TDMCXXXXE0I GaN Motor-Drive Development Kit

User's Guide

Introduction

TDMC series motor-drive kits from Transphorm provide an easy way to evaluate the performance advantages of GaN power transistors in off-line motor-drive applications. The kits provide the main features of a three-phase inverter in a proven, functional configuration, operating at or above 100kHz. Design features necessary for high-speed operation have already been incorporated. This relieves the user of either having to adapt existing circuit boards and firmware for high-speed switching (which is generally difficult to do), or of creating a new design specifically for evaluation of GaN technology. The kit is intended for use with any three-phase motor technology, including AC induction motors and AC permanent magnet motors. It can be used in open-loop (V/F) or closed-loop modes, using sensor or sensorless techniques. At the core of the inverter is a module with six GaN transistors configured as three half bridges. The module is mounted to a printed circuit board which provides tightly coupled gate-drive circuits, highly flexible microcontroller options, and convenient communication connection to a PC. Also included on the board are output filters which provide pure sinusoidal output waveforms to the motor.

Because this development kit is intended for use with a broad range of motor types, with widely varying characteristics, a flexible method for generating the drive signals and controlling the motor is required. For this reason, the control portion of the circuit is designed around the popular C2000™* family of microcontrollers from Texas Instruments and is code compatible with motor demo boards from TI based on those controllers. In this way, a great deal of source code is available to the user, along with related support information direct from TI. In addition to this general resource, however, Transphorm provides original firmware which comes loaded in flash on the microcontroller. The source code, configured as a complete project, is also provided on the USB memory stick which comes with the kit. This project is a convenient starting point for further developments. The microcontroller itself resides on a small, removable control card, supplied by TI, so that different C2000 devices may be used if desired. Should the user wish to use an alternate microcontroller family, an appropriate control card can be designed to insert into the DIM100 socket. The schematic for the TDMCXXXXE01 circuit board, along with pin assignments for the connector, are provided on the USB memory stick.

Kit Contents

The kit comprises

- A TDMCXXXXE0I three-phase inverter assembly (PCB, base plate, heatsink)
- A Texas Instruments F28335 controlCARD
- A 12V power supply with universal AC adaptors
- A 400W servo motor (for out-of-the-box evaluation)
- Related media (documentation and software) on a USB memory stick
- Cables for motor, high-voltage DC input, and USB communication

*C2000™ is a trademark of Texas Instruments Incorporated.

Warning

While this kit provides the main features of a motor-drive inverter, it is not intended to be a finished product. Our hope is that this will be a tool which allows you to quickly explore ideas which can be incorporated in your own inverter design. Along with this explanation go a few warnings which should be kept in mind:

To keep the design simple, and to provide ready access to signals of interest, high-voltages are present on exposed nodes. It is up to you to provide adequate safeguards against accidental contact, or use by unqualified personnel, in accordance with your own lab standards.

There is no short-circuit or over-current protection provided at the motor outputs. Current-sense devices are connected to the motor outputs, and may be used for over-current protection, but it should not be assumed that the firmware, as delivered, includes such a feature.

Be aware that the aluminum base plate is an integral part of the heat exchange system, and can become hot under high-power operation.

Hardware Reference Guide

Inverter Assembly

A typical inverter assembly is pictured in Figure 1. The PCB is mounted on an aluminum base plate, to which both the GaN module and heat sink are thermally coupled. Note the microcontroller card in the DIM100 connector.

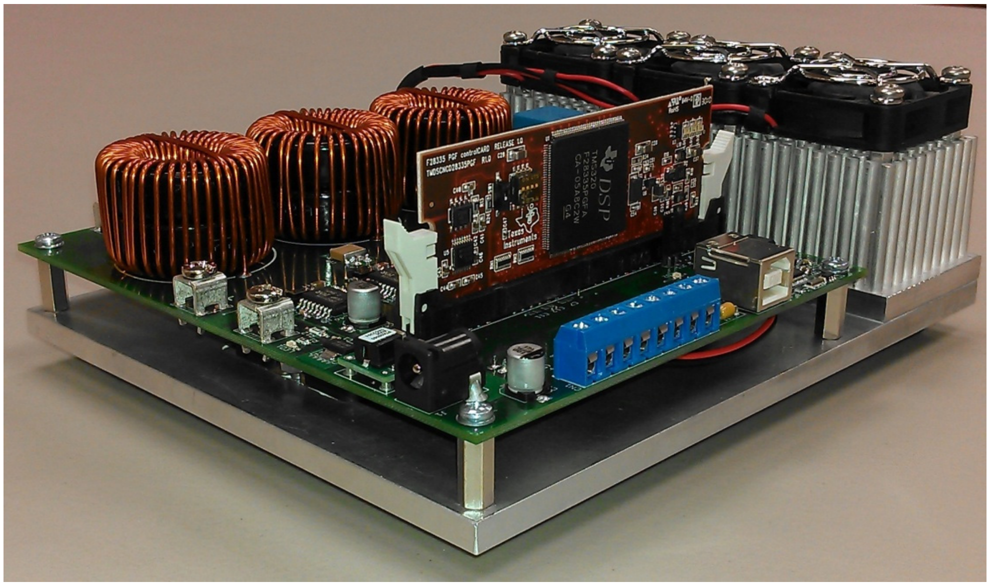


Figure 1. A typical TDMC inverter assembly, including controlCARD

Circuit Overview

Refer to figure 2 for a block diagram of the inverter circuit. A detailed schematic is also provided in pdf format on the USB stick which comes with the kit.

The TDMC motor drive is essentially a simple three-phase voltage-source inverter. Three GaN half bridges, integrated in a single module, are driven with pulse-width modulated command signals to create the three sinusoidally varying outputs. Output filters largely remove the switching frequency, effectively making the drive a three-phase class-D amplifier. The high-frequency (100kHz+) PWM signals are generated by the TI microcontroller and connected directly to three high-speed, high-voltage gate drivers. External connection to the microcontroller is provided by an isolated USB interface. There are also six general-purpose I/O signals, available at screw terminal block CN1. These signals are intended for connection to a shaft-angle encoder, but may be used for any desired purpose with appropriate programming. Except for the high-voltage supply for the power stage, all required voltages for the control circuitry are derived from one 12-15V input.

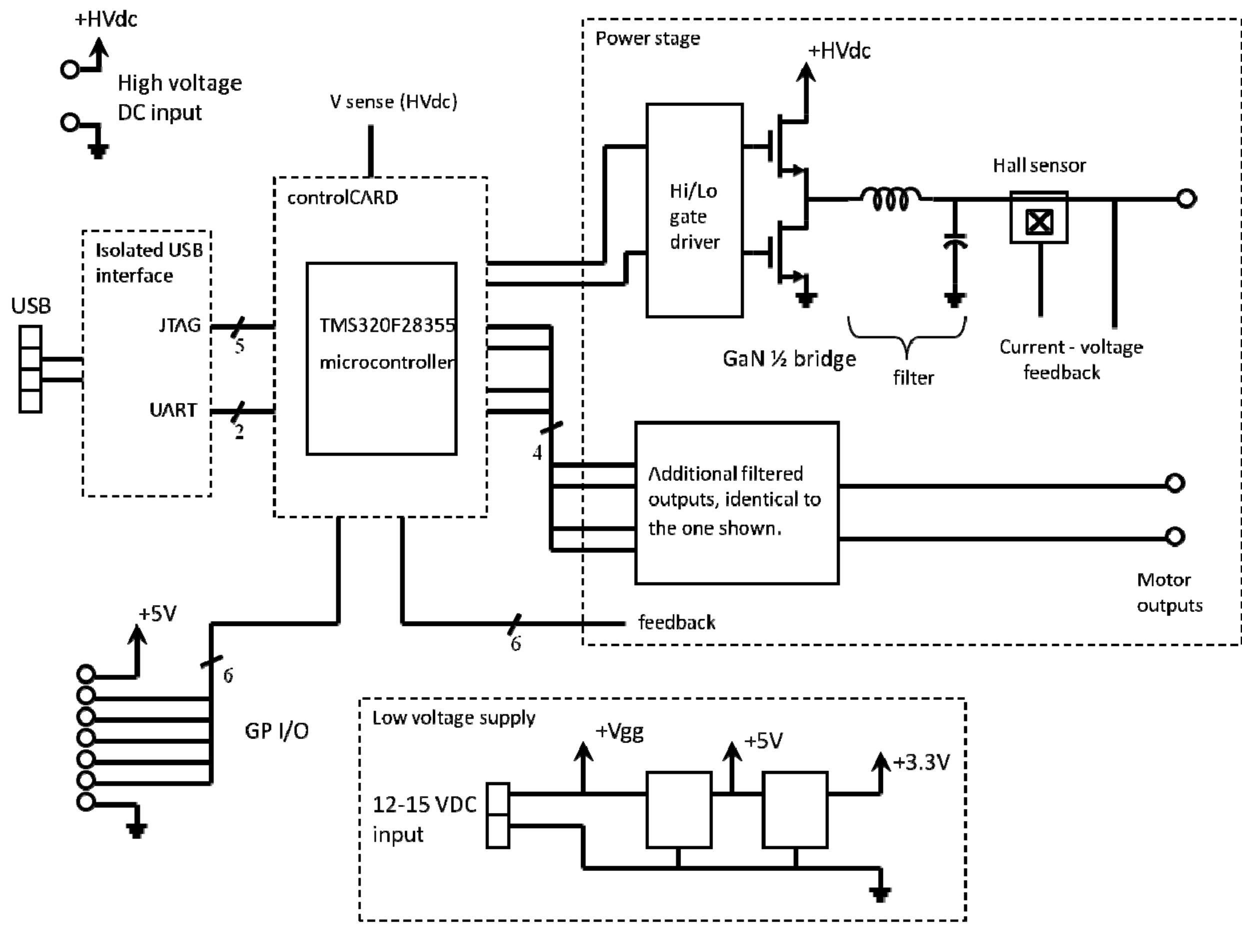


Figure 2. Circuit block diagram

The inverter takes advantage of diode-free operation*, in which the freewheeling current is carried by the GaN HEMTs themselves, without the need of additional freewheeling diodes. For minimum conduction loss, the gates of the transistors are enhanced while they carry the freewheeling current. The high and low-side Vgs waveforms are therefore pairs of non-overlapping pulses, as illustrated in figure 3.

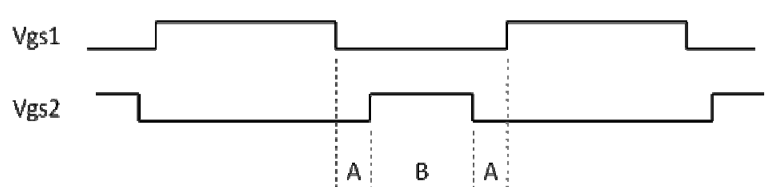


Figure 3: non-overlapping gate-drive pulse. A is a deadtime set in the firmware

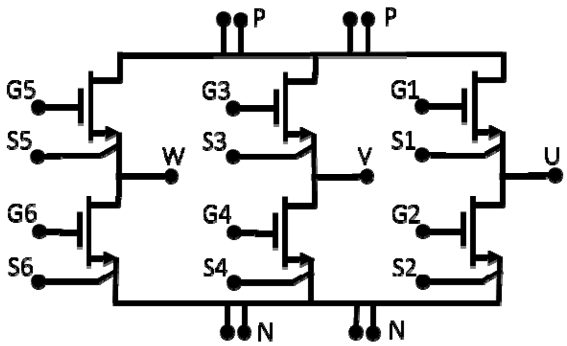
GaN Module

The GaN high-electron mobility transistors (HEMTs) are standard Transphorm 600V dies, selected for the power rating of the demo board, and mounted in a module specifically designed for evaluation in inverters. The module itself is not necessarily a standard product, and as such, is only available for evaluation purposes, and not for design-in.

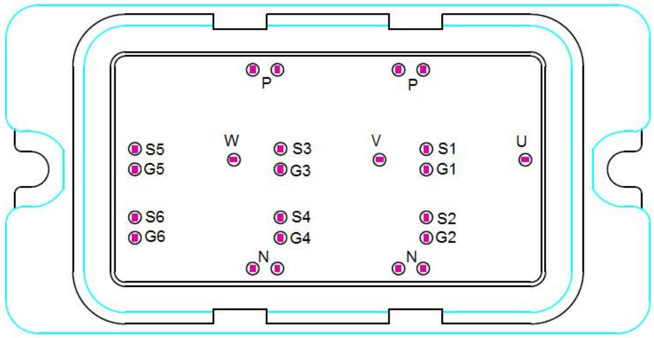
*US patent 7,965,126 B2

(a)

(b)



(c)



(d)

Figure 4. GaN 6-transistor module (a) bottom view (b) top view (c) schematic (d) pin assignments

Gate Drivers

High-voltage integrated drivers supply the gate-drive signals for the high and low-side power transistors. These are 600V high-and-low-side drivers (International Rectifier IRS2113 or similar), specifically chosen for high-speed operation without automatic deadtime insertion. The deadtime between turn-off of one transistor in a half bridge and turn-on of its mate is set in the firmware.

Output Filter

Simple LC filters on each output (L3, L4, L5, and connected capacitors) attenuate the switching frequency, producing clean sinusoidal waveforms for the motor connections at terminals J4-6. The filters also serve to decouple the switching nodes from the motor and motor cable; that is, the high-speed GaN transistors do not directly drive the cable and motor capacitances, while the motor is likewise relieved from sustaining non-torque producing harmonics associated with the switching waveform. Without this decoupling, additional losses would occur in both the inverter and the motor, not to mention the various transients that would be generated.

The filter inductors and capacitors used on the demo board were chosen to provide an optimal combination of benefits: low loss, good attenuation of the switching frequency, and small size. Consult the schematic and/or bill of materials provided for the specific revision and model of your demo board to verify values, but in general the cutoff frequency will be around 10-20kHz, to accommodate 100kHz switching. The inductors have powder cores with relatively low permeability (60-90) and soft saturation characteristics. The inductors and/or capacitors can be changed to evaluate different filter designs. If the capacitors are to be changed, however, refer to the section *Removing the PCB assembly*.

Transphorm considers the use of small, integrated output filters as a key benefit to motor drives, which is enabled by high-speed/high-frequency GaN transistors. These filters are nonetheless discretionary. If you wish to evaluate performance without the filters present, it is certainly possible. Please observe the following:
Do not simply place a short across the inductors. This will connect the filter capacitance directly to the half-bridge outputs. Instead, remove the inductors and solder the motor leads to the inductor pads connected to the module outputs. Or, alternately, remove the filter capacitors and then place a short across the inductors.
Any capacitance in the cable and motor will now be charged and discharged directly by the GaN transistors at a very high slew rate. The current spikes associated with these transients can be extremely large. Inclusion of some minimal EMI filtering might be prudent.

Current sensing

Hall sensors U8, U10, and U12 provide linear current feedback to the microcontroller. Note that these are placed downstream of the output filters; the currents sensed are the motor phase currents with minimal ripple current superposed. Refer to the bill of materials to confirm the sensor part numbers, but typical would be the Allegro ACS712-20A sensor, which has a ±20A range (100mV/A). These parts are pin compatible with ±5A and ±30A versions of the ACS712, should higher or lower ranges be desired. An external capacitor, connected to pin 6 of each sensor, provides internal filtering. An additional level of filtering is provided by capacitors placed across the A/D inputs to the microcontroller. Note that resistor dividers scale the 5V outputs for the 3V range of the A/D.

Communication

Communication between the microcontroller and a computer is accomplished with the USB cable provided. The isolated USB interface enables simultaneous operation of two physical ports to the microcontroller: a JTAG port for debug and loading of firmware, and a UART for communication with a host application.

Control Card

The microcontroller resides on a removable card, which inserts in a DIM100 socket on the inverter PCB. The socket can accept many of the C2000™ series controlCARDs from Texas Instruments. The F28335 controlCARD supplied with the kit provides capability to experiment with a wide variety of sophisticated algorithms, and comes loaded with firmware to allow immediate (out-of-the-box) operation with the servo motor supplied with the kit, via Transphorm's TDMCx000E0I demo utility software. Should the user wish to use an alternate microcontroller family, an appropriate control card can be designed to insert into the DIM100 socket.

Heat Sink

The 6-transistor power module is mounted on an aluminum base plate, alongside a heat-sink and fan assembly. This arrangement provides a compact, stable platform for ease of use on the lab bench. The heat flow provided is adequate for most testing (about 0.5 ^{o}C/W from the module base plate to ambient, with fans running). Should absolute minimum temperature rise be desired during high-power operation, additional airflow across the base plate and circuit board (provided with any convenient fan) would be beneficial. The filter inductors in particular would benefit from additional air flow.

Connections

Power for the motor is derived from the HV DC input. This will typically be a DC power supply with output voltage up to 370Vdc. The maximum DC value is actually limited by the resistor values in the dividers for the voltage sense signals. A 2uF, low ESR, film capacitor is provided as a bypass capacitor for the HV supply, along with several lower valued ceramic capacitors in parallel. This is not intended to provide significant energy storage. It is assumed that the power supply contains adequate output capacitance.

The control, communication, and gate-drive circuits are all powered from a single 12-15V input (Vgg). The wall-plug adaptor provided generates the appropriate voltage (typically 12V) and power level.

Note that only the USB port is isolated; all other signals on the board are referenced to the negative terminals of the high and low voltage supplies, which are tied together on the PCB.

The heat sink and base plate are isolated, but may be grounded with the grounding screw. The potential of the base plate should be within the range of the HV supply. For example, if the base plate is connected to earth ground, then either the negative terminal, positive terminal, or midpoint, of the HV supply should also be at earth ground potential.

Connection sequence

Refer to figure 5.

Insert the microcontroller card in the DIM100 connector before applying any power to the board. Switch SW1 on the F28335 controlCARD should be in the Off position to enable direct connection of the RS232 signals from the TDMC board to the F28355 port.

To use the preloaded firmware, verify that jumper JP1 is removed. This releases the JTAG port and allows the microcontroller to boot from flash. For communication with a host over the JTAG port, JP1 should be installed.

With the supply turned off, connect the high-voltage power supply to the +/- inputs (J2 and J3).

For unloaded evaluation of the outputs, no motor connection is required; but if a motor is to be driven, connect the motor leads to the motor outputs J4, J5, and J6. To drive the servo motor which comes with the kit, connect red to J4 (U), blue to J5 (V), white to J6 (W), and green to the ground screw on the base plate. This connection results in counterclockwise rotation, as viewed from the shaft end of the motor, given a positive speed reference.

Ground wires can be connected to the ground screw in the inverter base plate. Motor-frame ground and power-supply/earth ground are example connections. Apart from any connection to the ground screw or standoffs, the base plate is floating.

Connect the USB cable from the computer to the USB connector (CN3). LED2 should illuminate, indicating isolated +5V power is applied over the USB cable.

Insert the Vgg (12V) plug into jack J1.   LED1 should illuminate, indicating power is applied to the 5V and 3.3V regulators. The fans on the heat sink should also turn on. Depending on the specific control card used, one or more LEDs on the control card will also illuminate, indicating power is applied.

Verify correct functionality before applying high voltage power. When using the demo utility (see the software reference guide, below), initialize the inverter and verify communication prior to applying high voltage.   Likewise, if changes have been made to firmware or hardware, verify that the circuit and firmware are functioning correctly before applying high-voltage. For unloaded testing (without motor), it is recommended to turn up the HV supply slowly, monitoring the output signals for correct operation. With a motor connected, be aware of the possibility of high current draw at low voltage conditions. Applying a known adequate supply voltage before starting rotation is recommended. Set the current limit on the dc supply. This is important if the motor stalls.

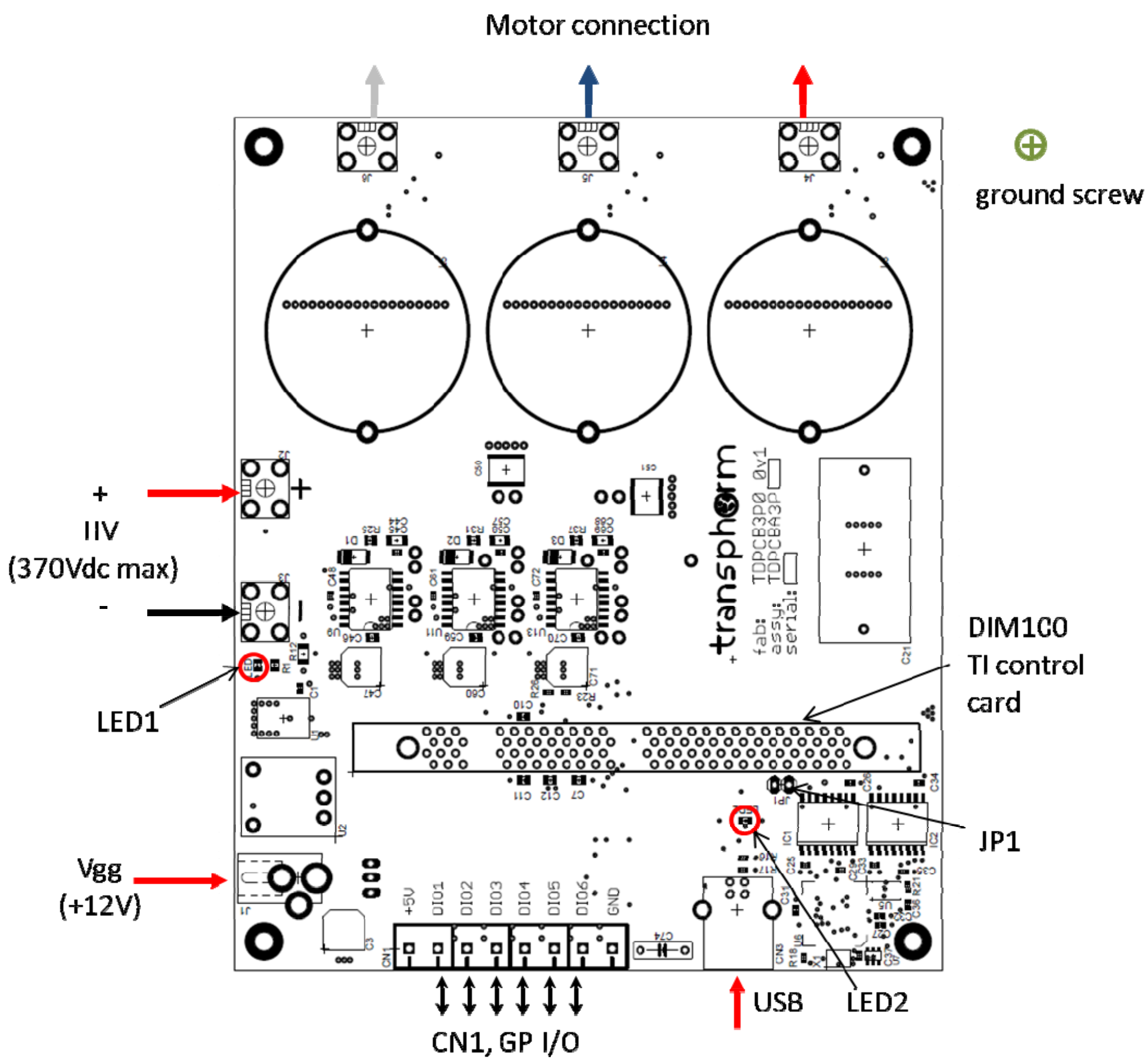


Figure 5. Connections

An angle encoder is not mandatory, but will be automatically detected if connected to the general pupose I/O terminals at CN1. The connections should be:

CN1:	+5V	DIO1	DIO2	DIO3	DIO4	DIO5	DIO6	GND
Encoder:	PG5V	A+	B+	C+	A-	B-	C-	PG0
Wire color:	red	blue	green	yellow	violet	gray	white	black

The complimentary signals, A-, B-, and C- are not actually used and may be left disconnected.

Probing the high-voltage signals

The high-speed signals at the switching nodes are best observed with a soldered probe, as illustrated in figure 5. The probe and ground wire are soldered to the high-side and low side Kelvin sense pins (pins S1-S6 in figure 4) of the module. If an extremely short (<2cm) ground clip is not available with your oscilloscope probe, one can be made by wrapping bus wire around the probe's ground strap. Be extremely careful to solder the probe ground and the probe tip to the correct pins (and only with power off). When the probe is de-soldered, be careful that no solder bridges are left. See also Transphorm application note AN0003: *PCB Board Layout and Probing for Fast Switching GaN HEMTs.*

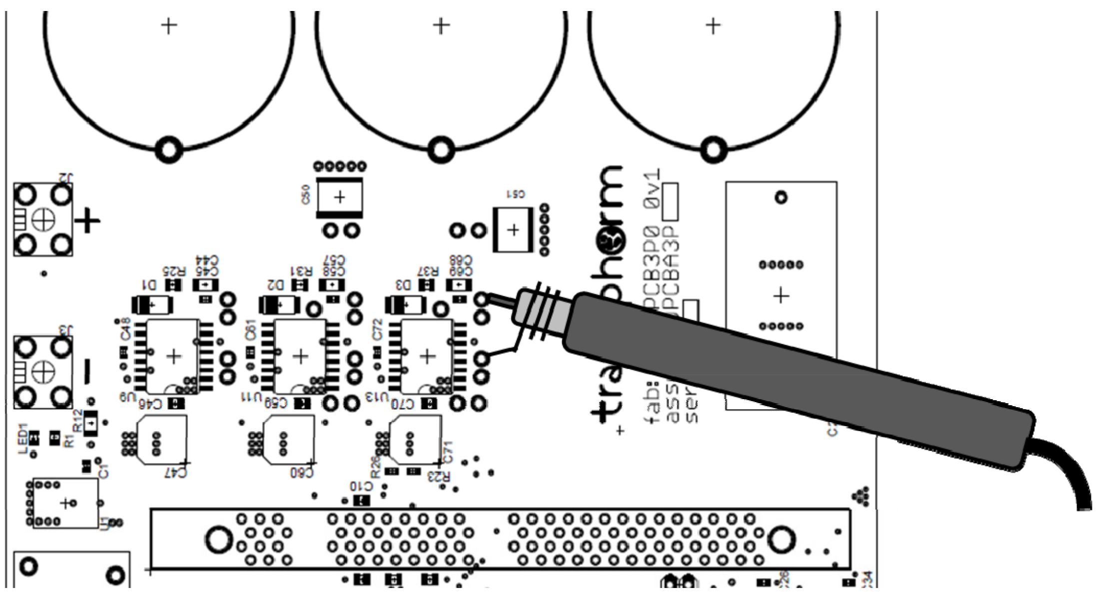


Figure 6: Probing a switching node with a soldered scope probe.

Removing the PCB assembly

The only reason to remove the PCB assembly from the base plate is to change the capacitors in the output filter. The GaN module is soldered to the PCB, but is also secured to the base plate with two screws and nuts. See figure 7. These must first be removed. Note that the nuts are not fixed to the module. Also be aware that there is a layer of rather messy thermal grease between the module and the base plate. Once the two module-mounting screws are loosened, the four screws at the corners of the PCB can be removed and the PCB lifted from the standoffs. Lift the PCB just enough to disconnect the fan cable before completely removing from the base plate.

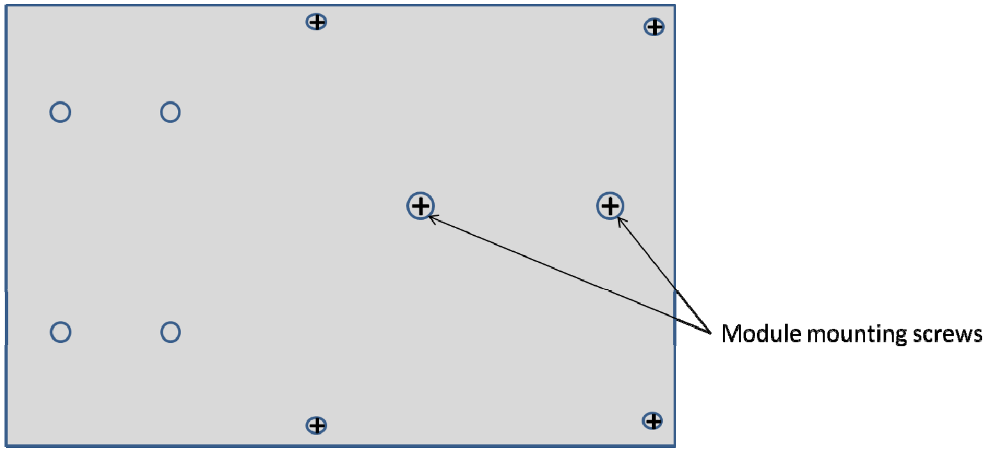


Figure 7. View of the base-plate backside

Servo motor

A 400W servo motor is included with the kit as an easy starting point for test and evaluation. The firmware pre-loaded on the microcontroller includes parameters specific to this motor, related to both the mathematical model of the motor and the tuning of the control loop. These parameters are required for operation of the sensorless control algorithms, and can be modified for use with other motors, as described in the firmware reference guide.

Motor specification: Estun Automation Technology, model EMJ-04APB22, available in the USA from Anaheim Automation. A data sheet is included on the USB memory stick.

Software Reference Guide

TDMCX000E0I Demo utility

Transphorm's TDMCX000E0I demo utility runs on a PC and communicates with the inverter. It provides a means of driving motors for test and evaluation using the firmware which is pre-loaded in the microcontroller's flash memory, while also allowing access to key variables. The initial release supports two modes of motor control: permanent-magnet sensorless or AC induction motor V/F. Permanent-magnet servo motors like the one supplied with the kit may be run in a sensorless closed-loop mode, with either speed or current control. Alternately, induction motors may be run in open-loop (V/F) mode. The utility is written in C#, and the source code is provided.

Installation

On the USB memory stick is a single folder titled "Transphorm". Copy this folder in its entirety to the root directory of your computer (C:\). Within this folder are subdirectories with files related to the microcontroller firmware, the PC utility software, and support documentation. Note: Do not run programs directly from the USB stick.

The demo utility communicates with the F28335 microcontroller over a serial port. The firmware was developed with TI's Code Composer integrated development system, and depends on serial-port drivers installed with it. For that reason, Code Composer must be installed on your computer before the demo utility can be used. Download instructions are included on the USB stick in document *Downloading Code Composer Studio*.

Getting Started

Once Code Composer is installed, the TDMCx000E0I demo utility can be used with Code Composer running or not running. The easiest way to get started is to not run Code Composer, and simply allow the microcontroller to boot from flash, as described in the following steps.

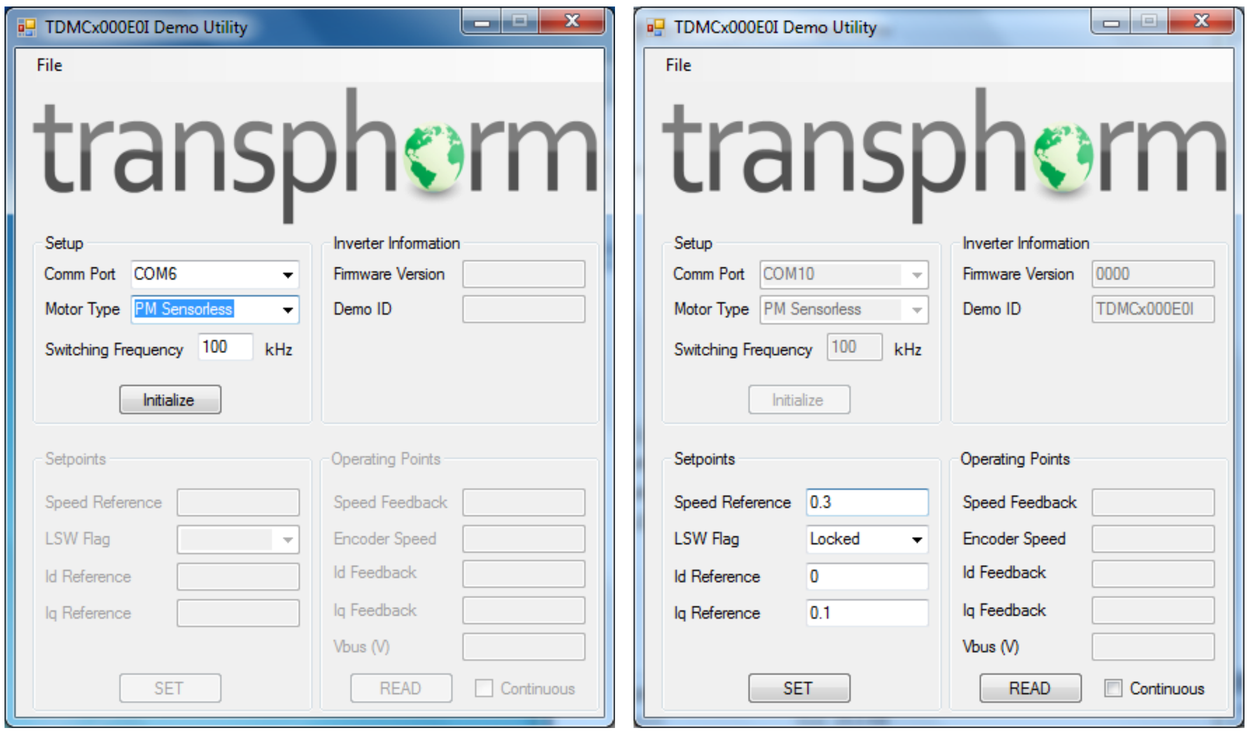
Verify that jumper JP1 on the TDMC circuit board is removed. This releases the JTAG port and allows the microcontroller to boot from flash. (keep the jumper for use with Code Composer.) Follow the steps in the Connection Sequence section of the preceding hardware guide. Verify that the current limit of the DC supply is set just beyond what is required for the motor (for the servo motor which comes with the kit, operating without load, a current limit of 1.0A should be adequate.)

The TDMCx000E0I demo utility is located in the following folder:

C:\Transphorm\TDMDx000EOI\TDMDx000EOIDemoSW\TDMDx000EOIDemoSW\bin\Debug

Start the application, TDPCB3P0Demo, from the location given above. The utility will identify available comm ports. Select the appropriate port (probably not Com1, since this is generally assigned to a device on the computer). Select the motor type and mode: Permanent Magnet Sensorless or AC

Induction motor, V/F. For the servo motor which comes with the kit, select PM Sensorless. Select a switching frequency. Switching frequency may only be changed prior to initialization. Click *Initialize*. See figure 8.



(a) (b)

Figure 8. (a) selecting com port, motor type, and switching frequency (b) communication initialized

Values will immediately appear in the boxes for Inverter Information and Setpoints, as in figure 8(b). If values do not immediately appear, the communication link has not been established. This could result if the 12V power was applied to the board before connecting the USB cable, in which case disconnecting and reconnecting 12V power should permit communication.

With communication established, enable the inverter for motor drive by clicking the Set button, leaving the LSW flag in the locked state. Until the inverter is enabled the motor outputs are held at the voltage of the negative HV terminal. Once enabled, all three outputs will rise to the neutral state, which is ½ the HV supply. This reflects the equal use of the two null vectors in the PWM generation algorithm.

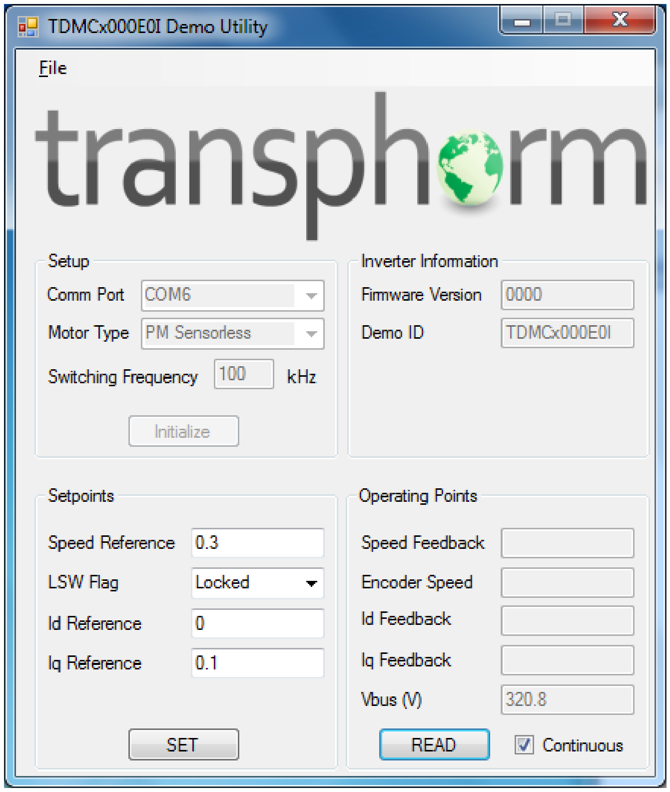


Figure 9: inverter enabled with continuous reading of variables, PM mode, rotor locked

Check the *Continuous* box and click *READ* for continuous monitoring of variables. Note that the firmware variables displayed (apart from bus voltage) are intentionally left in the native units of the firmware. Think of this as a simplified watch window, where actual register contents are displayed. If desired, however,the C# code may be modified to change the scaling of the displayed variables. Figure 14 provides a block diagram of the microcontroller firmware and indicates the significance of the variables displayed. These are the following:

Set Points

Speed Reference: Commanded shaft speed in native units. Varies from 0 to 1, where 1 is full speed (as defined by constant BASE_FREQ_ACI). For induction motors, a value of 0.5 corresponds to 60Hz and 1.0 corresponds to 120Hz.

LSW Flag: A soft switch variable which manages the loop settings

lsw=0, lock the rotor of the motor.
lsw=1, close the current loop.
lsw=2, close the speed loop.

Id Reference: Commanded current level for the direct axis. In an induction motor, this is the component of the current which produces the rotor flux. In a permanent magnet motor, where the rotor flux is provided by the magnets, Id Reference will be set to zero.

Iq Reference: Commanded current level for the quadrature axis. For any motor type, this is the component of the current which produces torque. In speed-control mode the outer speed loop generates a torque command, and the value given for Iq Reference is ignored.

Operating Points

Speed Feedback: The shaft speed, in the same units as the speed reference. This is an estimated value derived from the measured motor currents and voltage.

Id Feedback: Feedback value of Id, as determined by the Park transform. Signal Ds in the block diagram of figure 14.

Iq Feedback: Feedback value of Iq, as determined by the Park transform. Signal Qs in the block diagram of figure 14.

Vbus (V): The high-voltage supply, as measured on the PCB. This is an approximate, non-calibrated value.

Starting the motor: Permanent-magnet sensorless control mode

Verify that the voltage and current limit of the bus-voltage supply are at the desired levels. In PM Sensorless mode, set the motor in motion by entering a Speed Reference value between 0 and 1. Select current loop. Click Set. The motor will ramp up to the commanded speed and then maintain that speed with a constant amplitude quadrature current. The default value of 0.1 for Iq is adequate to start the motor, but is generally excessive for continuous operation. Figure 10 shows one phase current during start up.

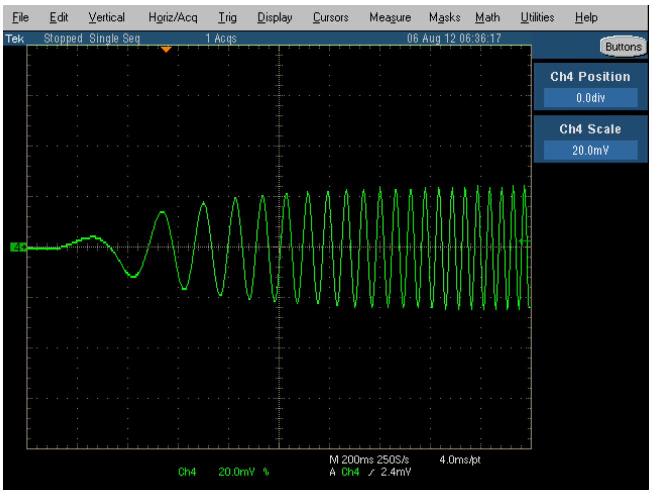


Figure 10: current of one motor phase during start-up in current loop.

Always start the motor with LSW Flag set to current loop, since the speed-estimation algorithm in the firmware requires shaft rotation in order to estimate speed. Iq_reference should be set higher than the expected running current, to allow for start-up torque requirements. Once the shaft is rotating, the LSW flag can be changed to speed loop. In speed loop the estimated speed is maintained at the commanded value. Normally there will be a drop in current when control switches to speed-loop.

Figure 11 shows the screen for typical operation in current loop (a) and speed loop (b). If an incremental encoder is connected to the GP I/O (CN1) it will automatically be detected and its output used for the Encoder Speed display. Keep in mind that for this *sensorless* control mode, the encoder is not used for speed control.

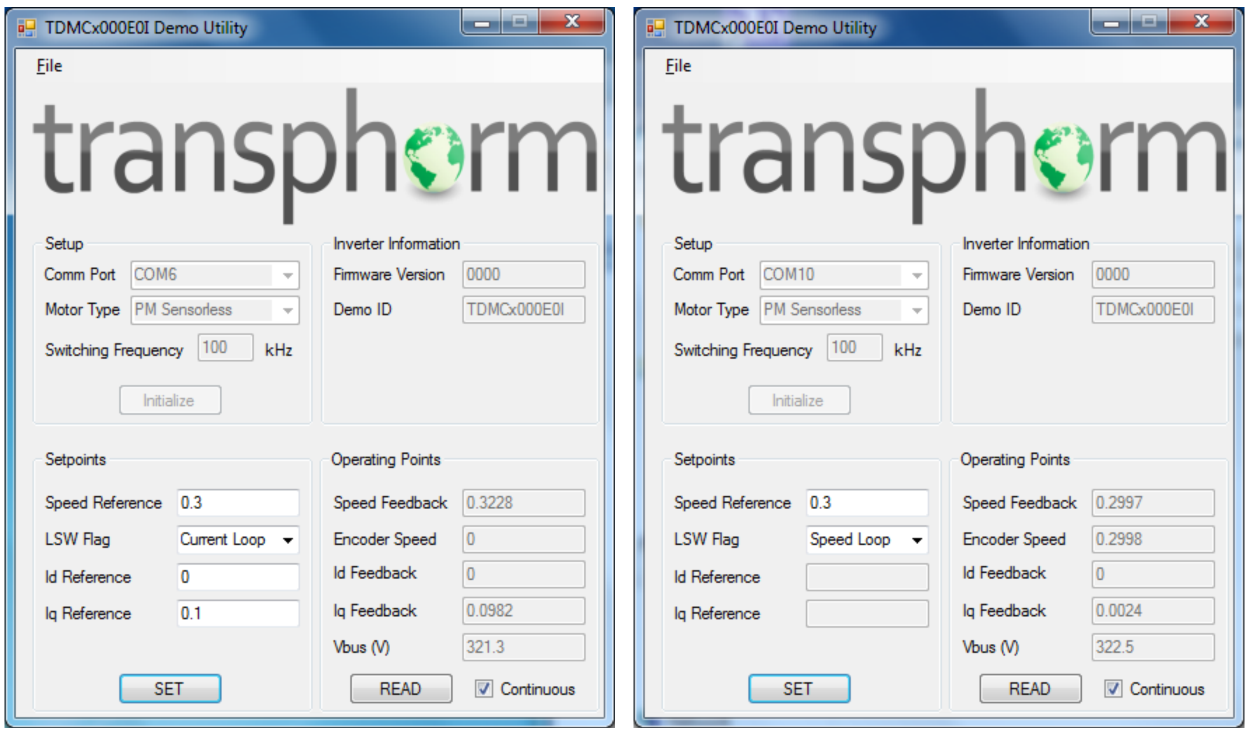


Figure 11 (a): inverter enabled, PM mode, Current Loop, no encoder
(b): inverter enabled, PM mode, Speed Loop, with encoder

Starting the motor: AC Induction motor open-loop V/F mode

The V/f mode for induction motors is an open-loop mode which simply sets the amplitudes of the three output phase voltages to a value directly proportional to the commanded speed (frequency). In ACI V/f mode, set the motor in motion by entering a Speed Reference value between 0 and 1, after first verifying that the voltage and current limit of the bus-voltage supply are at the desired levels. For induction motors, a speed reference of 0.5 corresponds to 60Hz, and is the maximum value for proportional V/F operation. From 0.5 to 1.0 (60Hz to 120Hz), V is held constant, corresponding to field weakening. Any change in speed is achieved with a ramp time of a few seconds. Figure 12 shows the screen for typical operation in ACI V/f mode. Figure 13 shows the phase voltages for three values of speed reference.

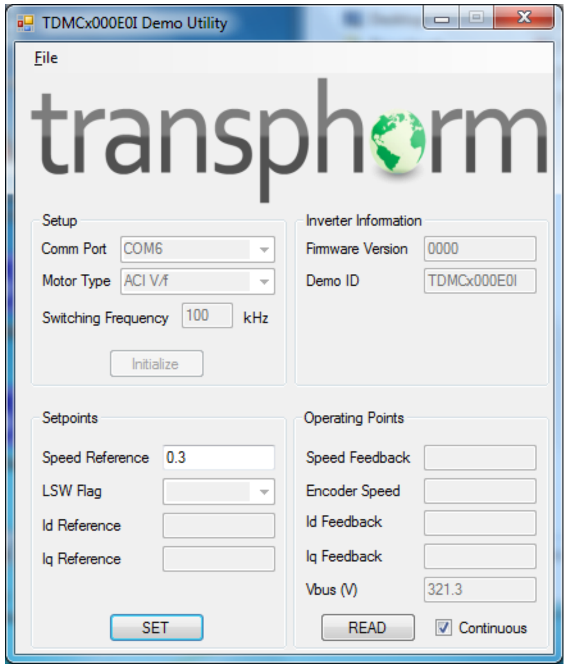
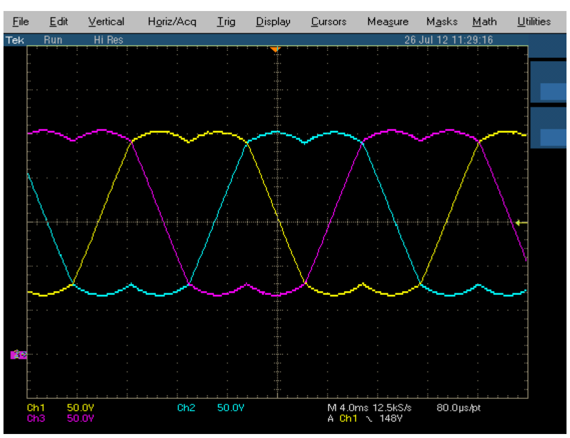
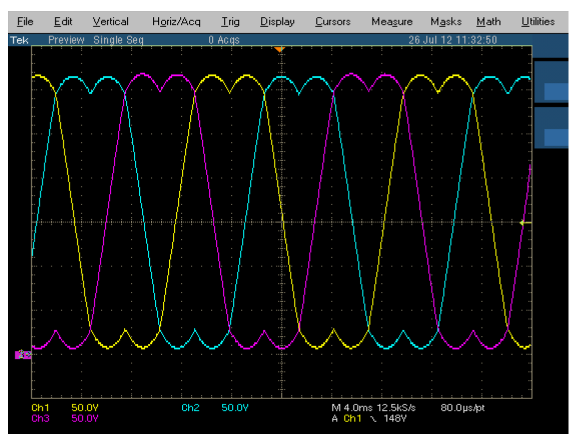


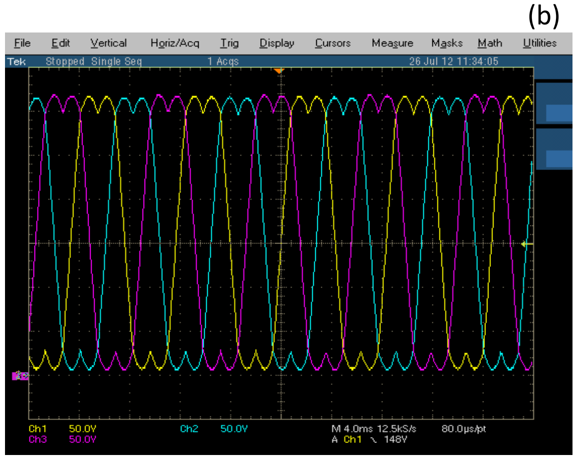
Figure 12: inverter enabled ACIM V/F mode



(a)



(b)



(c)

Figure 13: Phase voltages for an ACIM at three values of speed reference (a) 0.30 (b) 0.50 (c) 1.0

Stopping the motor

Stop the motor and turn off the high-voltage power before exiting the program. The motor can be stopped by either setting the speed reference to zero while in current-loop or ACI V/f mode, or by setting the LSW flag to locked. Be aware, however, that locking the rotor occurs instantaneously, with no ramping of the speed reference.

Notes and Hints

Setting the current limit on the dc supply is important if the motor stalls.

No change in any setpoint is communicated to the microcontroller until you click Set.

The motor outputs are not enabled until the first Set command. Even with LSW set for Locked, you will notice the current draw from the HV supply change from zero to a small value following the first Set command.

Speed loop is optimized in the pre-loaded firmware for speed reference values between 0.3 and 0.8.

If the encoder speed is incorrectly reported as zero, reverse either the motor phase connections or the encoder A/B connections.

Motor Type may only be changed when the utility is first started. Once the inverter is enabled, motor type cannot be changed.

Don't change loop mode (PM Sensorless Motor type) at high speed (>0.5)

Customization for a specific motor

To drive PMAC motor other than the one provided, or to use a closed-loop algorithm with an induction motor, a number of parameters in the firmware characteristic of the motor must be modified. This is accomplished using the Code Composer Studio integrated development environment from Texas Instruments. Full documentation for Code Composer Studio is provided by TI, and comes with the software. An overview of how to use Code Composer specifically with the Transphorm motor demo is given in the TDMCX0000E0I Firmware Reference Guide.

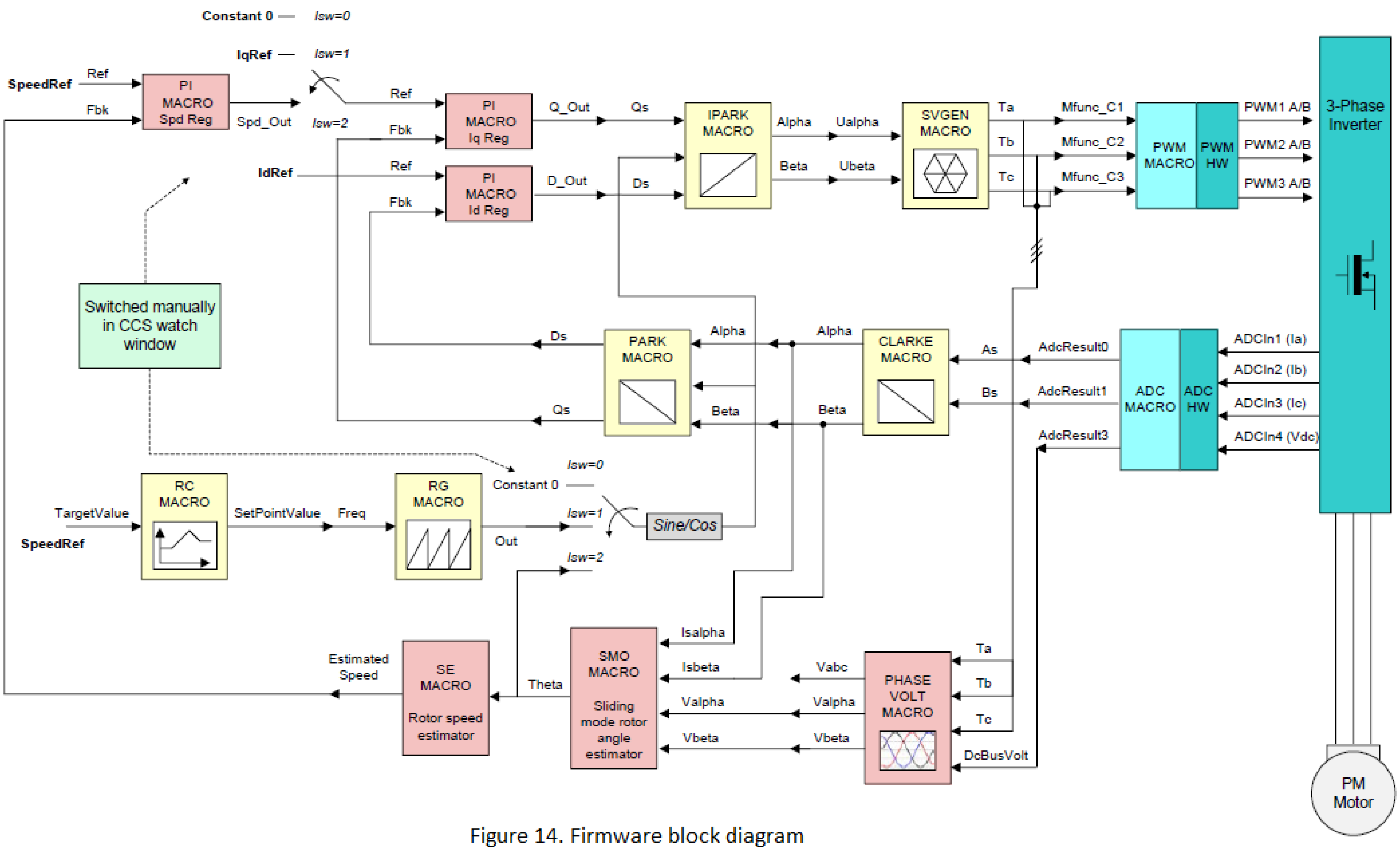


Figure 14. Firmware block diagram

From *Sensorless Field Oriented Control of 3-Phase Permanent Magnet Synchronous Motors Using 2833x,* B.Akin, M.Bhardwaj, Texas Instruments Incorporated