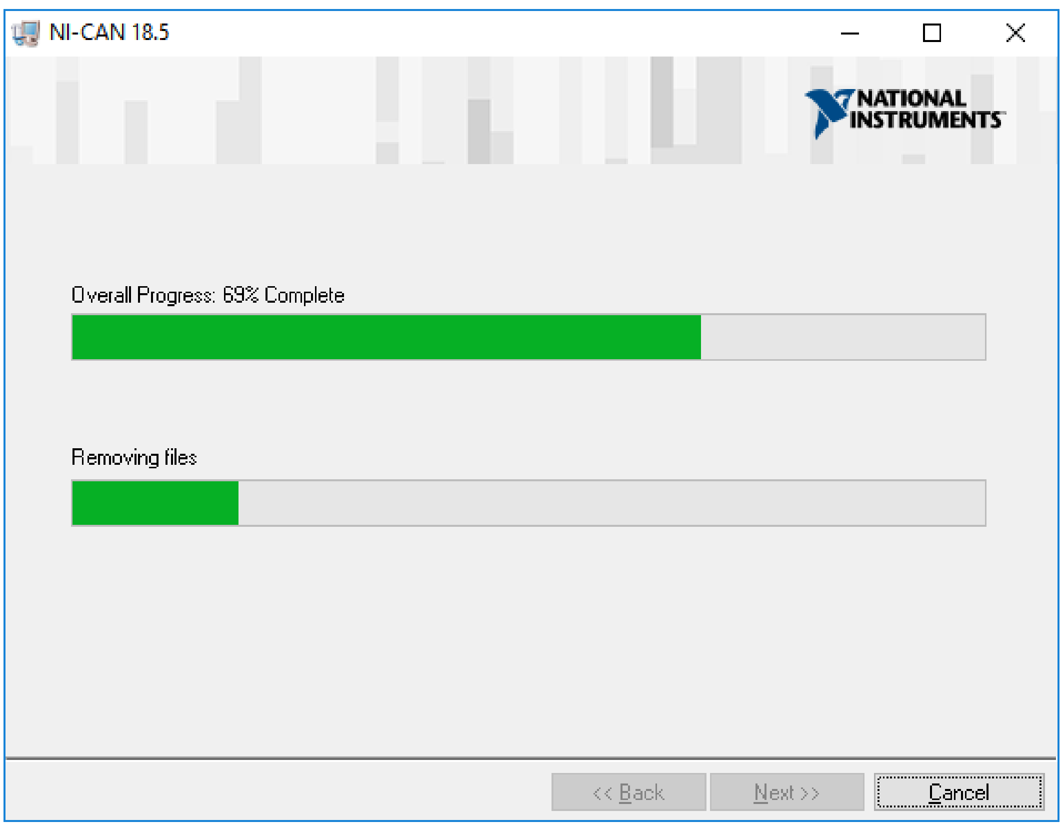
If there is a Windows pop-up to trust National Instruments and you wish to do so, click Trust to allow for the installation to run.  Decide whether to disable fast startup (NI recommends doing so, as illustrated below) and then click Next.



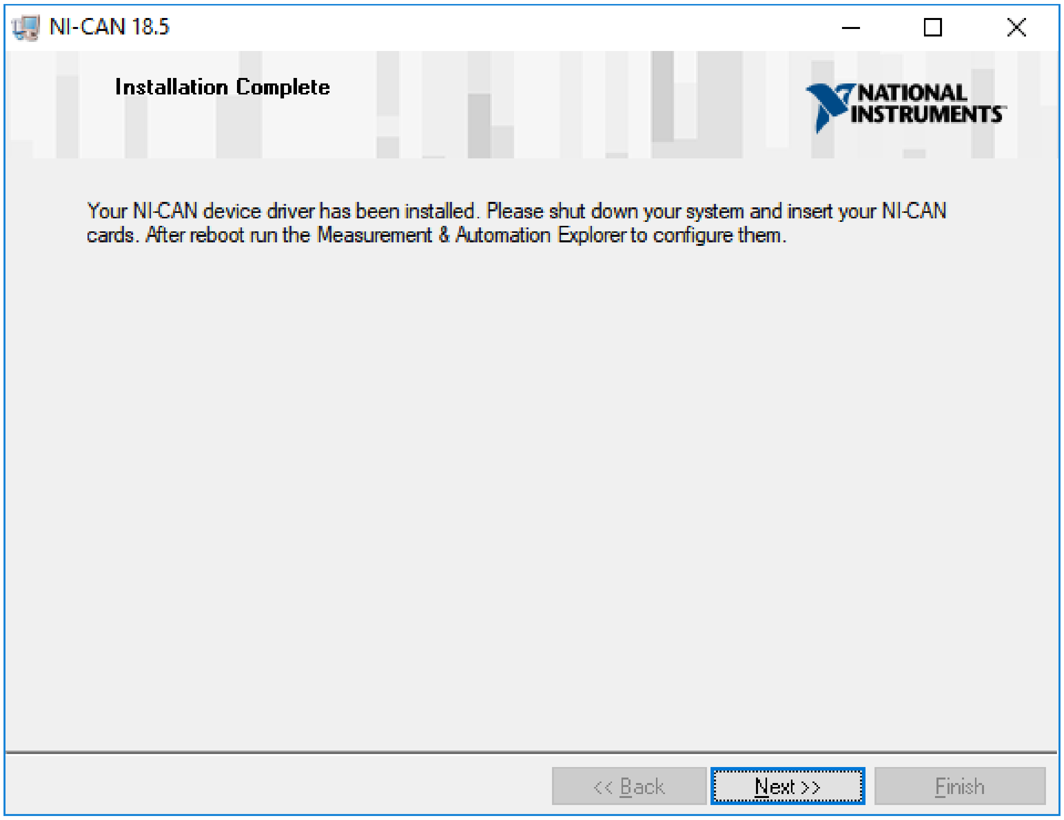

The next screen reviews what software is going to be installed or upgraded. If you have never used NI software all the features will be under Adding. Click Next.



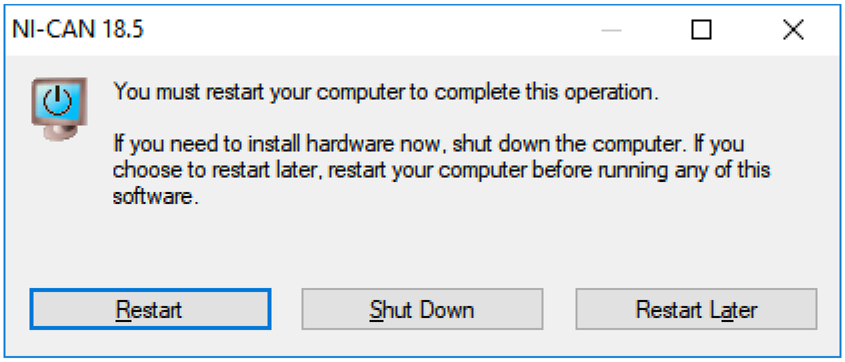

The installation process will now start. It will likely take several minutes to complete.




After the installation has finished successfully click Next.


NI-CAN 18.5
Installation Complete
NATIONAL INSTRUMENTS
Your NI-CAN device driver has been installed. Please shut down your system and insert your NI-CAN cards. After reboot run the Measurement & Automation Explorer to configure them.
<< Back
Next >>
Finish

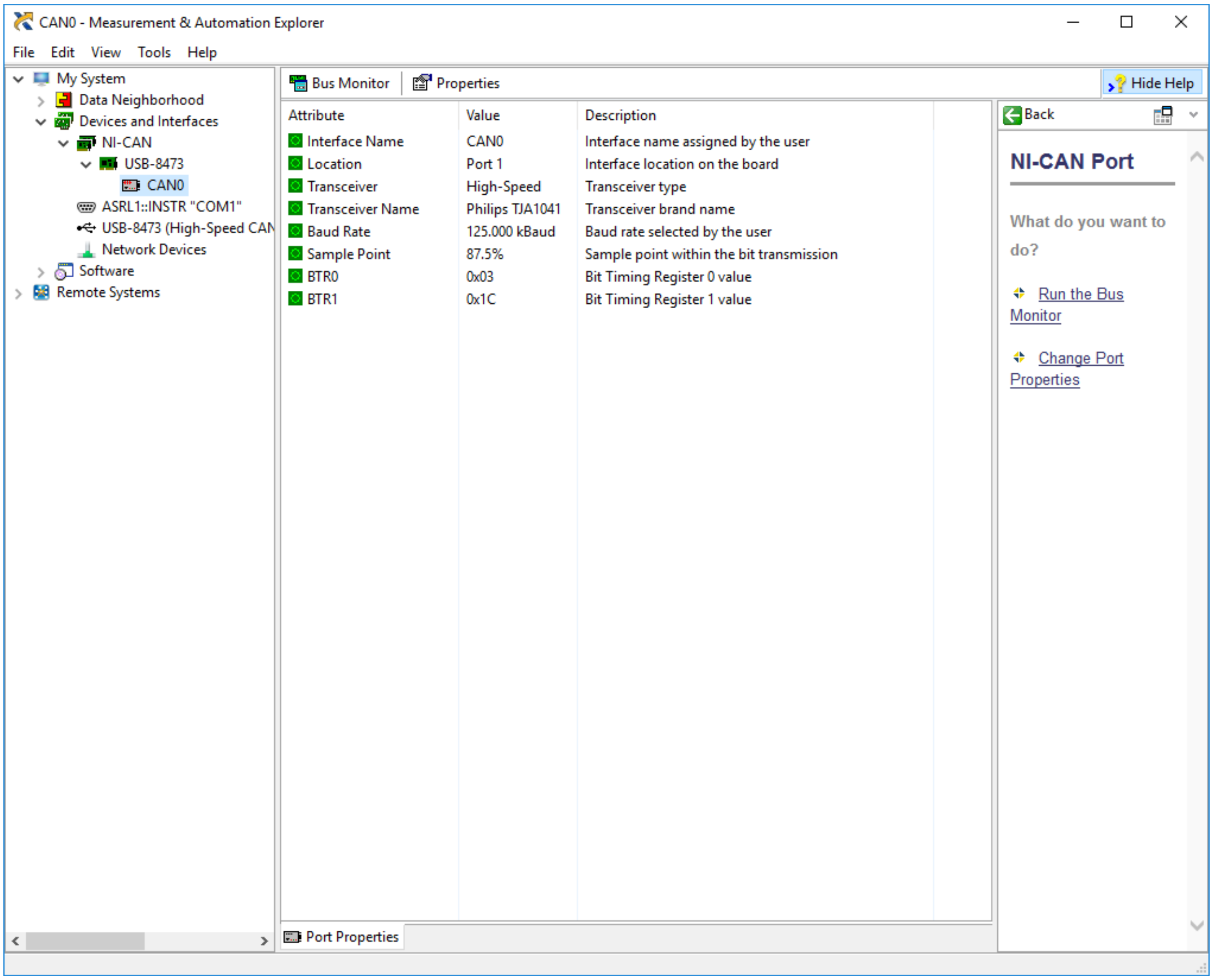
After installation is complete save any other work or programs that are open and click Restart.



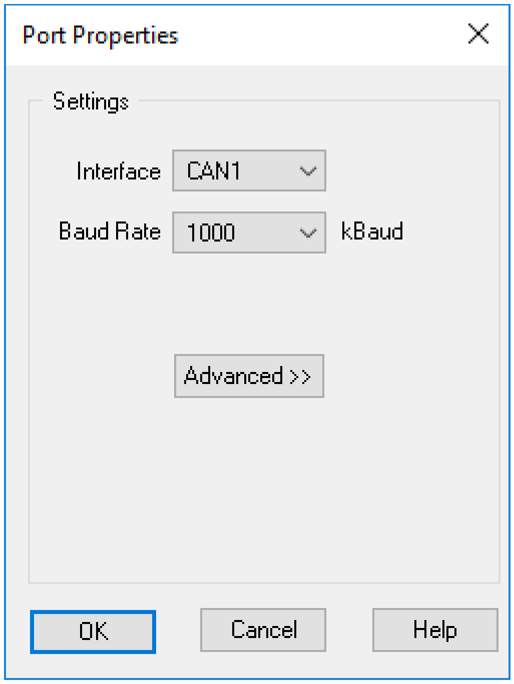
### 7.2.2 Configure the USB-8473

Go to the start menu and open the newly installed NI MAX.

Under Devices and Interfaces -> NI-CAN -> USB-8473, right-click on the “CAN0” and select Properties.



On the properties dialog change the Interface to CAN1 and the Buad Rate to 1000 kBuad. Click OK




You can now close the NI MAX software.

The USB-8473 adapter must be connected to the host computer and the DE-9 cable installed between the USB-8473 and the isolated CAN port (J9) on the XM3 Inverter's Controller. The location of the CAN port is shown in Figure 6 and the pinout for this connector is given in Table 6. Connect the 12 V power supply to the DC barrel jack (J11). If the CAN interface fails to communicate ensure that the pinout of the DE-9 cable matches the pinout in Table 6.

Figure 19 shows a XM3 3-Phase Inverter Reference Design connected with the USB-8473 to the host computer. In this example the inverter is not connected to a high-voltage source or load. Testing the controller and gate driver in this manner is recommended to gain familiarity with the system prior to testing while the inverter is energized.

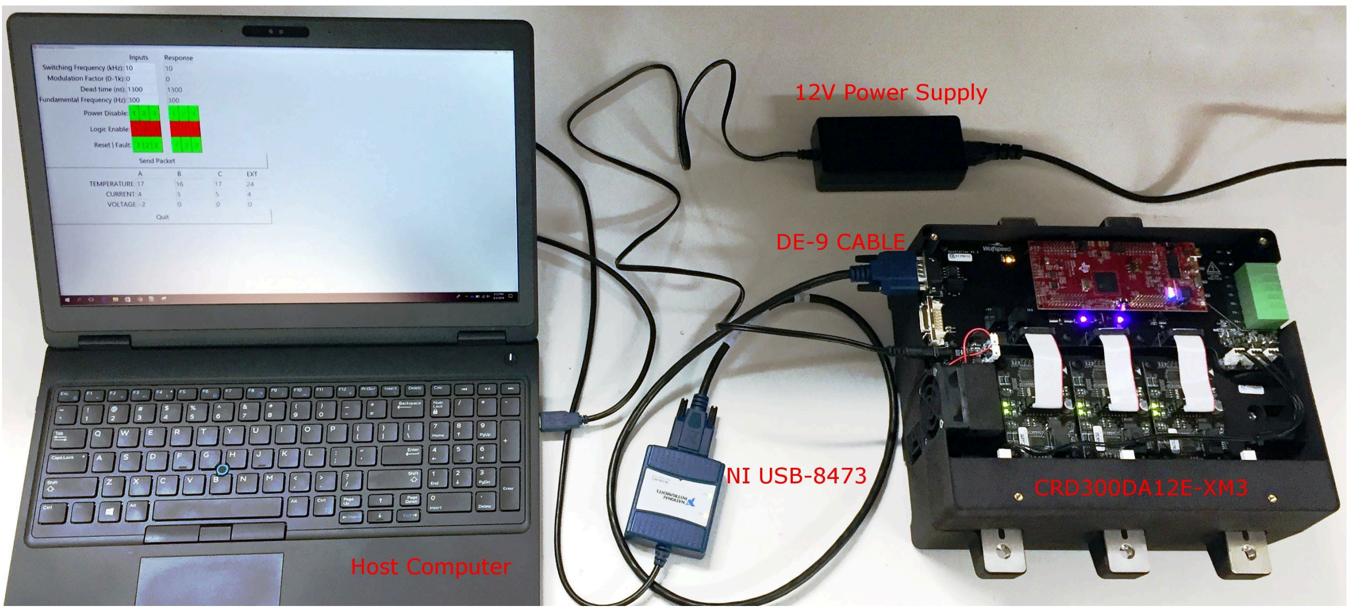
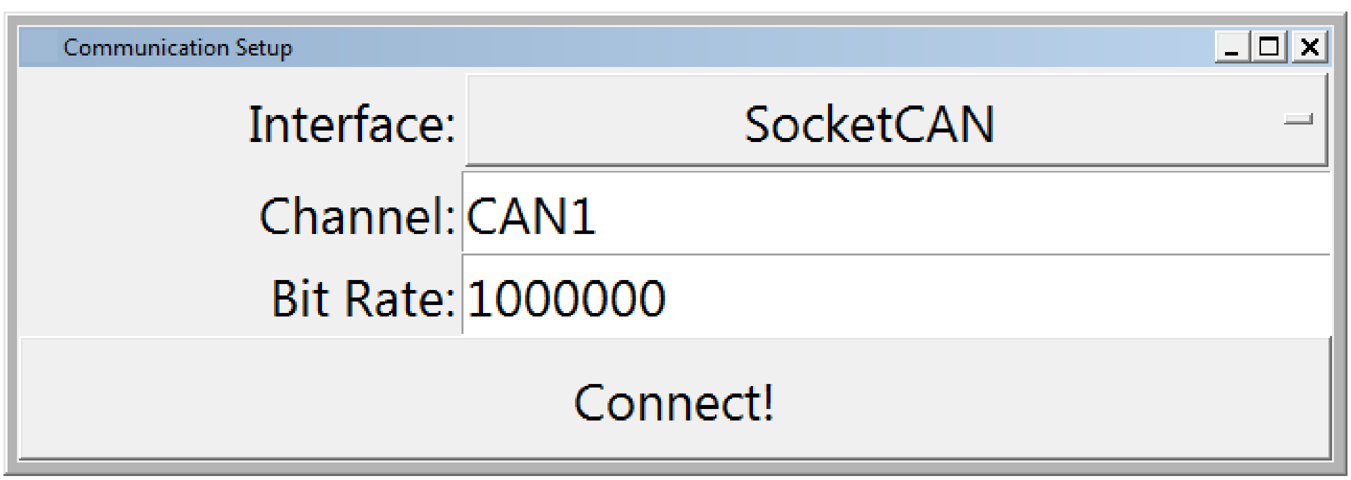
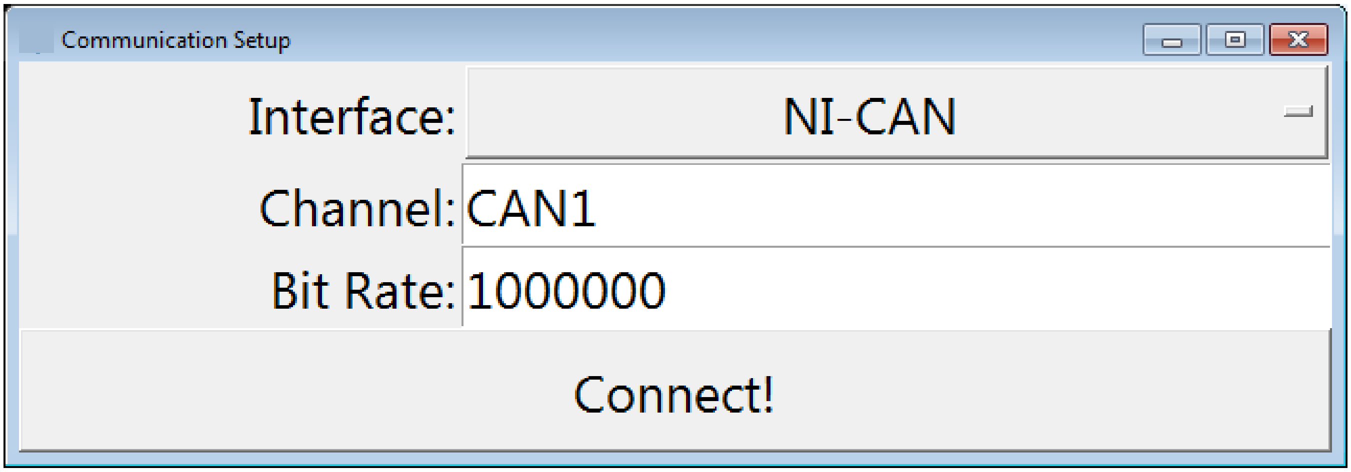



*Figure 19. Example Setup with NI USB-8473*

Run the "XM3 Inverter CAN Interface.exe" file and the following Communication Setup dialog should appear.



Click on the drop-down menu to the right of Interface and select NI-CAN Interface from this menu. In the box next to Channel you will need to enter CAN1. The box next to Bit Rate identifies the bit rate of the CAN bus and should be left as default of 1000000.




The NI USB-8473 hardware is now setup for use with Wolfspeed's XM3 Inverter CAN Interface. Skip to Section 8 to begin using the software.

## 7.3 Install Korlan USB2CAN

Using the Korlan USB2CAN CAN adapter with Wolfspeed's XM3 Inverter CAN Interface requires the Korlan software to provide the device driver for the USB2CAN hardware.

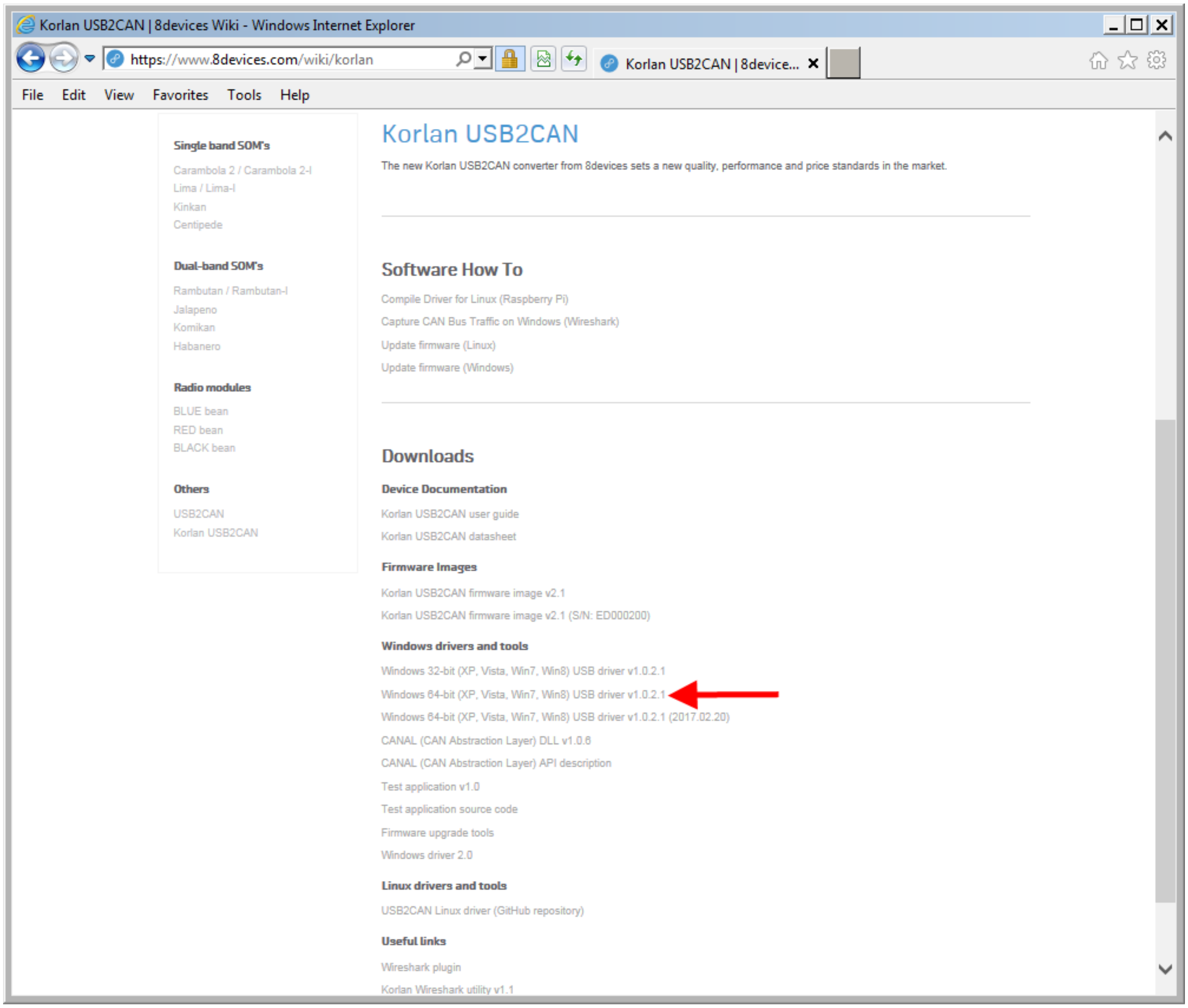
**REQUIREMENTS:**

- Korlan USB2CAN high-speed CAN adapter
- Korlan USB2CAN driver
- Microsoft Windows 10
- USB 2.0 port

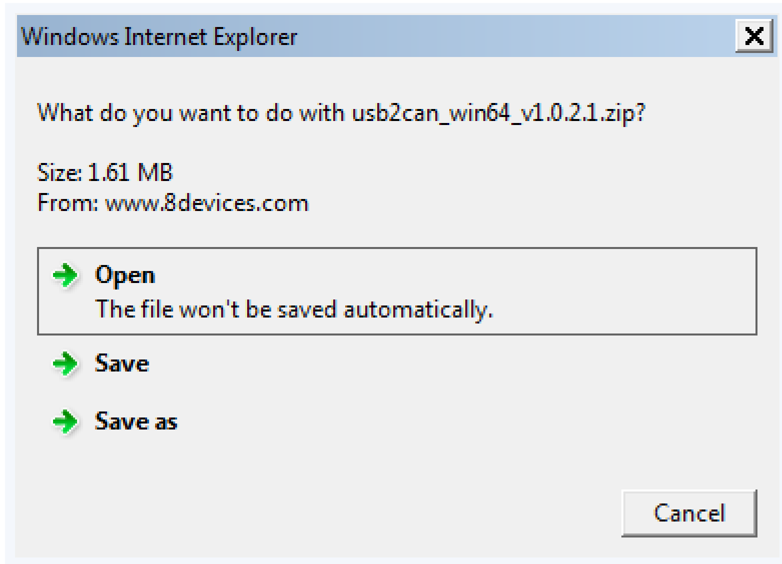
### 7.3.1 Download USB2CAN

Open a web browser and navigate to the download page for USB2CAN at the following link.
https://www.8devices.com/wiki/korlan

Click on the link to download the “Windows 64-bit (XP, Vista, Win7, Win8) USB driver v1.0.2.1”



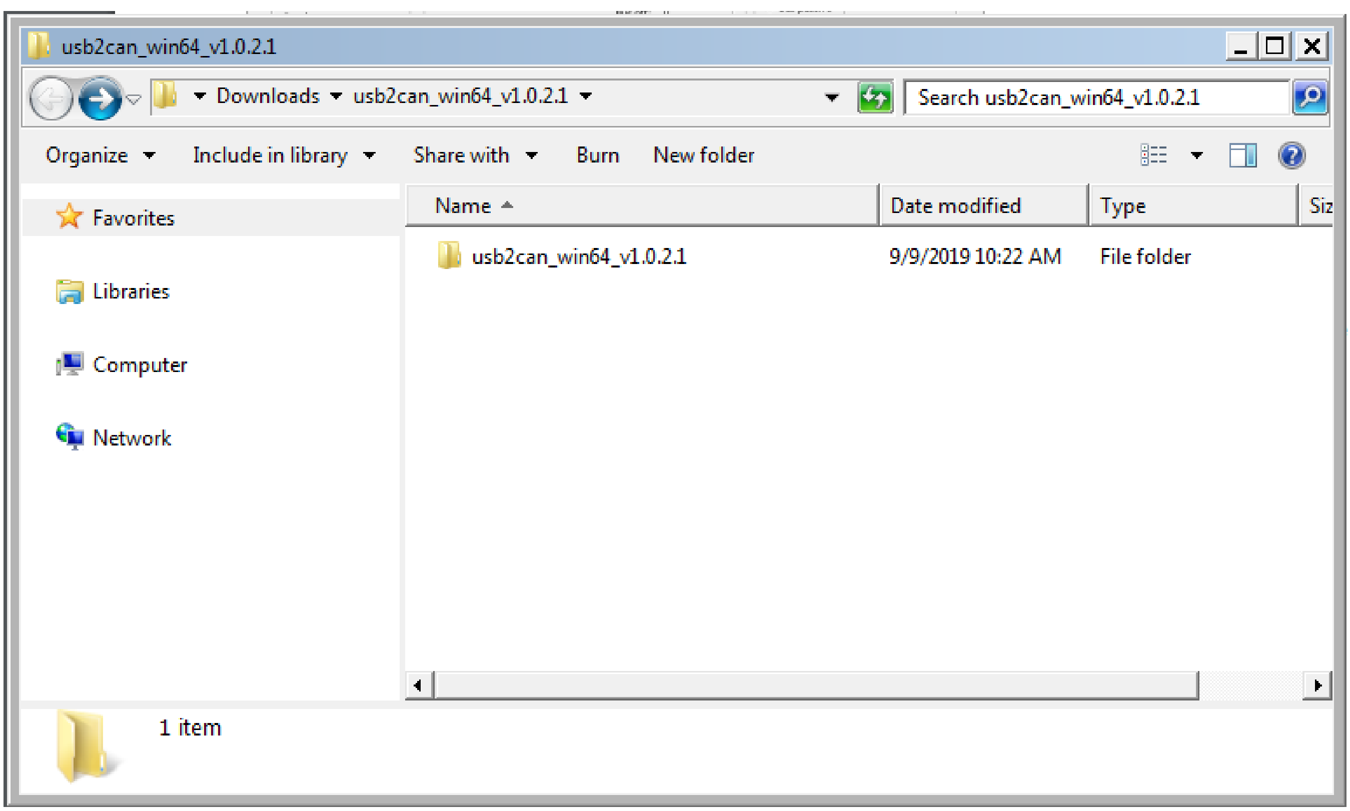
Click save to download the “usb2can_win64_v1.0.2.1.zip” file.



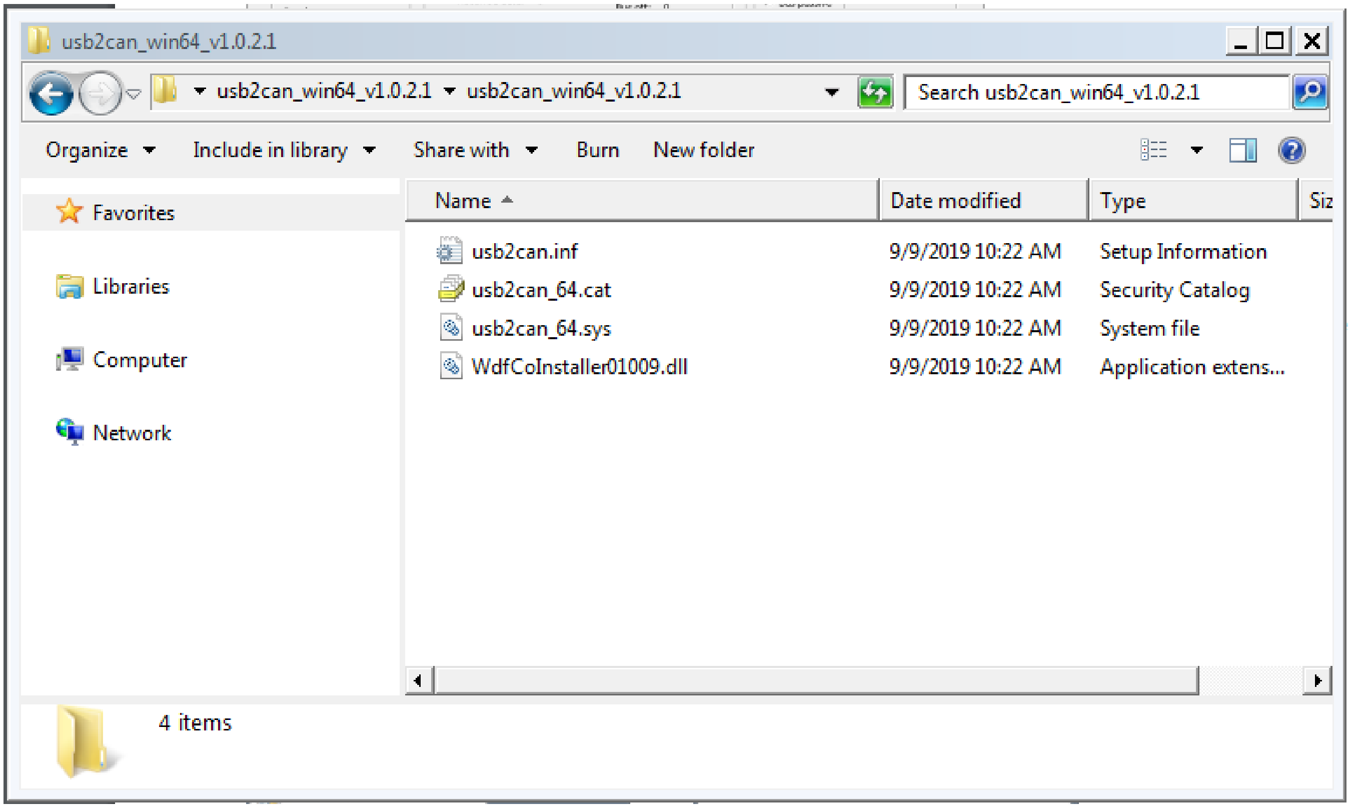

Navigate in File Explorer to the directory where you save the download.

Right-click on the zip file and select Extract All.

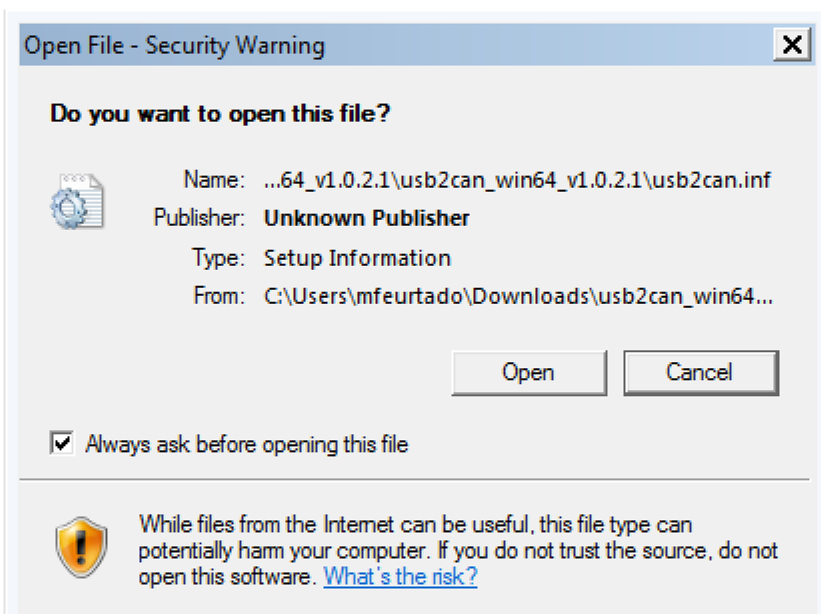
There will be a single folder inside the resulting directory.



Open the directory and then right-click on the file “usb2can.inf”. Select Install.



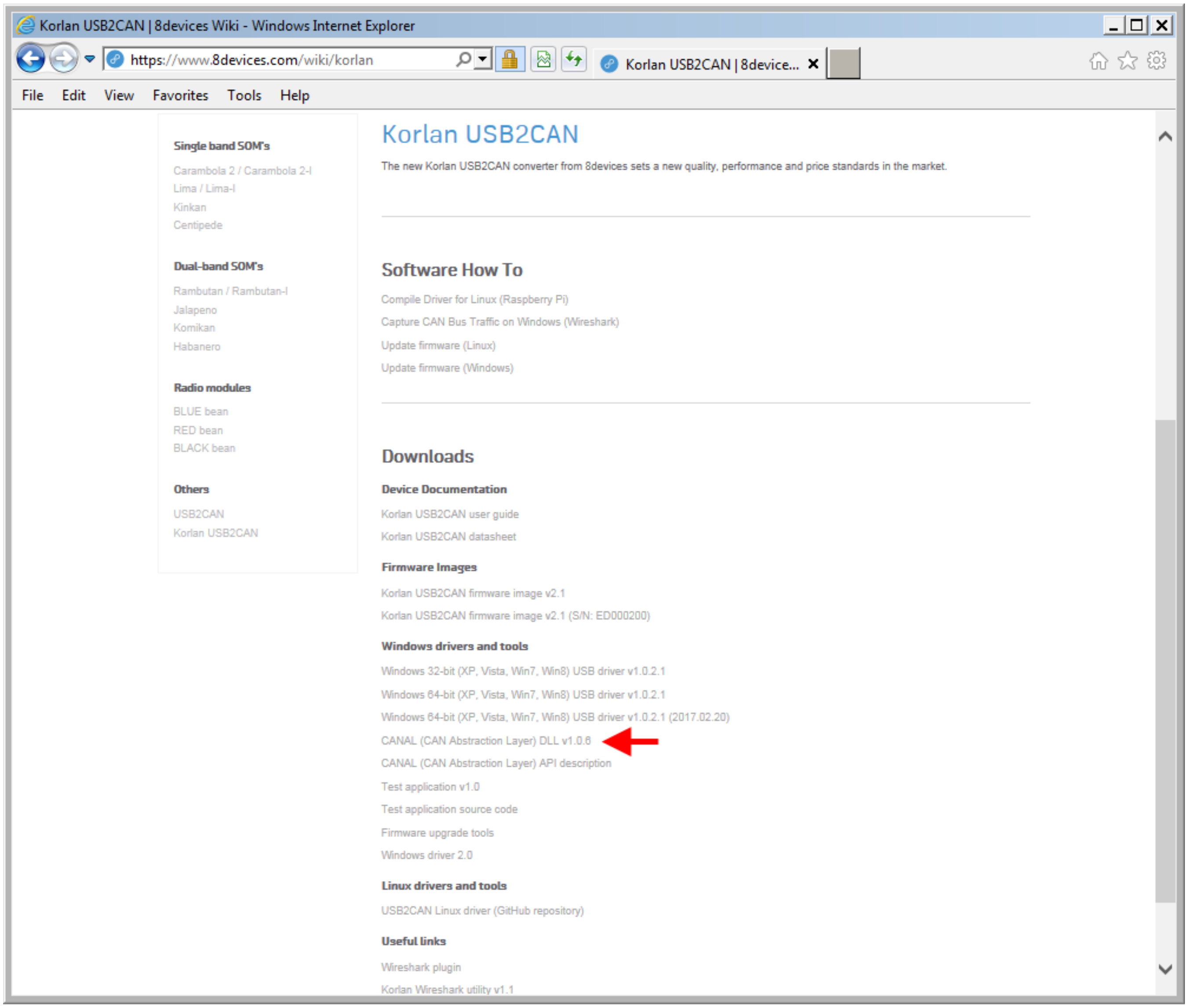

On the following dialog box select Open to continue with the installation of the driver.



Open a web browser and navigate to the download page for USB2CAN at the following link.

https://www.8devices.com/wiki/korlan

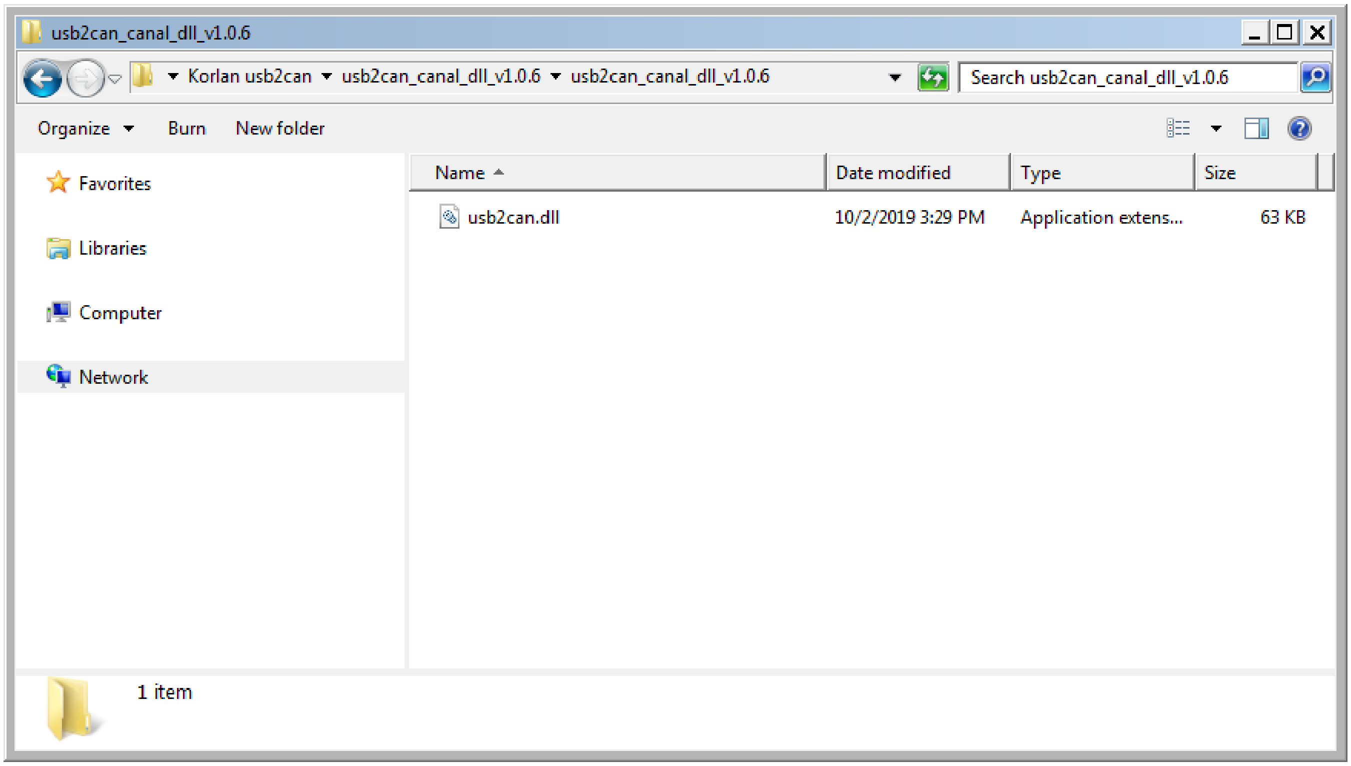
Click on the link to download the "CANAL (CAN Abstraction Layer) DLL v1.0.6"



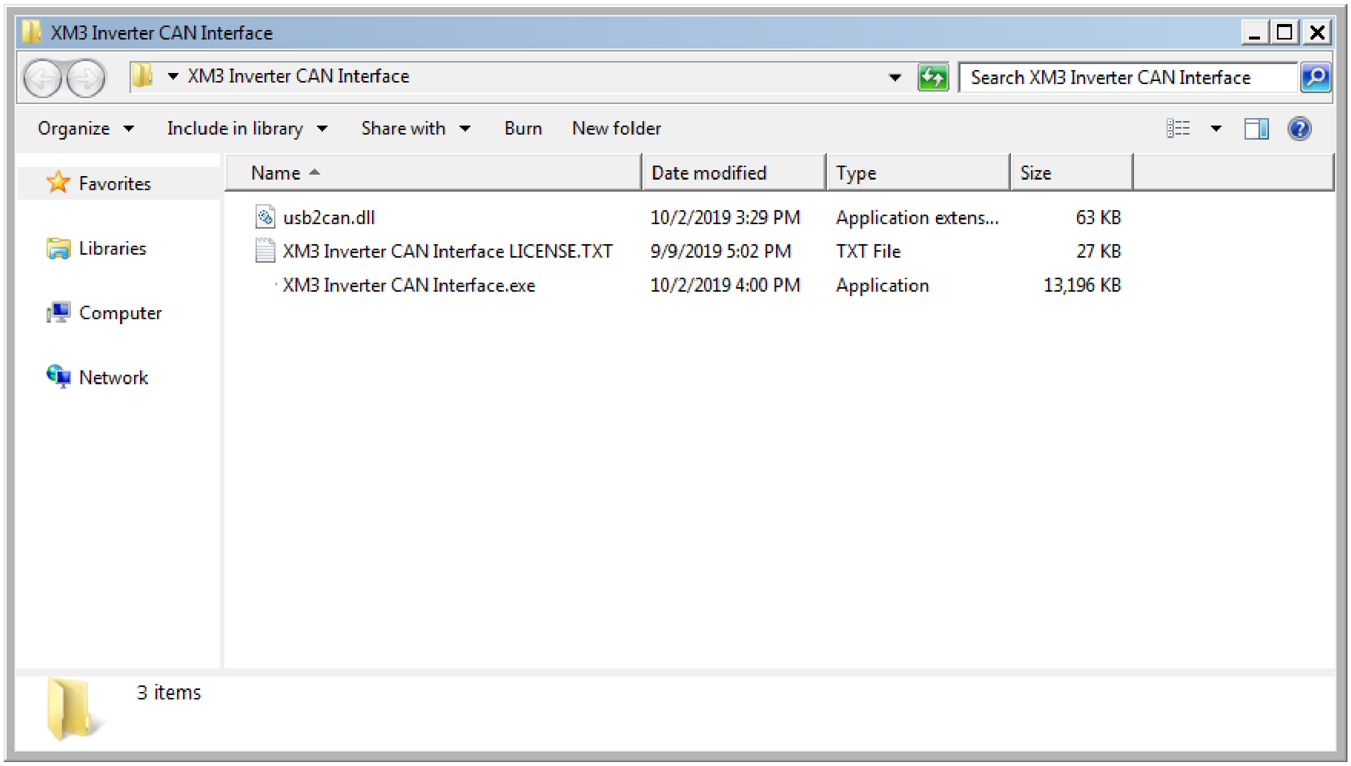
Navigate in File Explorer to the directory where you save the download.

Right-click on the zip file and select Extract All.

There will be a single folder inside the resulting directory. Open this directory.



Copy the file "usb2can.dll" to the directory where "XM3 Inverter CAN Interface.zip" was unzipped. The directory should now show the following files.



## 7.3.2 Configure USB2CAN adapter

The USB2CAN adapter must be connected to the host computer and the DE-9 cable installed between the USB2CAN and the isolated CAN port (J9) on the XM3 Inverter's Controller. The location of the CAN port is shown in Figure 6 and the pinout for this connector is given in Table 6. Connect the 12 V power supply to the DC barrel jack (J11). If the CAN interface fails to communicate ensure that the pinout of the DE-9 cable matches the pinout in Table 6.

Figure 20 shows a XM3 3-Phase Inverter Reference Design connected with the USB2CAN to the host computer. In this example the inverter is not connected to a high-voltage source or load. Testing the controller and gate driver in this manner is recommended to gain familiarity with the system prior to testing while the inverter is energized.

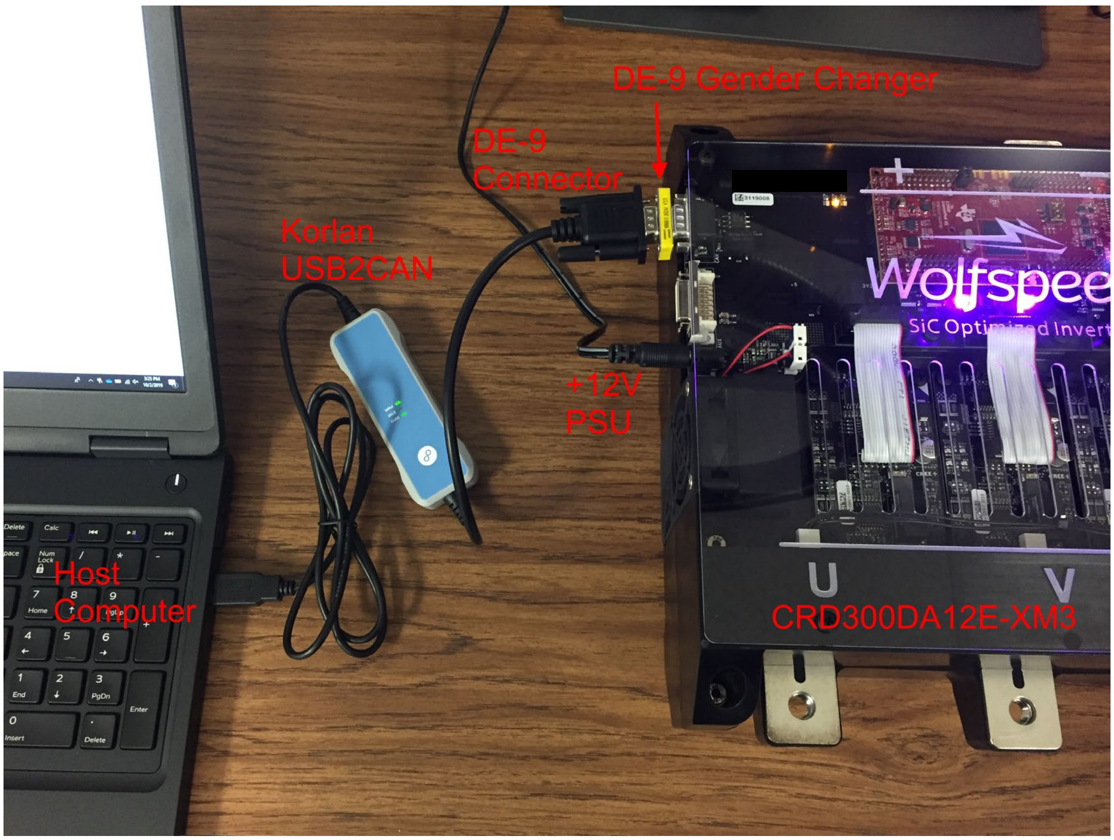
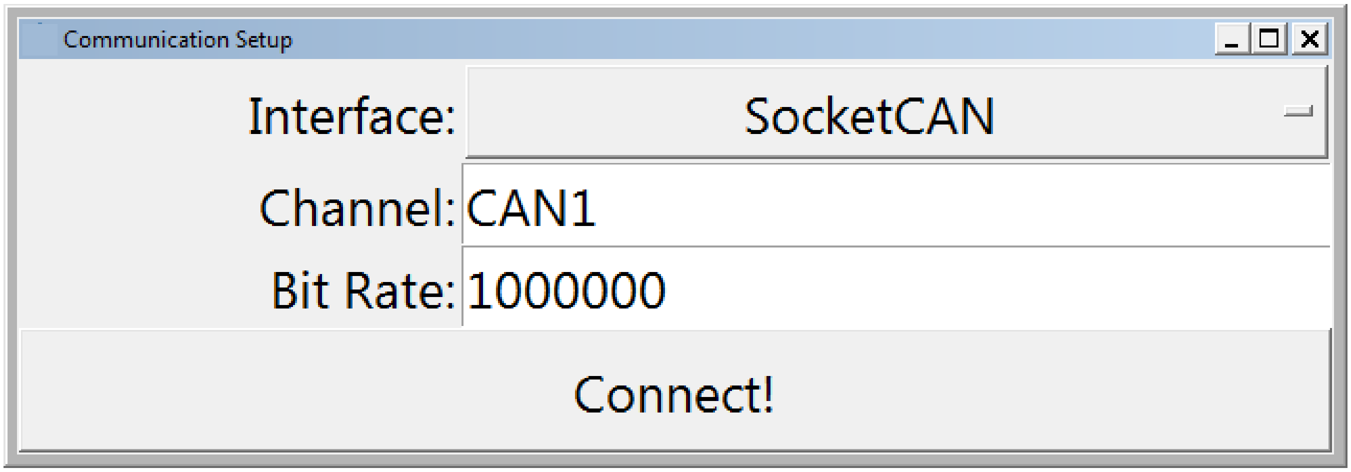
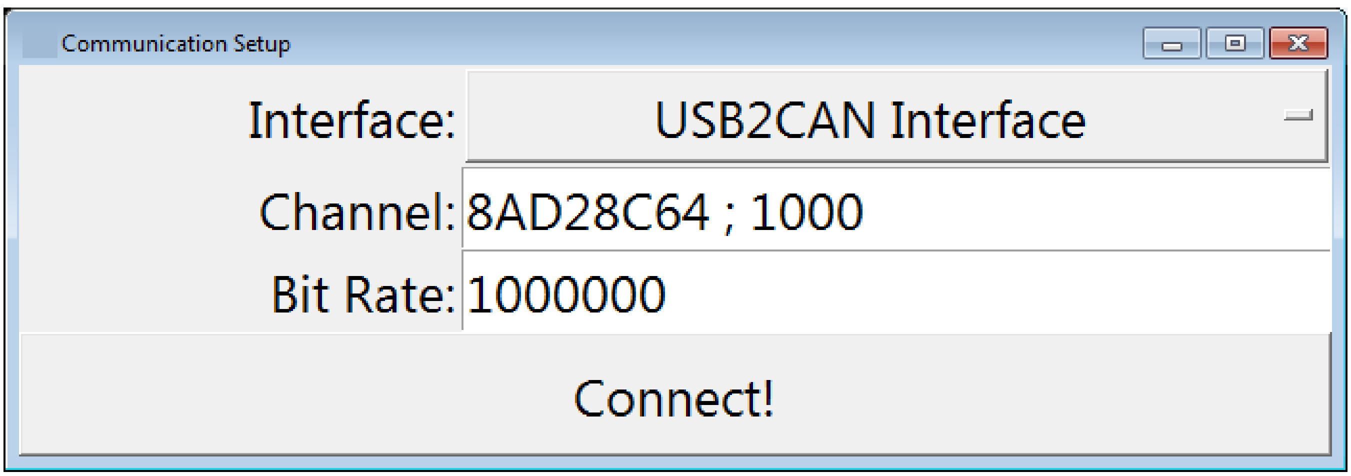



*Figure 20. Example Setup with USB2CAN adapter*

Run the “XM3 Inverter CAN Interface.exe” file and the following Communication Setup dialog should appear.




Click on the drop-down menu to the right of Interface and select USB2CAN Interface from this menu. In the box next to Channel you will need to enter the serial number of the Korlan USB2CAN device followed by a semicolon and 1000 for the bit rate in kbits. The serial number should be 8 characters long and is printed on the bottom label on the adapter. The box next to Bit Rate identifies the bit rate of the CAN bus and should be left as default of 1000000.

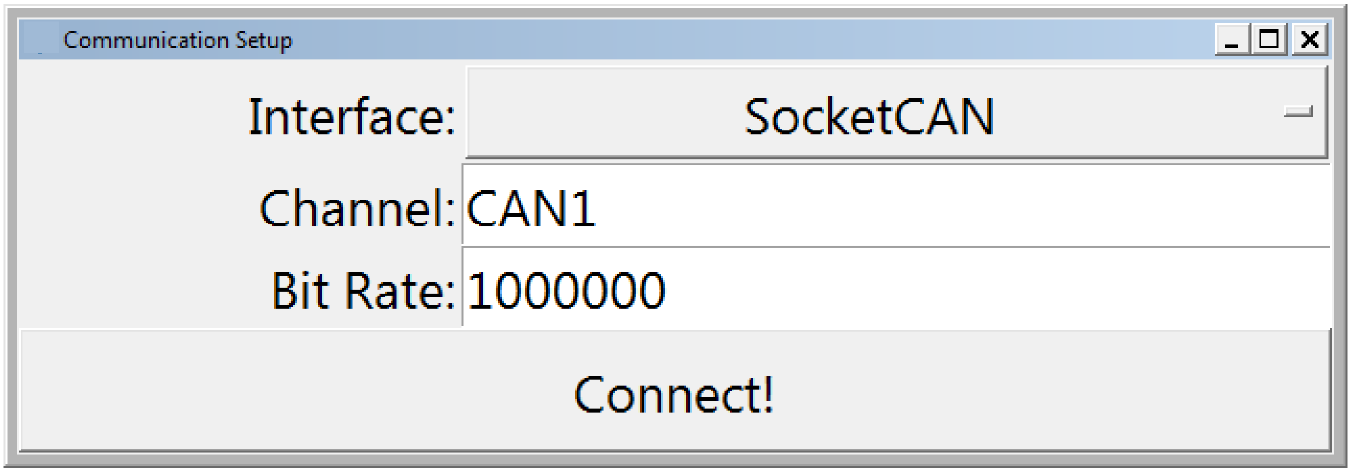



The USB2CAN hardware is now setup for use with Wolfspeed’s XM3 Inverter CAN Interface. Skip to Section 8 to finish the setup.

# 8. Using Wolfspeed's XM3 Inverter CAN Interface

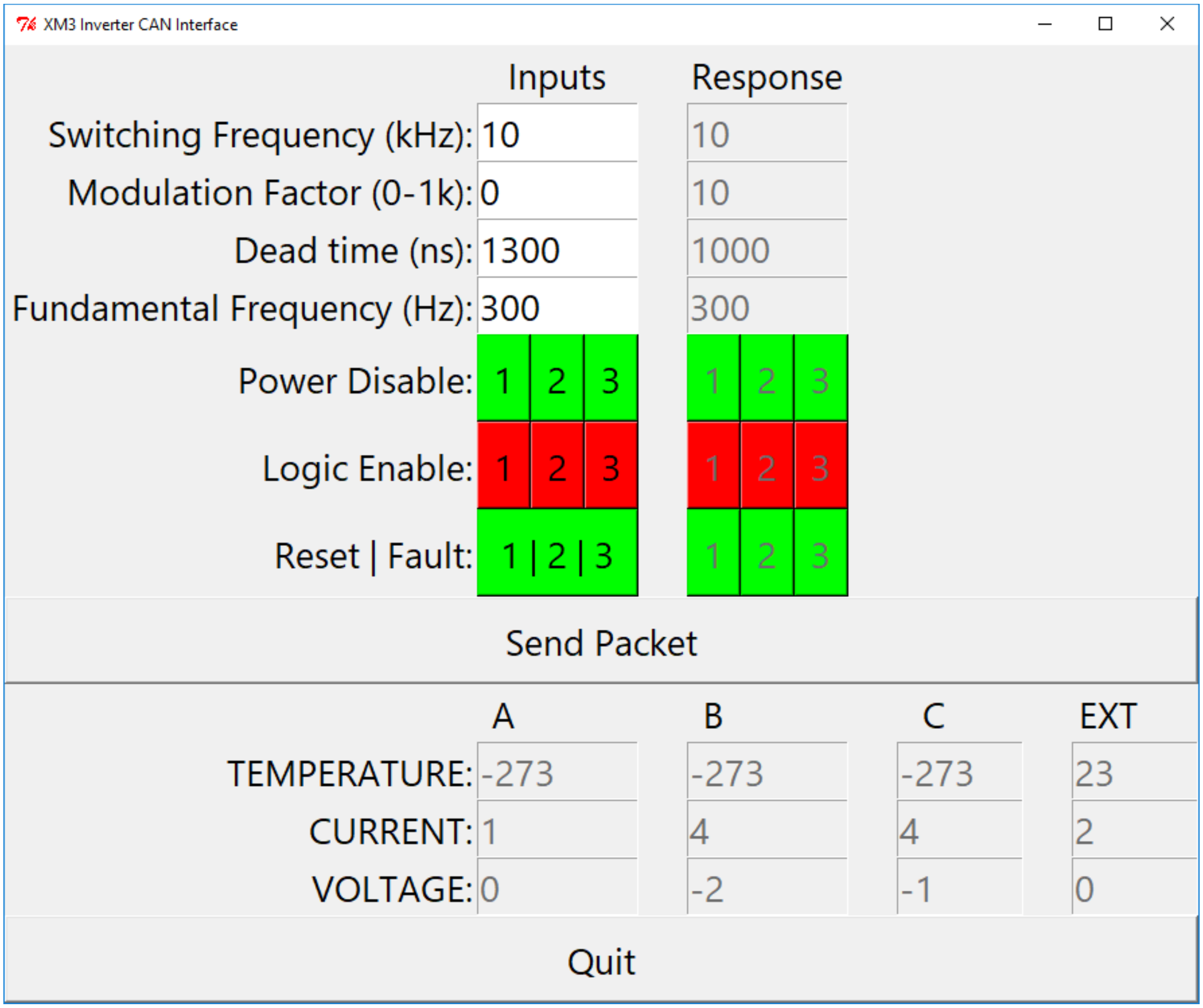
Open File Explorer and navigate to the directory where the "XM3 Inverter CAN Interface.exe" file was saved. Double click on the executable to run the application.

Run the application and two windows will pop up. The first window is a command window which will print out a log of the raw CAN packets that are transmitted between the host and the controller. This window will also print any error messages from the application. The second window is the Communication Setup dialog. This is where the CAN adapter is configured based on the type of adapter being used. Refer to sections 7.2.2 and 7.3.2 for the appropriate settings for the NI USB-8473 or Korlan USB2CAN adapter.




After selecting the correct settings Click Connect! and the Communication Setup dialog will close and the GUI control window will pop up.

With the controller connected and powered the window will look similar to what is shown below.



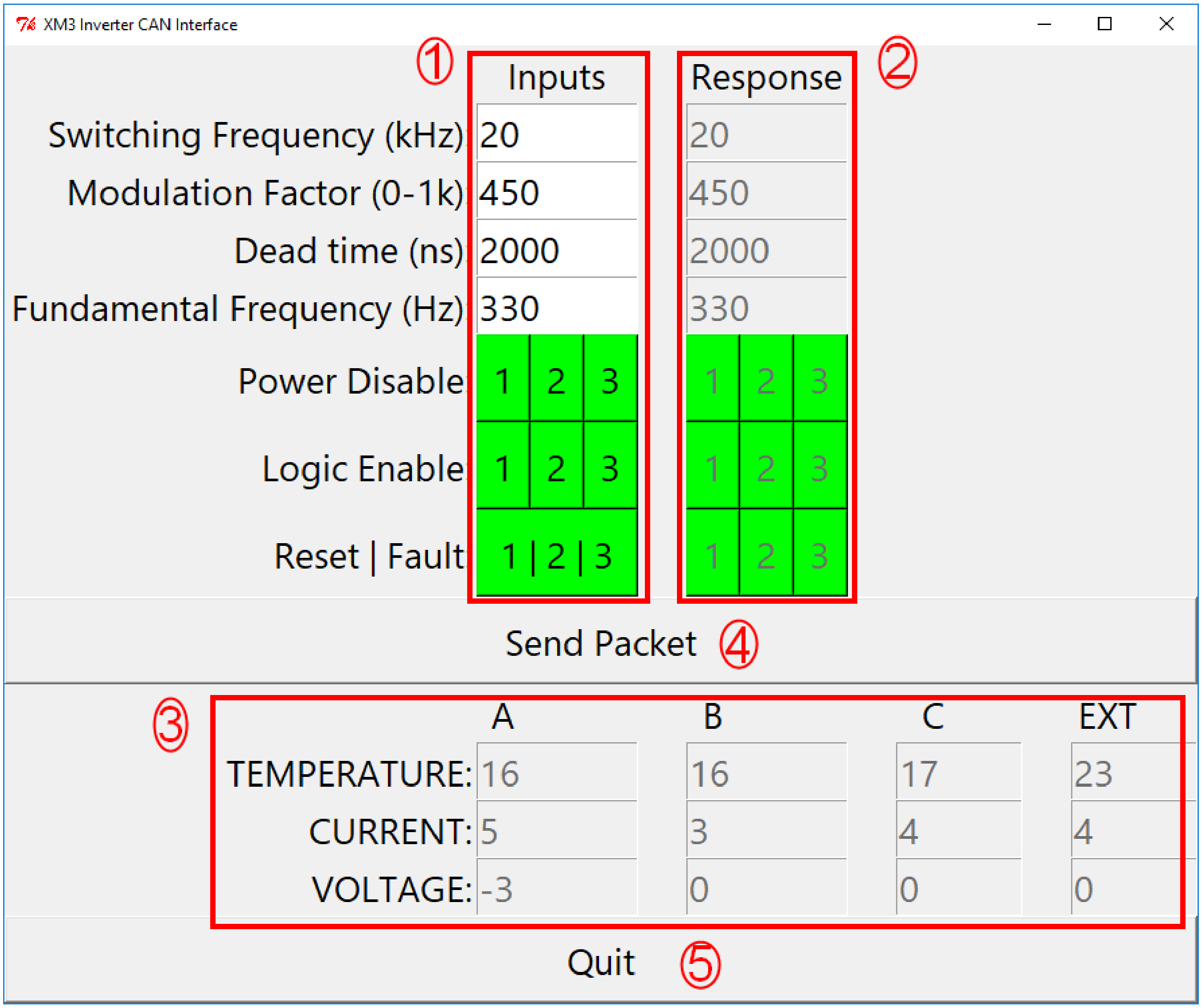
The command window will show a log of the raw CAN packets that are sent and received on the CAN bus. If there is an invalid packet a warning will be printed and any errors will be displayed in this window.

C:\Users\ \Desktop\XM3 Inverter CAN Interface.exe

```
2019-09-04 09:30:58.893000
Timestamp: 1567607459.324068        ID: 00fe    S                DLC:  8    00 02 00 04 00 04 00 02     Channel: CAN1
2019-09-04 09:30:58.893000
Timestamp: 1567607459.324192        ID: 00fd    S                DLC:  8    ff ff ff fe 00 00 00 00     Channel: CAN1
2019-09-04 09:30:58.893000
Timestamp: 1567607460.391562        ID: 0000    S                DLC:  8    0a 02 8f a1 2c 70 00 00     Channel: CAN1
2019-09-04 09:30:59.955000
Timestamp: 1567607460.391685        ID: 00ff    S                DLC:  8    00 00 00 00 00 00 01 29     Channel: CAN1
2019-09-04 09:30:59.955000
Timestamp: 1567607460.391809        ID: 00fe    S                DLC:  8    00 02 00 03 00 02 00 02     Channel: CAN1
2019-09-04 09:30:59.955000
Timestamp: 1567607460.391933        ID: 00fd    S                DLC:  8    ff ff ff fe ff ff 00 00     Channel: CAN1
2019-09-04 09:30:59.955000
Timestamp: 1567607461.459307        ID: 0000    S                DLC:  8    0a 02 8f a1 2c 70 00 00     Channel: CAN1
2019-09-04 09:31:01.019000
Timestamp: 1567607461.459431        ID: 00ff    S                DLC:  8    00 00 00 00 00 00 01 29     Channel: CAN1
2019-09-04 09:31:01.019000
Timestamp: 1567607461.459553        ID: 00fe    S                DLC:  8    00 02 00 03 00 03 00 02     Channel: CAN1
2019-09-04 09:31:01.019000
Timestamp: 1567607461.459677        ID: 00fd    S                DLC:  8    ff ff ff fe 00 00 00 00     Channel: CAN1
2019-09-04 09:31:01.019000
Timestamp: 1567607462.527084        ID: 0000    S                DLC:  8    0a 02 8f a1 2c 70 00 00     Channel: CAN1
2019-09-04 09:31:02.075000
Timestamp: 1567607462.527208        ID: 00ff    S                DLC:  8    00 00 00 00 00 00 01 29     Channel: CAN1
2019-09-04 09:31:02.085000
Timestamp: 1567607462.527330        ID: 00fe    S                DLC:  8    00 01 00 03 00 03 00 02     Channel: CAN1
2019-09-04 09:31:02.085000
Timestamp: 1567607462.527458        ID: 00fd    S                DLC:  8    00 00 ff fe ff ff 00 00     Channel: CAN1
2019-09-04 09:31:02.085000
```

## 8.1 GUI Window Description

The GUI window is broken into three sections which are described below.




1. Inputs Fields: Four numerical input fields for controlling the open-loop sine PWM parameters, switching frequency, modulation factor, dead-time, and fundamental output frequency. Below the numerical input boxes are the toggle buttons for controlling the state of the gate drivers. There are three buttons next to "Power Disable" and three buttons next to "Logic Enable" The buttons toggle between the colors green and red to indicate on and off respectively. Next to "Reset | Fault" is a single button to send a reset command to all gate drivers.

1. Response Fields: Each numerical field or toggle button correspond to a field or button in the input field and display the state from the most recent control response packet received from the controller. These fields are all disabled and will be updated after each control packet is sent successfully. These fields indicate whether the correct control parameters were communicated to the controller as well as indicating the current state of the gate driver fault status.

2. Feedback Fields: Display the most recently received feedback values for measured temperature (in Celsius), current (in amps), and voltage (in volts). Each feedback type has four measurement channels, three channels that correspond to the three output phases and the fourth channel that provides the external (EXT) measurements. The EXT channel for temperature is the ambient temperature of the controller PCB. The EXT channel for current is the optional external current sensor input. The EXT channel for voltage is the DC BUS voltage measurement. The feedback packets are not synchronized to the control loop and are transmitted approximately once per second.
3. Send Packet Button: Pressing this button sends a new control packet with the current values for the Input Fields (1). After the packet is sent the controller will send back a response packet for the new values which will be displayed in the Response Field (2).
4. Quit Button: Pressing this button stops and closes the application.

### 8.1.1 Input Field Descriptions

**Switching Frequency** field is the frequency of the output PWM in kHz. Example 20 = 20 kHz switching frequency. Input range 1 – 65.

**Modulation Factor** field is the modulation factor of the output PWM scaled by a factor of 1000. Example 100 = 0.1 MF. Input range 0 – 1000.

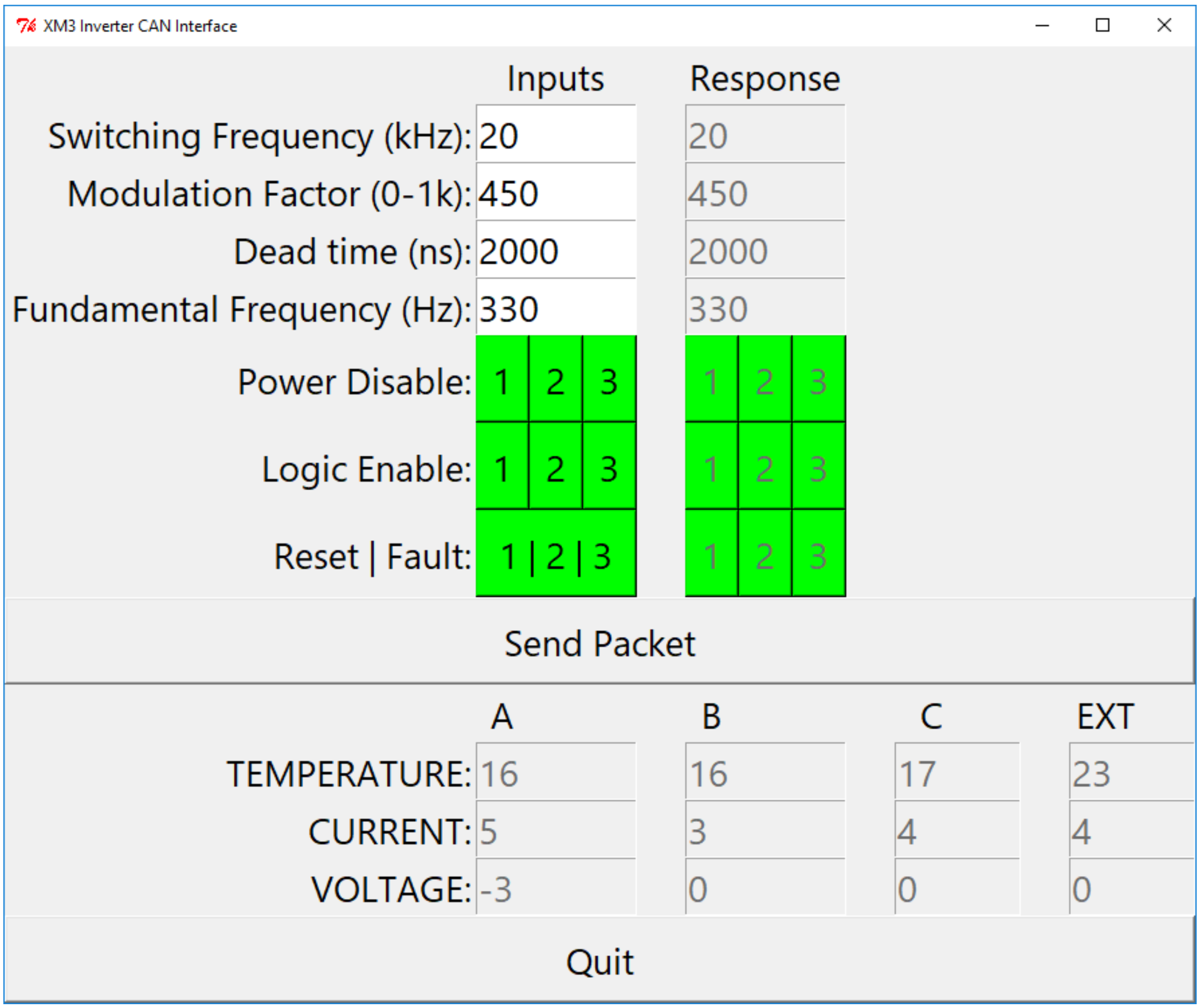
**Dead time** field is the dead-time between the upper switch and lower switch PWM for each half-bridge in nanoseconds. Example 1300 = 1.3 µs dead-time. Input range 100 – 2000.

**Fundamental Frequency** field is the fundamental output frequency in Hz. Example 60 = 60 Hz. Input range 1 – 500.

## 8.2 Using the XM3 Inverter CAN Interface

To use the XM3 Inverter CAN Interface first input the desired parameters into the Input Fields and set the state on the control buttons. Then press the Send Packet button. The Response Field will update with the parameters and status from the most recent control response packet received from the controller.

Recommended parameters for initial testing of CRD300DA12E-XM3 are Switching Frequency = 10, Dead-time = 1300, and a low Modulation Factor (such as 50). The Fundamental Frequency will depend on the connected load.

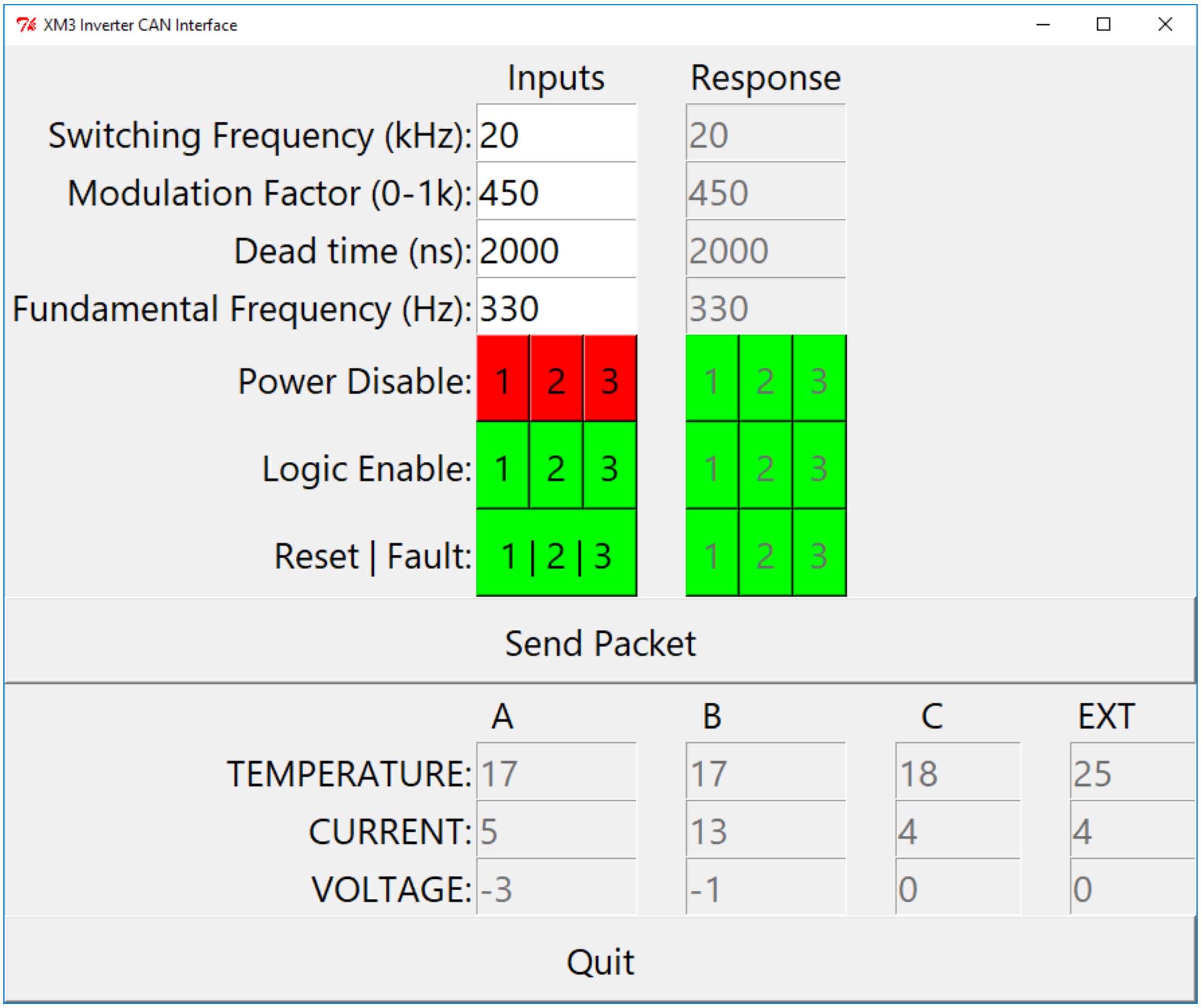



Each time a packet is received the yellow status LED on the controller will toggle.

### 8.2.1 Disabling the Gate Driver Power

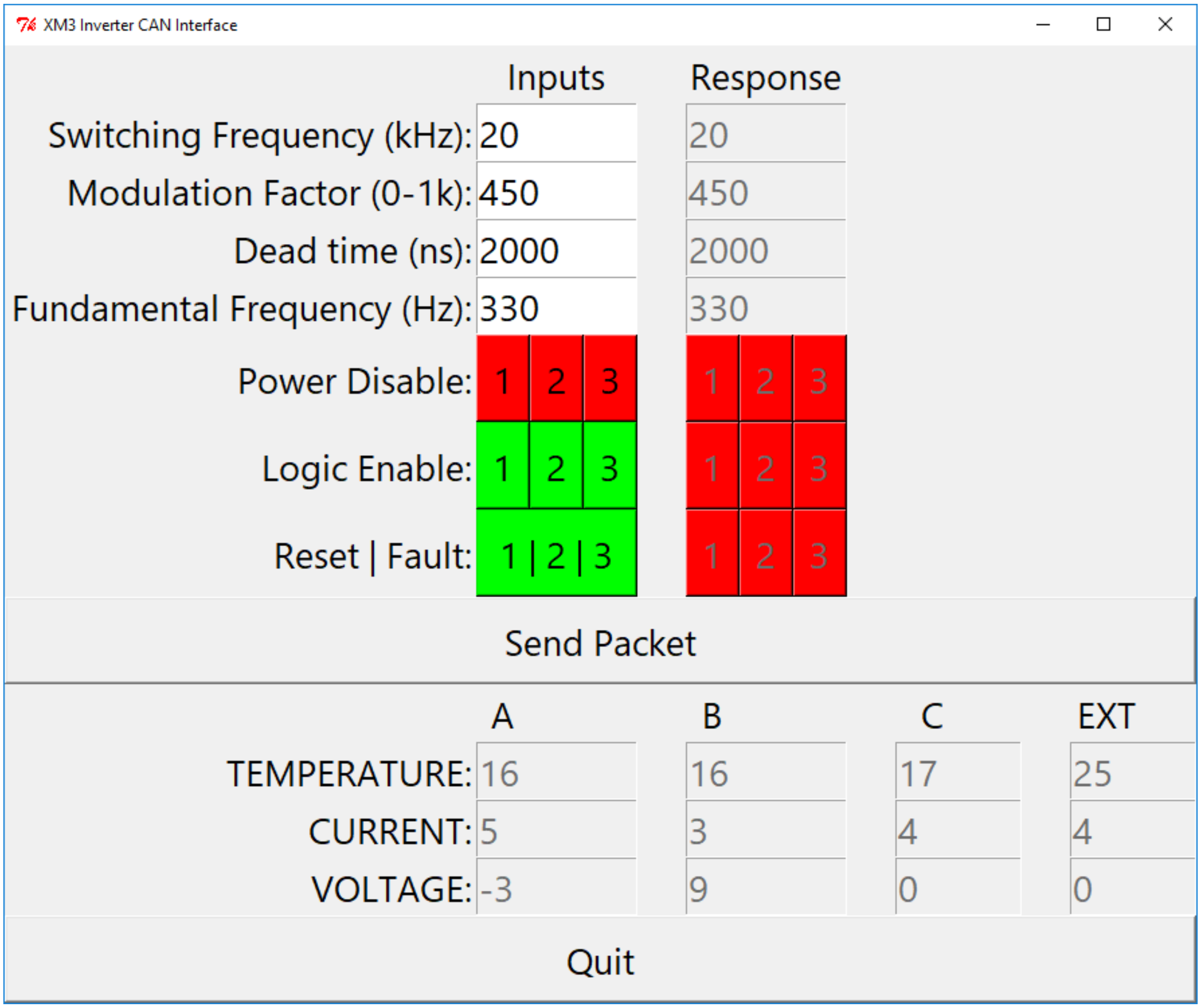
Disabling the gate driver power supplies will completely shutdown the isolated secondary power supplies for each gate driver channel. This should only be down when the inverter's DC bus is deenergized, as gate driver outputs will be disabled and only the weak gate-source resistor holding the device off.

Press the power disable buttons in the Inputs Field to select which gate drivers to turn-off. The red button indicates the channel will be turned-off.



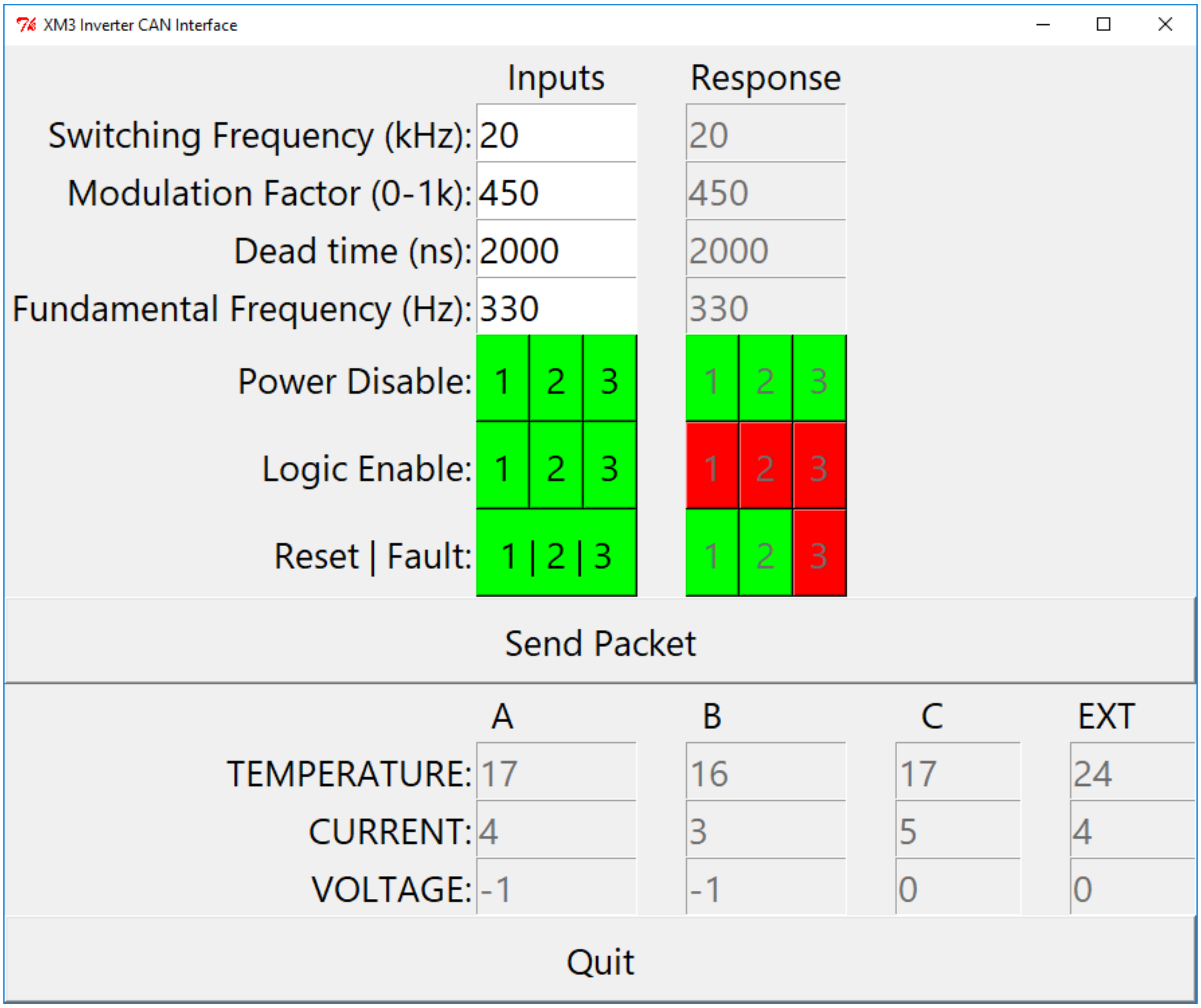

Then press the Send Packet button.

After the packet is sent the gate driver power will be disabled. Typically, a fault will be detected when the gate driver loses power and the controller will respond by disabling all of the Logic Enable signals and displaying a Fault status in the Response Field. As a result, all of the nine status boxes will be red even though only a power disable was sent.

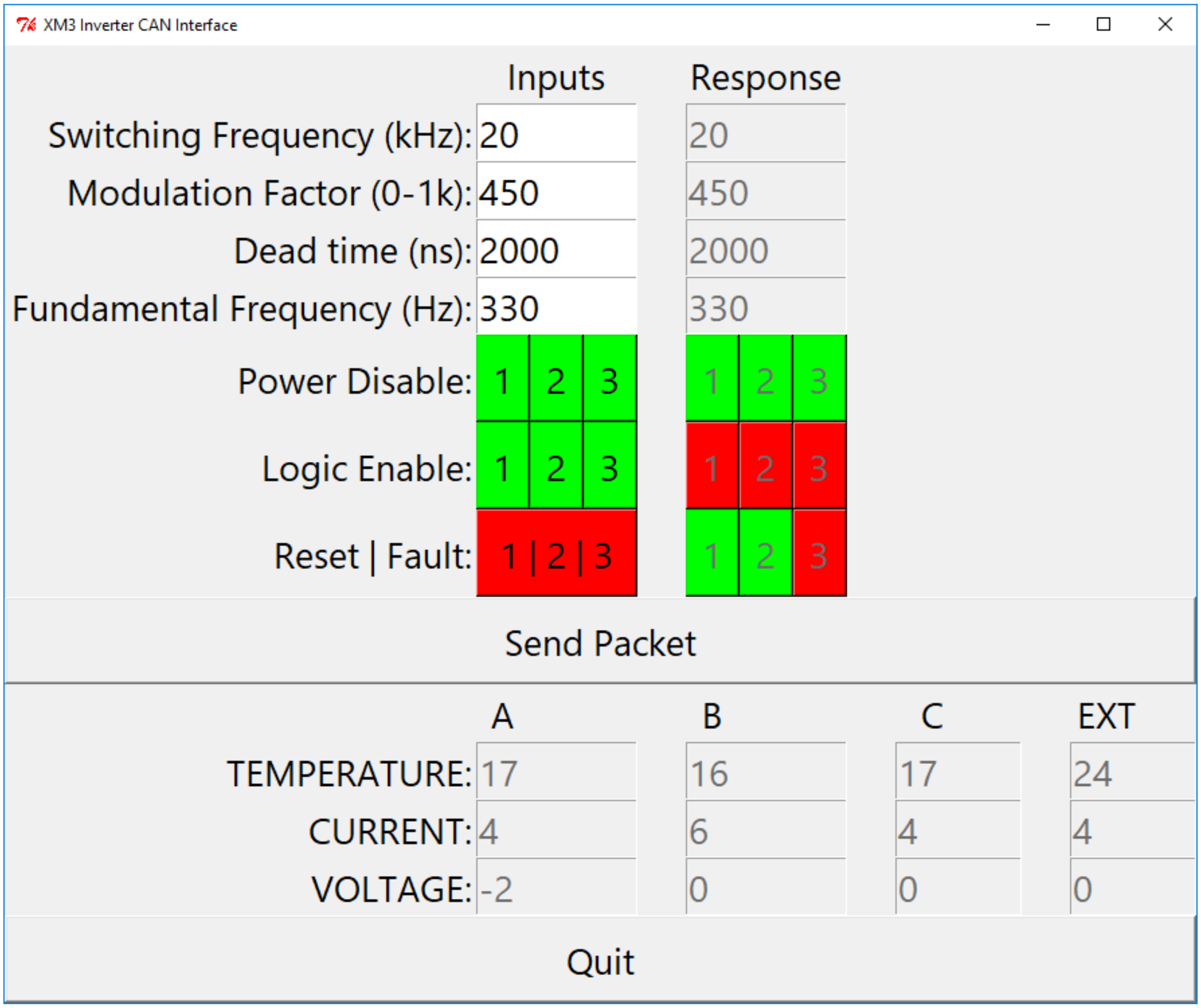


## 8.2.2 Clearing a Gate Driver Fault Condition

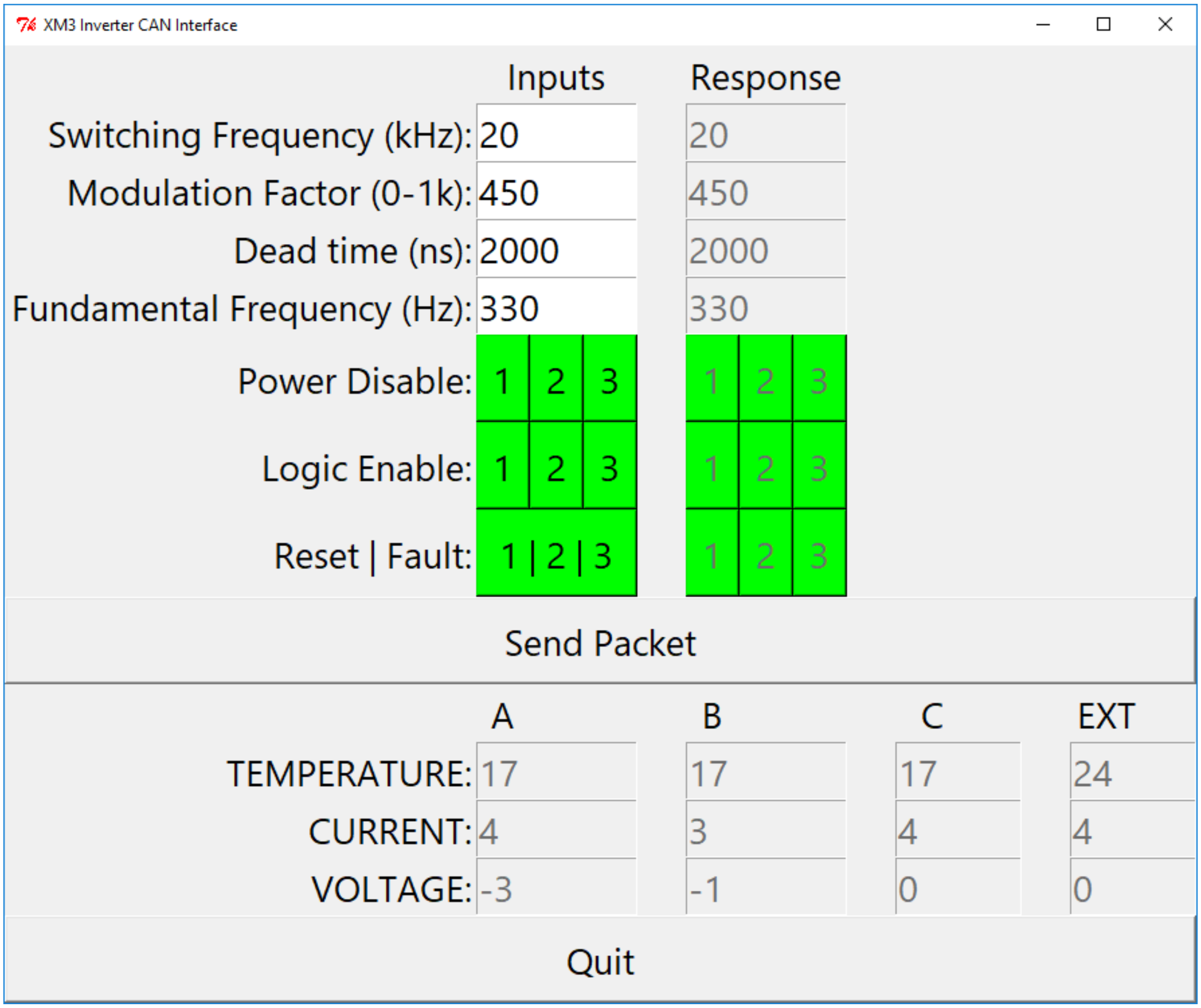
If one of the gate drivers indicates a fault condition the controller will detect the fault and immediately disable all gate driver channels to prevent potential damage to the devices. This will be indicated by one or more of the Fault indicators in the Response Field being red on the channel corresponding to where the fault was detected. Additionally, all the Logic Enable status indicators will be red in the Response Field. An example is shown below.



After determining it is safe to do so and any fault condition has been removed, the latched fault status can be cleared by transmitting a Reset signal to the gate drivers. This is done be pressing the button in the Inputs Field next to “Reset | Fault” to toggle it to red. Then press the Send Packet Button.

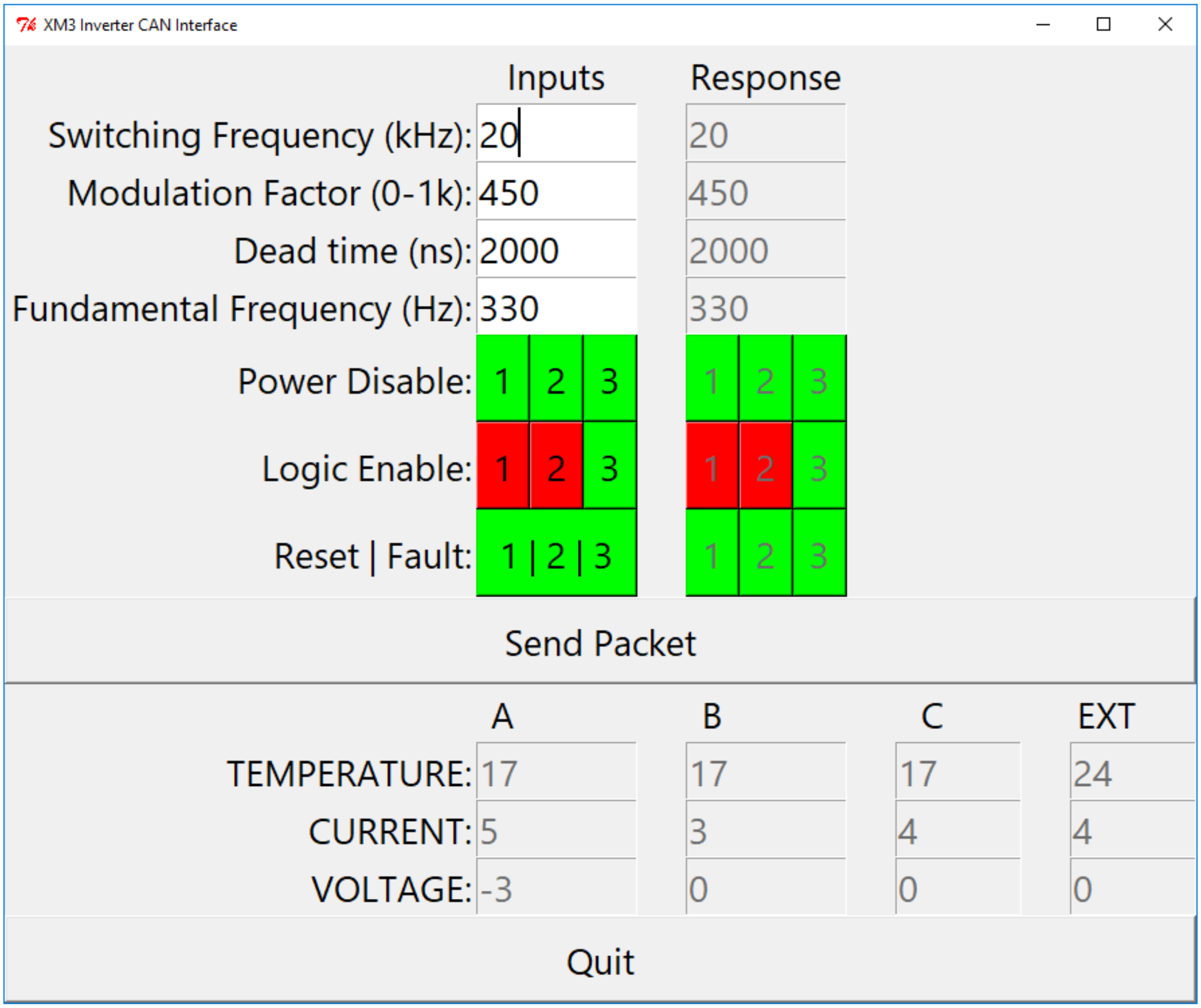


After the packet is sent the Reset Input button will change back to green. In the Response Fields the Fault will be cleared and changed back to green and the Logic Enable will also be enabled and set back to green for all channels.



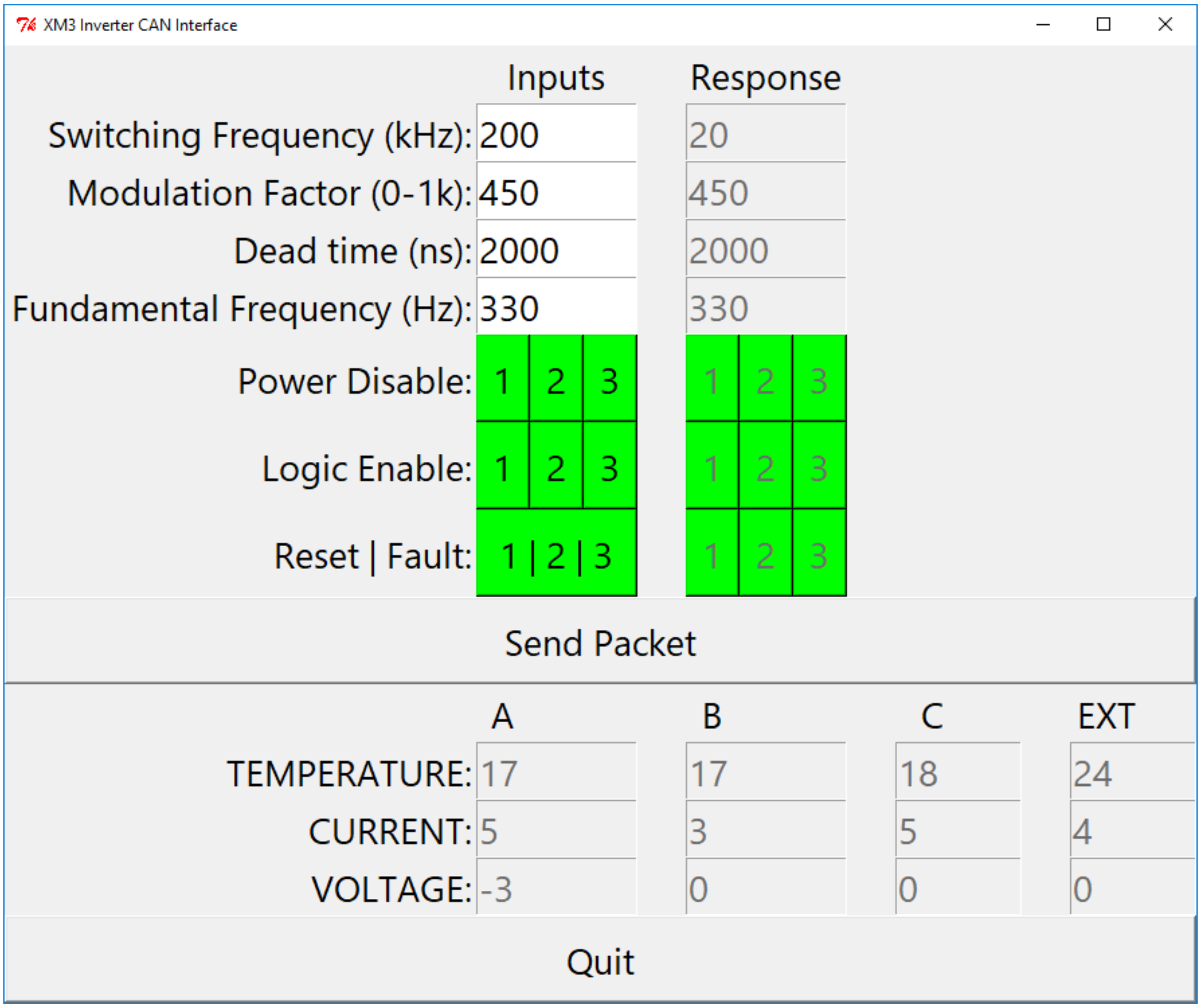
### 8.2.3 Toggling Logic Enable

The output PWM on one of the gate driver channels can be turned off by disabling the Logic Enable signal for that gate driver and forcing the outputs to be held low. To disable the Logic Enable signal press the button next to Logic Enable to set the desired channels to red. Then press the Send Packet Button. After pressing the button the selected channel's Logic Enable indicator will be red in the Response Field as shown below.

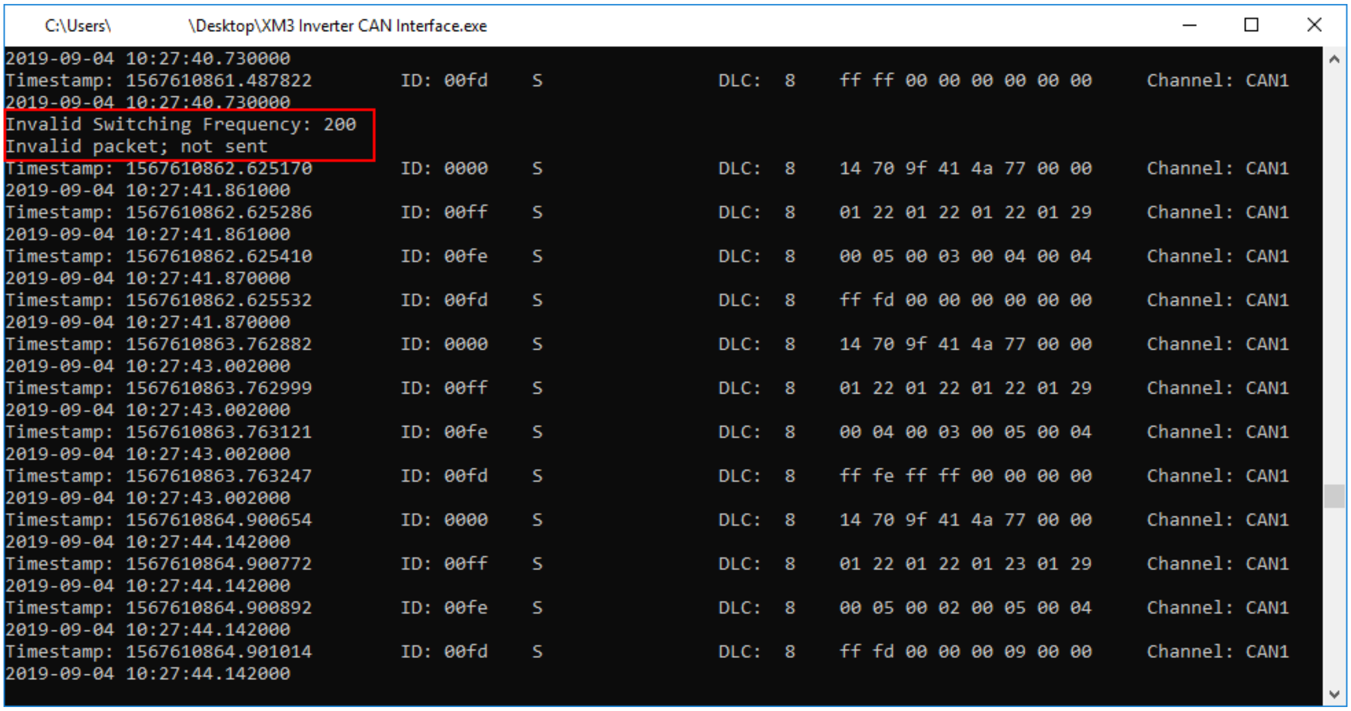


### 8.2.4 Invalid Packets

Both the GUI application and the controller firmware perform rudimentary error checking on the input control parameters to confirm that they are within an appropriate range. This prevents potential damage from sending a typo or otherwise incorrect parameter. In the example below the switching frequency parameter was set to 200 kHz instead of 20 kHz.

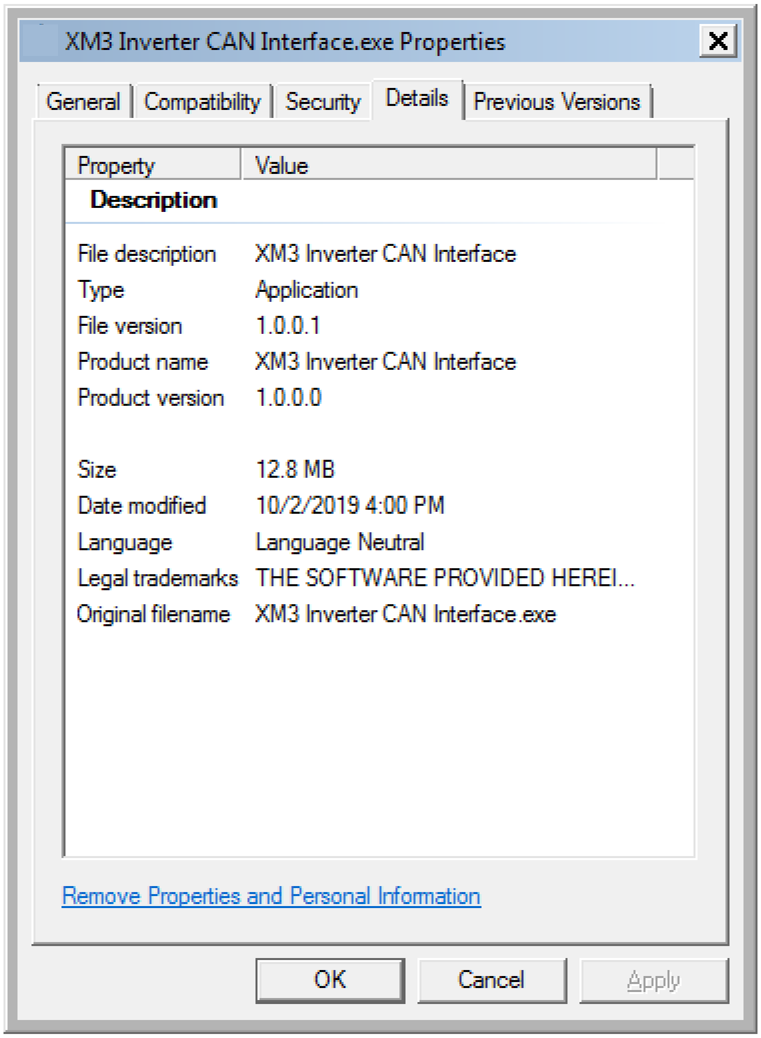


The packet was determined to be invalid and was not transmitted. A message indicating the invalid packet will be printed in the command window. This window will continue to scroll so it may be necessary to use the scroll bar to find the message. The message indicating that 200 was not a valid input for the switching frequency is highlighted below.



### 8.2.5 Determining the Software Version

The version of the XM3 Inverter CAN Interface can be displayed by right-clicking on the “XM3 Inverter CAN Interface.exe” file and selecting Properties. Click on the Details tab and the software version will be displayed next to File Version and Product Version.



## Appendix

Full dimensioned drawing PDF, and full controller schematic PDF may be obtained upon request by contacting Wolfspeed on our forum at https://forum.wolfspeed.com/categories/module-products.

## Revision History

| Date | Revision | Changes |
|---|---|---|
| June 2019 | 1 | Initial Release |
| July 2019 | 2 | Updated Note, page 2 |
| November 2019 | 3 | Update Table 8, Product Dimension Drawings, Added CRD200DA12E-XM3 |
| January 2021 | 4 | Added Software User Guide, added NTC temperature to frequency |
| January 2024 | 5 | Updated Formatting |

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