Abstract

This design implements a complete control and drive solution for 3-phase brushless DC motors up to about 3 kW in power rating. The design includes analog circuits, digital processor, and software to spin BLDC motors without the need for position feedback from Hall effect sensors or quadrature encoder. Operation is demonstrated with a 1 kW motor operating from a 12V supply, similar to many automotive applications. Test data shows the type of results which are easily measured at the board test points. References for the software and user documentation are provided to speed development time for similar BLDC motor applications.

Figure 1 Test set-up

Equipment used:

DRV830x-HC-C2-KIT

The kit has the following features

• Three-Phase Power Stage, DRV830x capable of driving 3-phase brushless DC motors and Permanent Magnet Synchronous Motors.
  o 60 VDC max input voltage
  o 60A peak output current per phase
  o Up to 200kHz driver switching frequency
o Integrated 1A buck converter to provide logic and analog power
o Dual integrated current sense amplifiers
• Isolated CAN and SPI communication
• Closed-loop digital control with feedback using the C2000’s on-chip PWM and ADC peripherals
  • On-board isolated JTAG emulation through the SCI peripheral and the FTDI chip.
  • JTAG connector for external emulators
• Quadrature Encoder Interface available for speed and position measurement
• Hall Sensor Interface for sensored three-phase motor control
• High precision low-side current sensing using the C2000’s high-performance ADC and current sense amplifiers integrated into the DRV830x
• Four PWM DAC’s generated by low pass filtering the PWM signals to observe the system variables on an oscilloscope to enable easy debug of control algorithms.
• Over current protection on the inverter stage, DRV830x
• Hardware Developer’s Package that includes schematics and bill of materials is available through controlSUITE.
The software available with the kit is completely open source, and hence can be easily modified to tune and run a customer’s motor.

CC2803x ISO DIMM REV 1.3

The F28035 Piccolo controlCARD is one of a series of controlCARDs from Texas Instruments. These are ideal products for OEMs to use for initial software development and short run builds for system prototypes, test stands, and many other projects that require easy access to high-performance controllers. The controlCARDs are complete board-level modules that utilize an industry-standard DIMM form factor to provide a low-profile single-board controller solution. All of the C2000 controlCARDs use the same 100-pin connector footprint to provide the analog and digital I/Os on-board controller and are completely interchangeable. Each controlCARD provides an isolated RS-232 interface for communications. The host system needs to provide only a single 5V power rail to the controlCARD for it to be fully functional. ControlCARDs from TI support the 60 MHz TMX320F28027 and F28035 (Piccolo), the 100MHz TMS320F2808 (P/N TMDSCNCD2808) and the 150MHz floating-point TMS320F28335 (P/N TMDSCNCD28335).

Features

TMS320F28035 "Piccolo" Microcontroller controlCARD
Small form factor - 9cm x 2.5cm
Standard 100-pin DIMM interface
F28x analog I/O, digital I/O and JTAG signals at DIMM interface
Isolated RS-232 interface
Single 5V power rail for full operation
Standalone JTAG emulator required for debug.
Bosch 36V 1kW 3-phase Brushless DC (BLDC) motor

The brushless DC motor has stator windings and permanent magnets on the rotor. The windings are connected to the control electronics and there are no brushes and commutators inside the motor. The electronics energize the proper windings similar to a commutator; the windings are energized in a moving pattern that rotates around the stator. The energized stator windings lead the rotor magnet.

BLDC motors are more efficient, run faster and quieter, and require electronics to control the rotating field. BLDC motors are also cheaper to manufacture and easy to maintain.

Three-phase inverters are required to drive BLDC motors. The inverter consists of three half H-bridges, where upper and lower switches are controlled using complementary signals. It is important to keep a delay between high-side switch turn off and low-side switch turn on. This will eliminate a potential short across the switches.

The motor specifications are as follows:

- Power 1kW
- 8 Magnet Poles
- 12 Coils
- 2A without load
- 30A with 3Nm Load
- 36v voltage (9-cell Li-ion)
- Stator resistance: 0.042 Ohms
- Stator inductance: 0.175 mH
InstaSPIN-BLDC software – InstaSPIN BLDC Example GUI

Targeted at low cost BLDC applications, InstaSPIN-BLDC is a sensorless control technique based on the premise that “simple is better”. In field tests with over 50 different motor types, InstaSPIN-BLDC was able to get each motor up and running in less than 20 seconds! The reason for this incredible robustness is because InstaSPIN-BLDC doesn’t require any knowledge about motor parameters to work, and you only need to adjust a single tuning value.

Unlike other sensorless BLDC control techniques based on back-EMF zero-cross timing, InstaSPIN-BLDC monitors the motor’s flux to determine when to commutate the motor. With the help of a free GUI the user can watch the flux signal in a plot window, and set the “Flux Threshold” slider to specify at what flux level the motor should be commutated. Optimal commutation can be verified by observing the phase voltage and current waveforms, which are also displayed.

In addition to its ability to work with just about ANY BLDC motor, InstaSPIN-BLDC has demonstrated incredible resilience to speed transient perturbations. With zero-cross timing, you are always using PAST information to predict FUTURE commutation events. But InstaSPIN-BLDC monitors a real-time flux waveform to determine the appropriate time to commutate. Abrupt speed changes will be reflected in the flux waveform in real time, so that it will still cross the specified threshold value at exactly the right time to commutate.

Using flux for commutation vs. back-EMF zero-cross timing also enables more stable operation at lower speeds. Unlike the flux signal, the back-EMF signal amplitude diminishes at lower speeds, resulting in poor signal-to-noise performance. InstaSPIN-BLDC enables smoother operation at low speeds, and provides more reliable motor starting, even under heavy loads.

Code Composer Studio V5.4

Code Composer Studio™ (CCStudio) is an integrated development environment (IDE) for Texas Instruments (TI) embedded processor families. CCStudio comprises a suite of tools used to develop and debug embedded applications. It includes compilers for each of TI's device families, source code editor, project build environment, debugger, profiler, simulators, real-time operating system and many other features. The intuitive IDE provides a single user interface taking you through each step of the application development flow. Familiar tools and interfaces allow users to get started faster than ever before and add functionality to their application thanks to sophisticated productivity tools.

Code Composer Studio is based on the Eclipse open source software framework. The Eclipse software framework was originally developed as an open framework for creating
development tools. Eclipse offers an excellent software framework for building software development environments and it is becoming a standard framework used by many embedded software vendors. CCStudio combines the advantages of the Eclipse software framework with advanced embedded debug capabilities from TI resulting in a compelling feature-rich development environment for embedded developers.

Code Composer Studio supports running on both Windows and Linux PCs. Not all features or devices are supported on Linux please see Linux Host Support for details.

Magtrol HD-705-6N Hysteresis Dynamometer (300W continuous, 1400W 15 min.)

Magtrol M-TEST 5.0 Motor Testing Software

![Figure 3 Hardware configuration tab of M-Test software](image1)

![Figure 4 Test pattern configuration panel for M-Test software](image2)

Tektronix DPO 3034 Oscilloscope

Tektronix P6139B Voltage probes (3)
Operational set-up

EVM board and controlCARD Connections

The TMS320F28035 controlCARD is inserted into the DIMM-100 connector on the DRV8301-HC-EVM board. Alignment ridges in the DIMM-100 socket prevent insertion of the controlCARD in an incorrect orientation. The side latches close to retain the controlCARD in the DIMM-100 connector.
Power Connections

The DRV8301-HC-EVM is capable of operation up to 60 Amps at 60V; the motor is rated for 36V and 30 Amps. The power supply is set to 12V, with a current limit of 30 Amps. The supply voltage (+) is connected to screw terminal J25 on the EVM board. The supply ground (-) is connected to screw terminal J26 on the EVM board. Refer also to section 3.2 in the Hardware Guide for additional information on jumper settings.

![Initial set-up - no connection to dynamometer](image)

Motor to EVM board connections

The 3 motor phases are connected to the EVM board at the “Motor” terminal block. AWG-8 size wire is used to ensure sufficient current-carrying capability. Note that the motor will operate with any assignment of the three motor phases to the three drive outputs on the board. There are 3 equivalent arrangements (A-B-C, B-C-A, C-A-B) which will cause clockwise motion, and 3 equivalent arrangements (C-B-A, B-A-C, A-C-B) which will cause counterclockwise motion. Either arrangement is valid as long as the user is satisfied with the polarity convention. If the user wishes to reverse the rotation for a given command, any two phases can be swapped.
Figure 7  BLDC motor (right) connected through coupling to dynamometer (left)

Figure 8  Motor and dynamometer in operation
Code Composer Studio (CCS) is executed from the Start Programs menu, or from the desktop icon. Following the procedure indicated in the MotorWare labs, import the example project InstaSPIN-BLDC Example GUI. See the directory structure in Figure 9. Configure the target to TMS320F28035. Build the project, and start a Debug session. See additional details in reference 3, the DRV830x-HC-C2-KIT How to Run Guide.

At this point, the red LED Dxxx on the controlCARD will begin blinking to indicate the program is loaded and running on the TMS320F28035 controlCARD. If not, check the connections, emulator, and program, and re-load and re-initialize the debug session as necessary.
Start the ControlSuite program by clicking on the icon. Select “English”, then “Development Tools”, then “Motor”, then DRV830x-HC-KIT...” and finally “InstaSPIN-BLDC Example GUI” as shown in Figure 9. Launch the InstaSPIN-BLDC GUI by clicking on the link in the right panel. This GUI is used to command motor states (enabled, duty cycle, speed, etc.).
Unloaded motor testing

On the InstaSPIN-BLDC graphical user interface, click to check the “Enable Motor” box on the Main tab. The motor should begin to rotate according to the setting for the motor speed control knob. Note that at relatively low commanded speeds (duty cycle < 0.20) there may be significant “cogging” as the motor switches from one magnet pole to the next.

The commanded duty cycle can be adjusted using the control knob on the main tab.
Figure 11 shows the motor voltages as oscilloscope traces as the motor rotates. Channel 1 is measuring test point TP12 (output A), channel 2 is measuring test point TP13 (output B), and channel 3 is measuring test point TP14 (output C). Note that the traces do not show the details of the pulse-width modulated (PWM) outputs, but the general characteristics of the waveforms can be seen.

Table 1 Phase relations during motor rotation

<table>
<thead>
<tr>
<th></th>
<th>Phase A</th>
<th>Phase B</th>
<th>Phase C</th>
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</thead>
<tbody>
<tr>
<td>1</td>
<td>Increasing</td>
<td>Mostly Low</td>
<td>Mostly High</td>
</tr>
<tr>
<td>2</td>
<td>Mostly High</td>
<td>Mostly Low</td>
<td>Decreasing</td>
</tr>
<tr>
<td>3</td>
<td>Mostly High</td>
<td>Increasing</td>
<td>Mostly Low</td>
</tr>
<tr>
<td>4</td>
<td>Decreasing</td>
<td>Mostly High</td>
<td>Mostly Low</td>
</tr>
<tr>
<td>5</td>
<td>Mostly Low</td>
<td>Mostly High</td>
<td>Increasing</td>
</tr>
<tr>
<td>6</td>
<td>Mostly Low</td>
<td>Decreasing</td>
<td>Mostly High</td>
</tr>
<tr>
<td>7</td>
<td>Increasing</td>
<td>Mostly Low</td>
<td>Mostly High</td>
</tr>
<tr>
<td>8</td>
<td>Mostly High</td>
<td>Mostly Low</td>
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<tr>
<td>9</td>
<td>Mostly High</td>
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<td>10</td>
<td>Decreasing</td>
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<tr>
<td>11</td>
<td>Mostly Low</td>
<td>Mostly High</td>
<td>Increasing</td>
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<tr>
<td>12</td>
<td>Mostly Low</td>
<td>Decreasing</td>
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</table>
Figure 12: Detail of motor phase voltages (A,B,C) during operation.
Speed versus current (controlled by Duty Cycle setting)

In the following tests, the motor was connected to the dynamometer, but no braking torque was applied by the dynamometer. Even without an active load, the dynamometer does apply some rotational friction, as well as providing an inertial load during changes in rotational speed. The command to the motor drive system was made by directly setting the PWM duty cycle in the InstaSPIN-BLDC GUI control panel (refer to Figure 10).

![Current vs Speed - brake: off](image)

**Figure 13** Speed versus supply current, with inactive dynamometer

Figure 13 shows the results of a series of measurements of supply current from the 12VDC supply as well as dynamometer torque readings at various motor speeds. Note that the torque measured on the dynamometer shaft increases slightly as the speed increases. The supply current varies almost linearly with speed; note that the supply current is a summation of the motor current in all three phases as well as the bias current in the microcontroller and other on-board circuits.

Figure 14 and Figure 15 show the typical waveforms of motor phase voltage (Vag), motor phase current (Ia), and magnetic flux which are captured by the InstaSPIN-BLDC GUI software. Note that in both cases the motor is connected to the dynamometer, but no braking torques is applied.
Figure 14 shows measurements for a duty cycle of 17%, which results in a rotational speed of 130 RPM. The plot shows about 1 complete cycle for phase A versus time. Note that the flux crossings occur at 3 times the rate of the rotational speed, indicating the 3 phases of the motor.

![Graph showing voltage, current, and flux measurements for a duty cycle of 17%, resulting in a rotational speed of 130 RPM.](image)

*Figure 14 Voltage, current and flux measurements, 12V supply, supply current = 243 mA, commanded duty cycle = 0.17, speed = 130 RPM, no brake applied*

Figure 15 shows measurements for a duty cycle of 69%, which results in a rotational speed of 810 RPM. Compared to the previous plot, the frequency of measured cycles has increased. The amplitude of the phase voltage has significantly increased, ranging from 0.03 to 0.15, again centered at 0.09.

The Vag trace is a filtered (or averaged) version of the PWM voltage applied to the motor winding. The actual PWM voltage switches at high frequency (~50 kHz) as shown in oscilloscope plots in later sections. Note that the filtered voltage waveform in these figures has a trapezoidal shape versus time. The InstaSPIN-BLDC uses trapezoidal commutation which provides a simple and effective way to start spinning Brushless DC motors. For higher efficiency and performance, other InstaSPIN versions are available with sinusoidal commutation, see reference 5.
Figure 15  Voltage, current and flux measurements, 12V supply, supply current = 900 mA, commanded duty cycle = 0.69, measured speed = 810 RPM, no brake applied, measured torque = 0.047 Nm

Loaded motor testing

Current versus load @ speed (controlled by Duty Cycle setting)

Figure 16 shows the relationship between motor speed and motor current as a braking torque load is applied by the dynamometer, with a constant duty cycle commanded by the InstaSPIN-BLDC GUI software control panel. At low braking torques, the speed is approximately 800 RPM. As the braking load is increased, the rotational speed decreases, and the supply current increases. In BLDC motors, this relationship can be explained by the decrease in back EMF (electro-motive force) as the rotational speed decreases due to the applied load. As the torque load is applied, the speed decreases until the reduced speed, and thus reduced back EMF, leads to increased motor current which then balances the torque load with applied torque from the motor.
Torque transient tests

Torque and speed versus time (constant Duty Cycle setting in InstaSPIN-BLDC GUI control panel)

With duty cycle selected as the control mode in the GUI, the PWM duty cycle to the motor can be manually set between -1.00 (100% in one direction) and +1.00 (100% in the other direction). This is basically open-loop control of the motor, as there is no position or velocity feedback. However, the InstaSPIN software does use flux measurements to correctly determine the motor angle for commutation.

For any given duty cycle setting, the motor speed is reduced when a torque disturbance is applied using the dynamometer. This is illustrated in Figure 17, where a 2 N-m torque step is applied, causing the motor speed to decrease from about 300 RPM to about 260 RPM. When the torque load is removed, the motor speed recovers back to the original level.

Figure 16: Motor speed (blue) and supply current (red) versus dynamometer load
The InstaSPIN-BLDC GUI can also be set to Velocity control mode. In this mode, the software monitors the actual motor speed, and adjusts the commanded PWM duty cycle to maintain the selected speed. In this case, the main control knob is used to set the desired motor speed.

Figure 17 Speed response to torque disturbance in duty cycle mode
Figure 18 Response to a torque step, with velocity command 750 RPM

Speed 1000 torque 2 current 950 mA, 2.7A

Figure 19 Response to a torque step, with velocity command 1000 RPM

Figure 19 shows the system response to a 2 N-m torque disturbance when operated in velocity control mode. The system is initially running with the dynamometer load disabled. The speed is set to about 1000 RPM\(^1\), and the actual speed is 993 RPM. When the torque step is applied by the dynamometer, the speed initially decreases to about 967 RPM, it then recovers to very close to the original speed, while the torque is still applied. When the torque load is removed, the speed initially increases above the desired setpoint, to about 1015 RPM. The speed then recovers to the desired speed. The power supply current was measured as 950 mA before and after the torque load was in effect. During the torque load, the power supply current increased to 2.7A.

\(^1\) The InstaSPIN-BLDC GUI control knob settings are not truly continuous, but are digitized into small steps. Therefore, setting the velocity to exactly 1000 RPM is not always practical.
Figure 20 and Figure 21 show plots of the voltage, current, and magnetic flux for two cases of motor speed, dynamic braking torque load, and commanded duty cycle. In the first case, the power supply is supplying 7.4A to the system, which corresponds to total power consumption of 89 Watts. At a rotational speed of 636 RPM and torque of 1 N·m, the dynamometer is consuming 67 Watts\(^2\). So the overall electrical to mechanical efficiency is 75%. For the second case (Figure 21) the power supply is supplying 132 Watts, and the dynamometer load is dissipating 105 Watts, for 79% efficiency.

\[^2\text{Conversion factor 1 N-m x 1 RPM = 0.1047 Watts}\]
Figure 22 Voltage (Ch.1) and Current (Ch.2) with 4 second torque disturbance transient
Figure 22 shows the voltage (Channel 1) and current (Channel 2) of a single motor phase before, during and after a dynamometer torque step is applied to the motor. Note that the phase voltage does not change, remaining constant at the duty cycle set by the control knob. However, the phase current increases during the torque disturbance, and then recovers after the step is removed.

Figure 23 shows a single motor phase voltage (channel 1) and the corresponding phase current. Here the phase voltage is switching between the high-level set by the 12V supply, and the low-level, which is ground (0V) for this system. The current trace (channel 2) is taken at the current test points made available on the DRV8301 board; TP16 is a measure of the Phase B current (IB-FB), TP17 is a measure of the Phase A current (IA-FB), and TP19 is a measure of the Phase C current (IC-FB). See also Table 20 in the DRV830x-HC-CS-KIT Hardware Reference Guide (reference 2).

Figure 23  Voltage (Ch.1) and Current (Ch.2) with 0.3 N-m load at 750 RPM
Figure 24 shows the relationships between the three motor phases (A, B, C) versus time during normal motor operation.

**Figure 24** Phase A, B, C Voltages, showing 50 usec PWM period
PWM switching noise induced on power supply lines

In automotive applications, the conduction of electrical noise from any motor or switching supply back into the battery electrical system is a potential concern. Figure 25 and Figure 26 show oscilloscope plots of the motor PWM voltage (phase A in this case) and the 12Vdc supply voltage. Note that all three motor phases switch at the same time. In this plot, the switching “spikes” which appear on the supply voltage line have amplitude up to about 300 mV.

![Figure 25 Power supply with PWM switching noise](image)

In Figure 26 the detail shows the noise waveform appears to have a fundamental frequency of about 30 ns, corresponding to a fundamental frequency of about 30 MHz. If this level of conducted electrical noise is undesirable, filtering components can be added to reduce these conducted emissions.
Figure 26  Detail of power supply with PWM switching noise

References:

2. DRV830x-HC-C2-KIT Hardware Reference Guide, Version 1.0 – August 2011, http://e2e.ti.com/cfs-file.ashx/_key/communityserver-discussions-components-files/312/1222DRV830x_2D00_HC_2D00_C2_2D00_KIT_5F00_HWGuide.pdf
Appendix

Additional oscilloscope plots showing voltage (Channel 1) and current (Channel 2) relationships versus time for various instants during normal motor operation.
Additional oscilloscope plots showing voltages of the three motor phases relationships versus time for various instants during normal motor operation.
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