TI Designs: TIDA-010031

25.2-V, 30-A High-speed sensorless (> 100 krpm) brushless DC motor drive reference design

Description

This reference design is for high-speed sensorless trapezoidal control of 6–33.6 V DC-fed brushless DC (BLDC) motors up to 900 W and motor speeds of up to 180,000 rpm (verified up to 100,000 rpm). A cost-effective smart microcontroller with a hardware detection of the commutation points accelerates the sensorless trapezoidal control using speed-adaptive Back EMF (BEMF) detection. The BLDC power stage is compact, optimized for efficiency, and fully protected against short circuit, motor stall, and overtemperature, due to the smart three-phase gate driver.

Resources

TIDA-010031	Design Folder
DRV8320	Product Folder
MSP430FR2355	Product Folder
CSD18514Q5A	Product Folder
TPS709	Product Folder

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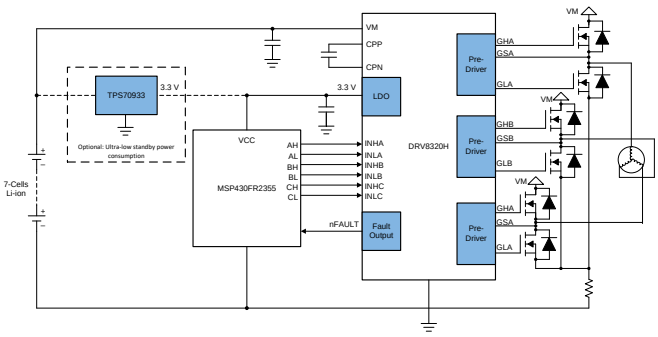
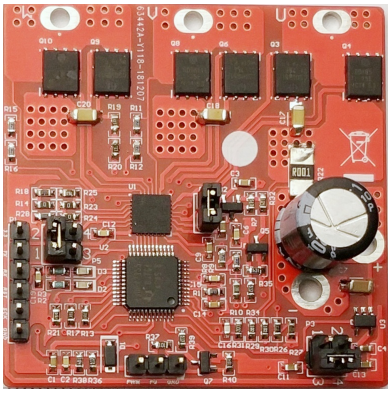
Features

- High-speed, sensorless trapezoidal control up to 3-kHz motor electrical frequency
- Speed-adaptive dual-algorithm for BEMF detection
- Operates at voltage ranging from 6 V to 33.6 V delivering up to 900-W output power
- Continuous output current up to 30A RMS
- Standby current consumption as low as 22 µA
- Optimized FET switching for best efficiency and EMI
- Cycle-by-cycle overcurrent, motor stall and short-circuit latch protection by MOSFET VDS monitoring
- Operating ambient: –20°C to 55°C

Applications

- Cordless vacuum cleaner
- Vacuum robots
- Appliance pumps and fans
- Brushless DC motor drives





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1 System Description

Vacuum cleaners are commonly used in many households. Battery-powered vacuums are popular because they are compact and lightweight. Improvement in the energy density of batteries and advancements in rechargeable-battery technology allow more vacuum cleaners to be cordless. Higher torque density, improved efficiency, high-speed operation (due to the absence of brushes) and the extended life of brushless DC (BLDC) motors compared to the brushed DC and mains powered universal motors, makes the BLDC motor as the favorites in cordless vacuum cleaner designs.

The advanced cordless vacuum cleaners require compact size and at the same time should create powerful suction. The key design challenge in achieving the powerful suction with compact size is by running the suction motor at speed as high as 100 krpm, or even more. The brushless DC motor with trapezoidal would be the obvious choice to achieve high-speed motor operation. The sensored trapezoidal control at high-speed using hall elements or hall Effect sensors may add challenges due to the requirement of high bandwidth sensors and extra sensor and assembly cost. The sensorless trapezoidal algorithm is widely preferred but faces challenges at high speed due to the requirement of high speed processing, position detection error at extreme (both low and high) speeds and optimizing the algorithm over a wide range of speed.

This reference design demonstrates more than 100 krpm speed-adaptive sensorless trapezoidal control for BLDC motor drives. TI's cost effective 16-bit microcontroller MSP430FR2355 enable hardware detection of the commutation points using speed adaptive Back EMF detection to achieve high speed sensorless operation. The smart analog combo (SAC) available in the MCU eases the sensorelss algorithm implementation. The three phase smart gate driver, DRV8320 provides an optimized solution for driving and protecting the external power MOSFETs. The smart gate driver helps the system designers to adjust the MOSFET slew rate, optimize switching and EMI performance, decrease bill of materials (BOM) count, automatically generate minimum required dead time, and provide additional protection for the external power MOSFETs and motor system. The reference design uses TI's NexFETs CSD18514Q5A in SON 5 × 6 package to achieve a compact, robust and cost effective inverter stage. The low power mode of MSP430 control enable the use of inbuilt LDO in the DRV8320 gate driver that helps in reducing the overall BOM. The reference design also have an option of external LDO TPS70933, having ultra low quiescent current and shut down current to makes it perfect for battery powered application. The test report evaluates the performance of the design at 100 krpm using a high speed BLDC motor. The test results shows the motor voltage and currents waveforms at 100 krpm, maximum voltage and RMS current capability, back EMF sensing waveforms, protections and board thermal images.

1.1 Key System Specifications

Table 1. Key System Specifications

PARAMETER	MIN	NOM	MAX	UNIT
DC input voltage[1]	22.4	25.2	29.4	V
Input power	-	500	900	W
Output current (RMS)	-	20	30	A
Electric frequency [2]	-	-	3000	Hz
Operation temperature	–20	25	55	℃

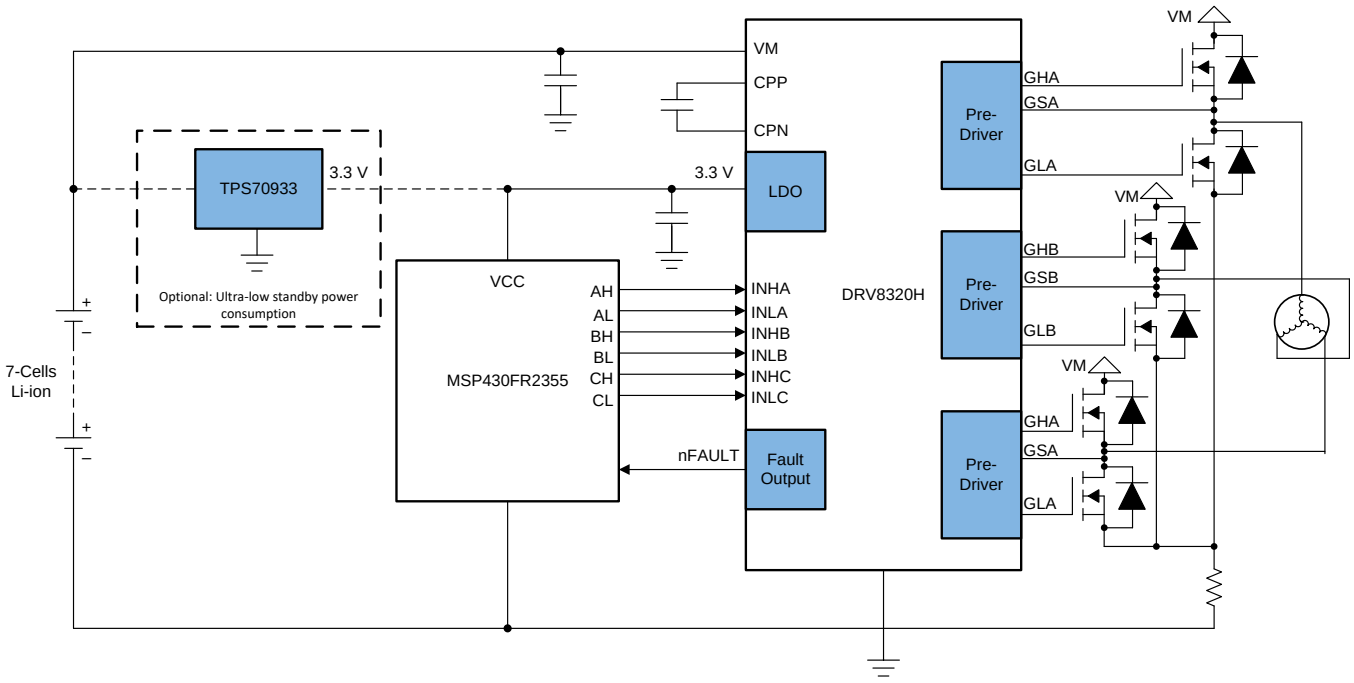
(1) This design can accept a 6-V to 33.6-V power supply, which fits the motor rated voltage. For this test setup, a 25.2-V nominal value (equals to 7-cells Li-ion Battery) is used to run the specified motor.

(2) The maximum electrical frequency for the design is calculated as 3000 Hz. This parameter and poles of the motor determine the maximum mechanical speed of the target motor. The maximum speed of the motor, which is used in test setup of this design, is 100000 RPM with 2 poles which electric frequency is 1667 Hz.

2 System Overview

2.1 Block Diagram

Figure 1. TIDA-010031 Block Diagram



2.2 Design Considerations

The character of the high-speed, low-voltage motor is small inductance with very small resistance. Considering this kind of special motor design, the motor control should be designed to enable the very low magnitude back EMF detection at low speed and at the same time achieve fast commutation at high speed.

2.3 Highlighted Products

The following subsections detail the highlighted products used in this reference design, including the key features for their selection. See their respective product data sheets for complete details on any highlighted device.

2.3.1 MSP430FR2355

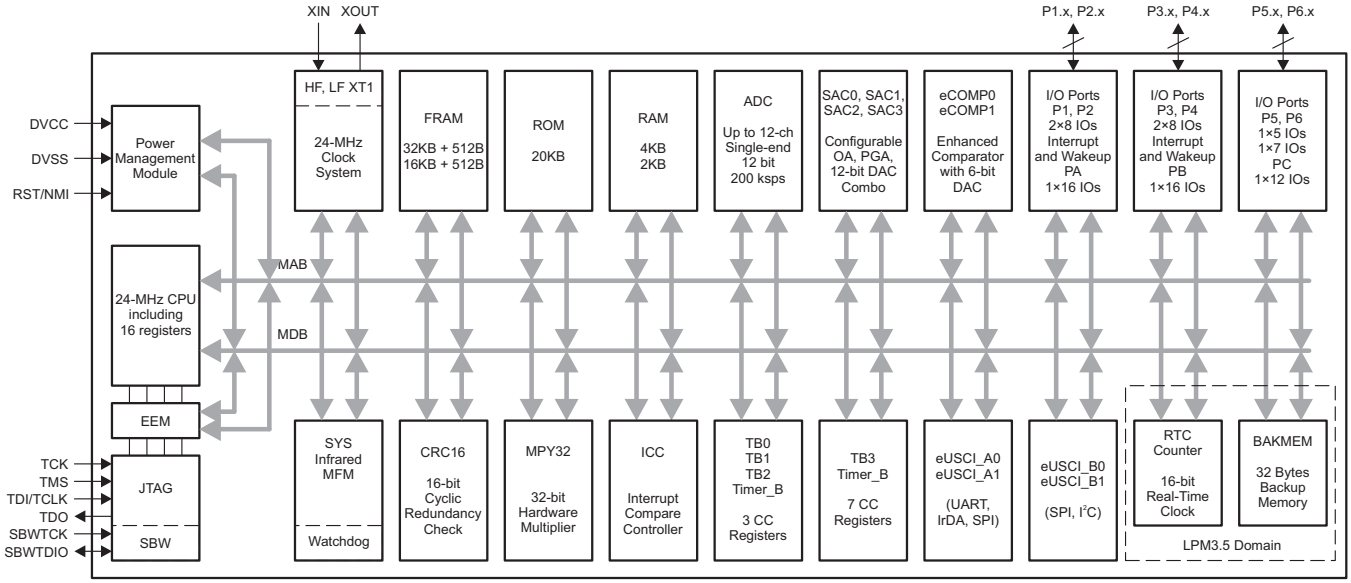
MSP430FR235x microcontrollers (MCUs) include configurable signal-chain elements and an extended operating temperature up to 105°C to meet the requirements of industrial systems. The devices are part of the MSP430™ MCU value line portfolio of ultra-low-power low-cost devices for sensing and measurement applications. The MSP430FR235x devices integrate four smart analog combos, each of which can be used as a 12-bit DAC or a configurable programmable gain op amp to meet the specific needs of a system while reducing the BOM and PCB size. The device also includes a 12-bit SAR ADC and two comparators. The MSP430FR215x and MSP430FR235x MCUs all support an extended temperature range from –40° up to 105°C, so higher temperature industrial applications benefit from the FRAM data-logging capabilities of the devices.

The MSP430FR215x and MSP430FR235x MCUs feature a powerful 16-bit RISC CPU, 16-bit registers, and a constant generator that contribute to maximum code efficiency. The digitally controlled oscillator (DCO) allows the device to wake up from low-power modes to active mode typically in less than 10 μs.

The MSP430 ultra-low-power (ULP) FRAM microcontroller platform combines uniquely embedded FRAM and a holistic ultra-low-power system architecture, allowing system designers to increase performance while lowering energy consumption. FRAM technology combines the low-energy fast writes, flexibility, and endurance of RAM with the nonvolatile behavior of flash.

The MSP430FR235x MCU integrates Smart Analog Combo (SAC) which includes a high-performance low-power operational amplifier, up to 33x gain PGA, and a 12-bit digital-to-analog converter (DAC) core. The SAC can be used for signal conditioning for either the input or output path.

Figure 2. MSP430FR235X Block Diagram



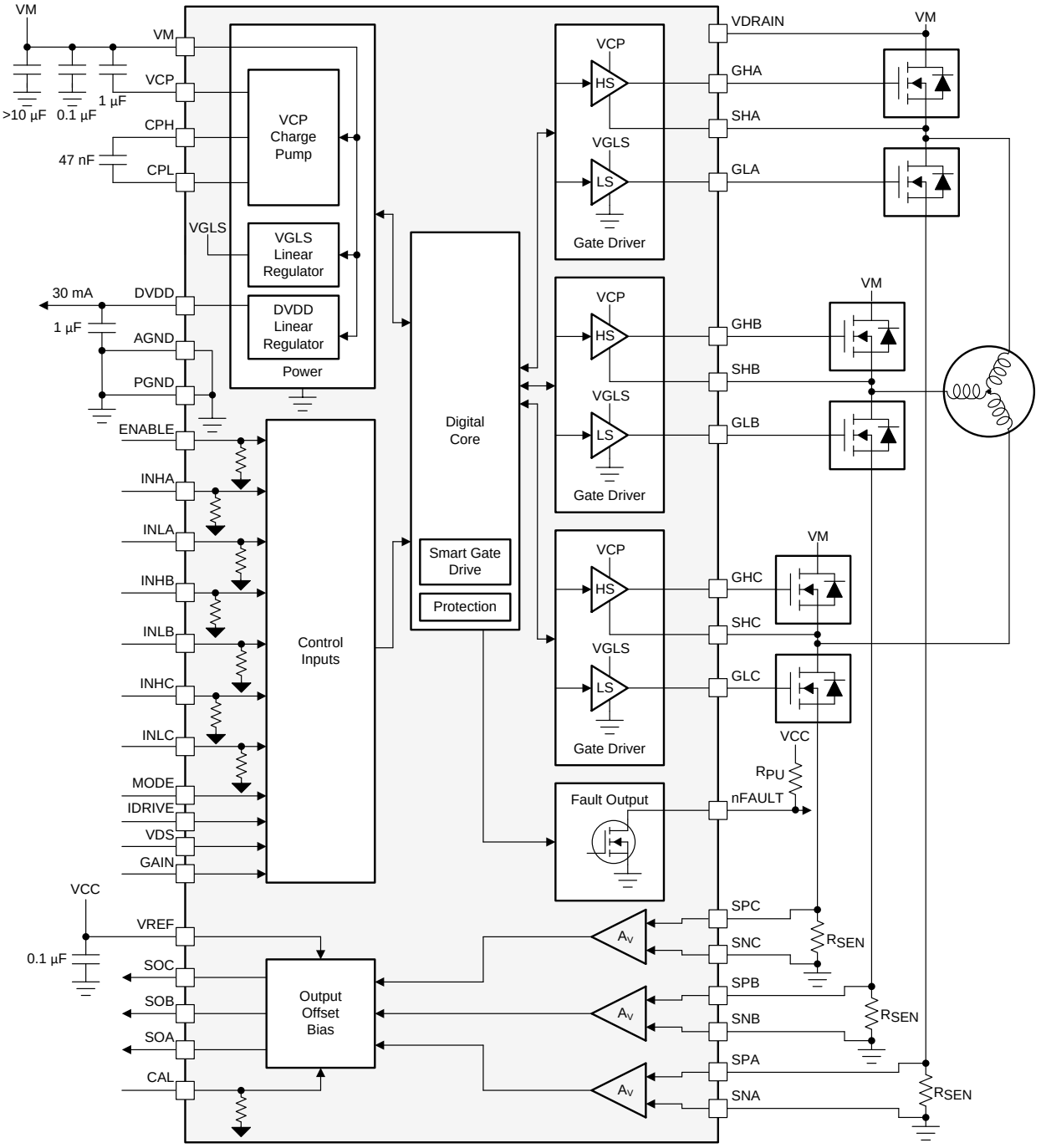
2.3.2 DRV8320H

The DRV832x family of devices is an integrated gate driver for three-phase applications. The devices provide three half-bridge gate drivers, each capable of driving high-side and low-side N-channel power MOSFETs. The DRV832x device generates the correct gate drive voltages using an integrated charge pump for the high-side MOSFETs and a linear regulator for the low-side MOSFETs. The Smart Gate Drive architecture supports peak gate drive currents up to 1-A source and 2-A. The DRV832x can operate from a single power supply and supports a wide input supply range of 6 to 60 V for the gate driver and 4 to 60 V for the optional buck regulator.

The 6x, 3x, 1x, and independent input PWM modes allow for simple interfacing to controller circuits. The configuration settings for the gate driver and device are highly configurable through the SPI or hardware (H/W) interface. The DRV8323 and DRV8323R devices integrate three low-side current sense amplifiers that allow bidirectional current sensing on all three phases of the drive stage. The DRV8320R and DRV8323R devices integrate a 600-mA buck regulator.

A low-power sleep mode is provided to achieve low quiescent current draw by shutting down most of the internal circuitry. Internal protection functions are provided for undervoltage lockout, charge pump fault, MOSFET overcurrent, MOSFET short circuit, gate driver fault, and overtemperature. Fault conditions are indicated on the nFAULT pin.

Figure 3. DRV832X Block Diagram



2.3.3 TPS70933

The TPS709 series of linear regulators are ultra-low, quiescent current devices designed for power-sensitive applications. A precision band-gap and error amplifier provides 2% accuracy over temperature. Quiescent current of only 1 μA makes these devices ideal solutions for battery-powered, always-on systems that require very little idle-state power dissipation. These devices have thermal-shutdown, current-limit, and reverse-current protections for added safety.

Shutdown mode is enabled by pulling the EN pin low. The shutdown current in this mode goes down to 150 nA, typical.

The TPS70933 device can be enabled as an optional choice in the reference design to evaluate the ultra-low standby power consumption.

Figure 4 shows the typical application circuit.

Figure 4. TPS70933 Typical Application Circuit

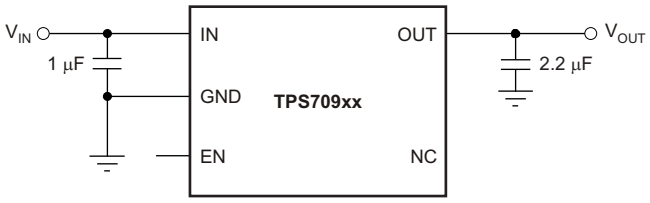


Figure 5.

2.4 System Design Theory

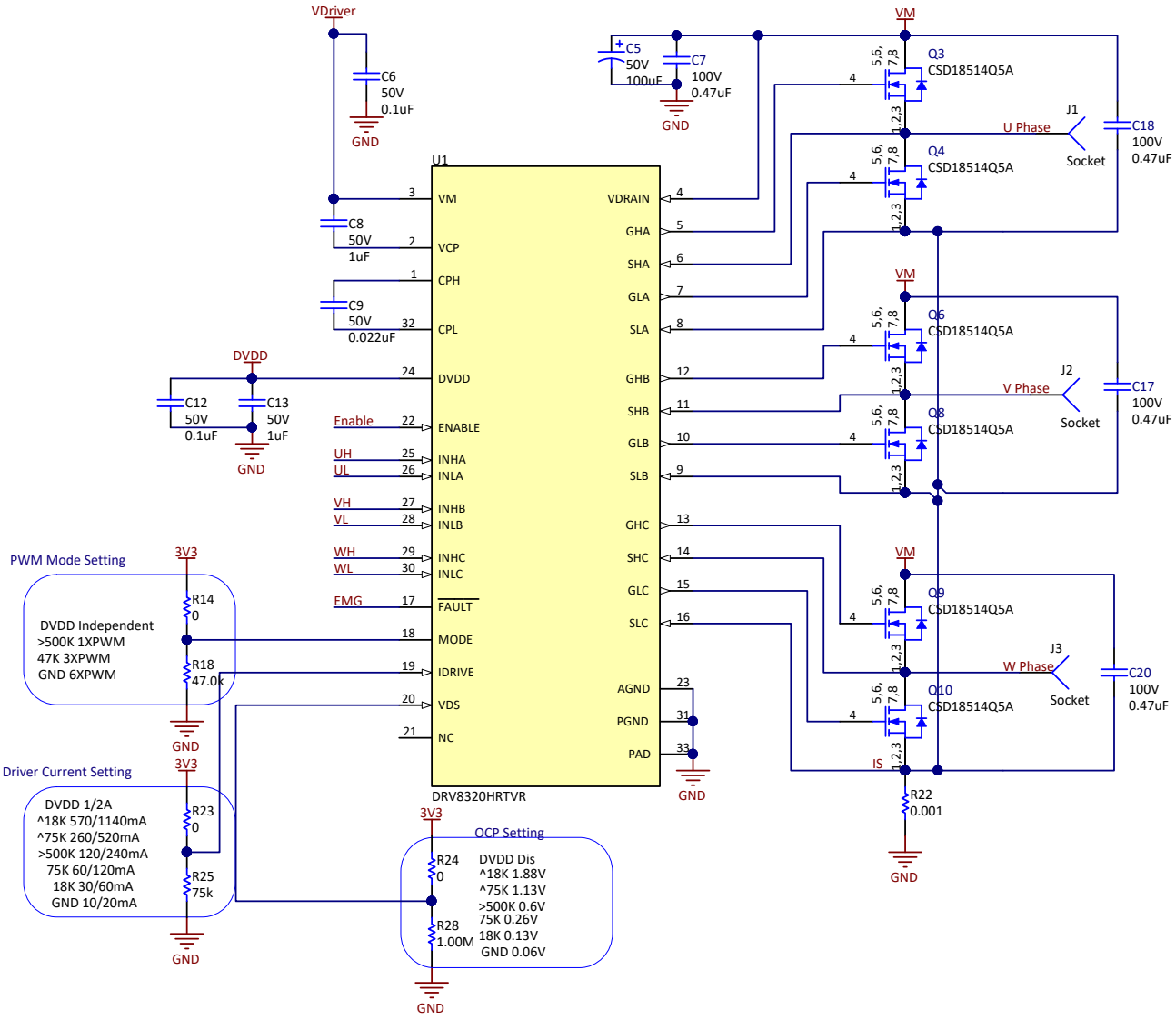
The motor BEMF detection method is key in achieving high-speed trapezoidal sensorless motor control and reliable start-up from zero speed. The MSP430FR2355 MCU detects the BEMF by sensoring the motor phase voltage using the internal comparator and ADC. The DRV8320 device provides a robust pre-driver with full protections. The CSD18514Q5A device provides a 40-V, 50-A, 4.1-mΩ $R_{DS(on)}$ MOSFET to reduce the power consumption.

- MSP430FR2355 – User interface, BEMF detection, commutation and software-based protection.
- DRV8320 – Robust pre-driver, hardware-based protections
- CSD18514Q5A – 40 V, 50 A, 4.1 mΩ $R_{DS(on)}$ MOSFET

2.4.1 Motor Driver Hardware

The DRV8320 and CSD18514Q5A devices make up the inverter circuit (see Figure 6).

Figure 6. Motor Drive Schematic



The DRV8320 device is a smart gate driver enabling optimum gate drive current selection without external components. The smart gate driver removes the external gate driver components. The output of the driver can directly connect to MOSFET and the driver current can be selected by an external setting from IDRIVE pin. The setting can easily tune the slew rate and do the EMI reduction. The gate driver short and dv/dt protection can be achieved by integrated gate driver monitor. Also the smart gate driver can automatically insert and minimized the dead time.

Select the input mode with R14 and R18. Table 2 shows the mode selection table:

Table 2. Mode Selection

MODE	R14	R18
Independent	0 Ω	Not connect
1x	Not connect	> 500 kΩ, 5%
3x	Not connect	47 kΩ, 5%
6x	Not connect	0 Ω

Select the MOSFET drive current using R23 and R25. Table 3 shows the MOSFET drive current selection table.

Table 3. MOSFET Drive Current Selection

DRIVE CURRENT (IDRIVE)	R23	R25
1/2 A	0 Ω	Not connect
570/1140 mA	18 kΩ, 5%	Not connect
260/520 mA	75 kΩ, 5%	Not connect
120/240 mA	Not connect	> 500 kΩ, 5%
60/120 mA	Not connect	75 kΩ, 5%
30/60 mA	Not connect	18 kΩ, 5%
10/20 mA	Not connect	0 Ω

Select the V_{DS} overcurrent protection threshold with R24 and R28. Table 4 shows the V_{DS} protection voltage table.

Table 4. V_{DS} Protection Voltage Selection

V_{DS}	R24	R28
Disabled	0 Ω	Not connect
1.88V	18 kΩ, 5%	Not connect
1.13 V	75 kΩ, 5%	Not connect
0.6 V	Not connect	> 500 kΩ, 5%
0.26 V	Not connect	75 kΩ, 5%
0.13 V	Not connect	18 kΩ, 5%
0.06 V	Not connect	0 Ω

2.4.2 BEMF Detection

Generally, a BLDC motor is driven by a three-phase inverter with what is called six-step commutation. The conducting interval for each phase is 120° by electrical angle. Therefore, only two phases conduct current at any time, leaving the third phase floating. This opens a window to detect the back EMF in the floating winding.

For the direct back EMF sensing scheme, the PWM signal is applied on high side switches only, and the back EMF signal is synchronously sampled during the PWM off time. The low side switches are only switched to commutate the phases of the motor. The true back EMF can be detected during off time of PWM because the terminal voltage of the motor is directly proportional to the phase back EMF during this interval. Also, the back EMF information is referenced to ground, which eliminates the common mode noise; and the synchronous sampling rejects the high-frequency switching noise. Only three resistors are required to detect the back EMF, as Figure 7 shows.

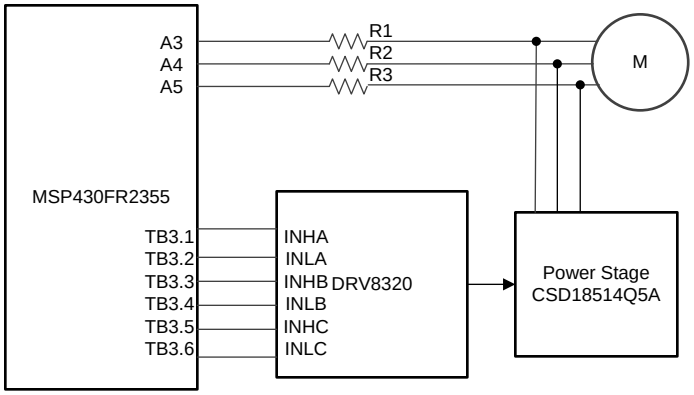
Ideally, the terminal voltage for the floating phase is directly proportional to the back EMF signal in steady state during PWM off time. The equation follows:

$$V_{a,b,c} = \frac{3}{2} e_{a,b,c} \quad (1)$$

where

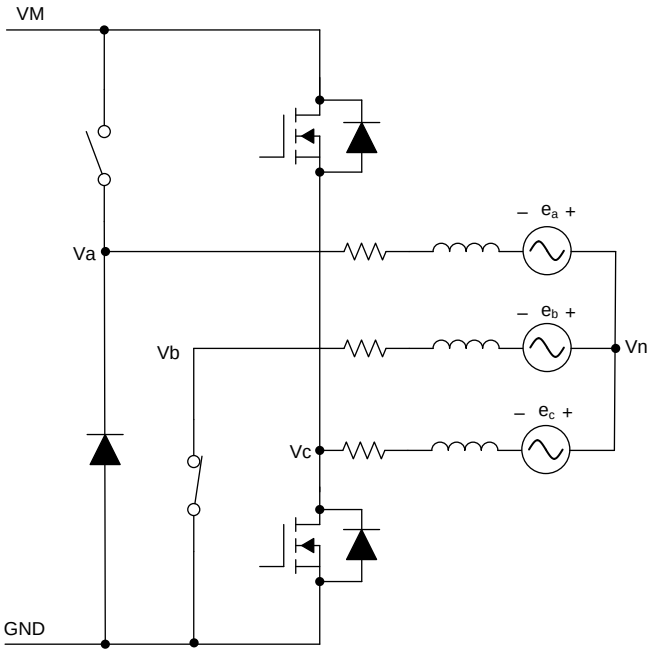
- V_x is the terminal voltage
- e_x is the back EMF of the floating phase

Figure 7. Direct BEMF Sensing Block Diagram



Assuming at a particular step, phase A and B are conducting current, and phase C is floating. The upper switch of phase A is controlled by the PWM and lower switch of phase B is on during the whole step. The terminal voltage Vc is measured.

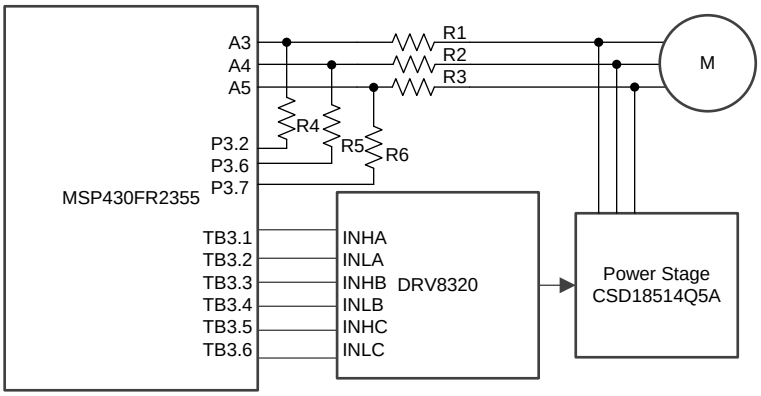
Figure 8. Circuit Model of Proposed BEMF Detection During the PWM off Time



From the circuit model Figure 8 shows, simplify the circuit by using the neutral voltage Vn = ½ × e_c during PWM off time.

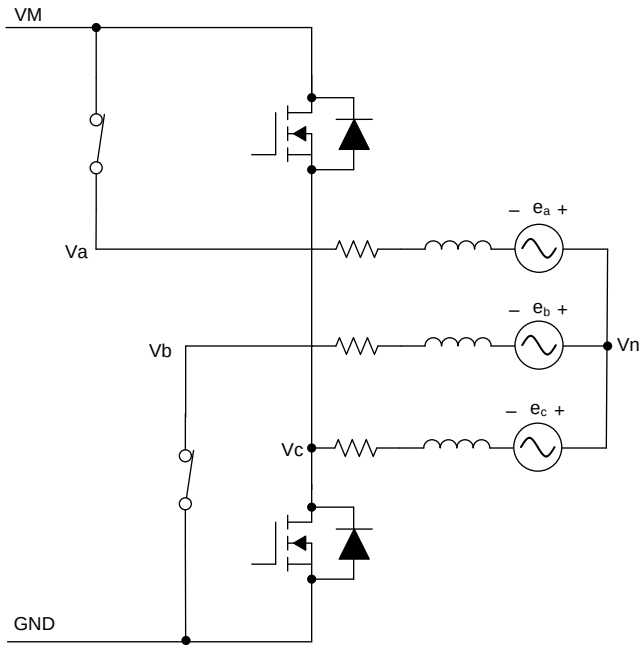
When the PWM duty is increased to high duty cycle, the PWM off time is limited and the detection window will be unavailable. At that time, change the detection method into *PWM on* mode.

Figure 9. BEMF Sensing at PWM On Stage



First, derive the floating phase terminal winding voltage during PWM on time. Assume phase A and B are conducting current and phase C is floating.

Figure 10. Circuit Model Proposed BEMF Detection During the PWM on Time



From phase A, Equation 2:

$$V_n = V_{dc} - R \times i - L\frac{di}{dt} - e_a \quad (2)$$

- Vn- motor neutral point voltage measured from board ground
- R- Motor phase resistance
- L- Motor phase inductance
- ea, eb, ec - Back emf of phase a, b, c respectively

From phase B:

$$V_n = R \times i + L\frac{di}{dt} - e_b \quad (3)$$

The voltage drop on the power devices is ignored.

From Equation 2 and Equation 3,

$$V_n = \frac{V_{dc}}{2} - \frac{e_a + e_b}{2} \quad (4)$$

Also from the balance three-phase system, considering fundamental frequency only, we have:

$$e_a + e_b + e_c = 0 \quad (5)$$

From Equation 4 and Equation 5,

$$V_n = \frac{V_{dc}}{2} + \frac{e_c}{2} \quad (6)$$

So, the terminal voltage Vc:

$$V_c = e_c + V_n = \frac{3}{2}e_c + \frac{V_{dc}}{2} \quad (7)$$

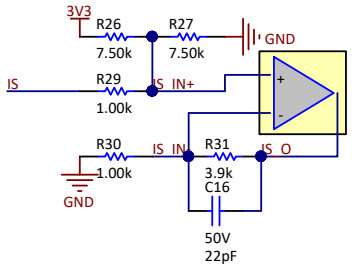
During PWM on time, if the terminal voltage is compared to half of the DC voltage, the zero crossing of the back EMF is able to be detected.

The MCU will capture the time between commutation and zero-crossing. The time will be treated as a 30° rotation. After the zero-crossing is detected, the next commutation will be enabled after another 30° time.

2.4.3 Current Sense

The MSP430FR2355 has integrated the *Smart Analog Combo* (SAC) module. SAC integrates a high-performance low-power rail-to-rail output operational amplifier. This OA can be configured to work independently in general purpose (GP) mode. SAC OA contains 3-channel input selections on both the noninverting and inverting inputs of the amplifier for which NSEL and PSEL selects the inputs respectively. The inverting inputs include the OAx- pin, PGA, and the output of the paired OA. The noninverting inputs include the OAx+ pin, 12-bit DAC core, and the output of the paired OA. For motor driver usage, we chose the differential OA pin input to reduce the common noise.

Figure 11. BEMF Sensing Circuit Schematic



In the circuit, the U_BEMF,V_BEMF, W_BEMF and U_Ctrl, V_Ctrl, W_Ctrl are connected to the I/O pins of the MSP430 device.

Using the the op-amp calculations:

$$V_o = \frac{R_{30} + R_{31}}{2R_{30} + R_{27}}(3.3\ V + \frac{R_{27}}{R_{29}}V_i) \quad (8)$$

If R_{27} = $2R_{31}$, then the following is true:

$$V_o = \frac{3.3\ V}{2} + \frac{R_{31}}{R_{29}}V_i \quad (9)$$

The output gain is R_{31} / R_{29} and the offset is 3.3 V/2.

3 Hardware, Software, Testing Requirements, and Test Results

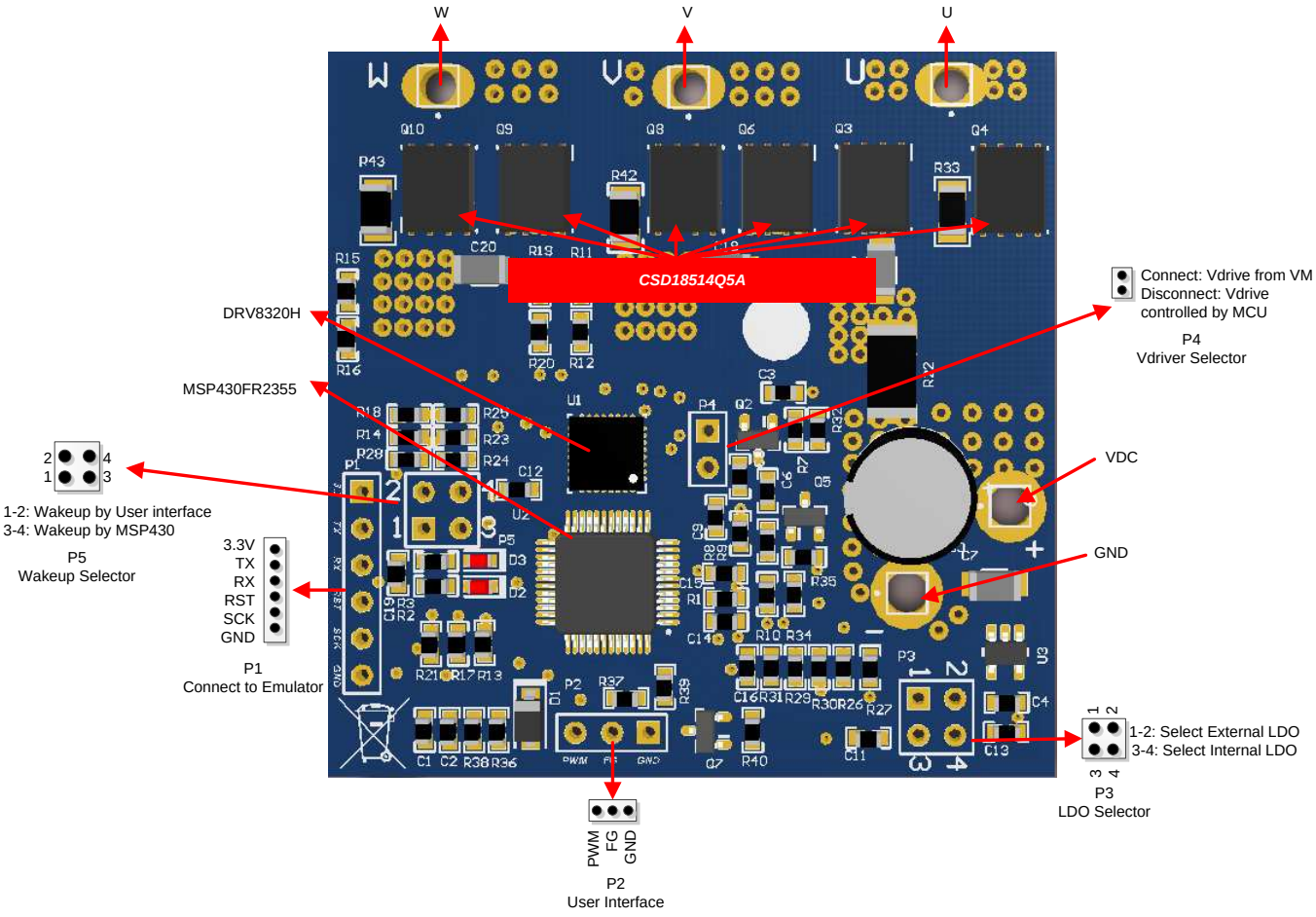
3.1 Required Hardware and Software

3.1.1 Hardware

3.1.1.1 Hardware Overview

Figure 12 shows the overview of the PCB for the TIDA-010031 design.

Figure 12. TIDA-010031 Hardware Overview



3.1.1.2 Programming Interface for MSP430™ MCU

P1 is reserved as the programming interface for the MCU. The designer can program the MSP430 MCU using the JTAG port, Spy-Bi-Wire (SBW), and the bootloader BSL. In this reference design, SBW has been adopted for programming and is a two-wire Spy-Bi-Wire interface. Spy-Bi-Wire can be used to interface with MSP430 development tools and device programmers. Table 5 lists the Spy-Bi-Wire interface pin requirements. For further details on interfacing to development tools and device programmers, see the *MSP430™ Hardware Tools* User's Guide.

Table 5. Spy-Bi-Wire Pin Requirements and Functions

P1 PIN #	DEVICE SIGNAL	DIRECTION	SBW FUNCTION
1	VCC	-	Power supply
2	TXD	OUT	TXD for the UART function
3	RXD	IN	RXD for UART function
4	RST/SBWTDIO	IN,OUT	Spy-Bi-Wire data input and output
5	TEST/SBWTCK	IN	Spy-Bi-Wire clock input
6	VSS	-	Ground

3.1.1.3 User Interface

The motor speed can be controlled using the interface P2. The PWM pin (pin 1) of P2 accepts a PWM signal to control motor speed as per the duty cycle of the PWM signal. A 400-Hz to 1-kHz signal can be used. Adjust the duty cycle of the PWM signal from 0 to 100% to control the motor speed from zero to maximum. The FG pin (pin 2) of P2 is an open drain output and the frequency of FG pin corresponds to motor speed. For example, if a 2-pole motor is running at 100 krpm, then the FG signal frequency is 1667 Hz = (Poles × RPM /120). Table 6 shows the interface specification.

Table 6. User Interface Specification and Functions

P2 PIN #	DEVICE SIGNAL	SPECIFICATION	FUNCTION
1	PWM	3.3 V; 400 Hz–1 kHz	Motor on-off control and speed control
2	FG	Open-drain output; maximum current: 30 mA	Motor speed output
3	GND		GND

3.1.2 Firmware

3.1.2.1 Application Firmware Description

The firmware of this reference design runs on the MSP430FR2355 MCU. The MCU executes the BEMF detection algorithm and sensorless motor control state machine. The firmware also monitors the DC voltage and current so the corresponding user-control methods such as reducing the output current at low voltage to protect the battery and expanding the operation time are available.

Table 7 lists the system components for the firmware of this reference design.

Table 7. TIDA-010031 Firmware System Components

ITEMS	DESCRIPTION
Integrated development environment (IDE)	Code Composer Studio™ v8.2
Target MCU	MSP430FR2355
MSP430 Flash Emulation Tool	MSP MCU Programmer and Debugger

3.1.2.2 Customizing the Reference Code

Select the Sensorless_Trap_Parameters_Setup.h file. The parameters at the top of the file can be optimized and are included as the configuration variables. The following section of code shows these parameters:

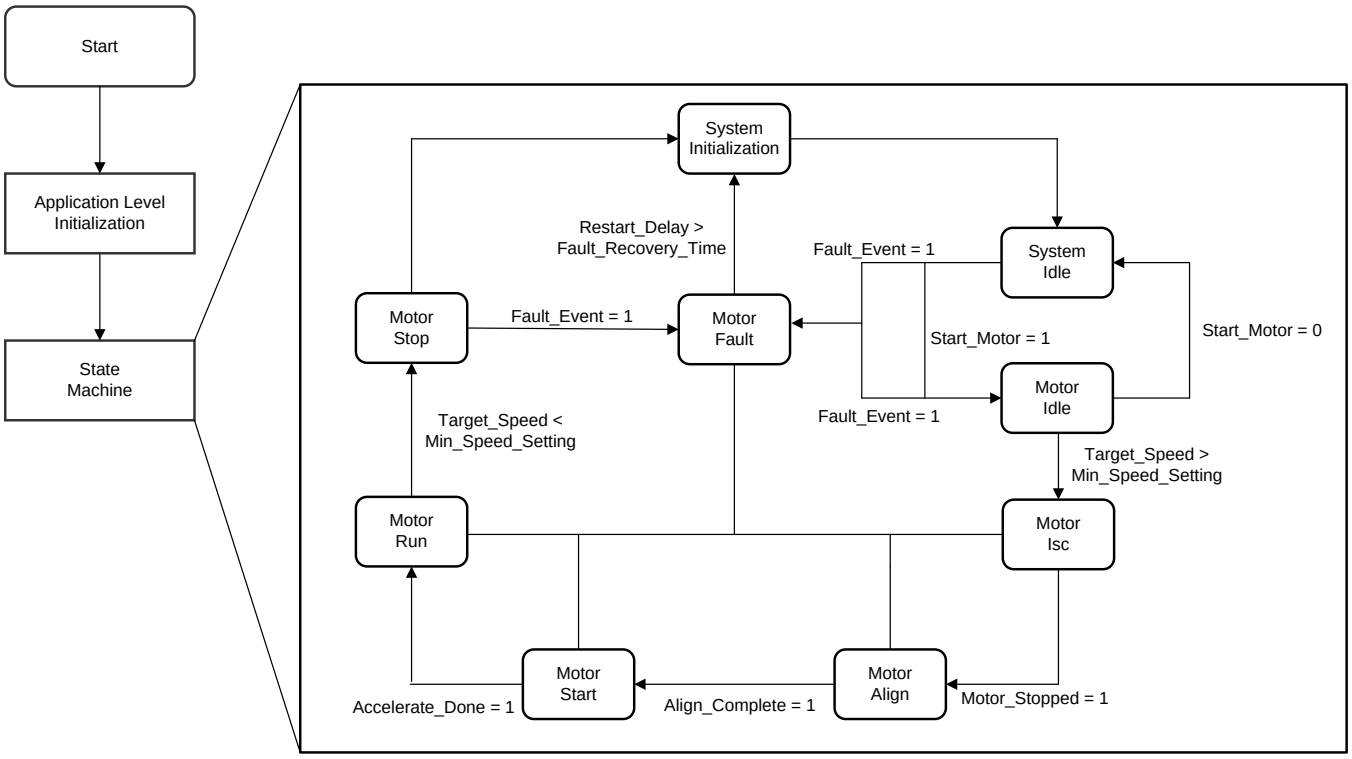
Align User Parameters:

```
// Align mode parameters:
#define ALIGN_SECTOR 1 //Select align commutation sequence (1-6)
#define ALIGN_WAIT_TIME 5000 //[*41us]Number of PWM cycles to Wait during align align time
seconds

//Acceleration parameters:
#define ACCEL_RATE 60 // {Hz/s}
#define ACCEL_STOP 120000 // {mHz}
#define ACCEL_VELOCITY_INIT 20000 // {mHz}

//Closed Loop User Parameters
#define BEMF_THRESHOLD 250 // BEMF Integration threshold according to calculations of BEMF
waveform
#define RAMP_RATE_DELAY 100 // This number controls the acceleration, duty cycle is updated after
( RAMP_RATE_DELAY * 1000) clock cycles
#define RAMP_RATE 1 // This is the change in dutycycle (increment/decrement) for every update
#define COMMUTATION_BLANK_TIME 2 // How many PWM cycles to blank before sampling the BEMF
#define PWM_BLANK_COUNTS 15 // How many clock cycles before the center of PWM the BEMF is sampled
#define PWM_DUTY_THRESHOLD 250 // PWM duty threshold to select PWM on or off window during which
BEMF is monitored

//PWM setting parameters
#define MAX_DUTY_CYCLE 500 // relative to PWM_PERIOD
#define MIN_OFF_DUTY 80 // relative to PWM_PERIOD
#define MIN_ON_DUTY 80 // relative to PWM_PERIOD
#define START_UP_DUTY_CYCLE 60 // relative to PWM_PERIOD
#define PWM_FACTOR 0 // ADC 12 bit to PWM width ratio , by default 0 represents 12 bit scaling

// Fault Dectection Setting Parameters
/* Fault handling setup */ /*ADC Max ref voltage is 3.3v , VCC is scaled by 0.0573 internally
(5/88 Ohms bridge) so that VCC ref input to ADC never cross 3.3v The maximum supply voltage is
57.5v.*/
#define UNDER_VOLTAGE_LIMIT (712) /* Under Voltage set for below 10.0V - (10*4096)/57.5 = 712 */
#define OVER_VOLTAGE_LIMIT (2137) /* Over Voltage set for above 20.0V - (30*4096)/57.5 = 2137 */
#define STALLDETECT_REV_THRESHOLD (1) /* Number of revolutions below which stall fault will be
flagged */
#define STALLDETECT_TIMER_THRESHOLD (200) /* Time in milli seconds above which if motor doesnt
spin min revolutions specified above(STALLDETECT_REV_THRESHOLD) a stall fault is triggered */
#define MOTOR_PHASE_CURRENT_LIMIT (900) /* Defines the max allowed motor phase current in digital
counts . Motor phase current is monitored every electrical cycle , and when ever current limit is
reached an OC fault is Triggered */
#define AUTO_FAULT_RECOVERY_TIME (3000) /* Delay in milli Seconds after which system
reinitialises itself if fault gets cleared */
```

3.1.2.3 Motor Control Flowchart

Figure 13 shows the motor control flow chart. TI offers a firmware example in which a sensorless motor drive state machine is implemented. The user can set and modify motor drive parameters to fine tune the motor control.

Figure 13. Motor Drive Flowchart



3.2 Testing and Results

3.2.1 Test Setup

3.2.1.1 Get Prepared

Table 8 lists the tools and equipment required for creating the test set up in lab. The user can use a different motor, but must adjust the firmware before testing.

Table 8. Materials for Test Setup

MATERIALS	USAGE	COMMENTS
MSP-FETFlash emulation tool	Debug and program	Emulation tool for the MSP430FR2355 MCU
Computer	Debug and program	Code Composer Studio v8.2 installed PC with a USB port
TIDA-010031 board	Main driver board	With firmware programmed
Suction motor	Main motor	100-krpm suction motor with load
DC source	Power supply	30 V, 25 A power source
Signal source	User control input	Waveform generator: square wave, 400 Hz–1 kHz, duty 1%–100% adjustable, 3.3-V output

3.2.1.2 Test Setup Procedure

The following steps show how to set up the test platform in the lab during the test:

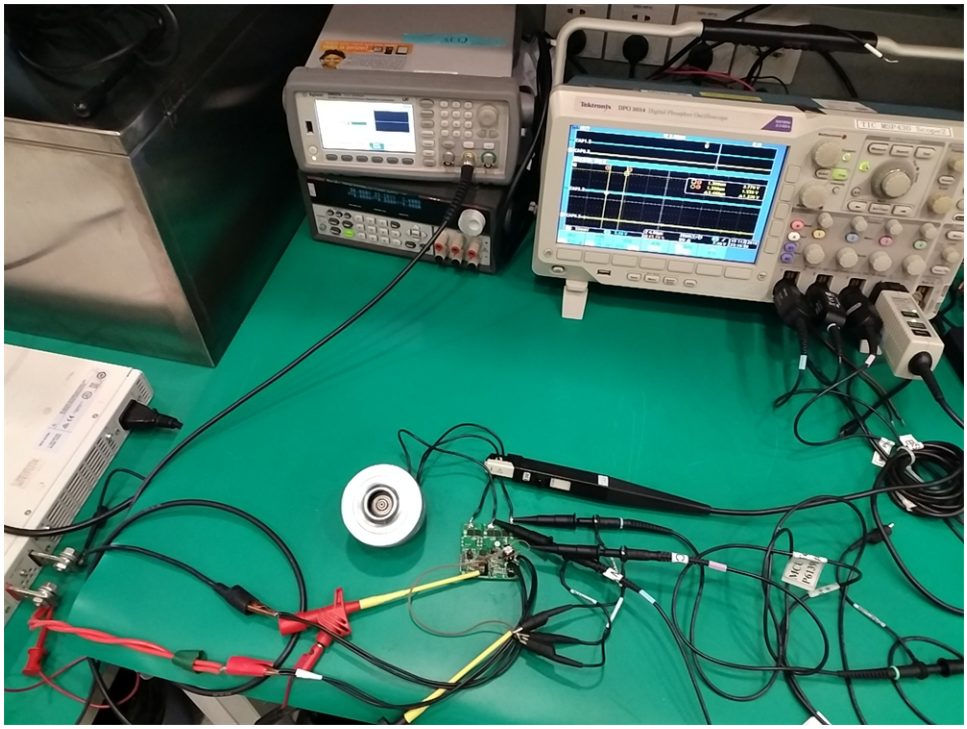
1. Ensure that the firmware has been programmed into the MCU (see Section 3.1.2)
2. Connect the three-phase output U, V, and W to the motor windings.
3. Connect the DC power source to the TIDA-010031 board. Keep the power OFF. Set the power output voltage from 22.4 V to 29.4 V. Set the current limitation up to 25 A.
4. Connect the waveform generator output to P2-PWM and GND.
5. Set the output voltage of the waveform generator to 3.3 V, 1% duty, 400 Hz. Keep output off.
6. Power on the board.
7. Enable the output of the waveform generator.
8. Tune the PWM duty to enable the motor spin and set the different speed. The minimum duty cycle is set to 45% in this reference design. This setting is adjustable in the software. From 45% to 100% duty, the output of the motor can be adjustable.

Figure 14 shows the test setup in the lab, where the reference design is driving the 80-krpm motor. The motor specification is in Table 9.

Table 9. Motor Specification for Test Setup

DESCRIPTION	SPECIFICATION
Voltage	25.2 V for 7 cells Li-ion battery
Current	25 A
Poles	2
Speed range	0–100000 rpm
Phase inductance	7 µH
Phase resistance	0.04 Ω

Figure 14. Test Setup



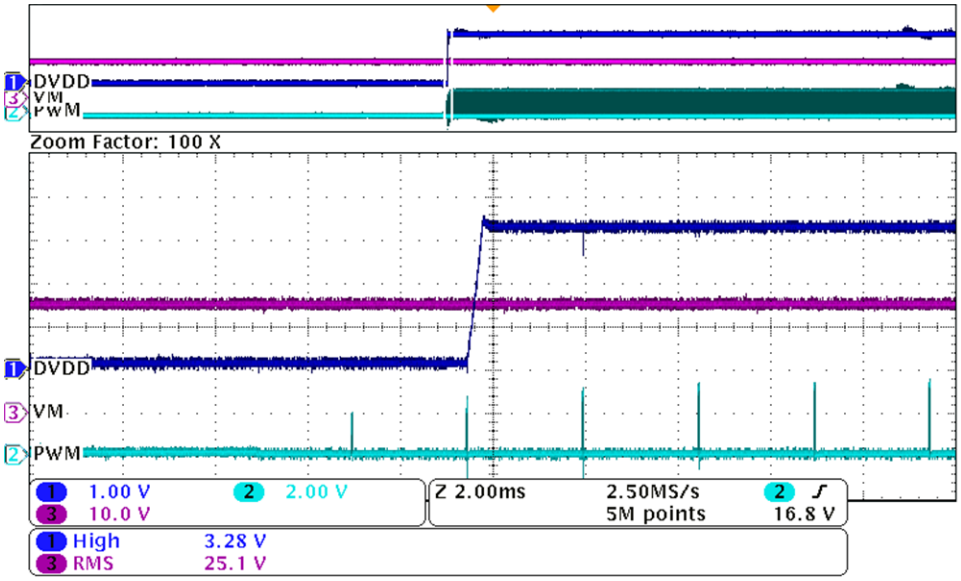
3.2.2 Test Results

The test includes the power supply test, runtime waveform, BEMF detection, acceleration, speed adjustment, and different protections tests.

3.2.2.1 Power Supply

Figure 15 shows the 3.3 V generated from the DRV8320 device. A 3.3-V, 30-mA linear regulator is integrated into the DRV832x family of devices and is available for use by external circuitry. This regulator can provide the supply voltage for a low-power MCU or other circuitry supporting low current.

Figure 15. 3.3-V Power Supply



When the PWM input, the DRV8320H will be enabled with the LDO output. Table 10 shows the static power consumption.

Table 10. Static Power Consumption

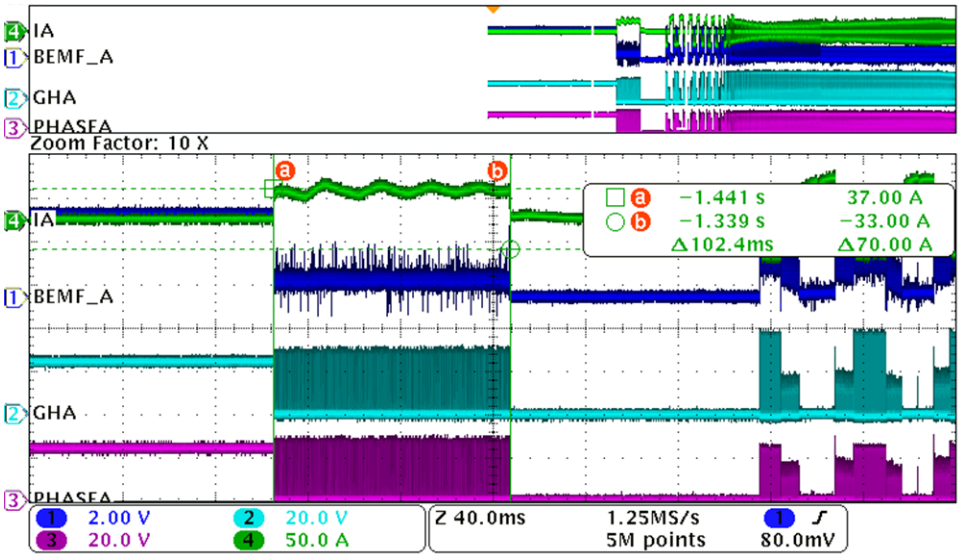
MODE	POWER CONSUMPTION
Sleep mode	22 µA
Wakeup mode	14.3 mA

3.2.2.2 Motor Drive

3.2.2.2.1 Align Mode

Figure 16 shows the motor align state. Before start the spin, motor will be in align mode to initialize the first position.

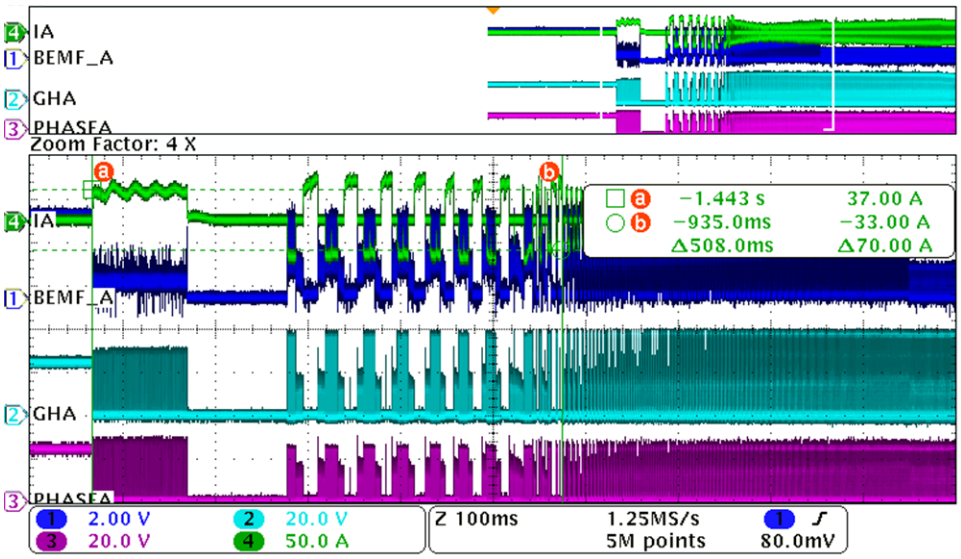
Figure 16. Align Mode



3.2.2.2.2 Force Mode

Figure 17 shows the motor in force state. During the period, the motor starts spin and the commutation is open-loop without the BEMF detection.

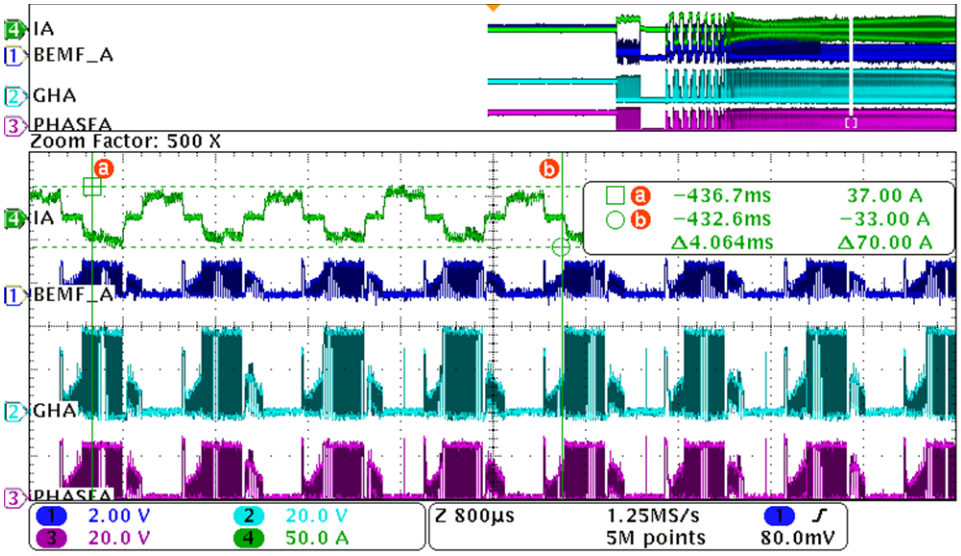
Figure 17. Force Mode



3.2.2.2.3 Steady Mode

Figure 18 shows the motor in steady state. During the period, motor commutates by the BEMF feedback.

Figure 18. Steady Mode

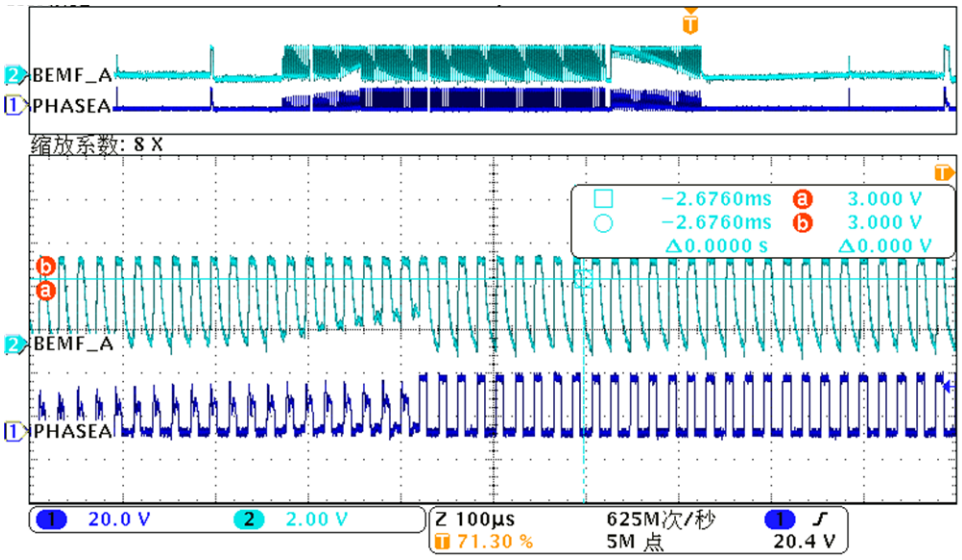


3.2.2.3 BEMF Detection

3.2.2.3.1 BEMF Detection at PWM off

Figure 19 shows the U phase BEMF signal from the MCU pin. The zero cross signal can be detected clearly by the MCU.

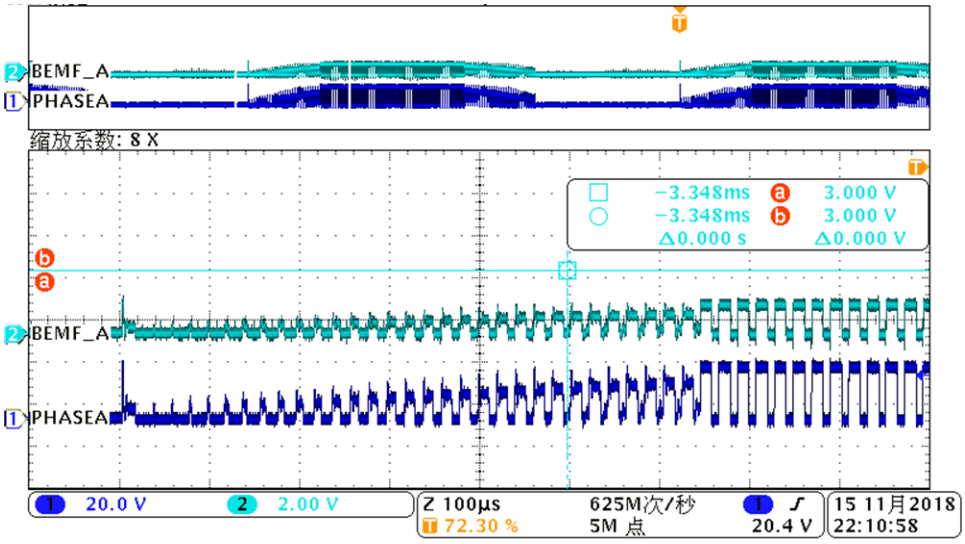
Figure 19. BEMF Detection at PWM off



3.2.2.3.2 BEMF Detection at PWM on

Figure 20 shows the U phase BEMF signal from the MCU pin. The zero cross signal can be detected clearly by the MCU.

Figure 20. BEMF Detection at PWM on

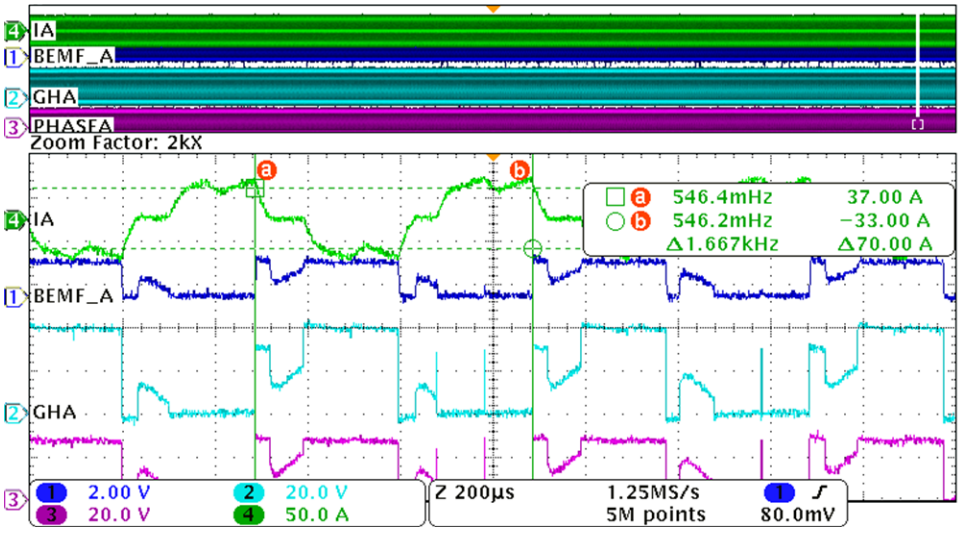


3.2.2.4 Speed Test

3.2.2.4.1 Full Duty

Figure 21 shows the phase voltage, phase current, high-side gate drive and BEMF at full-duty output.

Figure 21. Full-Duty Run

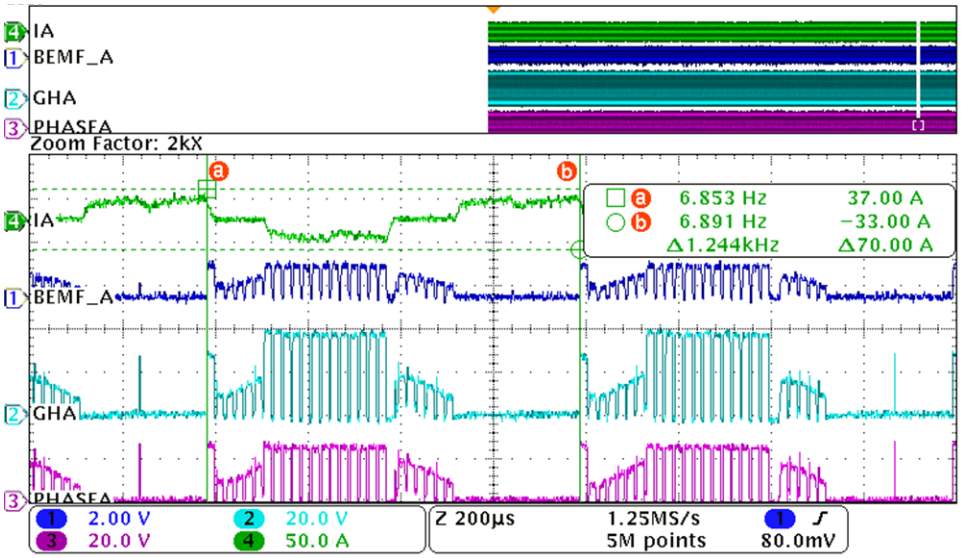


The commutation frequency is 1667 Hz. The motor speed is 100 krpm.

3.2.2.4.2 75% Duty

Figure 22 shows the phase voltage, phase current, high-side gate drive and BEMF at 75% duty output.

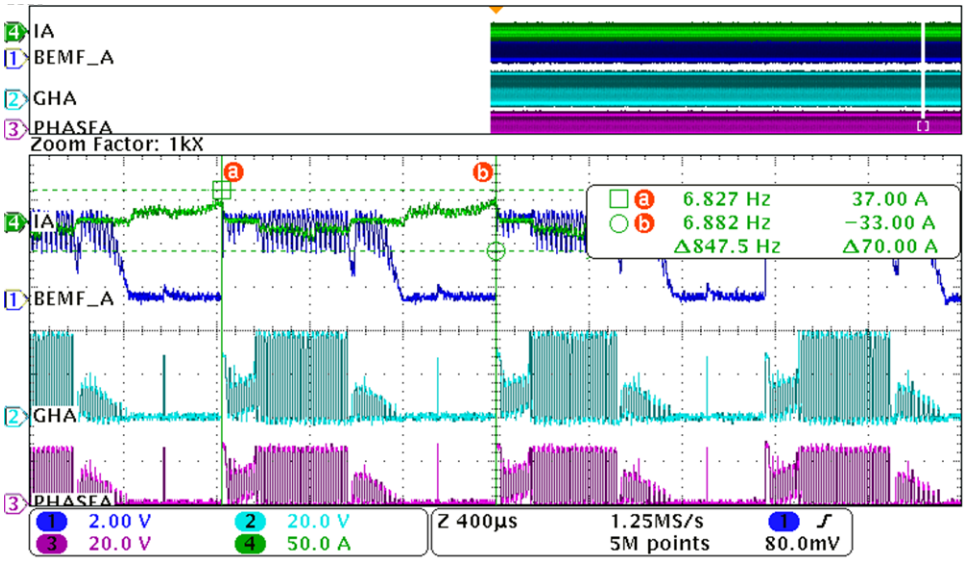
Figure 22. 75% Duty Run



3.2.2.4.3 50% Duty

Figure 23 shows the phase voltage, phase current, high-side gate drive and BEMF at 50% duty output.

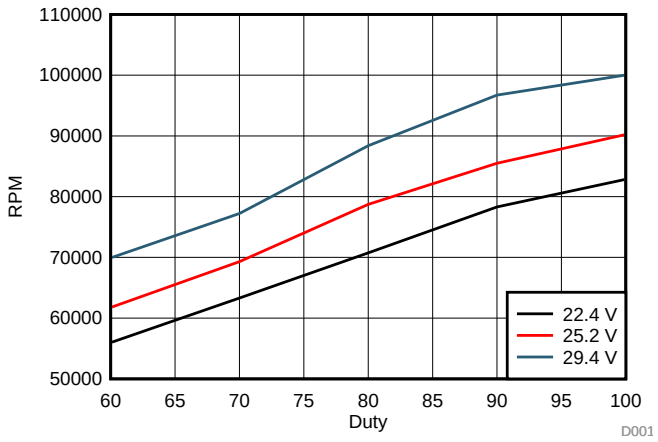
Figure 23. 50% Duty Run



3.2.2.4.4 Speed Test Result

The motor speed varies under different input voltages. By testing the speed at different voltages, the following speed voltage graph is obtained (see Figure 24).

Figure 24. Speed-Voltage Graph



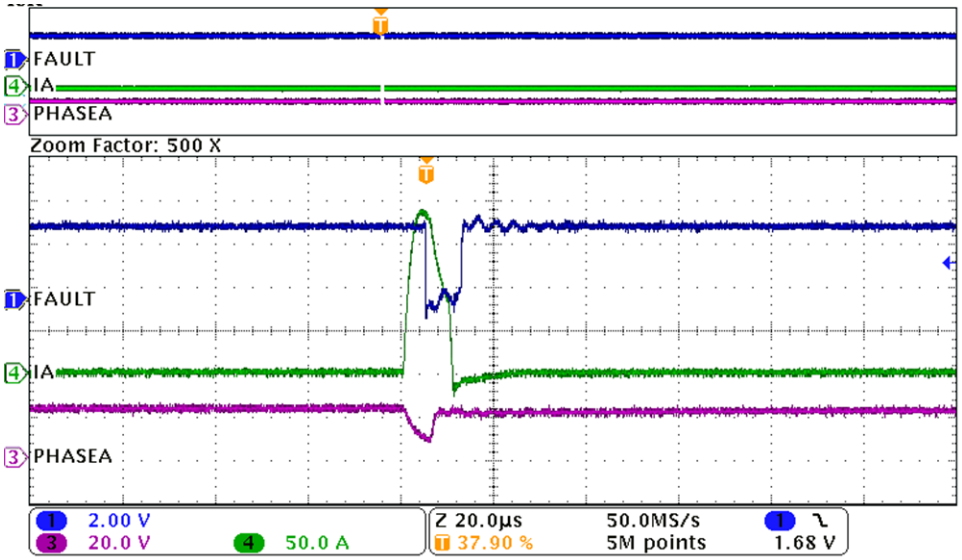
3.2.2.5 Protections

3.2.2.5.1 Overcurrent Protection

Figure 25 shows overcurrent protection. A MOSFET overcurrent event is sensed by monitoring the V_{DS} voltage drop across the external MOSFET $R_{DS(on)}$.If the voltage across an enabled MOSFET exceeds the V_{VDS_OCP} threshold for longer than the t_{OCP_DEG} deglitch time, a VDS_OCP event is recognized and the DRV8320 device executes the necessary action as per the setting. On the DRV8320H device, the V_{VDS_OCP} threshold is set with the VDS pin, the t_{OCP_DEG} is fixed at 4 µs. In the TIDA-010031 design, the VDS_ON resistance of the CSD18514Q5A is 4.1 mΩ. The V_{VDS_OCP} is set to 0.6 V. So the protection point is:

$$I = \frac{V_{VDS\_OCP}}{R_{VDS\_ON}} = \frac{0.6}{0.0041} = 146 \ A \quad (10)$$

Figure 25. Overcurrent Protection



3.2.2.5.2 Overvoltage, Undervoltage Protection

The overvoltage protection is process by software. When input voltage is higher than the software setting, the protection occurs. The parameters can be changed from:

```
#define UNDER_VOLTAGE_LIMIT (712)
#define OVER_VOLTAGE_LIMIT (2137)
```

Figure 26. Undervoltage Protection

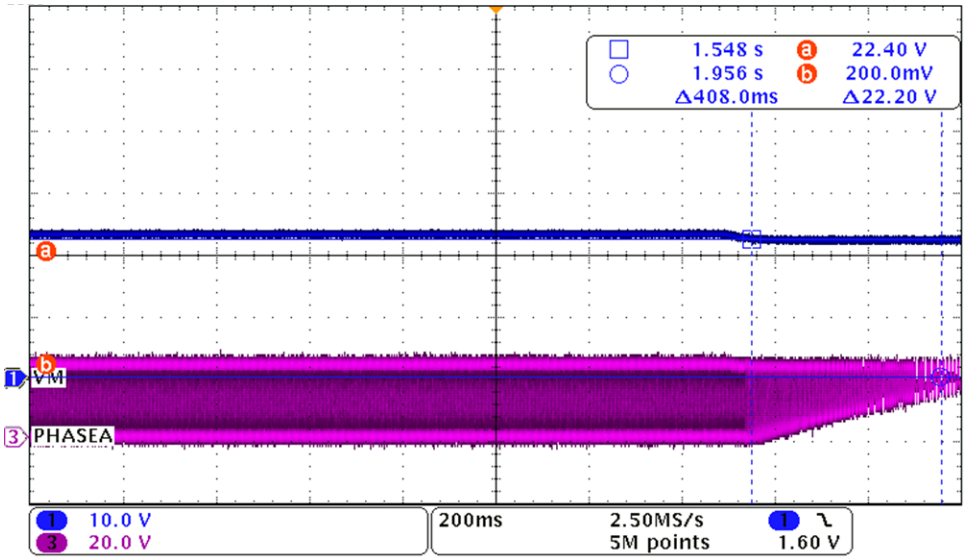
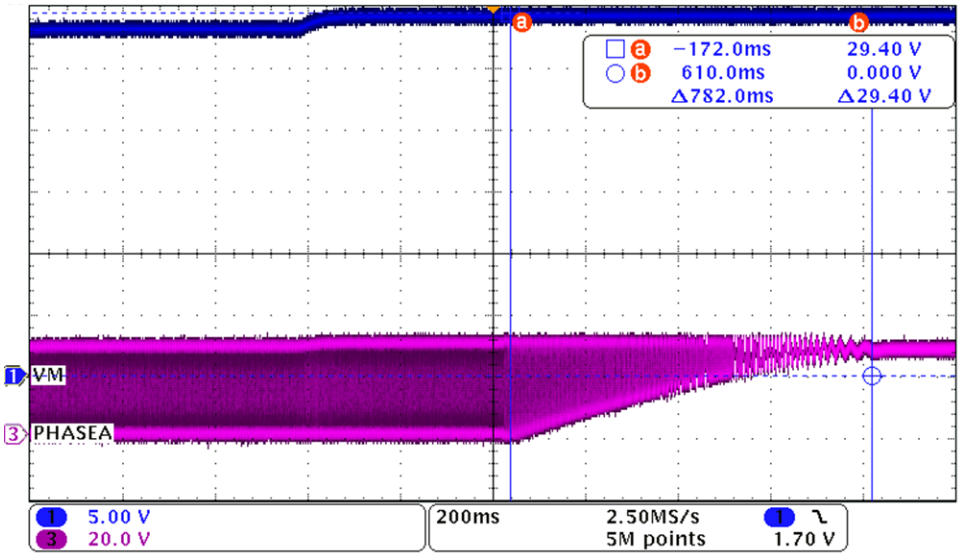


Figure 27. Overvoltage Protection

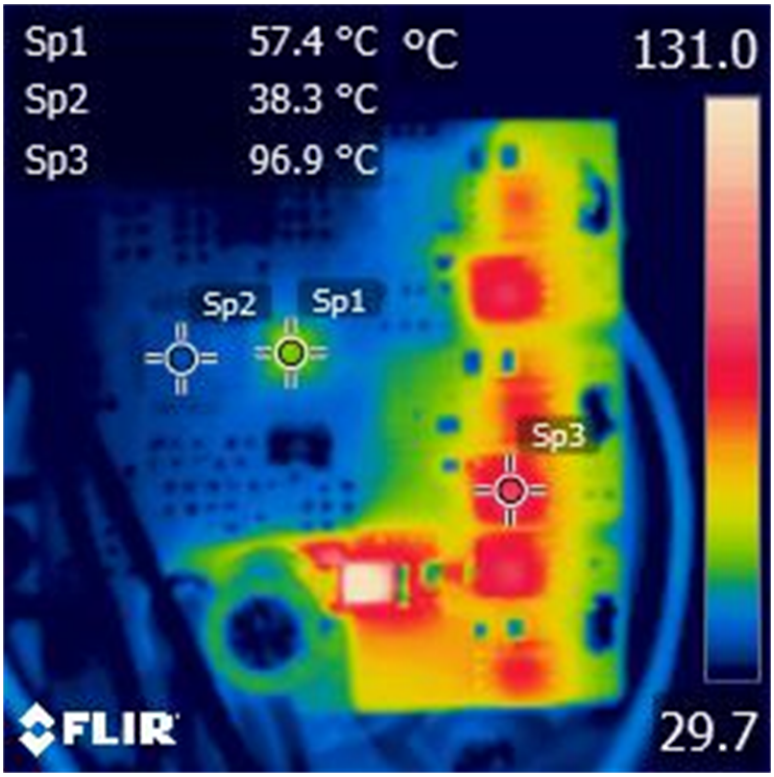


3.2.2.6 Thermal Test

To better understand the temperature of power components and the maximum possible operating temperature, the thermal images were plotted at room temperature (25°C) with a closed enclosure, motor generated airflow, and at 100% duty output conditions.

Figure 28 shows the thermal image for the top side of the board. The airflow of the motor is from 10 cm height onto the board.

Figure 28. Thermal Image



4 Design Files

4.1 Schematics

To download the schematics, see the design files at TIDA-010031.

4.2 Bill of Materials

To download the bill of materials (BOM), see the design files at TIDA-010031.

4.3 PCB Layout Recommendations

The PCB layout is one of the critical factors in a suction motor drive design because the systems are expected to deliver a significant amount of power with a compact design. The PCB is dense because space is limited in vacuum cleaner applications. The layout of the PCB design must be planned to avoid cross-coupling as a result of large voltages and current transients that occur during the motor operation. The following layout recommendations are not comprehensive, but are based on standard practice. Users must optimize the design according to each application.

Electrolytic Capacitor Selection and Placement

The electrolytic capacitor in an inverter is subjected to transients during each PWM cycle to deliver the required current. The capacitor must be sized so it can deliver the required current at full low. Selecting a capacitor with a low series resistance contributes to a lower loss and less heat dissipation in the capacitor, extending the lifetime of the capacitor and the vacuum tool. Selecting a capacitor with a higher charge-discharge cycling contributes to improved system life. The electrolytic capacitor must be placed sloe to the energy source, minimizing the distance between the capacitor and the MOSFET power stage. The capacitor sizing must be selected based on parasitic inductance between the battery and the motor drive board, allowable DC voltage ripple at the rated power, motor control method, and braking methods.

Ground Routing

Power ground (PGND) and signal ground must be kept separate and tied together at the ground connection to the power source. Tying the PGND and signal ground together at only one point, minimizes possible signal path-ground bouncing that results from PWM switching in the power stage. High current-carrying paths must be properly sized to deliver the required amount of current.

4.3.1 Layout Prints

To download the layer plots, see the design files at TIDA-010031.

4.4 Altium Project

To download the Altium Designer® project files, see the design files at TIDA-010031.

4.5 Gerber Files

To download the Gerber files, see the design files at TIDA-010031.

4.6 Assembly Drawings

To download the assembly drawings, see the design files at TIDA-010031.

5 Software Files

To download the software files, see the design files at TIDA-010031.

6 Related Documentation

1. Texas Instruments, *MSP430™ Hardware Tools User's Guide*
2. Texas Instruments, *MSP430FR4xx and MSP430FR2xx Family User's Guide*
3. Texas Instruments, *BOOSTXL-DRV8320x EVM User's Guide*

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7 Terminology

PWM— Pulse width modulation

BLDC— Brushless DC motor

PMSM— Permanent magnet synchronous motor

MCU— Microcontroller unit

FETs, MOSFETs— The metal–oxide–semiconductor field-effect transistor

ESD— Electrostatic discharge

rpm— Rotations per minute

RMS— Root mean square

8 About the Author

Fan (Hawken) Li is a systems engineer at Texas Instruments, where he is responsible for developing reference design solutions for the industrial segment. Hawken brings to this role his extensive experience in home appliances, including motor driver, EP, analog circuit design, and so forth.

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