Lit Number: TIDA-00620

Date: 8/26/2015

TI Designs

12V to 24V, 27A Brushed DC Motor Reference Design

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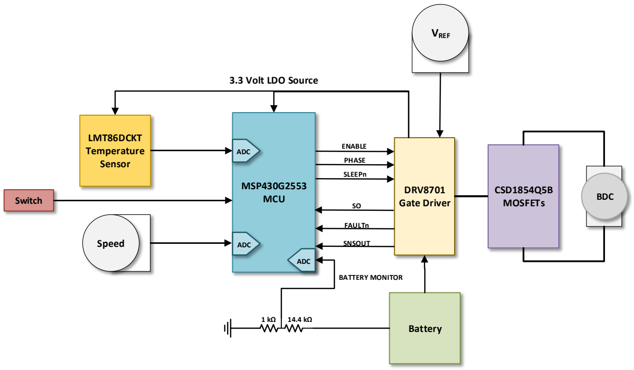
Design Resources

TIDA-00620	Design Folder
DRV8701	Product Folder
MSP430G2553	Product Folder
CSD18540Q5B	Product Folder
LMT86DCKT	Product Folder
Understanding IDRIVE and TDRIVE	Tools Folder

TI E2E™ Community

Ask The Analog Experts

Block Diagram



Design Features

- 343 Watt RMS Power Stage With MSP430G2553 Control Scheme
- Tested to Operate with 18 Volt External Battery
- Delivers up to 27.47 A_{RMS} Continuous Motor Current With No External Heat Sinking or Air Flow Aids
- Dual Layer, Small PCB Form Factor of 76.3 mm by 38.1 mm
- Utilizes TI's 60 V N-Channel NexFETs With an R_{DS} of 1.8 mΩ Packaged In a SON 5-mm × 6-mm footprint
- User Configurable Gate Drive Current Allows for Ease in Adapting to Custom MOSFET Selection

Featured Applications

- Industrial Brushed-DC Motors
- Robotics
- Power Tools
- Handheld Vacuum Cleaners
- Home Automation
- Industrial Pumps and Valves

Board Image

1 Key System Specifications

PARAMETER	SPECIFICAION			DETAILS
Max PCB Temperature	Maximum PCB temperature measured during motor load testing		127.7° C	See Section 8.7
Maximum PCB Current	Maximum amount of current run through PCB during motor load testing		27.47 A	See Section 8.7
3.3V LDO	Typical sustained 3.3 V supply measured on DVDD pin of DRV8701		3.3 V	See Section 8.1
4.8 V LDO	Typical sustained 4.8 V supply measured on AVDD pin of DRV8701		4.8 V	See Section 8.1
Current Limiting	Limiting current supplied to motor using VREF voltage measurement			See Section 8.5
Dead Time	Forcibly injected settling time between when opposite signals on the same side of the H-Bridge change state		380 ns	See Section 8.3
Direction Switch Debounce	Direction toggle switch routed through MSP430G2553 to debounce the state change prior to being routed to the DRV8701			See Section 8.4
Sense Amplifier Voltage	Amplifies the voltage drop across the sense resistor at the base of the H-Bridge and is measured on SO pin of DRV8701			See Section 8.6
Thermal Information	No motor load current of 2.85 Amps and maximum load current of 27.47 Amps	36.6° C	127.7° C	See Section 8.7
RMS Motor Power	No load at 2.85 Amps and maximum load at 27.47 Amps	28.25 W	343.4 W	See Section 8.8
IDRIVE	68 kΩ to AVDD Pin setting Source Current and Sink Current	150 mA	300 mA	See Section 2.4
Microcontroller	Texas Instruments MSP430G2553 programmed in circuit using a four wire SPI interface			See Section 4.7
MOSFETs	Four Texas Instruments N-Channel 60 V NexFETs			See Section 4.10
Driver	Texas Instruments DRV8701 Brushed DC Motor Driver			See Section 4.6

Figure 1. Key System Specifications

2 System Description

Brushed motors are a relatively popular option for motor designs because of their low price and simple control scheme. A brushed motor has a wire-wound rotor and permanent magnet stator. The commutation of the motor is achieved using conductive rings that are connected to the rotor using brushes that scrape against the commutator rings. This allows the direction of current through the motor to change based on the orientation of the brushes and different commutation rings. Utilizing an H-Bridge allows for easy direction and speed control changes to be applied quickly and efficiently to the brushed DC motor.

An electronic drive is required to control the motor currents in a brushed DC motor. The electronic drive circuit consists of:

- A power stage with two-phase inverter meeting the required power capability
- Microcontroller to implement the motor speed commands and fault handling
- Current sensing for motor startup / stall protection
- Gate driver for controlling the two-phase inverter
- Power supply for microcontroller and other low voltage devices

2.1 PWM and Phase Control

In a BDC motor, a simple Pulse Width Modulation (PWM) signal can be used to control the speed of the rotor. As the duty cycle of the PWM signal changes the average voltage delivered to the motor is varied allowing for different rotor speeds without burning up power through a resistive potentiometer. The direction of the motor is then controlled using a two-phase inverter that allows the direction of current supplied to the motor to be changed quickly using four independently controlled MOSFETs as shown in **Figure 2** below.

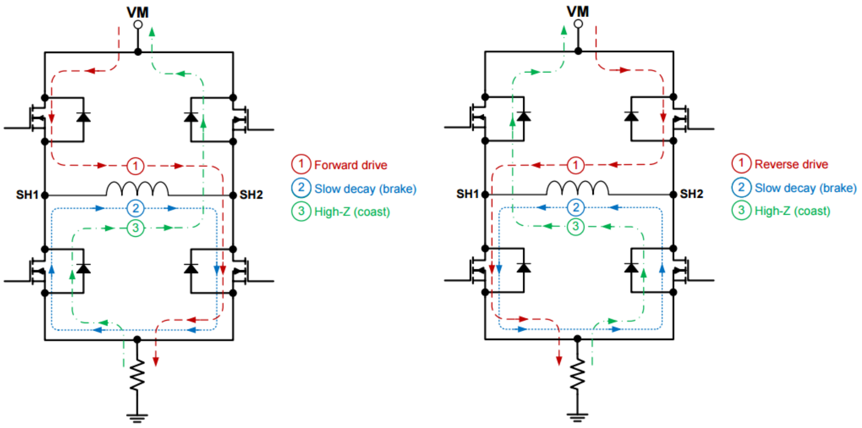


Figure 2. Two-Phase Inverter Current Directions

The PWM signals used to control the motor are generated using the MSP430G2553. By sampling the wiper voltage of the Speed potentiometer and comparing that sample to Timer_A of the MSP430 a PWM signal with varying duty cycle and a constant switching frequency is created as shown in **Figure 3** below.

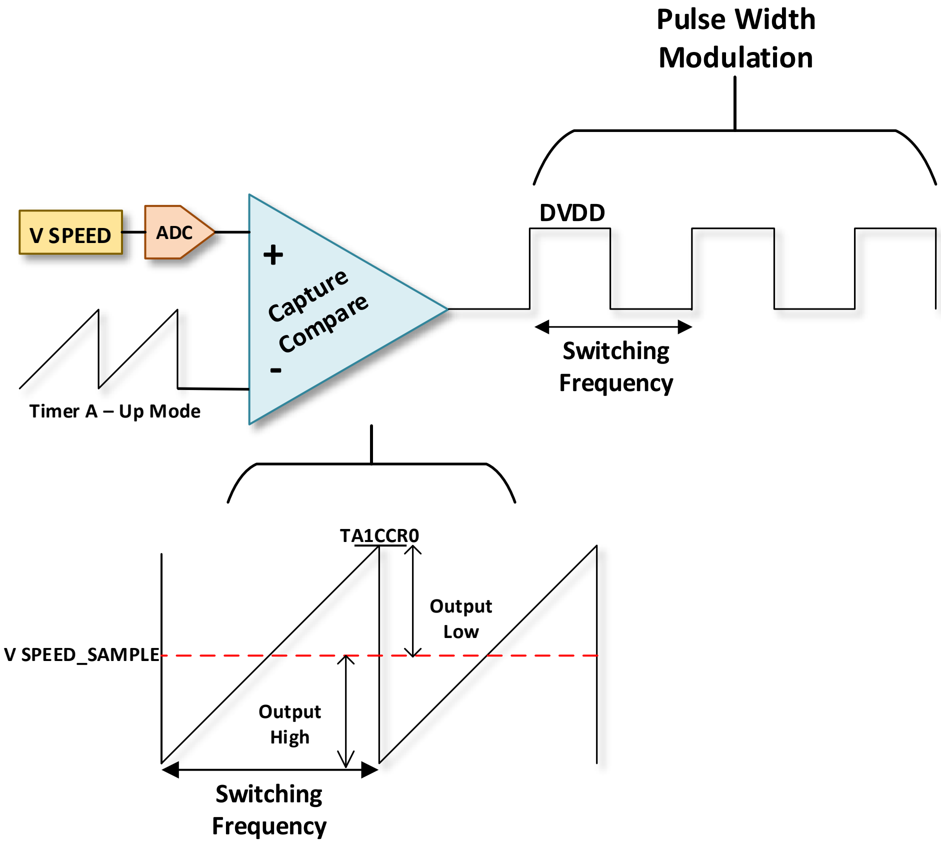


Figure 3. MSP430G2553 PWM Timer_A Scheme

2.2 Current Chopping Using V_{REF}

To control the current through the motor a sense resistor is placed at the base of the H-Bridge between the source of both low side MOSFETs and ground. An internal operational amplifier in the DRV8701 is then connected across the sense resistor and ground enabling the driver to measure the voltage drop and amplify it by a scaling factor A_V to generate a larger amplitude value. This voltage is referred to as V_{SO} and is compared to the voltage set on the V_{REF} pin; if V_{SO} is greater than or equal to V_{REF} the bridge stops generating gate signals until the voltage has dropped below V_{REF}, if V_{SO} is less than V_{REF} the bridge will continue to generate gate signals. V_{SO} relates to the current running through the motor using **Equation 1**:

$$V_{SO}=A_V * (I_{DRIVE} * R_{SENSE}) \quad \textbf{(1)}$$

In the event that V_{SO} is greater than or equal to V_{REF} the output of the SNSOUT Pin is pulled low to indicate a driver fault and the DRV8701 is current chopping the gate signals. While V_{SO} is less than V_{REF} the output of the SNSOUT pin can be pulled logic high using an external pull up resistor indicating that the device is operating in a typical drive current state. An example of a driving current scheme with current chopping is shown in **Figure 4** below.

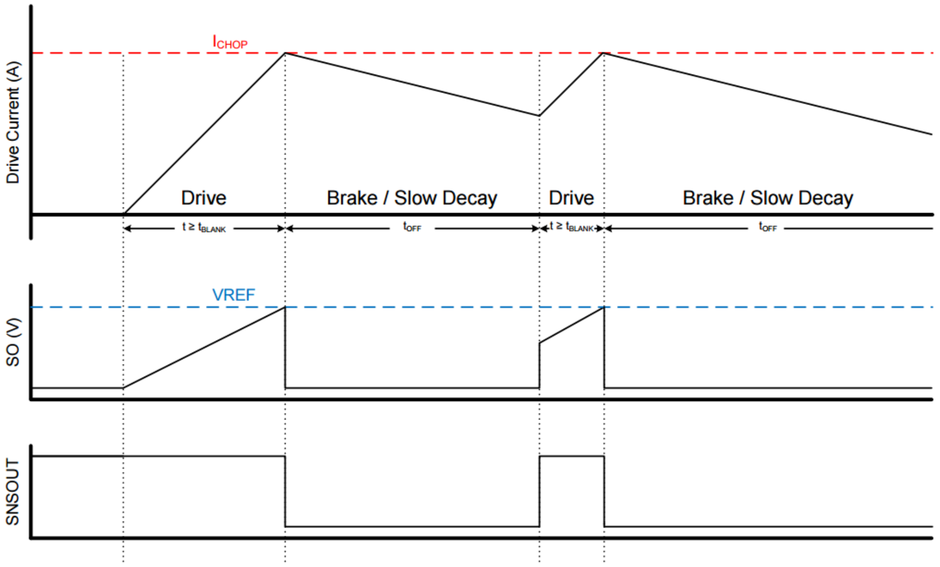


Figure 4. IDRIVE Current Chopping

In **Figure 4** above the motor is being initially driven and the current draw from the supply increases. Once the voltage measured across the sense resistor (V_{SO}) is equal to or greater than V_{REF} the SNSOUT Pin is pulled low and the output gate signals are cut off for the remainder of that PWM switching interval. On the next PWM switching interval the induction of the motor still retains some of the current run through the motor on the last drive cycle resulting in the driver spending a smaller amount of time driving the motor before V_{SO} is equal to V_{REF} and the gate signals to the bridge are cut off.

2.3 IDRIVE

Using the DRV8701 to provide gate signals to the MOSFETs in the two-phase inverter allows for the selection of I_{SINK} and I_{SOURCE} currents using the IDRIVE settings. The goal in controlling I_{SOURCE} and I_{SINK} is to tune the amount of current supplied to the gates of the four MOSFETs in the H-Bridge and achieve the desired slew rate between active and saturated regions without supplying excess current to the device. If the slew rate of the MOSFETs is too low the device will spend too much time in the Miller Region shown in **Figure 5** below.

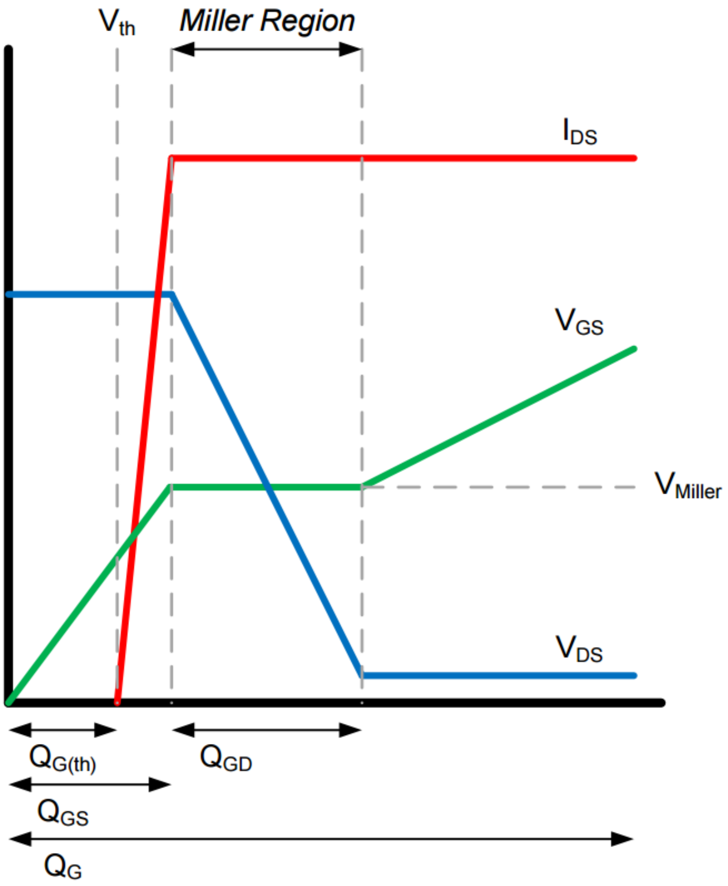


Figure 5. Miller Region of Typical MOSFET

While the device is operating in the Miller region the R_{DS} value of the MOSFET is changing from R_{DS_OFF} to R_{DS_ON} while the current is kept constant. Having a higher resistance as a large amount of current runs through the device results in the generation of heat for the period of time the device is operated in the Miller region. Properly matching the I_{SINK} and I_{SOURCE} currents to the gate capacitances of the selected MOSFETs generates a faster slew rate which results in less time spent in the Miller region and less heat dissipated through the device.

3 Block Diagram

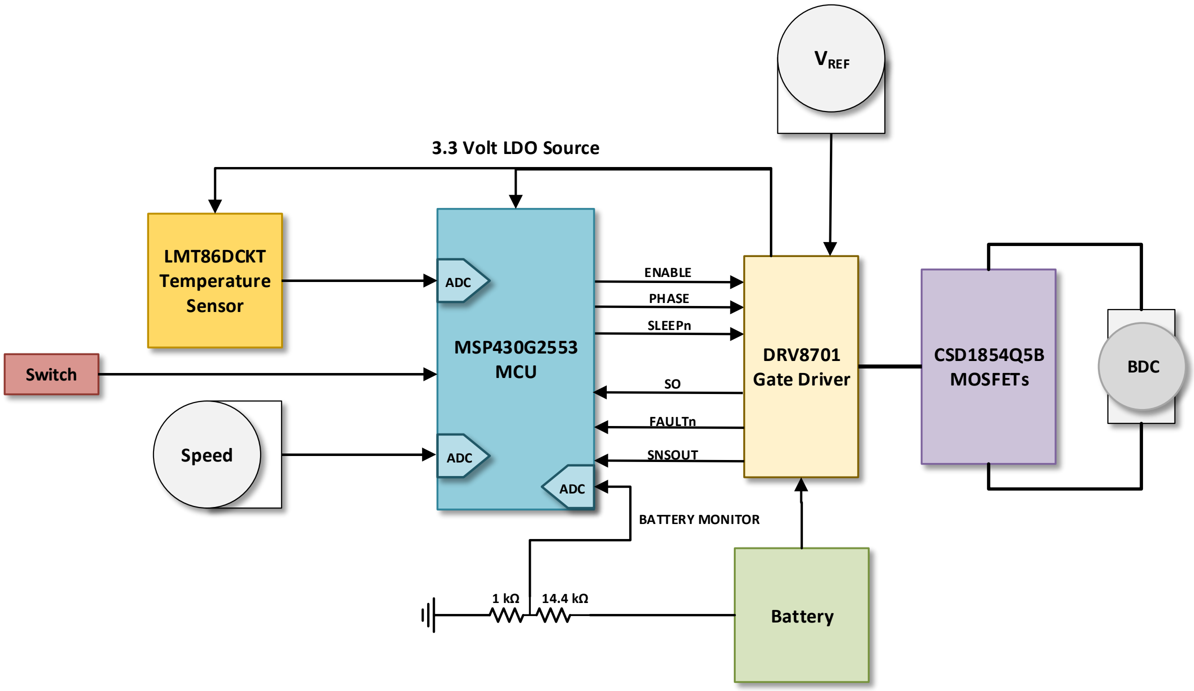


Figure 6. System Block Diagram

3.1 Highlighted Products

3.1.1 DRV8701ERGER

The DRV8701 is a single H-bridge gate driver that uses four external N-channel MOSFETs oriented in a two-phase inverter to drive one bidirectional brushed DC motor. The Phase / Enable (DRV8701E) control scheme allows simple interfacing to microcontroller circuits. An internal sense amplifier allows for adjustable current control using an external sense resistor. The gate driver includes the ability to control the winding current using fixed off-time PWM current chopping. The DRV8701 drives both high- and low-side FETs with 9.5-V VGS gate drive sourced from an integrated charge pump. The gate drive current for all external FETs can be configured with a single external resistor on the IDRIVE pin.

3.1.2 MSP430G2553IPW20

The MSP430G2553 is an ultra-low-power microcontroller that consists of many different device features. Some of these features include five different low-power modes, a 16-bit RISC CPU, 16-bit registers, and constant generators. Using the Digitally Controlled Oscillator (DCO) the MSP430G2553 can wake up from low-power modes in less than 1 µs.

3.1.3 CSD18540Q5B

The CSD18540Q5B is a 60 V N-Channel MOSFET with an R_{DS} rating of 1.8 mΩ. The device is desired for power conversion applications because of its design for minimized losses and small SON 5-mm × 6-mm footprint.

3.1.4 LMT86DCKT

The LMT86DCKT is a precision CMOS temperature sensor that utilizes an analog output voltage that is linearly and inversely proportional to temperature. This device can operate down to a 2.2 V supply with 5.4 µA making it an ideal device to use with battery operated applications.

4 System Design Theory

4.1 Board Layout

The PCB created for this application has two stages; the power stage and the control stage. The control stage consists of the MSP430G2553 and the DRV8701 along with the V_{SPEED} and V_{REF} potentiometers and direction microswitch. To flash the MSP430 with firmware changes a JTAG header is included to allow for SPI-by-wire in-circuit flashing. The power stage on this board includes four NexFETs, two 470µF bulk capacitors, R_{SENSE}, and a 30 A / 60 V fuse. This board was printed with 2 oz. copper and approximately 93% of the board was poured with copper.

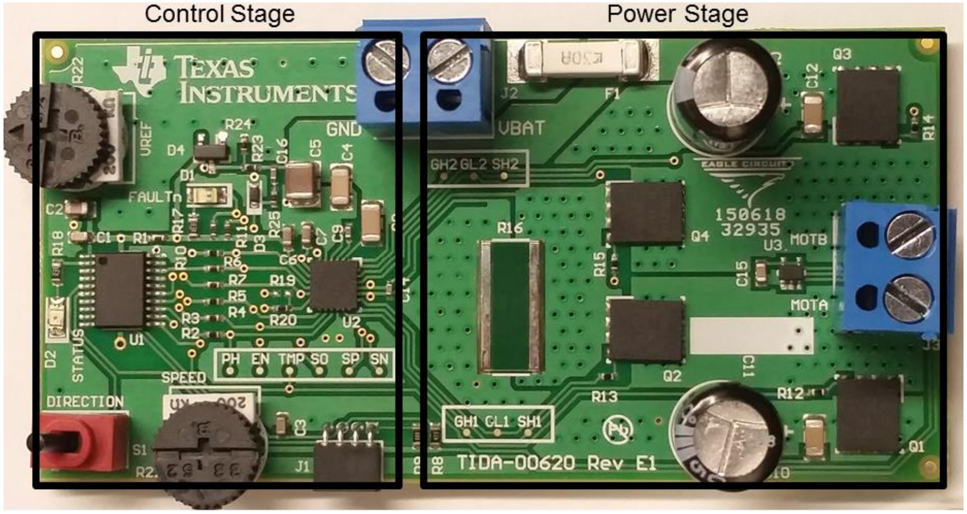


Figure 7. Board Stage Layout

The power stage takes up a large footprint on this board beause the copper planes on the PCB are used to descipate the heat generated by the sense resistor and four power MOSFETs instead of using an external finned heat sink. Each of these planes has a large number of vias linking the top plane with the bottom plane to help with curernt flow and move heat to the bottom plane to help with dissipation. The four NexFET MOSFETs have a R_{DS_ON} of 1.8 mΩ and the maximum amount of sustained current drawen in testing this PCB design was 27.47 Amps. Using equation **2** and **3** below each active MOSFET was dissipating approximately 1.358 Watts of power while the sense resistor was dissipating approximately 3.773 Watts.

$$P_{MOSFET\_DISSIPATED} = (27.47\ A)^2 \times\ 1.8\ \text{m}\Omega = 1.358\ \text{Watts} \quad \textbf{(2)}$$

$$P_{RSENSE\_DISSIPATED} = (27.47\ A)^2 \times 5\ \text{m}\Omega\ =\ 3.773\ \text{Watts} \quad \textbf{(3)}$$

4.2 Battery Monitoring Layout

Battery Monitoring in this application is achieved using a voltage divider to scale the voltage present on the Vbat monitor trace to a value safe for the ADC of the MSP430G2553 to sample and continuously monitor. The two diodes provide external paths for conditions where the voltage is too large or reversed in polarity. In the case of an overvoltage condition the diode connected between the Vbat monitor trace and DVDD will start conducting. The 13.3 kΩ resistor will be in series with the current path and limit the amount of current allowed to flood in to the DVDD rail. This condition would be superseded by the MSP430G2553 flagging the voltage and pulling down the SLEEPn pin, thus causing the DRV8701 to shut off and stop the LDO producing 3.3 V on DVDD. If the polarity of the battery were to be flipped the diode connected between Vbat monitor and ground would conduct and stop the reverse current condition from causing harm throughout the VM current path.

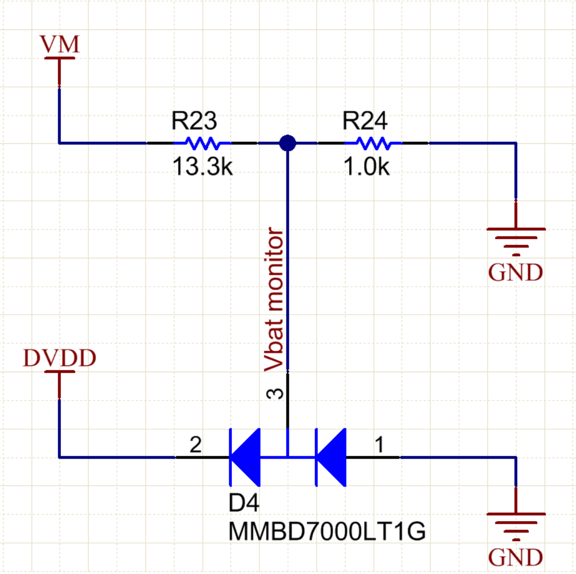


Figure 8. Battery Monitoring

4.3 SLEEPn Pin Startup

Once the device has been successfully powered on the RC circuit below will begin charging up from the V_M supply while the zener diode holds the voltage to 3.3V for the duration of the charge time of the RC circuit formed by C_{16} and R_{25}. The charge time before the RC circuit voltage drops below the zener voltage is calculated using **Equation 4** below.

$$t_{STARTUP} = -(\ln(V_{ZENER} / V_M)) * R_{25} * C_{16} = -(\ln(3.3\ V / 18\ V)) * 1\ k\Omega * .47\ \mu F = 797.33\ \mu s \quad \textbf{(4)}$$

During this time the DVDD LDO is turned on in the DRV8701 driver allowing for the MSP430G2553 to be powered on. As soon as the MSP430G2553 is powered on the GPIO pin connected to SLEEPn is pulled high for the duration of the devices operation.

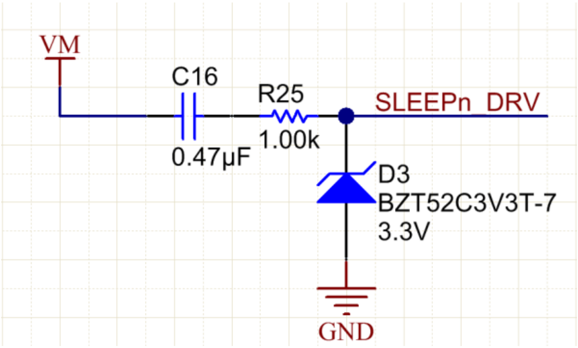


Figure 9. SLEEPn Pullup Pin

4.4 Temperature Sensor

The temperature sensor is placed between the two legs of the H-Bridge to allow for the most direct measurements of temperature between the four bridge MOSFETs. Placing the temperature sensor here allows for real time temperature interrupts that the driver would not be able to detect. This device outputs an analog voltage that is then measured using the MSP430G2553's ADC and if an internal interrupt is flagged as an over temperature condition the PWM output of the microcontroller is stopped until the temperature has dropped.

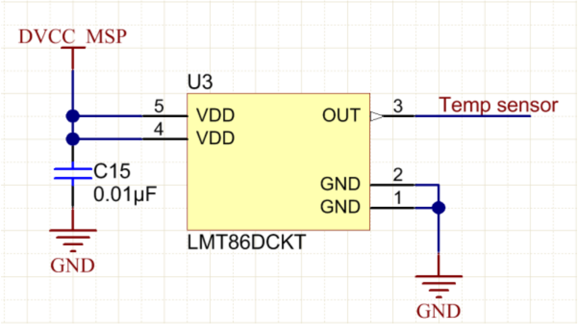


Figure 10. Temperature Sensor Schematic

4.5 H-Bridge

The N-Channel NexFET MOSFETs are used in each of the four switching positions in the H-Bridge as shown in **Figure 11** below. 0 Ω resistors are placed between the gate of each MOSFET and gate drive pins of the DRV8701 to allow for each MOSFET to be disconnected from the driver by quickly removing the resistor. Connections to the sense amplifier pins of the DRV8701 are tied to the drain and source of each corresponding MOSFET within the bridge to aid the driver in measuring V_{DS} of each of the four MOSFETs. R_{SENSE} also has a dedicated sense amplifier that allows the DRV8701 to monitor the voltage drop across R_{SENSE} and use this value to monitor the motor current. By measuring V_{DS} of each MOSFET the DRV8701 can protect against over current events and will flag a fault condition when V_{DS} is above 800 mV.

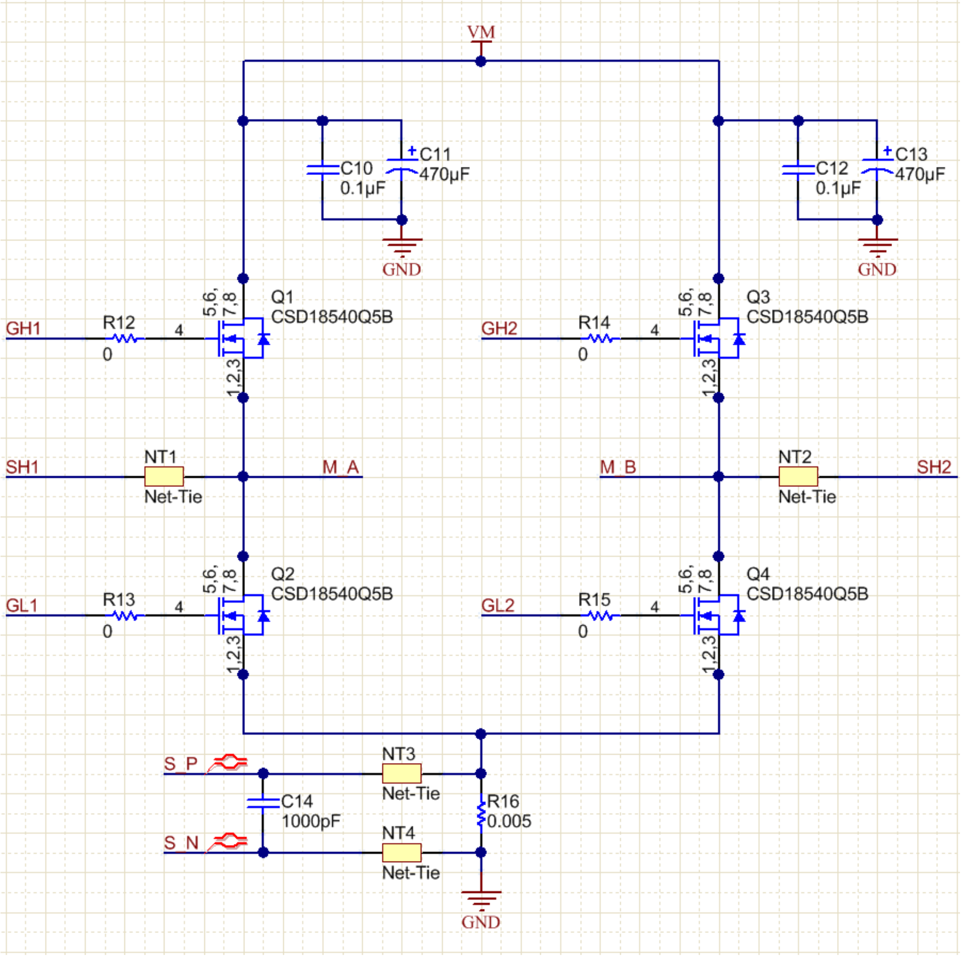


Figure 11. H-Bridge Schematic

4.6 DRV8701

The DRV8701 schematic below in **Figure 12** illustrates the placement of stabilization capacitors connected to the outputs of each LDO regulator and the DRV8701 supply voltage V_M. Both the 3.3 V and 4.8 V internal regulators are Low-Dropout (LDO) regulators which result in switching transients that need to be properly stabilized in order for the output voltage rail to be usable by other devices. The supply voltage V_M is tied to both a large bulk capacitor C_5 and a smaller capacitor C_4. This rail requires a large bulk capacitance close to the DRV8701 because it is shared with the switching components of the H-Bridge, meaning it is susceptible to possible voltage drooping that could damage the driver.

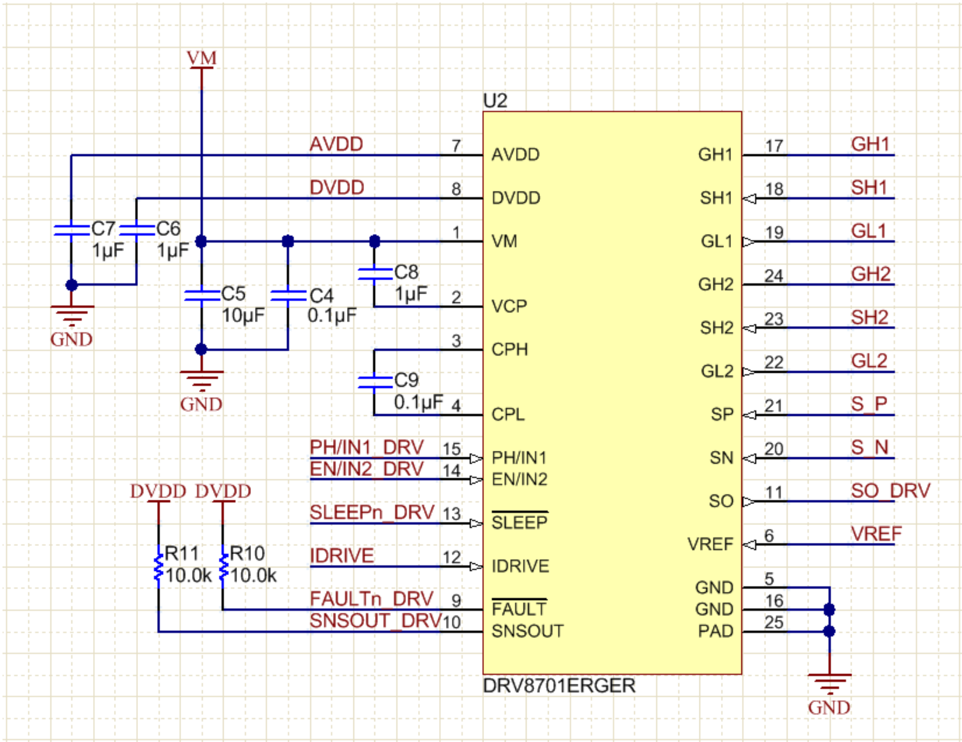


Figure 12. DRV8701 Schematic

4.7 MSP430G2553

Shown below in **Figure 13** is the schematic for the MSP430G2553 placement. Two capacitors are placed on the power pin DVCC_MSP to allow for adequate transiant filtering prior to the input pin of the device. This allows for any sudden and momentary drop in supply voltage to be filtered out of the rail prior to being supplied to the MSP430G2553. This configuration of the device does not need to utilize any external crystal oscillators or other peripheral timing connections. The supply voltage for the MSP430G2553 is sourced from the 3.3 V LDO of the DRV8701 and the devices are connected together using a 0 Ω resistor allowing for quick disconnection of the power rail in the event that the user wants to externally power the MSP430G2553.

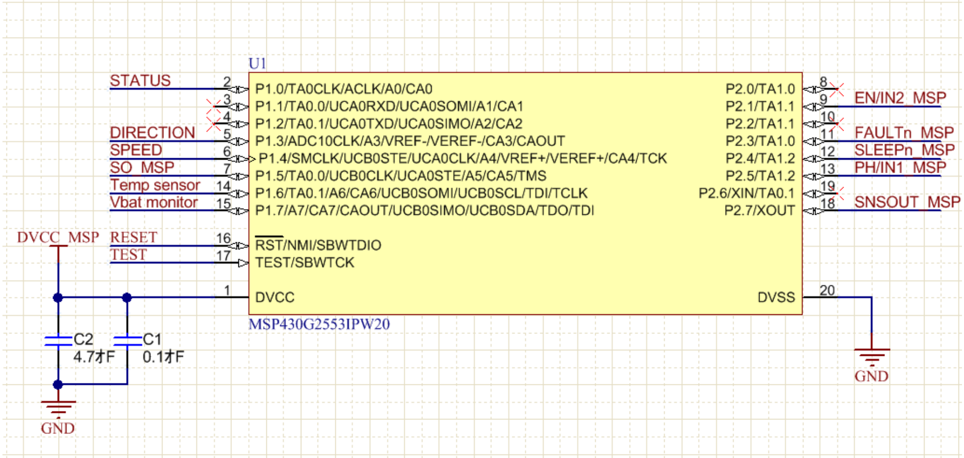


Figure 13. MSP430G2553 Schematic

4.8 R_{SENSE} Placement

Placing R_{SENSE} in an isolated position at the center of the board allows for the device to dissipate heat without harming other discrete devices in close proximity to it. The value of R_{SENSE} in this design is 5 mΩ and it is rated for 6 W. The maximum current pulled through the board during testing was 27.47 Amps, meaning this resistor dissipated 3.77 Watts during that time. R_{SENSE} ties the two low side FETs of the H-Bridge to ground so the device has to be able to sink continuous current while the motor is spinning in either direction. This continuous flow of current through the resistor results in the need for a large ground pour directly adjacent to the device to allow for an unimpeded path for current flow and adequate heat dissipation.

4.9 Bulk Capacitors

A result of using a Pulse Width Modulated scheme for motor control is sudden current draw from the supply voltage V_M. In order to compensate for this sudden change in current the bulk capacitors are placed very close to the high side voltage supply rails to help stabalize any resulting voltage sag in V_M. Stray inductance present in the supply lines will result in a slowed response in changing current which will momentarily pull down the voltage on V_M. Having the Bulk Capacitors properly placed will cushion this short period of voltage sagging.

4.10 MOSFET Selection

For this reference design the 60 Volt N-Channel NexFETs were selected because they have a relatively low R_{DS_ON} for this applications design constraints with power throughput. If the user were interested in running the board at lower power / very low current specifications and would like to achieve a much smaller footprint, the Texas Instruments 30 V N-Channel FemtoFET MOSFET could be selected. This device has an R_{DS_ON} of approximately 90 mΩ but resides in an ultra-small 0402 case footprint, which would result in a significant board reduction for a lower power solution. For a higher power solution with a larger footprint, the Texas Instruments 100 V N-Channel NexFET could be selected. This device has an R_{DS_ON} of 6.4 mΩ but can handle up to 110 Amps of continuous current at 25°C.

5 Getting Started Hardware

5.1 Control Overview

A labeled diagram of the different inputs and outputs on the TIDA-00620 board are shown below. The blue terminal blocks are used to screw down wires connecting the external power supply and motor wire leads to the contacts on the PCB board. To flash the firmware on the MSP430G2553 the SPI-Bi-Wire header can be connected to a TI Launch Pad using a 4 wire header soldered to the Launch Pad board.

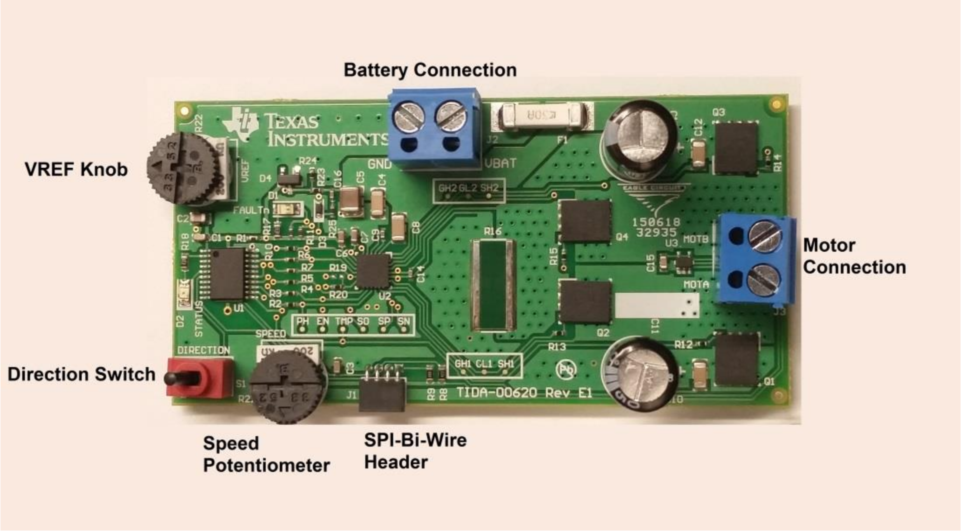


Figure 14. Labeled Board Interface

5.2 Initial Power On

This design can be operated anywhere between 12 and 24 Volts without causing any problems with the internal components. When connecting the power source to the board make sure the battery terminals are connected correctly to the VBAT (+ Battery Terminal) and GND (- Battery Terminal) correctly. Once power is applied if the MSP430G2553 has powered on and is generating control signals correctly the green status LED will turn on and stay on.

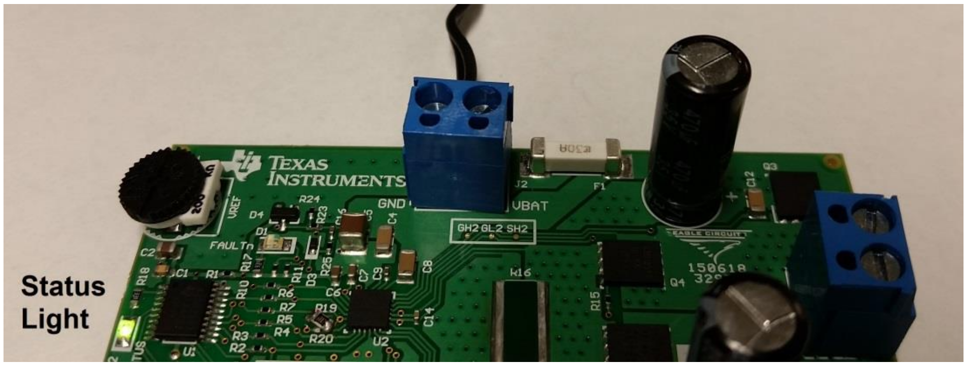


Figure 15. Status LED

5.3 Motor Connection

To connect the motor to the PCB the blue terminal block located on the right side of the board can be used to connect the motor. For this connection the wires in the terminals dictate the direction the motor will spin and the datasheet for each motor can be referenced to determine which motor terminal will result in a specific driving direction. The motor wires can be placed in each terminal using a flat head screw driver to tighten down the terminal block onto the bare wire as shown in **Figure 16** below.

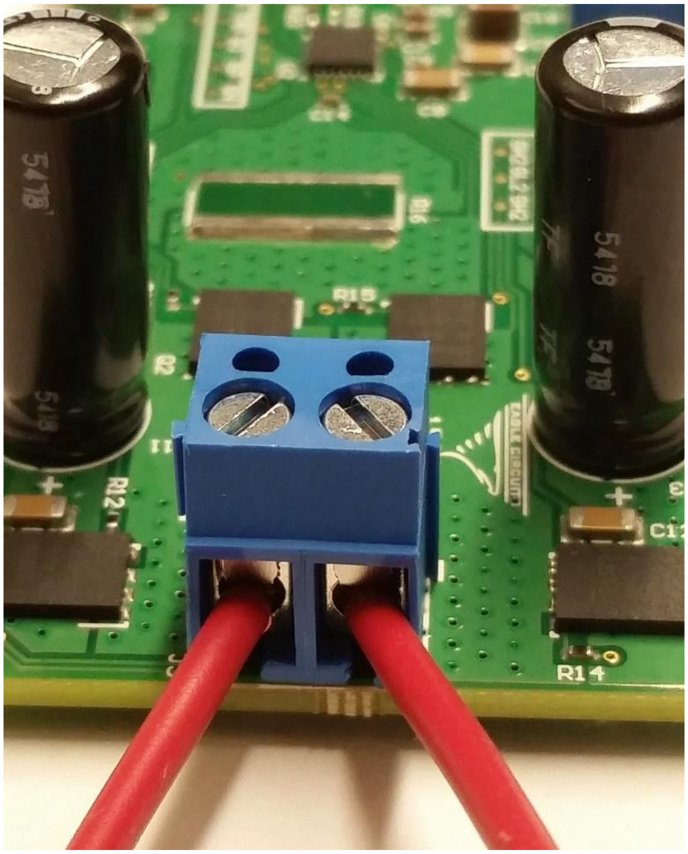


Figure 16. Motor Terminal Connections

6 Getting Started Firmware

6.1 Watch Dog Timer Control and DCO Initialization

The first thing the firmware will do upon startup is initialize global variables and function calls. The firmware will then disable the Watch Dog Timer and calibrate the Digitally Controlled Oscillator (DCO) to run at 8 MHz. This clock speed allows the MSP430G2553 to have the desired resolution / operating speed for all of the DCO sourced timers and ADC samples.

```
#include <msp430g2553.h>

int Speed;
int Temp;
int Battery_Voltage;

void Speed_Pole();
void Temp_Monitor();
void Battery_Monitor();

void main(void)
{
        WDTCTL = WDTPW + WDTHOLD;     // Stop Watch Dog Timer

        DCOCTL = CALDCO_8MHZ; // Calibrate DCO to 8 MHz as opposed to default 1 MHz
        BCSCTL1 = CALBC1_8MHZ;
```

6.2 SLEEPn Pin Pull Up

Next pin 2.4 of the MSP430G2553 is immediately initialized and pulled high. This pin is in charge of keeping the DRV8701 awake and on. When V_M is initially applied the Zener circuit shown in **Section 4.3** above will wake up the driver for a short period of time which enables the LDO to power up the MSP430. Eventually the RC time constant of the Zener circuit will drop below the required logic high voltage and the DRV8701 will go back to sleep, meaning the MSP430 must take control of this pin upon initial power up and hold it high to keep the 3.3 V LDO operating.

```
        P2DIR |= BIT4;          // Set Direction of P2.4 as output
        P2SEL &= (~BIT4);       // Set P2.4 as GPIO
        P2OUT |= BIT4;          // Set state of P2.4 to high
```

6.3 Low Power Mode Wakeup Timer

Once the sleep pin has been pulled high the firmware then enables and initializes Timer A0 which is used to wake the device up from low power mode and poll the user inputs every 1 ms. The timer is configured in Up Mode, meaning it will continuously count up to the value set in TA0CCR0. From the previously initiated DCO clock speed of 8 MHz, register TA0CCR0 is set to 8000 because it will take the microcontroller approximately 1 ms to count to that value using this clock speed. The 1 ms interrupt time is chosen for this application because this allows the microcontroller to significantly reduce its power consumption while still operating at a reasonable speed for human perception of the changes in input states.

```
TA0CCTL0 = CCIE;              // CCR0 interrupt enabled
TA0CTL = TASSEL_2 + MC_1;     // SMCLK, upmode
TA0CCR0 =  8000;              // Trigger interrupt once every 1 ms (8000 / 8MHz = 1ms)
P1OUT &= 0x00;                // Clear Registers
P1DIR &= 0x00;
```

6.4 Pin Initializations

With the system crucial pins and timers set the device now enters into initializing the desired GPIO pins for setting the states of the various inputs and outputs. These include the speed potentiometer, direction switch, FAULTn pin, Phase pin, Enable pin, Temperature sensor, and Battery Monitor.

```
P1DIR &= (~BIT3);     // Set Direction of P1.3
P1SEL &= (~BIT3);     // Set P1.3 as a GPIO Pin
P2DIR|=(BIT1+BIT5);   // Set Pin 2.1 and 2.5 as outputs
P2DIR &= ~BIT3 + ~BIT7;             // Set Pin 2.3 and 2.7 as an input
P2SEL|=BIT1;          // Route TA1.1 to output pin
P2SEL &= (~BIT7)+(~BIT5)+(~BIT3);   // Set Pin 2.7, 2.5, 2.3 as GPIO
P2REN |= BIT3 + BIT7;         // Assign Pull Up Resistor to P2.3 and P2.7
```

6.5 PWM Timer Control

In order to control the speed the motor is spinning at a PWM signal must be generated. To do this the MSP430G2553 utilizes Timer_A initialized to run in Up Mode where the timer will continuously count from 0 to the value set in register TA1CCR0 and then reset to 0. The value set in the TA1CCR0 register is 255, which results in a switching frequency of 31.372 kHz with the 8 MHz clock speed previously selected. Ideally the switching frequency selected should be greater than 20 kHz so that the PWM will not make an audible sound in the motor.

```
TA1CCR0 = 255;        // PWM Period, maximum value for Timer A1(8 MHz/255 = 31.372 kHz)
TA1CCTL1 = OUTMOD_7; // CCR1 reset/set
TA1CTL = TASSEL_2 + MC_1;     // Chooses SMCLK and Up Mode
```

6.6 Analog to Digital Converter Initialization

Once the PWM timer has been initialized the firmware then initiates the analog to digital converter connected to pin 1.4, or the V_{SPEED} connection from the Speed potentiometer. The ADC is configured to sample this voltage and convert the sample based on the 3.3 V supply voltage to the device. The result from this conversion is then stored in memory and written to the Speed variable.

```
    ADC10CTL0 = ADC10SHT_3 | ADC10ON;
    ADC10CTL1 = INCH_4;
    ADC10AE0  = BIT4;
    ADC10CTL0 |= ENC + ADC10SC;
    while (ADC10CTL1 & ADC10BUSY);
    Speed = ADC10MEM;
```

6.7 Status Light and Low Power Mode

Once all of the required timers and pins are properly configured the last thing the firmware will do in the main function is set the green LED status light to turn on. After this is completed the device then shuts off all other timers except the SMCLK which is sourced from the initial 8 MHz DCO and any general interrupts. This means that after this line in the firmware the device will simply sit and count up to TA1CCR0 for the PWM signal and TA0CCR0 where the interrupt service routine shown in **Section 6.11** begins.

```
       P1DIR |= BIT0;
       P1SEL &= (~BIT0);
       P1OUT |= BIT0;       // Set state of P1.0 to high (Status Light)

       _BIS_SR(CPUOFF + GIE);       // Enter LPM0 with interrupts
}
```

6.8 Speed_Pole Function

After initializing all of the static states of timers and pins in the MSP430G2553 the firmware then defines the Speed_Pole function. This function momentarily stops the ADC, changes the input pin to pin 1.4, takes a sample and writes that sample to the global Speed variable.

```
void Speed_Pole(void)
{

    ADC10CTL0 &= ~ENC;
    ADC10CTL1 = INCH_4;
    ADC10AE0  = BIT4;
    ADC10CTL0 |= ENC + ADC10SC;
    while (ADC10CTL1 & ADC10BUSY);
    Speed = ADC10MEM;

}
```

6.9 Battery_Monitor Function

The Battery_Monitor function is the next function to be initialized by the firmware. This function stops the ADC, changes the input pin to pin 1.7, samples the voltages and writes that value to the Battery_Voltage variable. This variable is then compared to two different values, 217 and 620. These values correspond to the voltage range available for use with this reference design and are calculated using the Battery Monitoring circuit in **Section 4.2** above. The battery voltages allowable using this function are shown in **Equation 5** and **Equation 6** below.

$$V_{BATT\_MONITOR\_LOWER} = (217 / (2^{10} - 1)) * 3.3 * 14.4 = 10.08 \text{ Volts} \quad (5)$$

$$V_{BATT\_MONITOR\_UPPER} = (620 / (2^{10} - 1)) * 3.3 * 14.4 = 28.8 \text{ Volts} \quad (6)$$

If the battery voltage for this design is dipped below 10.08 V or above 28.8 V the MSP430 will pull the SLEEPn pin of the DRV8701 low, thus disabling the 3.3 V LDO and shutting down the entire control / driver system. The board can be restarted by reapplying the correct voltage based on the above calculations.

```
void Battery_Monitor(void)
{

    ADC10CTL0 &= ~ENC;
    ADC10CTL1 = INCH_7;
    ADC10AE0  = BIT7;
    ADC10CTL0 |= ENC + ADC10SC;
    while (ADC10CTL1 & ADC10BUSY);
    Battery_Voltage = ADC10MEM;

        if (Battery_Voltage < 217 || Battery_Voltage > 620){
                P2OUT &= ~BIT4;       // Set state of P2.4 to low, putting DRV8701 to sleep
        }
        else{
        }
}
```

6.10 Temp_Monitor Function

The last function that is initialized in the firmware is the Temp_Monitor function. This function stops the ADC and reconfigures it to sample from pin 1.6. The value converted from pin 1.6 is then written to the Temp variable and compared to a static amount of 202. The 202 value corresponds to a voltage amount of 651.16 mV, which using the temperature tables found in the LMT86DCKT datasheet is approximately 130° C measured at the temperature sensor. If the voltage drops below this value that means the sensor is greater than 130° C so the firmware then writes a zero to the speed variable which will cause the PWM signal sent to the driver to stop until the temperature sensor has dropped below this temperature.

```
void Temp_Monitor(void)
{
    ADC10CTL0 &= ~ENC;
    ADC10CTL1 = INCH_6;
    ADC10AE0  = BIT6;
    ADC10CTL0 |= ENC + ADC10SC;
    while (ADC10CTL1 & ADC10BUSY);
    Temp = ADC10MEM;

       if (Temp < 202) {
               Speed=0;
       }
       else{
       }
}
```

6.11 Timer A Interrupt Service Routine

Once Timer A has reached the value stored in TA0CCR0 an interrupt service routine is entered and the MSP430G2553 will awake from low power mode. In this interrupt service routine the Direction pin (P1.3) is poled and if it is high the MSP430 sets the state of the Phase pin (P2.5) to be high and if P1.3 is low, P2.5 is set low. In this service routine the three functions defined above are called and the value stored in the Speed variable is normalized to fit in the 8 Bit TA1CCR1 register. Once these processes are completed the interrupt service routine is complete and the MSP430G2553 goes back into low power mode.

```
#pragma vector=TIMER0_A0_VECTOR
__interrupt void Timer_A (void)
{

       if((P1IN & BIT3) == BIT3){    // If P1.3 is pulled high then pull Pin 2.5 high
               P2OUT |= BIT5;        // Set State of Pin 2.5 as high
       }
       else{                         // If P1.3 is initially pulled low then pull Pin 2.5 low
               P2OUT &= (~BIT5);     // Set state of Pin 2.5 as low
       }
       Battery_Monitor();
       Speed_Pole();
       Temp_Monitor();
       TA1CCR1 = (Speed/4);  // Normalize 10BitADC Speed Value to 8Bit Timer A Register and
                             // write to TA1CCR1 Register

}
```

7 Test Setup

7.1 Block Diagram of Load Testing

The load test determines the thermal characteristics and current carrying capabilities of this designs power stage. **Figure 17** shows the load testing setup used for this reference design.

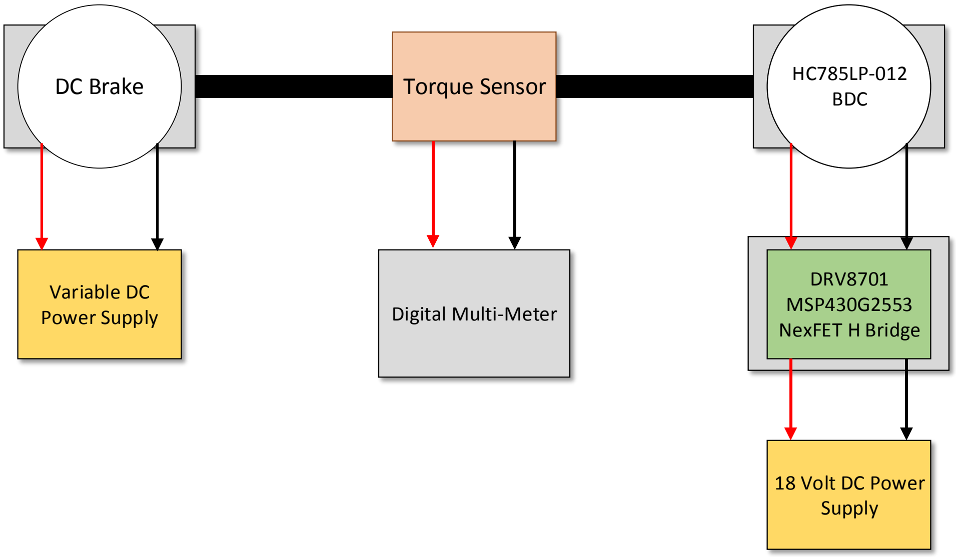


Figure 17. Load Test Diagram

The motor shaft is connected to a DC brake through a torque sensor. The brushed DC Motor is rated to deliver a shaft torque of 148.10 mNm at 19.99 Amps and 18310 RPM. The motor is loaded by means of a DC brake controlled by a variable DC supply. The speed of the motor is kept constant and the voltage supplied to the variable DC brake was incrementally increased to adjust the load needed to be produced by the DC motor. The motor supply current was incremented in 1 Amp intervals and the resulting torque reading from the torque sensor as well as maximum PCB temperature measured using a thermal camera were recorded. The RMS power delivered to the motor was also recorded by measuring the RMS current supplied to the motor and multiplying that by the RMS voltage measured across the motor terminals. The supply voltage (V_M) for the driver was kept at a constant 18 Volts. No exhaust fans or heat sinks were used for the maximum PCB temperature measurements.

7.2 Load Test Fixture

For the load testing of the TIDA-00620 board an aluminum test fixture was used to hold the DC Motor, Torque Sensor, and DC Brake. The fixture had a center channel bored through the center of the aluminum block which allowed for mounting L brackets holding the motor and brake aligned with each other. The Torque sensor was mounted at an offset from this center channel to accommodate the spindle of this device to be in line with the motor and brake. Flexible couplings were then used to attach the spindle of the motor to the left torque sensor spindle and the right spindle of the torque sensor to the brake spindle. These flexible couplings allow for any slight offset in alignment to be accounted for without overly stressing the mounting brackets of each device. Each of the devices shown in **Figure 18** below were connected to a respective control device as shown in **Figure 17** in Section 7.1.

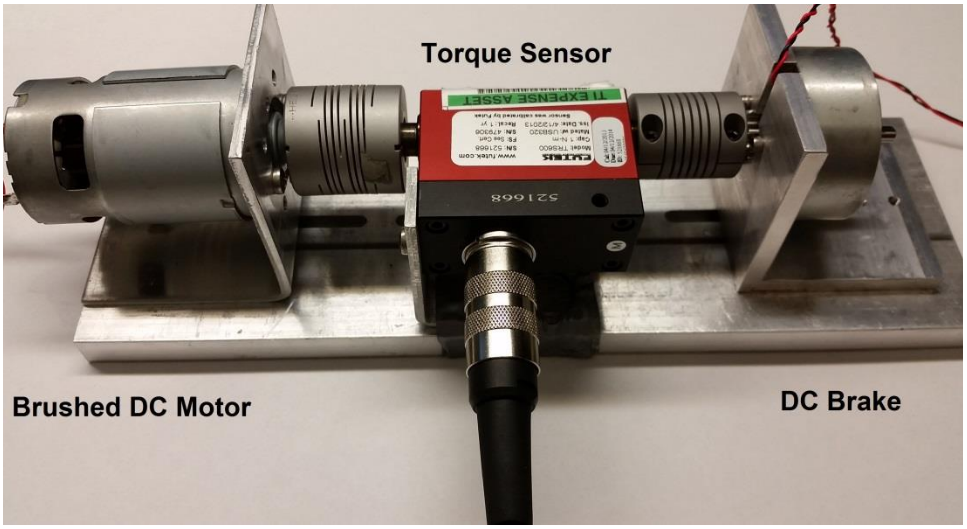
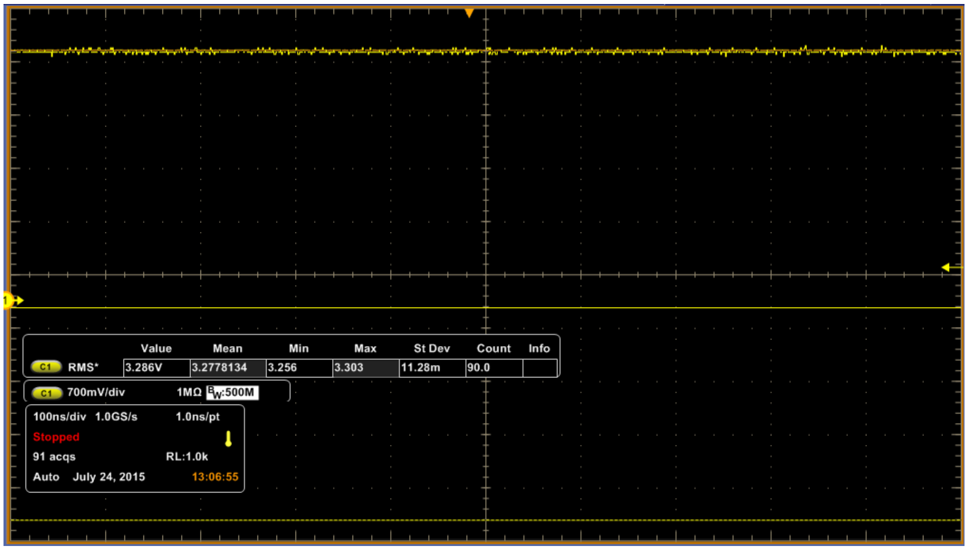


Figure 18. DC Motor / Torque Sensor / DC Brake Test Fixture

8 Test Data

8.1 DRV8701 Integrated 3.3 V and 4.8 V Low Drop-Out Regulators

Figure 19 below shows the 3.3 V generated by the onboard LDO in the DRV8701 connected to DVDD pin. **Figure 20** shows the 4.8 V genereated by the second onboard LDO in the DRV8701 connected to AVDD pin.

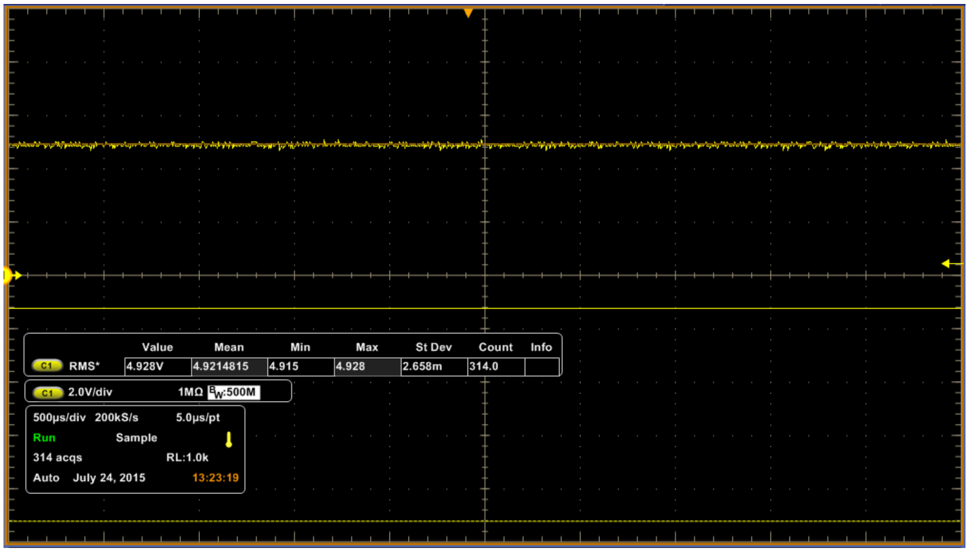


	Value	Mean	Min	Max	St Dev	Count	Info
C1 RMS*	3.286V	3.2778134	3.256	3.303	11.28m	90.0	

C1 700mV/div 1MΩ BW:500M

100ns/div 1.0GS/s 1.0ns/pt
Stopped
91 acqs RL:1.0k
Auto July 24, 2015 13:06:55

Figure 19. LDO Output Voltage of 3.3 V



	Value	Mean	Min	Max	St Dev	Count	Info
C1 RMS*	4.928V	4.9214815	4.915	4.928	2.658m	314.0	

C1 2.0V/div 1MΩ BW:500M

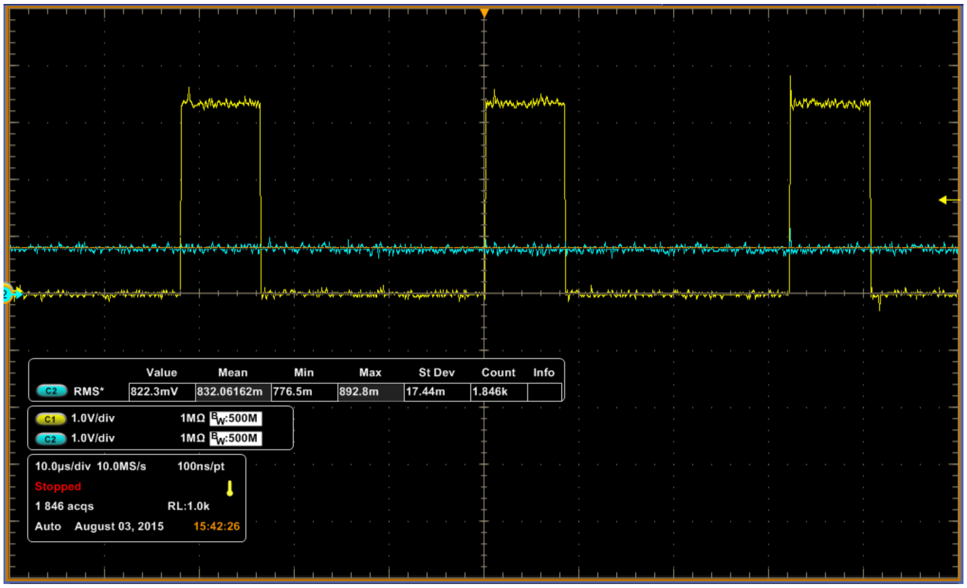
500µs/div 200kS/s 5.0µs/pt
Run Sample
314 acqs RL:1.0k
Auto July 24, 2015 13:23:19

Figure 20. LDO Output Voltage of 4.8 V

8.2 PWM Speed Control Using V_{SPEED} Reference

To Control the speed of the motor a PWM signal is generated by the MSP430G2553 based on the voltage level set by the SPEED potentiometer (V_{SPEED}) connected between DVDD and Ground. The wiper pin of the potentiometer is sampled and compared to TIMER_A of the MSP430. While the sampled V_{SPEED} is greater than the timer value the PWM output is high and while it is less than the timer the PWM output is low. The result is a varying duty cycle of the PWM signal based on the voltage measured at the speed potentiometer. The duty cycle of the PWM signal can be calculated using **Equation 7** below:

$$\%\_Duty\_Cycle = (V_{SPEED}/DVDD)*100 \qquad \textbf{(7)}$$

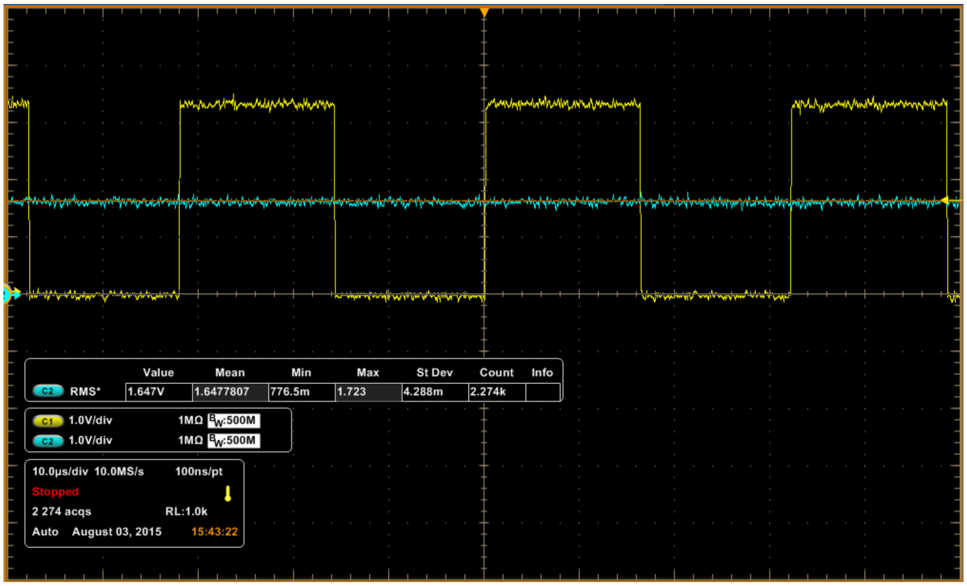


	Value	Mean	Min	Max	St Dev	Count	Info
C2 RMS*	822.3mV	832.06162m	776.5m	892.8m	17.44m	1.846k	

C1 1.0V/div 1MΩ B_W:500M
C2 1.0V/div 1MΩ B_W:500M

10.0µs/div 10.0MS/s 100ns/pt
Stopped
1 846 acqs RL:1.0k
Auto August 03, 2015 15:42:26

Figure 21. Resulting PWM Output with V_{SPEED} = 822 mV

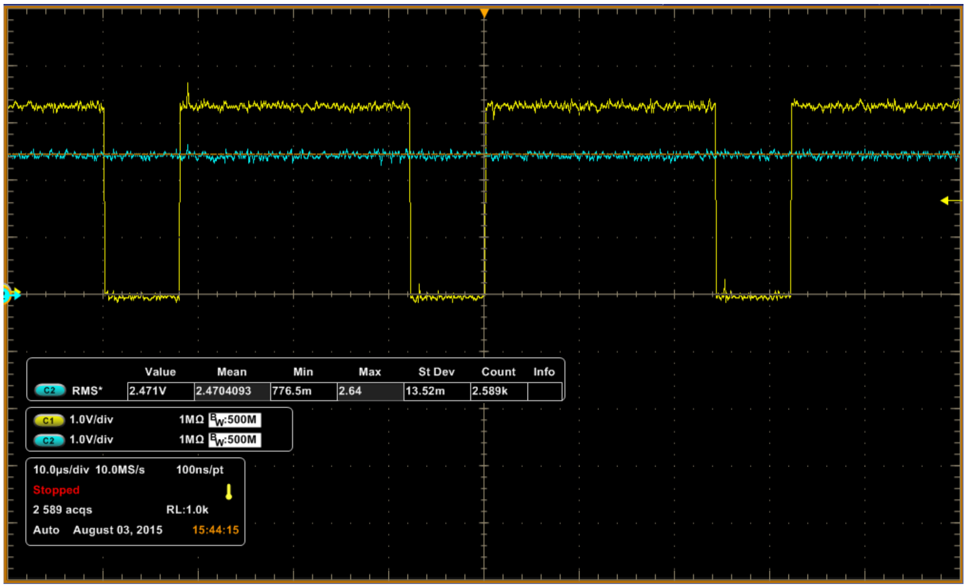


	Value	Mean	Min	Max	St Dev	Count	Info
C2 RMS*	1.647V	1.6477807	776.5m	1.723	4.288m	2.274k	

C1 1.0V/div 1MΩ B_W:500M
C2 1.0V/div 1MΩ B_W:500M

10.0µs/div 10.0MS/s 100ns/pt
Stopped
2 274 acqs RL:1.0k
Auto August 03, 2015 15:43:22

Figure 22. Resulting PWM Output with V_{SPEED} = 1.647 V



	Value	Mean	Min	Max	St Dev	Count	Info
C2 RMS*	2.471V	2.4704093	776.5m	2.64	13.52m	2.589k	

C1 1.0V/div 1MΩ BW:500M
C2 1.0V/div 1MΩ BW:500M

10.0µs/div 10.0MS/s 100ns/pt
Stopped
2 589 acqs RL:1.0k
Auto August 03, 2015 15:44:15

Figure 23. Resulting PWM Output with V_{SPEED} = 2.471 V

8.3 Inserted Dead Time

Figure 24 shows the low side and high side gate signals from the same leg of the external H-Bridge . When the high side MOSFET is not active the low side MOSFET turns on to recirculate current through the motor and the other low side MOSFET which is also held on. In order to prevent shoot through on the same side of the bridge 380 ns of dead time is forcibly inserted by the DRV8701 as shown in **Figure 25**.

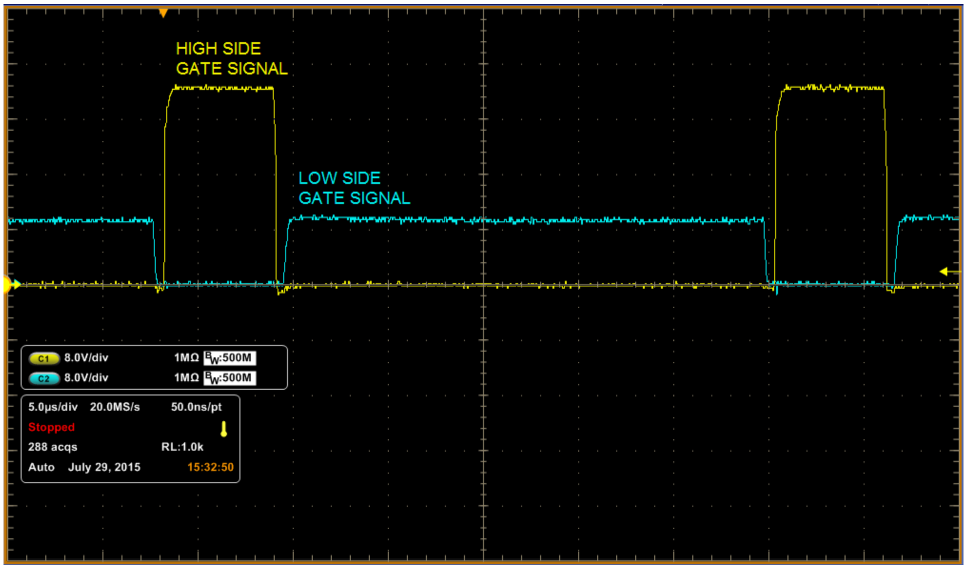


Figure 24. Complimentary High Side and Low Side Gate Signals

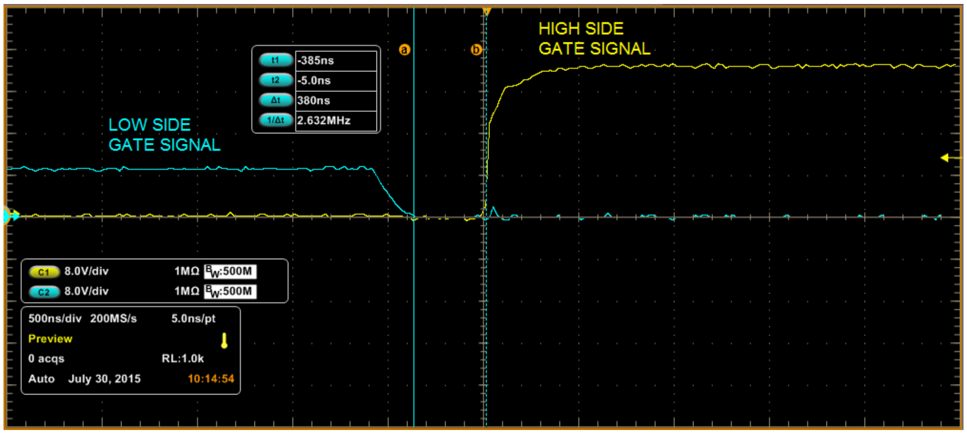


Figure 25. DRV8701 Inserted 380 ns Dead Time

8.4 Direction Pin De-bounce

One of the added benefits of using the MSP430G2553 as a control interface is the ability to debounce the phase switch input by periodically polling the state of the switch as opposed to constantly sampling. Instead of a short period of voltage chopping the state of the phase pin can be changed smoothly and quickly, as illustrated in **Figure 26** below.

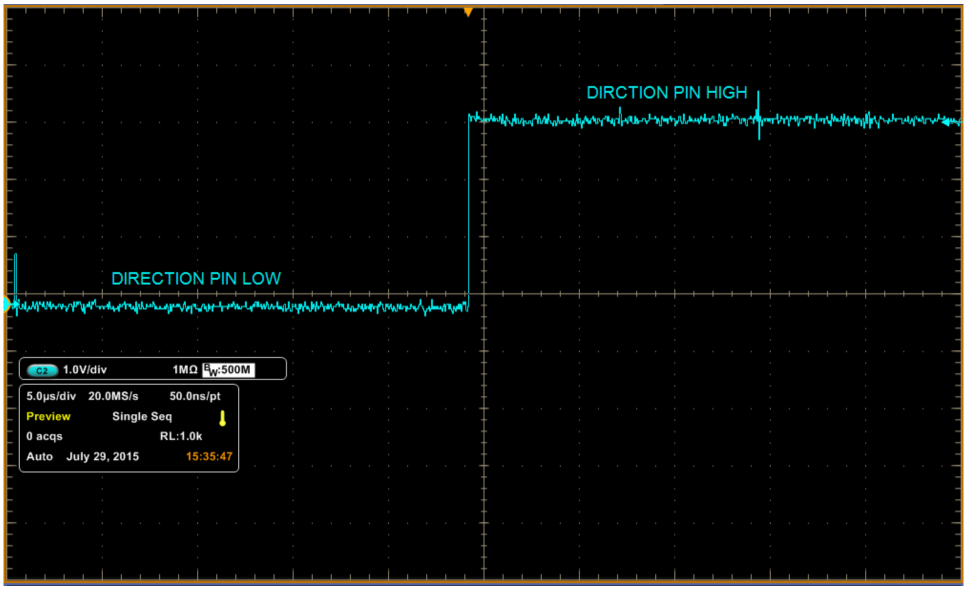


Figure 26. Phase State Change of MSP430G2553

8.5 Current Chopping Using V_{REF} Reference

The DRV8701 uses V_{REF} to set the value at which current chopping will occur by monitoring the voltage drop across R_{SENSE} and amplifying the voltage by a scaling factor A_V. The value of current at which chopping will begin can be calculated using **Equation 8** below:

$$I_{CHOP} = (V_{REF} - V_{OFFSET}) / (R_{SENSE} * A_V) \qquad \textbf{(8)}$$

An example of a typical startup current spike is shown in Figure 9. An example of current chopping based on a V_{REF} value of 1.07 V and the same startup condition is shown in **Figure 28**.

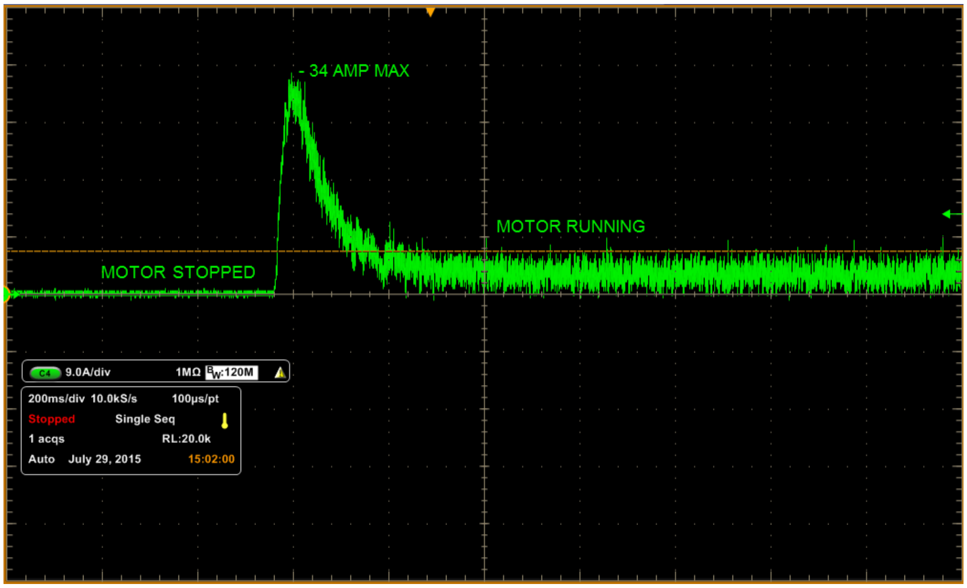
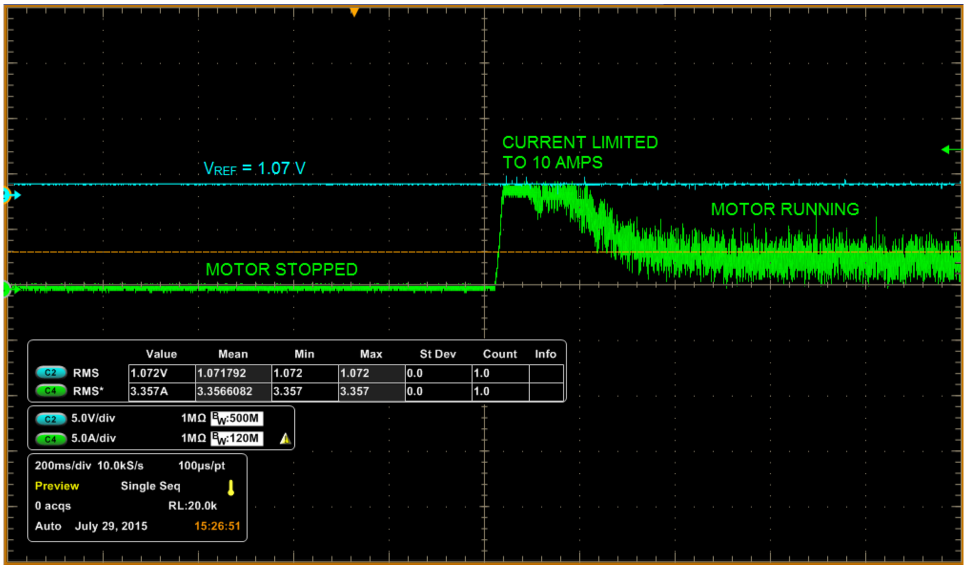


Figure 27. Startup Motor Current Spike



	Value	Mean	Min	Max	St Dev	Count	Info
C2 RMS	1.072V	1.071792	1.072	1.072	0.0	1.0	
C4 RMS*	3.357A	3.3566082	3.357	3.357	0.0	1.0	

Figure 28. Startup Motor Current With Current Chopping

8.6 Sense Amplifier Output as Motor Current Increases

The output of the sense amplifier measuring the voltage across R_{SENSE} can be viewed on the SO pin of the DRV8701. V_{SO} increases based as on the amount of time the motor is being driven for as shown in **Figure 29** below. When the output of the sense amplifier is measured to be equal to V_{REF} the DRV8701 will begin to limit the current running through the bridge until V_{SO} has dropped below V_{REF}. An example of V_{SO} increasing as the current through R_{SENSE} increases is shown **in Figure 30** below.

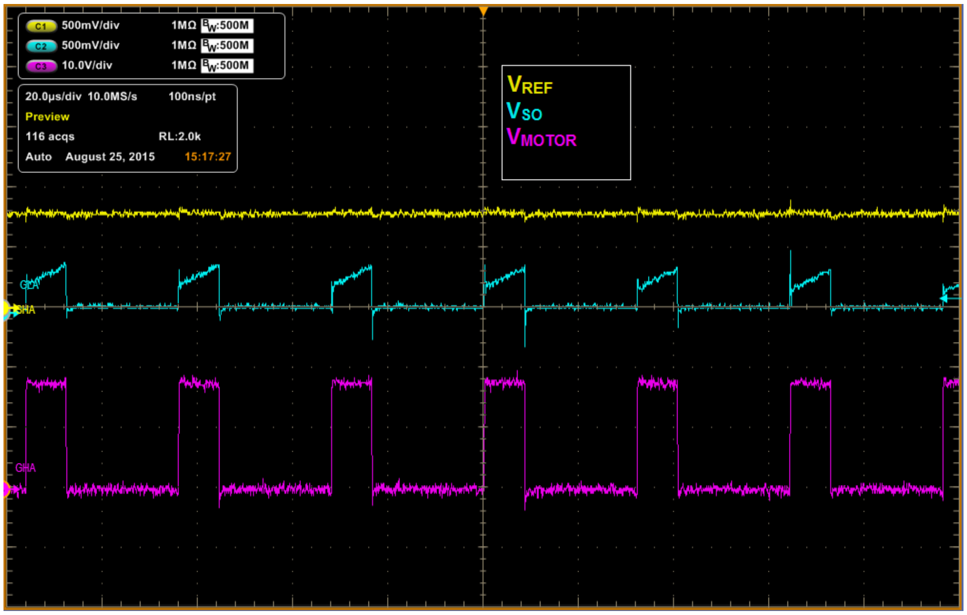


Figure 29. V_{SO} Increasing With PWM High Time

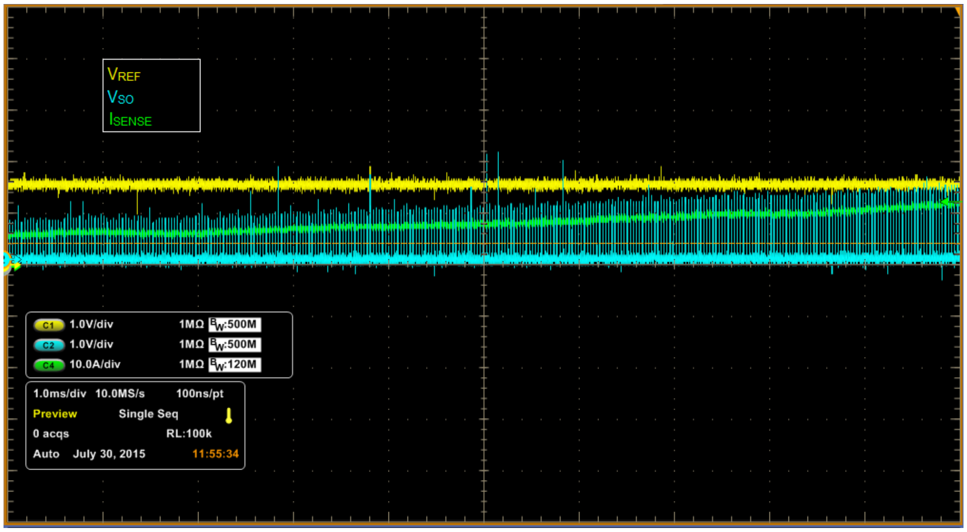


Figure 30. V_{SO} Increasing With I_{SENSE} Until V_{REF} Is Reached

8.7 Load Testing Thermal Data

Figures 31 through Figure 37 illustrate the maximum thermal point on the PCB as the current delivered to the motor was increased. The thermal images were captured in 5 Amp intervals, with the initial current delivered to the motor at 2.85 Amps and the final current delivered to the motor at 27.47 Amps. For each current interval the driver was operated for 10 seconds then shut off and allowed to cool down to room temperature (Approximately 20° C) before the next current level was tested.

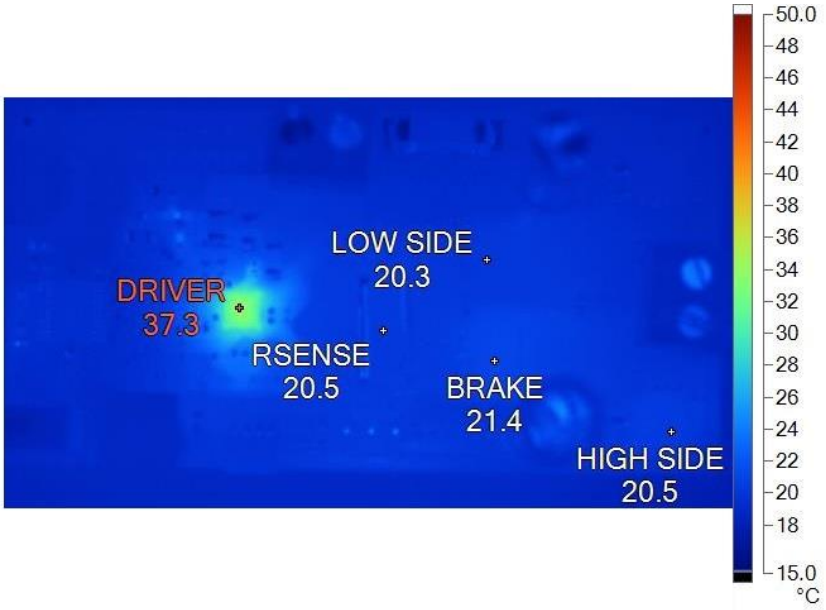


Figure 31. 2.85 Amps Continuous Current, 5.18 m-Nm Load

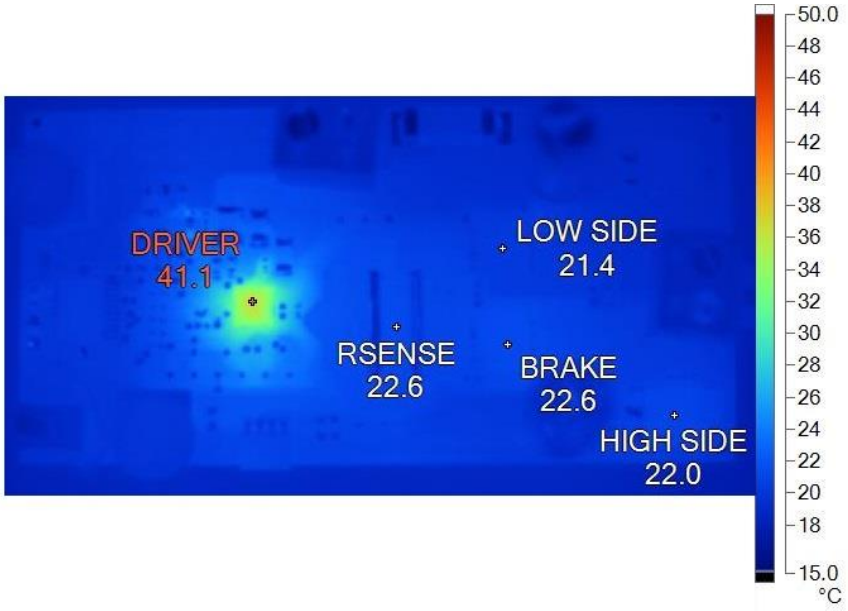


Figure 32. 5.14 Amps Continuous Current, 23.24 m-Nm Load

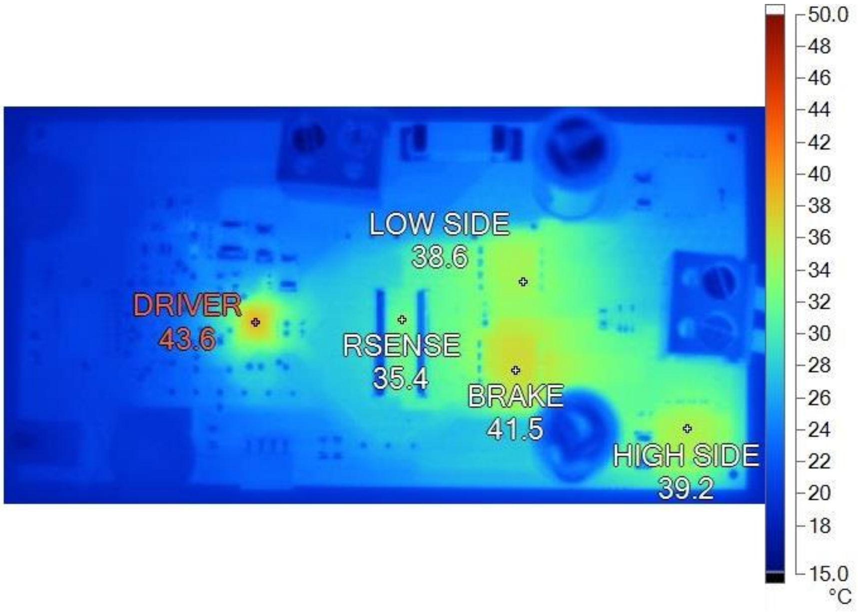


Figure 33. 10.17 Amps Continuous Current, 62.86 m-Nm Load

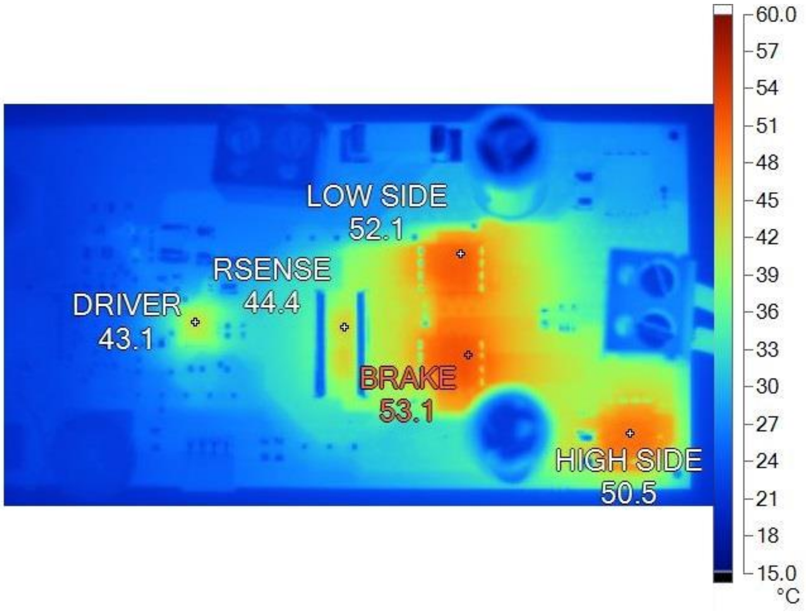


Figure 34. 15.46 Amps Continuous Current, 98.04 m-Nm Load

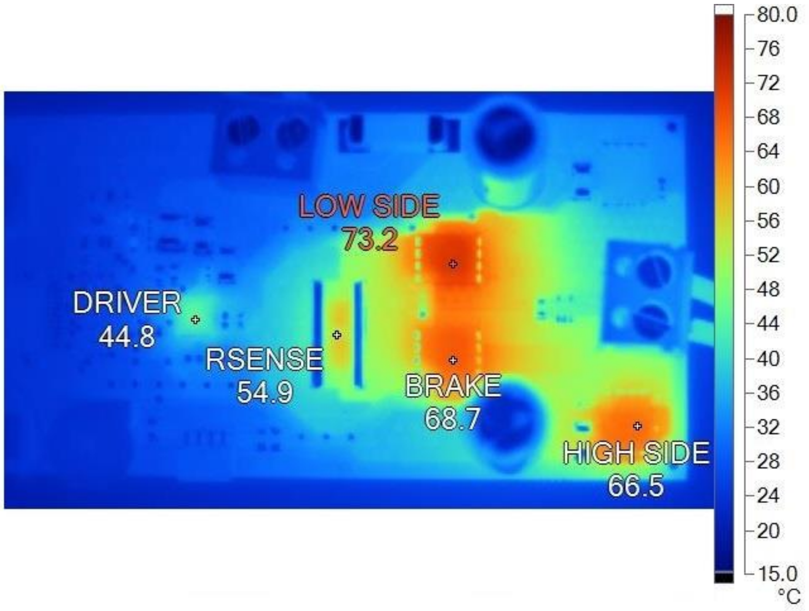


Figure 35. 20.49 Amps Continuous Current, 130.64 m-Nm Load

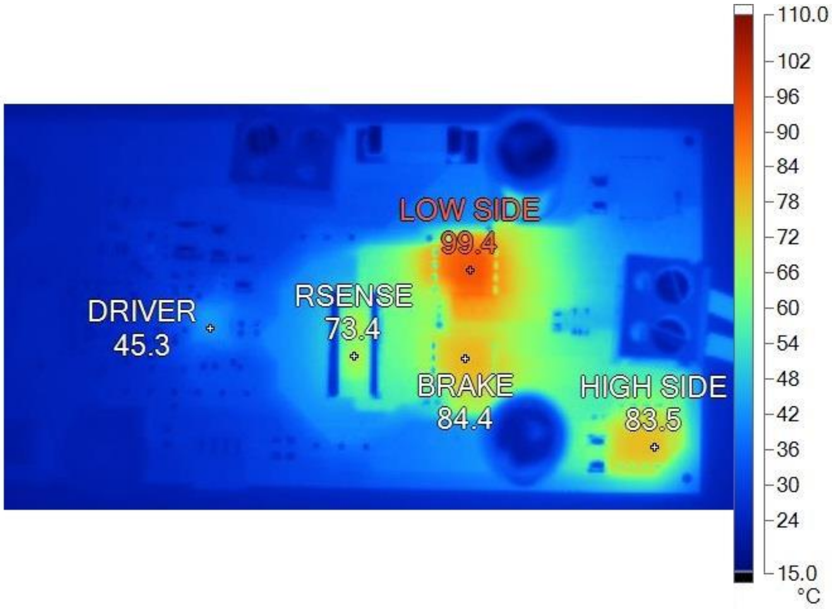


Figure 36. 25.47 Amps Continuous Current, 162.90 m-Nm Load

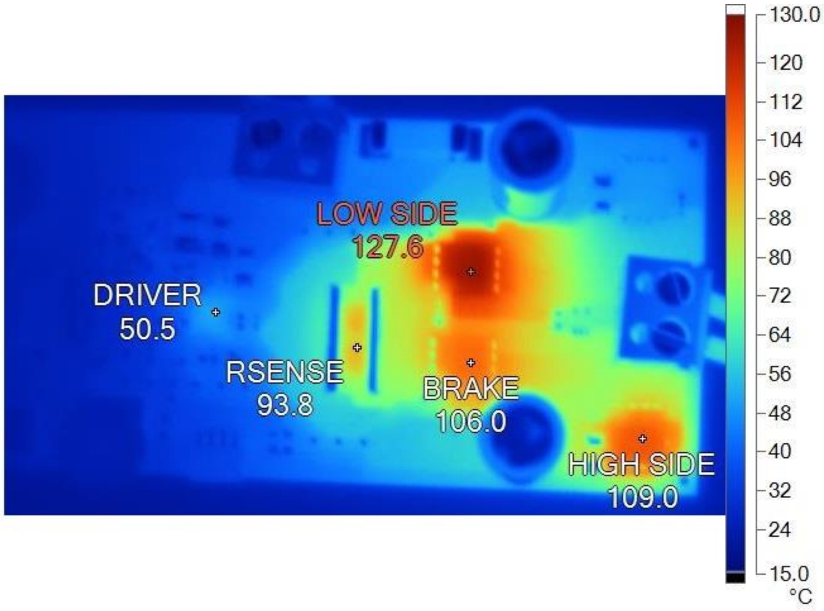


Figure 37. 27.47 Amps Continuous Current, 180.62 m-Nm Load

8.8 Temperature vs. Power Data

The RMS power delivered to the motor versus the maximum PCB temperature in degrees Celsius is shown in **Figure 38** below. The current supplied to the motor was measured using a current probe clamped to one of the cables connecting the motor to the terminal blocks of the PCB. An oscilloscope probe was then placed across the terminals of the motor and the voltage supplied to the motor was measured. Both current and voltage were measured and the RMS values were calculated for the 10 second testing interval for each torque load. To calculate the RMS power for each testing interval the equation below was used:

$$P_{RMS} = I_{RMS} * V_{RMS} \qquad \textbf{(9)}$$

The calculated RMS power in Watts versus the maximum PCB temperature in degrees Celsius for each 10 second test interval is graphed in **Figure 38** below.

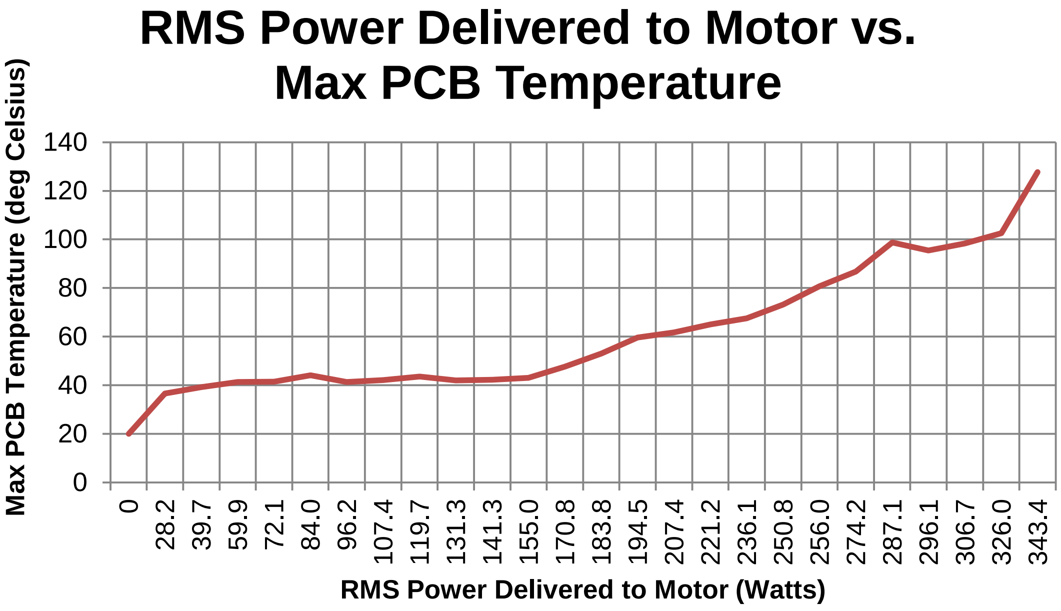


Figure 38. RMS Powered Delivered to Motor vs. Max PCB Temp

The device testing stopped at 127.6° C after the last 10 second interval because the recommended maximum temperature for operation is 125.0° C so the device was raised above this threshold for a very short period of time at the end of the last load test. If the device were to be operated at a higher power range it could safely deliver a larger power output if it the amount of time it was operated for were significantly decreased.

8.9 All Collected Load Test Data

All of the collected test data is shown in **Table 2** below. All of the data below was collected by connecting the reference design PCB to a Brushed DC Motor that spun a DC Brake and torque sensor in line with the motor shaft. The motor speed was kept constant while the torque resisting the motor turning was increased to draw more current from the power supply and through the board. For each test interval the PCB was allowed to cool down to room temperature before the load test began. This allowed for all of the thermal data to be exemplary of how the board would perform delivering the rated power amount to the motor from a startup state.

RMS Motor Voltage (Volts)	RMS Motor Current (Amps)	DC INPUT POWER (Watts)	MAX PCB TEMP (°C)	MOTOR SHAFT TORQUE (Nm)
0.00	0.00	0	0	0.000
9.90	2.85	28.25	36.6	0.005
9.89	4.01	39.66	39.2	0.020
11.66	5.14	59.93	41.3	0.023
11.71	6.16	72.13	41.5	0.031
11.67	7.20	83.98	44.1	0.038
11.80	8.15	96.21	41.3	0.046
11.79	9.11	107.43	42.1	0.054
11.77	10.17	119.70	43.6	0.063
11.83	11.10	131.31	42	0.070
11.72	12.06	141.34	42.3	0.075
11.94	12.98	154.98	43.1	0.080
12.00	14.23	170.76	47.7	0.090
11.89	15.46	183.82	53.1	0.098
11.94	16.29	194.50	59.7	0.105
11.86	17.49	207.43	61.8	0.112
11.95	18.51	221.19	65.1	0.117
12.06	19.58	236.13	67.6	0.126
12.24	20.49	250.80	73.2	0.131
11.94	21.44	255.99	80.7	0.138
11.98	22.89	274.22	86.8	0.147
12.17	23.59	287.09	98.7	0.151
12.11	24.45	296.09	95.5	0.161
12.04	25.47	306.66	98.4	0.163
12.33	26.44	326.01	102.6	0.169
12.50	27.47	343.38	127.7	0.181

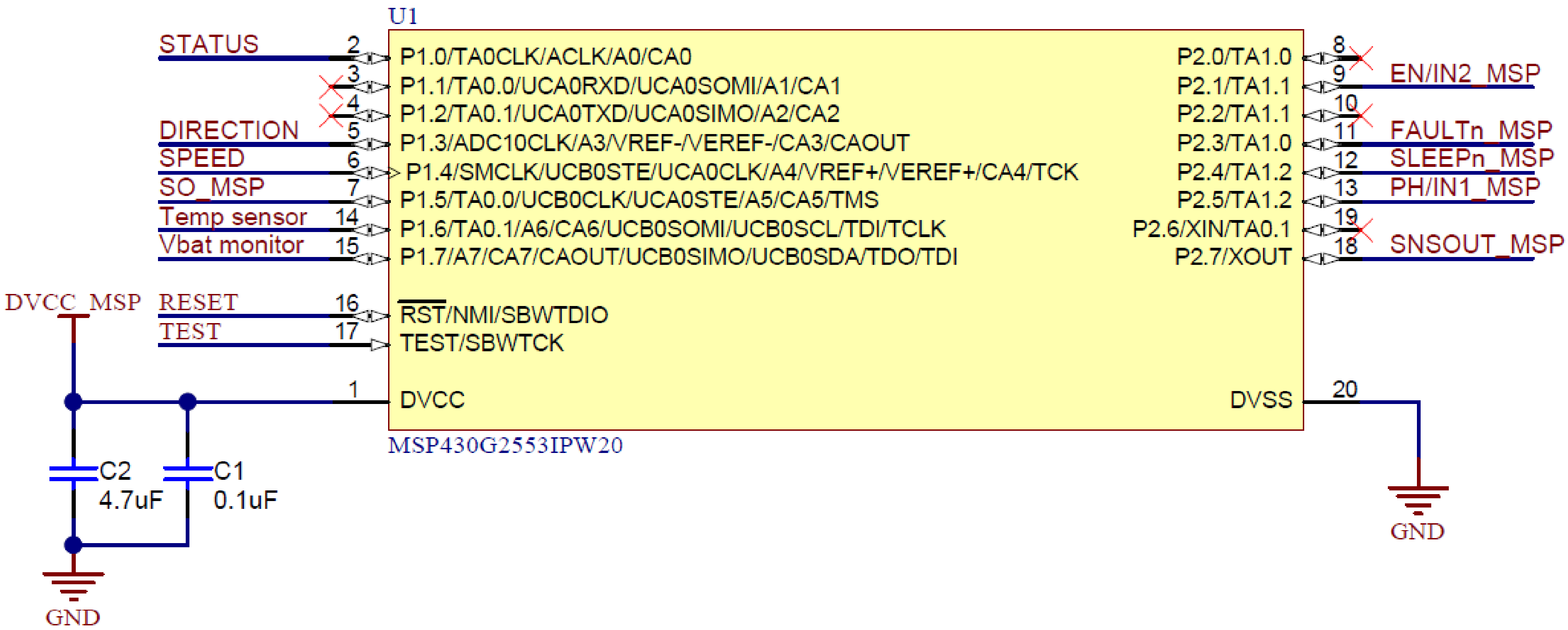
Table 2. Collected Load Test Data Between 2.85 – 27.47 A

The voltage and current delivered to the motor are represented as RMS values because the H-Bridge is supplying PWM signals to the motor, meaning a peak value for either voltage or current would only should how the supply is operating during a driving period of each PWM frame. A more realistic figure for power delivered to the motor is the RMS value which is reported showing the average power delivered over the 10 second test interval.

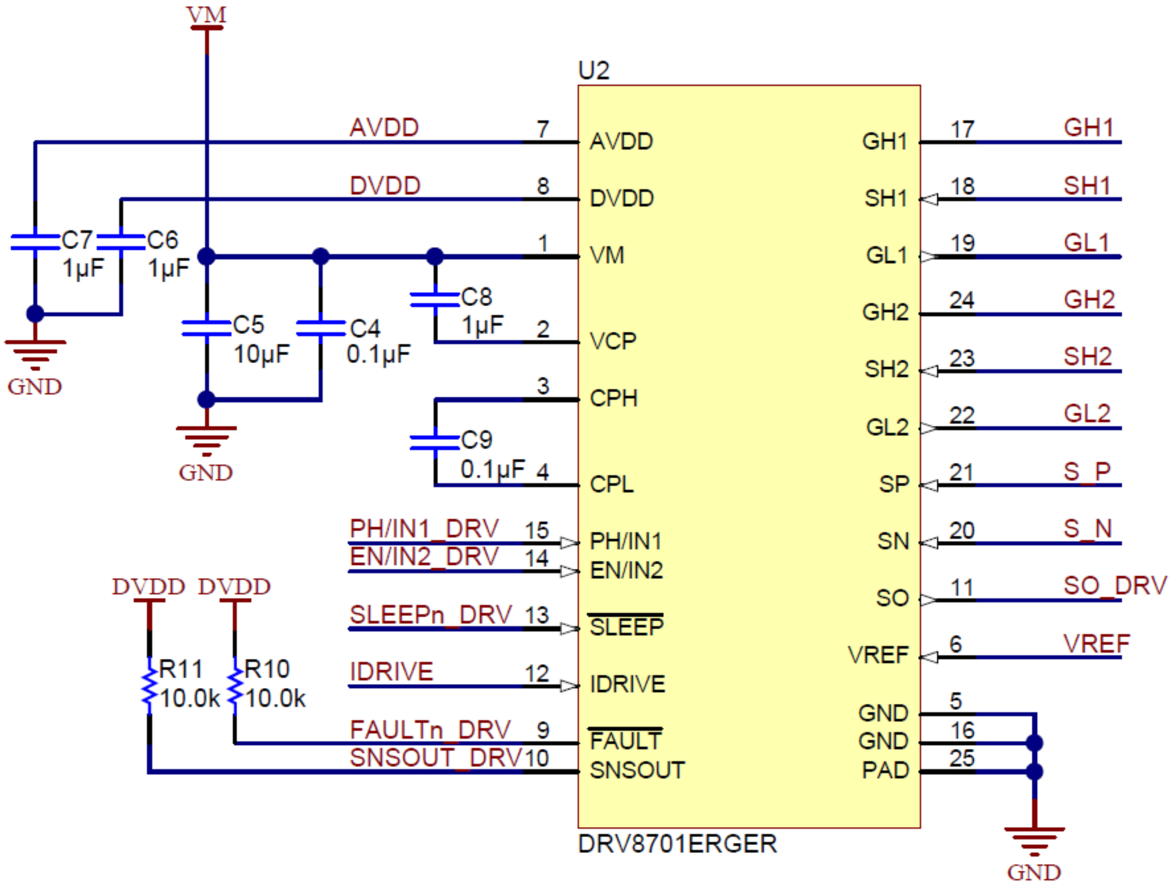
9 Design Files

9.1 Schematics

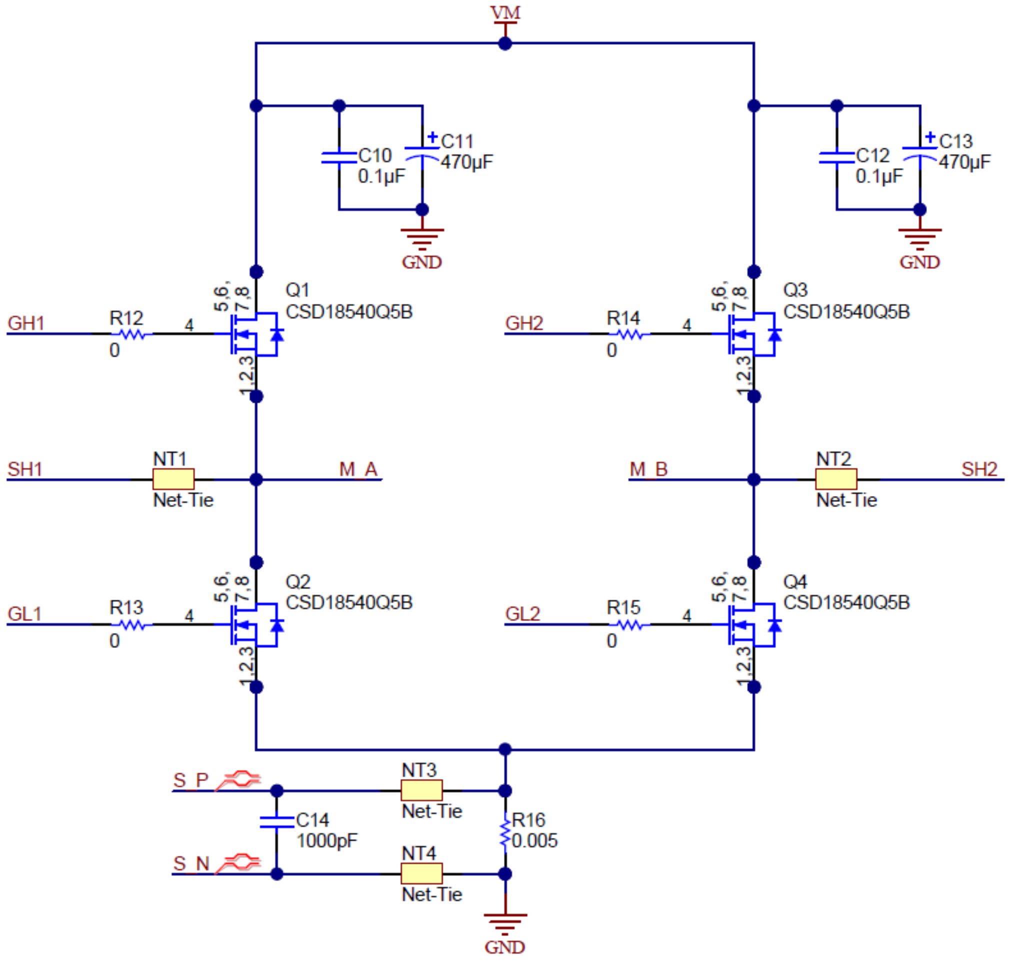
9.1.1 MSP430G2553



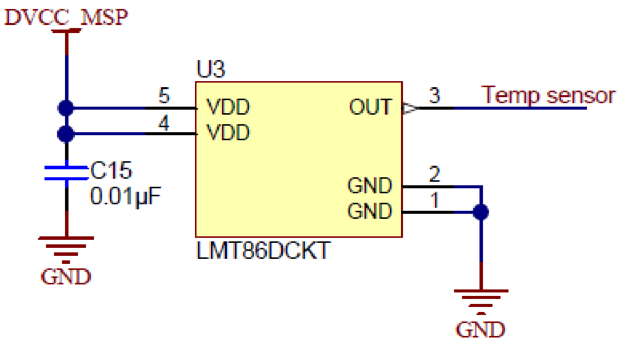
9.1.2 DRV8701

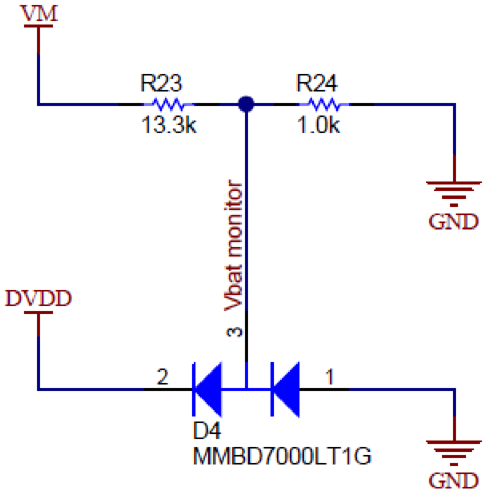

VM
U2
AVDD
DVDD
7
8
1
2
3
4
AVDD
DVDD
VM
VCP
CPH
CPL
C7
1µF
C6
1µF
C5
10µF
C4
0.1µF
C8
1µF
C9
0.1µF
GND
GND
PH/IN1_DRV
EN/IN2_DRV
15
14
PH/IN1
EN/IN2
DVDD
DVDD
SLEEPn_DRV
13
SLEEP
R11
10.0k
R10
10.0k
IDRIVE
12
IDRIVE
FAULTn_DRV
9
FAULT
SNSOUT_DRV
10
SNSOUT
DRV8701ERGER
GH1
17
GH1
SH1
18
SH1
GL1
19
GL1
GH2
24
GH2
SH2
23
SH2
GL2
22
GL2
SP
21
S_P
SN
20
S_N
SO
11
SO_DRV
VREF
6
VREF
GND
5
GND
16
PAD
25
GND

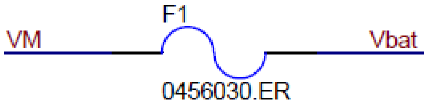
9.1.3 H-Bridge


VM
C10
0.1µF
C11
470µF
C12
0.1µF
C13
470µF
GND
GND
GH1
R12
0
4
5,6,7,8
1,2,3
Q1
CSD18540Q5B
GH2
R14
0
4
5,6,7,8
1,2,3
Q3
CSD18540Q5B
SH1
NT1
Net-Tie
M_A
M_B
NT2
Net-Tie
SH2
GL1
R13
0
4
5,6,7,8
1,2,3
Q2
CSD18540Q5B
GL2
R15
0
4
5,6,7,8
1,2,3
Q4
CSD18540Q5B
S_P
NT3
Net-Tie
C14
1000pF
R16
0.005
S_N
NT4
Net-Tie
GND

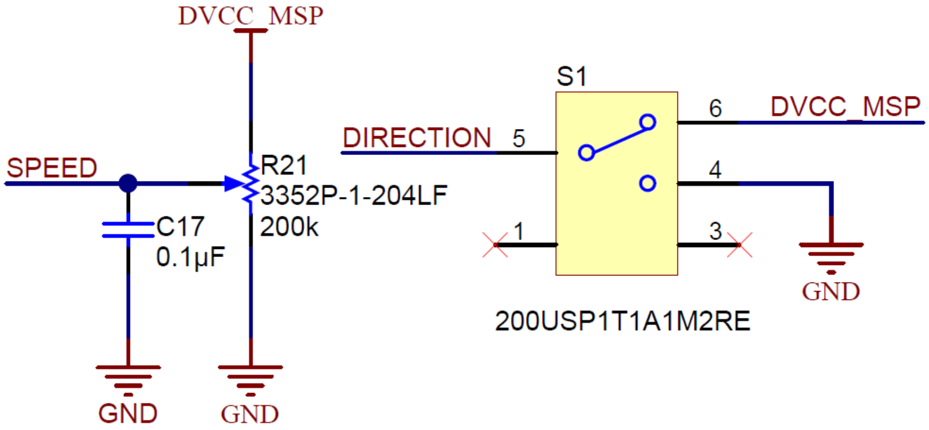
9.1.4 Protection



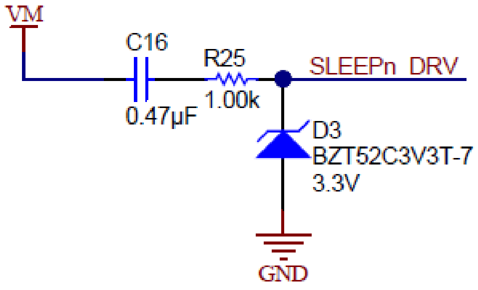




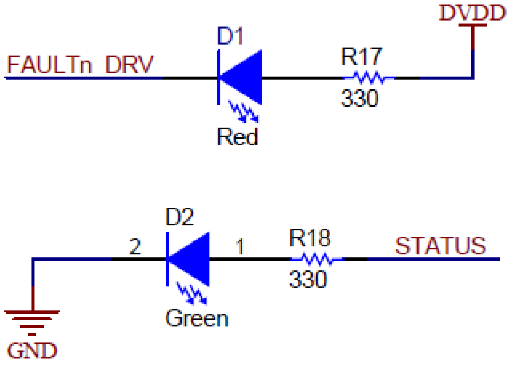
9.1.5 Speed + Direction



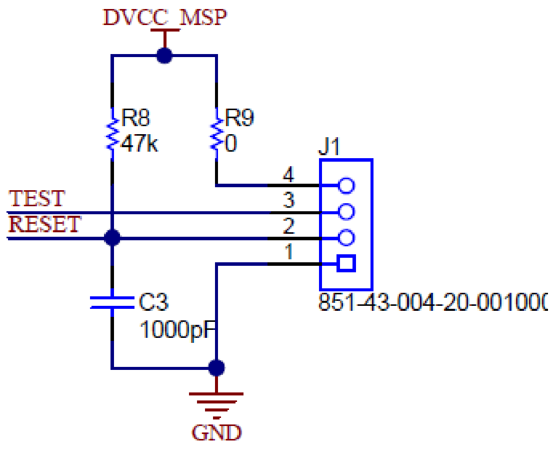
9.1.6 Sleep RC Time



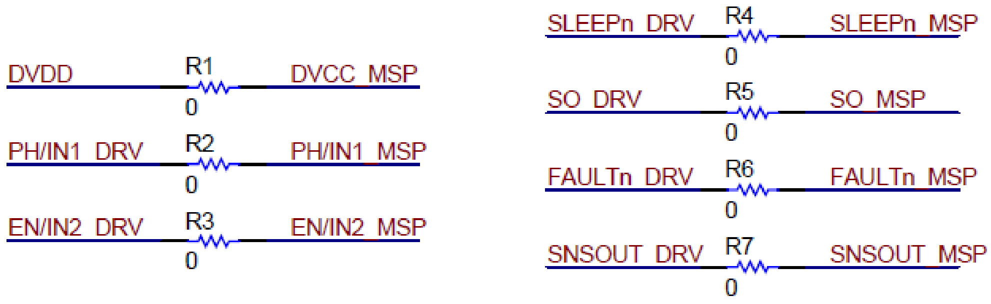
9.1.7 Fault + Status LEDs



9.1.8 SPI Header

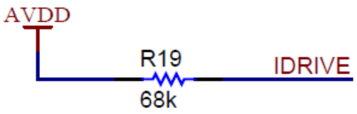


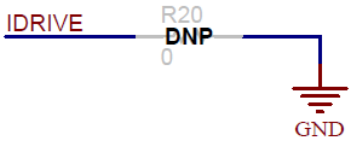
9.1.9 MSP430 – DRV8701 Connections



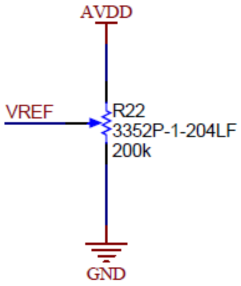
9.1.10 Terminal Block Connections

9.1.11 IDrive

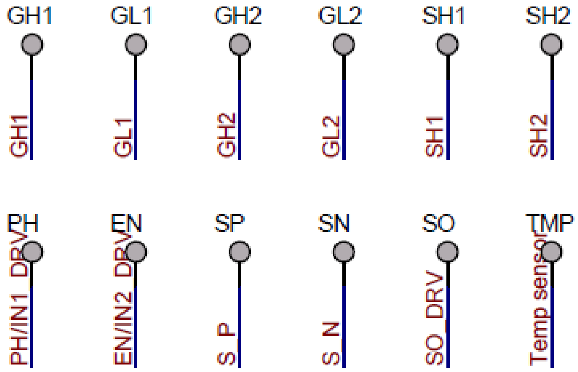




9.1.12 V_{REF} Pot



9.1.13 Test Points



9.2 Bill of Materials

TEXAS INSTRUMENTS

Bill of Materials

TIDA-00620

Item	Qty	Reference	Value	Part Description	Manufacturer	Manufacturer Part Number	PCB Footprint
1	1	!PCB		Printed Circuit Board	Any	TIDA-00620	
2	1	C1	0.1uF	CAP, CERM, 0.1uF, 10V, +/-10%, X7R, 0603	Kemet	C0603C104K8RACTU	0603
3	1	C2	4.7uF	CAP, CERM, 4.7uF, 10V, +/-20%, X7R, 0805	TDK	C2012X7R1A475M	0805
4	1	C3	1000pF	CAP, CERM, 1000pF, 16V, +/-10%, X7R, 0603	MuRata	GRM188R71C102KA01D	0603
5	3	C4, C10, C12	0.1uF	CAP, CERM, 0.1 µF, 50 V, +/-10%, X7R, 1206	MuRata	GRM319R71H104KA01D	1206
6	1	C5	10uF	CAP, CERM, 10 µF, 50 V, +/-10%, X7R, 1210	MuRata	GRM32ER71H106KA12L	1210
7	2	C6, C7	1uF	CAP, CERM, 1 µF, 6.3 V, +/-10%, X5R, 0603	MuRata	GRM188R60J105KA01D	0603
8	1	C8	1uF	CAP, CERM, 1 µF, 16 V, +/-10%, X7R, 1206	MuRata	GRM319R71C105KAA3D	1206
9	1	C9	0.1uF	CAP, CERM, 0.1 µF, 16 V, +/-10%, X7R, 0402	MuRata	GRM155R71C104KA88D	0402
10	2	C11, C13	470uF	CAP, AL, 470 µF, 35 V, +/-20%, 0.03 ohm, TH	Panasonic	EEU-FR1V471LB	RCAP, 8x20mm

11	1	C14	1000pF	CAP, CERM, 1000pF, 16V, +/-10%, X7R, 0402	MuRata	GRM155R71C102KA01D	0402
12	1	C15	0.01uF	CAP, CERM, 0.01 µF, 6.3 V, +/- 10%, X7R, 0603	MuRata	GRM188R70J103KA01D	0603
13	1	C16	0.47uF	CAP, CERM, 0.47 µF, 10 V, +/- 10%, X5R, 0402	MuRata	GRM155R61A474KE15D	0402
14	1	C17	0.1uF	CAP, CERM, 0.1 µF, 16 V, +/-10%, X7R, 0402	MuRata	GCM155R71C104KA55D	0402
15	1	D1	Red	LED, Red, SMD	Lite-On	LTST-C170KRKT	LED_0805
16	1	D2	Green	LED, Green, SMD	Lite-On	LTST-C171GKT	LED_0805
17	1	D3	3.3V	Diode, Zener, 3.3 V, 300 mW, SOD-523	Diodes Inc.	BZT52C3V3T-7	SOD-523
18	1	D4	100V	Diode, Switching, 100 V, 0.2 A, SOT-23	ON Semiconductor	MMBD7000LT1G	SOT-23
19	1	F1		Fuse, 30 A, 72 V, SMD	Littelfuse	0456030.ER	10.1x3.12mm
20	3	FID1, FID2, FID3		Fiducial mark. There is nothing to buy or mount.	N/A	N/A	Fiducial
21	1	J1		SOCKET .050" GRID SIP 4 POS R/A, TH	Mill-Max	851-43-004-20-001000	R/A 4x1 receptacle
22	2	J2, J3		Terminal Block, 5 mm, 2x1, Tin, TH	Wurth Elektronik	691 101 710 002	Terminal Block, 5 mm, 2x1, TH
23	4	Q1, Q2, Q3, Q4	60V	MOSFET, N-CH, 60 V, 28 A, SON 5x6mm	Texas Instruments	CSD18540Q5B	SON 5x6mm
24	11	R1, R2, R3, R4, R5, R6, R7, R12, R13, R14, R15	0	RES, 0, 5%, 0.063 W, 0402	Vishay-Dale	CRCW04020000Z0ED	0402
25	1	R8	47k	RES, 47k ohm, 5%, 0.1W, 0603	Vishay-Dale	CRCW060347K0JNEA	0603
26	1	R9	0	RES, 0 ohm, 5%, 0.1W, 0603	Vishay-Dale	CRCW06030000Z0EA	0603

27	2	R10, R11	10.0k	RES, 10.0 k, 1%, 0.1 W, 0402	Panasonic	ERJ-2RKF1002X	0402
28	1	R16	0.005	RES, 0.005, 1%, 6 W, 4320_WIDE	Susumu Co Ltd	KRL11050-C-R005-F-T1	4320_WIDE
29	2	R17, R18	330	RES, 330, 1%, 0.1 W, 0603	Yageo America	RC0603FR-07330RL	0603
30	2	R21, R22	200k	Trimmer, 200 K, 0.5 W, TH	Bourns	3352P-1-204LF	Thumbwheel Trimmer
31	1	R23	13.3k	RES, 13.3 k, 1%, 0.063 W, 0402	Vishay-Dale	CRCW040213K3FKED	0402
32	1	R24	1.0k	RES, 1.0 k, 5%, 0.063 W, 0402	Vishay-Dale	CRCW04021K00JNED	0402
33	1	R25	1.00k	RES, 1.00 k, 1%, 0.063 W, 0402	Vishay-Dale	CRCW04021K00FKED	0402
34	1	S1		Switch, SPDT, On-On, 2 Pos, TH	E-Switch	200USP1T1A1M2RE	Switch, 7x4.5mm
35	1	U1		16 MHz Mixed Signal Microcontroller with 16 KB Flash, 512 B SRAM and 24 GPIOs, -40 to 85 degC, 20-pin SOP (PW), Green (RoHS & no Sb/Br)	Texas Instruments	MSP430G2553IPW20	PW0020A
36	1	U2		H-Bridge Gate Driver, RGE0024F	Texas Instruments	DRV8701ERGER	RGE0024F
37	1	U3		Analog Temperature Sensors with Class-AB Output, DCK0005A	Texas Instruments	LMT86DCKT	DCK0005A
38	0	R19	68k	RES, 68 k, 5%, 0.063 W, 0402	Vishay-Dale	CRCW040268K0JNED	0402
39	0	R20	0	RES, 0, 5%, 0.063 W, 0402	Vishay-Dale	CRCW04020000Z0ED	0402

9.3 PCB Layout Recommendations

9.3.1 Layout Prints

To download the Layout Prints for each board, see the design files at http://www.ti.com/tool/DESIGNNUMBER

TOP SILKSCREEN

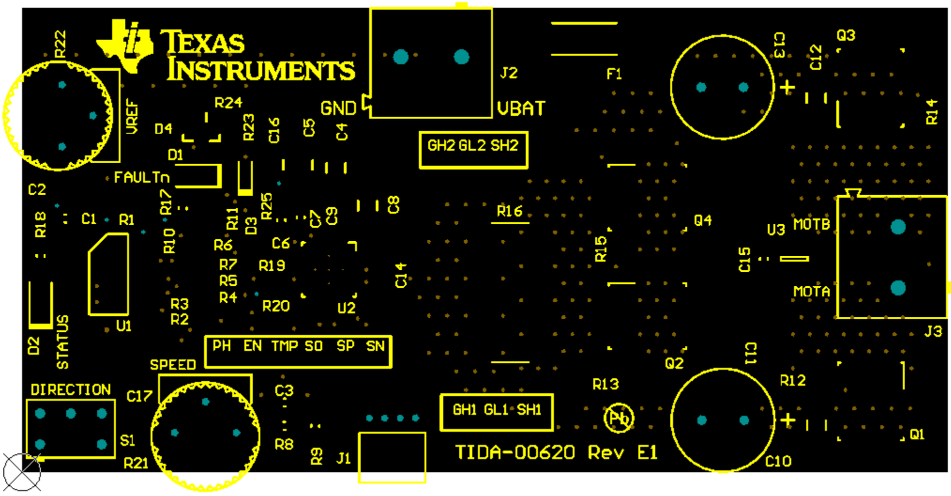


Figure 39. Top Silkscreen

TOP SOLDER MASK

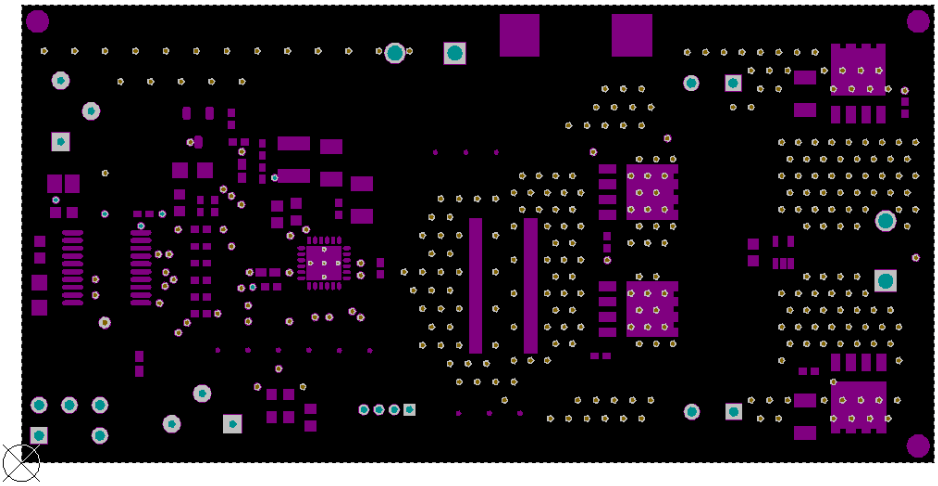


Figure 40. Top Solder Mask

TOP LAYER

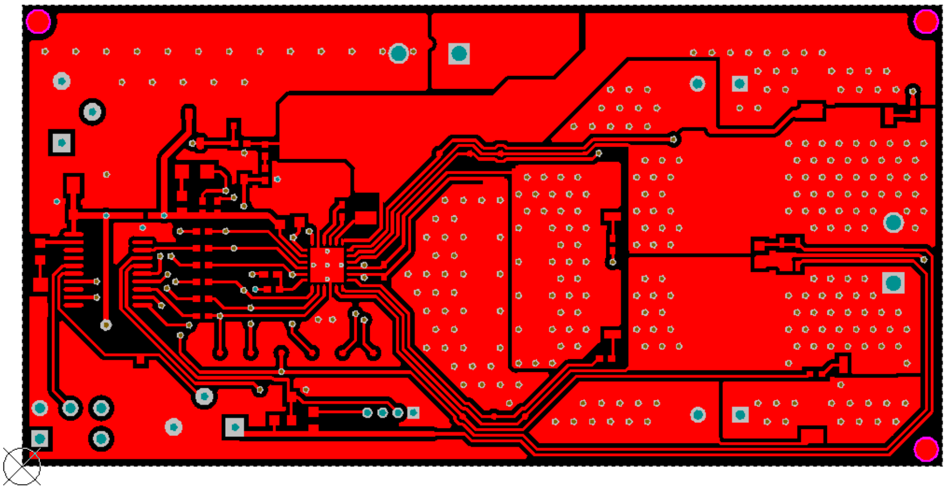


Figure 41. Top Layer

BOTTOM LAYER

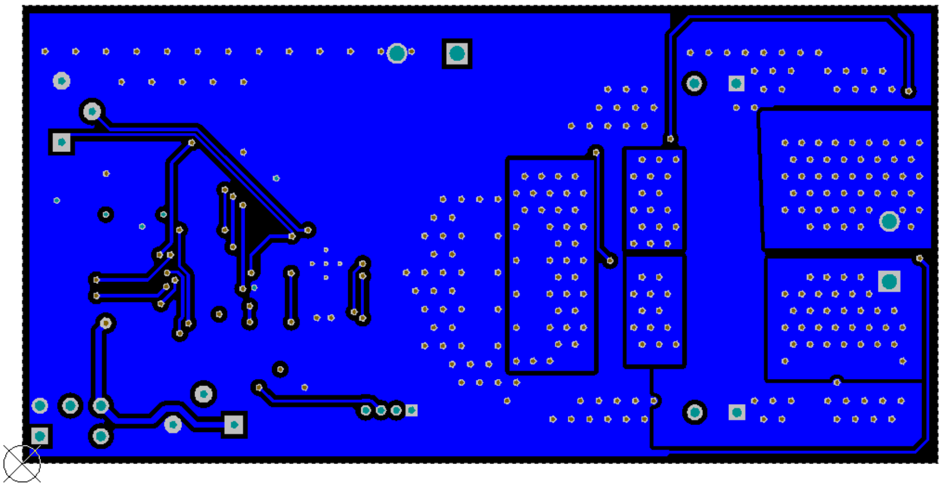


Figure 42. Bottom Layer

BOTTOM SOLDER MASK

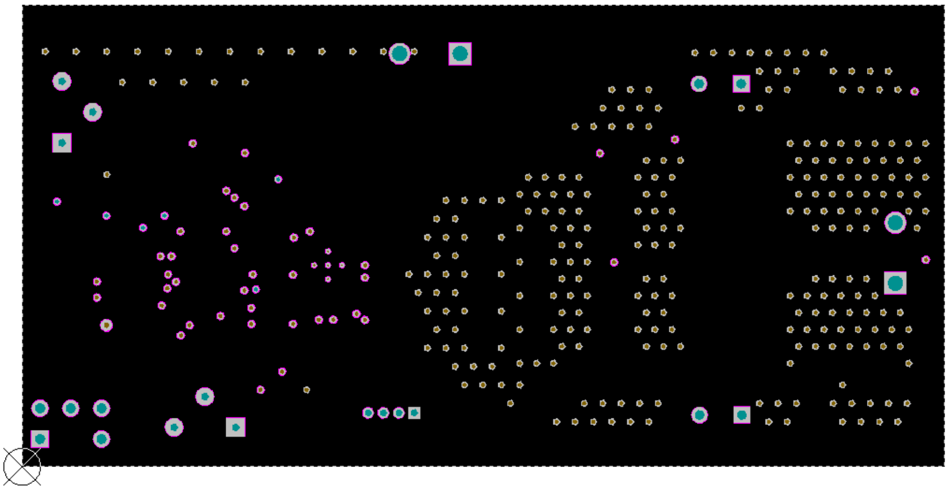


Figure 43. Bottom Solder Mask

BOTTOM SILKSCREEN

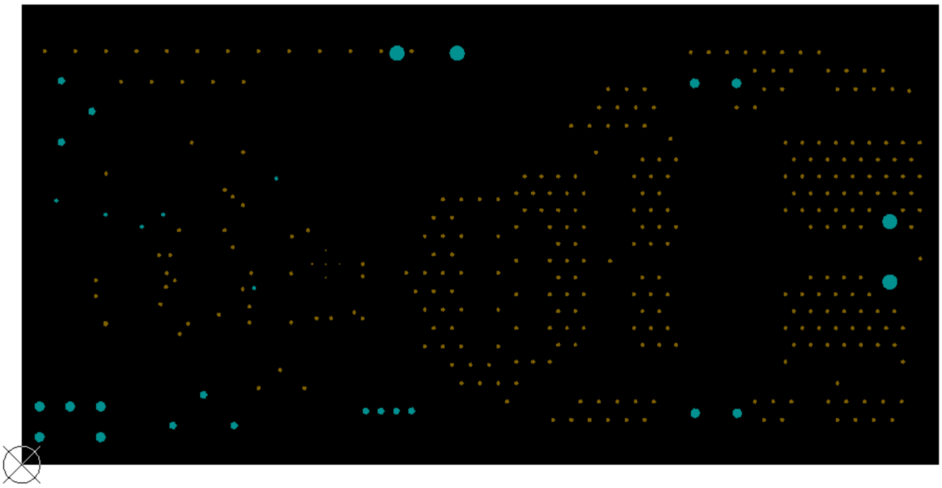


Figure 44. Bottom Silkscreen

MECHANICAL DIMENSIONS

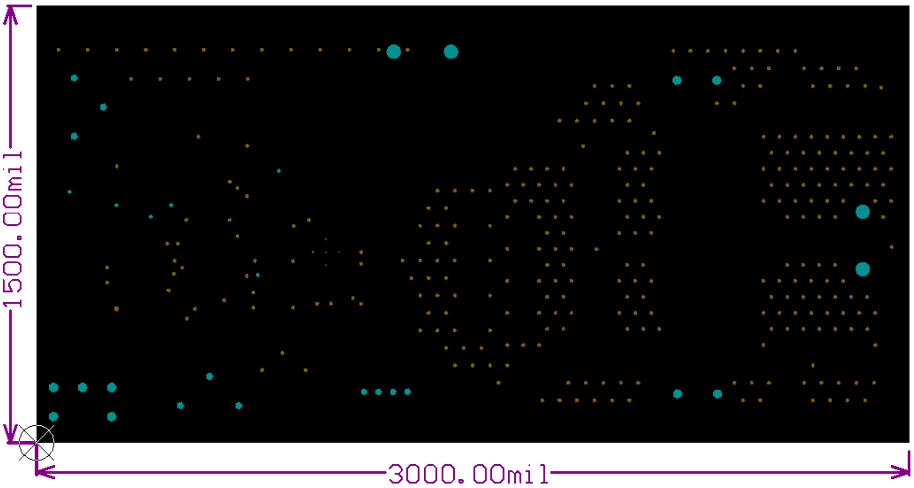


Figure 45. Mechanical Dimensions

9.4 Altium Project

To download the Altium project files for each board, see the design files at http://www.ti.com/tool/DESIGNNUMBER

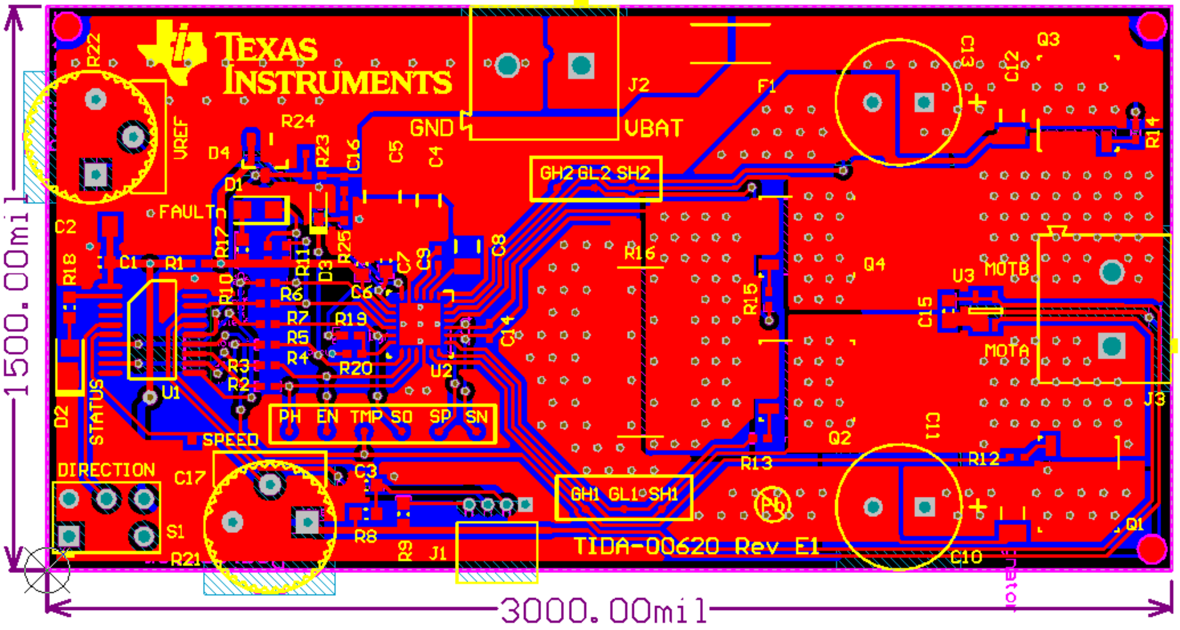
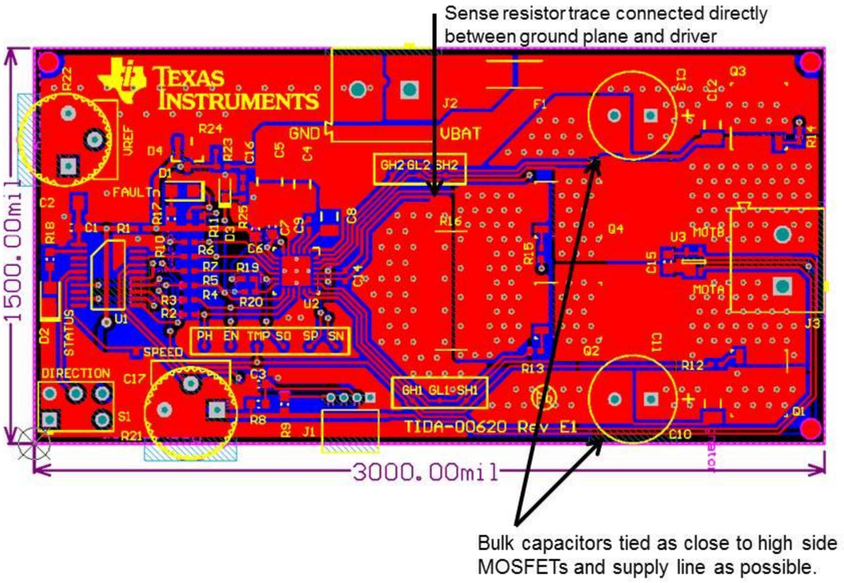


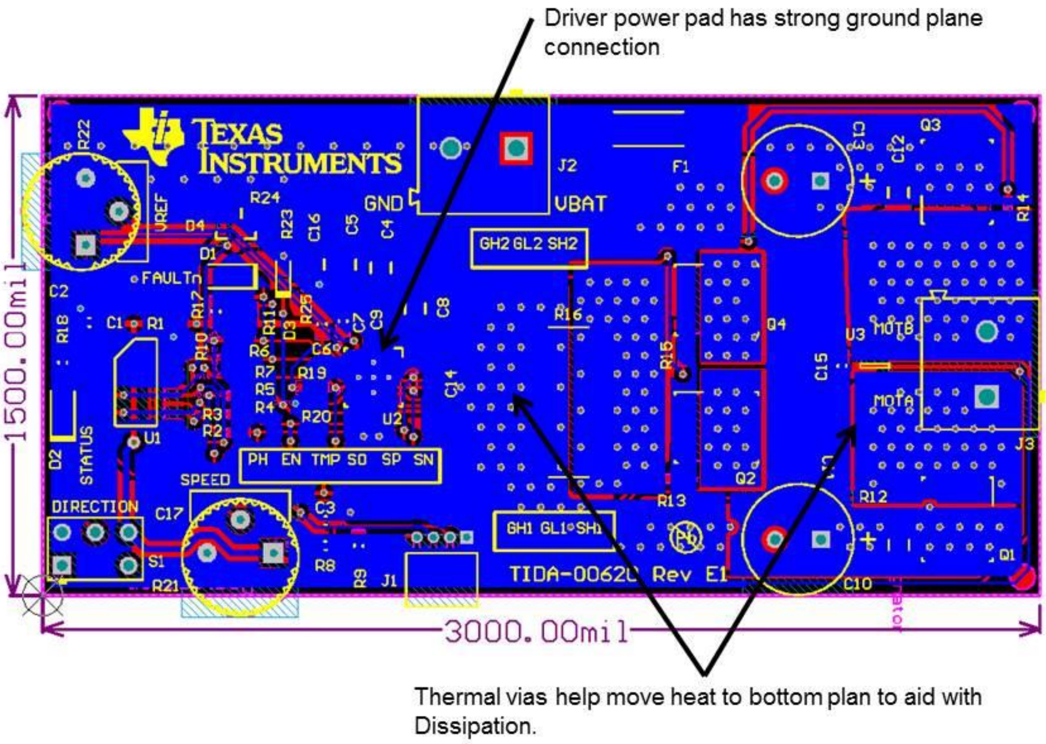
Figure 46. All Layers

9.5 Layout Guidelines


Sense resistor trace connected directly between ground plane and driver

Bulk capacitors tied as close to high side MOSFETs and supply line as possible.

Figure 47. Top Design Guide


Driver power pad has strong ground plane connection

Thermal vias help move heat to bottom plan to aid with Dissipation.

Figure 48. Bottom Design Guide

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